National Oceanic and Atmospheric Administration
U.S. Department of Commerce

Spectrum Pipeline Reallocation

1675–1680 MHz Engineering Study (SPRES)

Program Report

U.S. Department of Commerce
National Oceanic and Atmospheric Administration (NOAA)

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FOREWORD

In 2016, the Federal Communications Commission (FCC) issued a Notice of Proposed Rulemaking to consider sharing of the 1675-1680 MHz band between new commercial mobile operators and incumbent NOAA satellite operations. In January 2018, NOAA received funding under the Spectrum Pipeline Act authority to address the potential impact of spectrum sharing on its operations and awarded several task order contracts to three companies to perform the Spectrum Pipeline Reallocation Engineering Study (SPRES). The attached report (except for this overview) represents the contractors' products from those tasks.

The study identifies the Data Collection System (DCS), GOES ReBroadcast (GRB), and High-Rate Information Transmission (HRIT) as specific signals subject to additional risk for radio-frequency interference (RFI) from new commercial operations at 1675-1680 MHz.

> The DCS operates at 1679.7-1680.14 MHz. It acquires data from a wide variety of sensors, then formats and retransmits that data to earth stations throughout the United States. The DCS requires high reliability, because the data provides critical real-time information about weather, tides, river and reservoir levels, wildfire and other conditions, and is used by government agencies and private companies to manage billions of dollars of critical infrastructure. The primary DCS receive site, also used to retransmit the data to other users, is located at Wallops Island, Virginia. There is also a backup facility, the Consolidated Backup Unit (CBU), at Fairmont, West Virginia.
>
> The GRB operates at 1681.15-1692.05 MHz and consists of satellite ground stations, product development facilities, and dissemination infrastructure. It is used to disseminate critical, real-time information for weather, hydrologic, solar activity, and other environmental observations to a broad range of users in federal, state and local government agencies, and the private sector.
>
> The HRIT operates at 1693.5-1694.7 MHz and transmits near-real-time weather forecasts and warnings via satellite in a form well-suited for emergency managers. The signal incorporates weather event warnings, low-resolution GOES satellite imagery data, DCS messages, and other selected products.

The SPRES report finds that sharing presents low risk of causing impacts to HRIT given the frequency separation. The study found that the GRB signal is also at some risk of RFI at the ground stations, more so from commercial base station operations (downlinks) than from commercial user devices ("uplinks"). Given the revised thresholds in Appendix J, however, protection distances could be reduced if new entrants implement mitigations to limit out-of-band emissions. As for DCS, the report finds that, if the commercial operations are limited to uplinks, sharing would be manageable with modest protection zones. According to the study, the most significant obstacle to sharing involves potential anomalous propagation from downlinks causing harmful RFI to the GOES-R DCS ground station at Wallops Island, Virginia. RFI from ducting, also known as anomalous propagation, can occur due to trapping of radio signals within atmospheric layers. If the meteorological conditions giving rise to this layering effect are widespread, the radio signals are able to propagate with low attenuation well beyond line-of-sight distances.

While questions remain about how often or for how long anomalous propagation would cause harmful RFI, the study provided sufficient evidence to conclude that ducting presents significant risks to the high reliability of DCS operations that should be addressed before sharing with commercial mobile downlink operations at 1675-1680 MHz is considered.

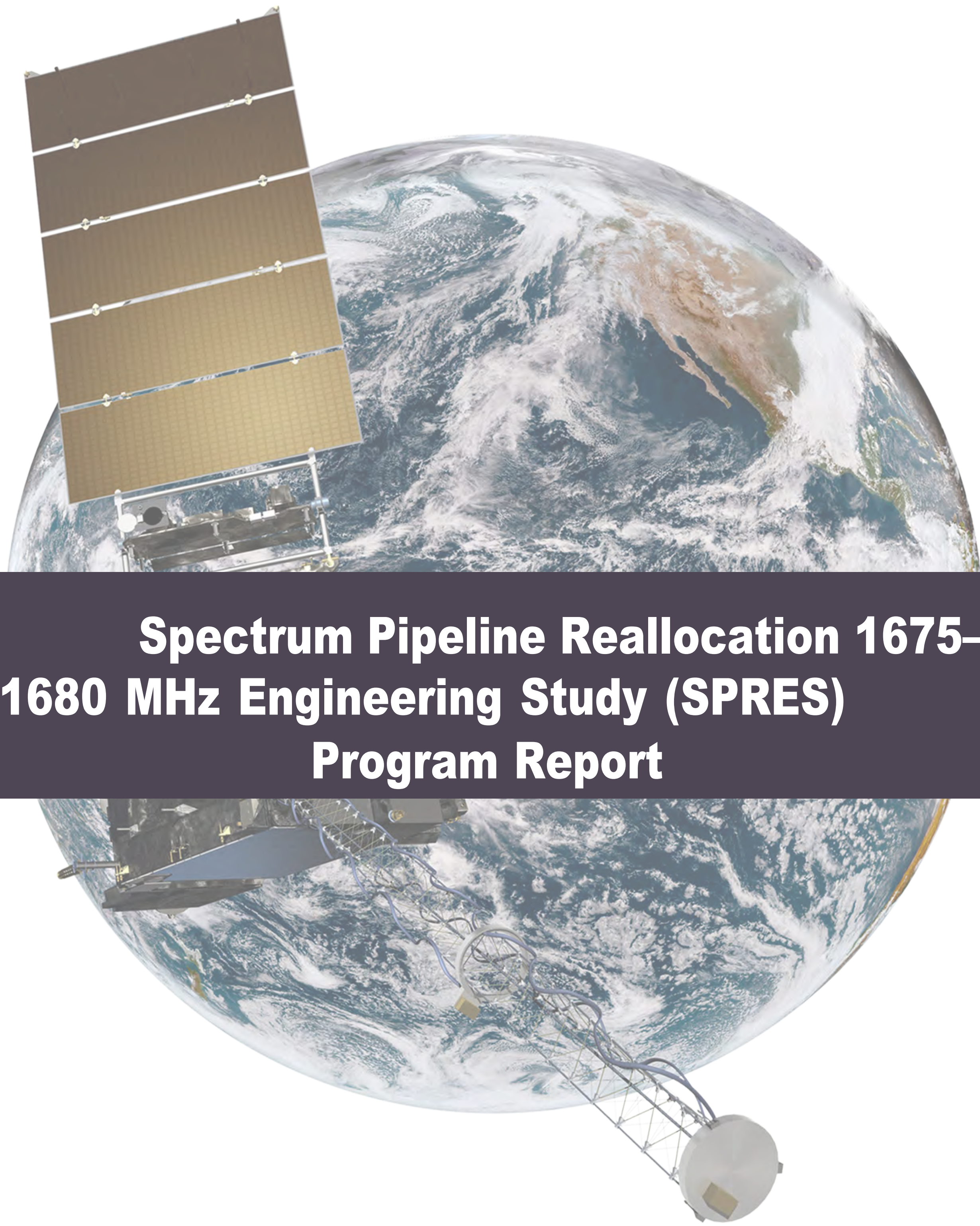
To reach a more definitive conclusion regarding the potential for sharing the 1675-1680 MHz band with commercial mobile, further study of the following potential solutions would need to be pursued:

Task #1. Reach a conclusion on the feasibility, including the cost and time required to establish appropriate redundant facilities for the DCS at key sites, to include Wallops Island and Fairmont, and possibly another site such as the Department of Interior site in Sioux Falls, South Dakota, to insure that the DCS data can be received and further distributed without interruption, high reliability, and low latency in the event that any one of these facilities experiences harmful RFI.

Task #2. Reach a conclusion on the feasibility, including the cost and time required, to provide a robust, high reliability and low-latency alternative means of near real-time distribution of the DCS data from the key sites to both federal and non-federal users -- one possible alternative is disseminating the data by streaming it from one or more of the key DCS facilities.

Task #3. Conduct further technical compatibility analysis to determine specific technical limits on commercial mobile operations to insure protection for the key DCS sites and certain GRB and HRIT sites. This latter work would consider limits on such things as the radiated power and out-of-band emissions of the commercial mobile system's transmitters and any guardband that might be used to limit in-band energy in protection zones around the DCS, GRB, or HRIT receiver sites.

Task #4. Determine what DCS, GRB and HRIT sites require protection for NOAA to meet its mission and where those sites are located. Part of that consideration would include review of the availability of online access by GRB users.



Spectrum Pipeline Reallocation 1675–1680 MHz Engineering Study (SPRES) Program Report

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This study addresses the question of whether, and under what conditions, the 1675–1680 MHz band could be made available for sharing with commercial wireless companies. Information from this report may offer guidance in the development of regulations governing sharing, to ensure that NOAA's mission of providing critical environmental and weather information is not placed at risk.

EXECUTIVE SUMMARY

Figure 1. GOES-R color image showing a hurricane over the Atlantic Ocean. *Courtesy of NOAA.*

1. Introduction: The Spectrum Pipeline Reallocation 1675–1680 MHz Engineering Study

The Federal Communications Commission (FCC) is considering an auction of the 1675–1680 megahertz (MHz) radio spectrum band for shared use by Long-Term Evolution (LTE) wireless broadband carriers. This 5 MHz band is currently used by National Oceanic and Atmospheric Administration (NOAA) satellites to transmit meteorological and other environmental data that is crucial for the public safety and economic prosperity of the United States. To assess the feasibility of such shared use, the Department of Commerce chartered the Spectrum Pipeline Reallocation Engineering Study (SPRES) in 2017. This report presents the results of the SPRES study. It addresses the question of whether, and under what conditions, the 1675–1680 MHz band could be made available for sharing with commercial wireless companies.

Environmental and weather information collected by satellites is crucial to the national security, economic health, and public safety of the United States. Twenty-four hours a day, seven days a week, NOAA satellites transmit vital information that fulfills a national mandate to develop daily weather forecasts, predict dangerous weather events, and monitor wildfires and flooding. NOAA's National Weather Service (NWS) provides information crucial for sound decision-making across the private and public sectors, impacting many areas of the U.S. economy. For example, environmental satellite information is used by the energy sector to predict energy usage and plan power generation, and by the transportation sector to route commerce and passengers. In addition, weather forecasters and emergency managers at all levels of government and in the private sector rely on real-time information from these satellites to warn communities of severe weather events and other hazards, thereby safeguarding life and property. The Department of Defense (DoD) uses environmental satellite information for national defense planning, defense operations, and managing national hydrological infrastructure. The value of some NOAA weather products for end users is based on the ability to receive information without delay.

Weather data has a significant impact on the U.S. economy. A 2007 economic study estimated the benefits and savings attributable to GOES satellites for aviation, irrigated agriculture, electricity, and natural gas to be more than $740 million in forecast 2015 dollars. Those sectors represented about 0.13% of value-added 2015 gross domestic product (GDP). Applying these values to the entire U.S. economy in 2020 dollars, the annual value of GOES weather data for those sectors can be estimated at more than $29 billion.[1]

Satellites perform a number of vital functions, including remote sensing, radio navigation, and communications. These functions involve the use of radio frequency (RF) spectrum, which is divided into sections, or bands, that are allocated for specific uses. These allocations are hard-wired into the satellite design; once a satellite is launched into orbit, its radio frequencies cannot be changed. Because radio spectrum is shared by many different users and applications—Federal and non-Federal, television and radio broadcasting, radio astronomy, satellites, GPS equipment, mobile phones, radar, Wi-Fi networks, and dozens more—its usage is governed by an intricate, bifurcated regulatory framework. In the U.S., the FCC manages commercial and other non-Federal uses of spectrum, and the National Telecommunications and Information Administration (NTIA) manages Federal use of spectrum. These agencies grant authorizations that allow conditional use of a band of spectrum in defined geographical areas. The regulatory process allocates scarce radio spectrum efficiently between an array of services with widely varying characteristics, such as directionality, transmitted power level, and receiver sensitivity, while minimizing interference between applications.

Radio frequency spectrum is finite, while demand for it has grown rapidly, especially as terrestrial wireless network operating companies (cellular carriers) seek to provide broadband services such as LTE for their customers. In the lower portion of radio spectrum that is particularly valuable to commercial carriers, from 225 to 3700 MHz, 17% of the spectrum is allocated for exclusive Federal use, 31% for exclusive non-Federal use, and 52% for shared use.[2] Especially over the past decade, there has been increasing pressure to shift those percentages and make more government-controlled spectrum available for commercial use.

In 2010 a Presidential memorandum, “Unleashing the Wireless Broadband Revolution,” directed the FCC and NTIA to identify 500 MHz of Federal and non-Federal spectrum that could be repurposed to terrestrial wireless broadband use within 10 years.[3] In the resulting NTIA-led “Fast Track” study of federal spectrum, 1675–1710 MHz was one of the bands considered.[4] The 1670–1710 MHz band is allocated globally for meteorological satellites (Met-Sats) and used by NOAA to operate the nation’s weather satellites.

The Fast Track study recommended 1695–1710 MHz for possible sharing because incumbent use occurred at a limited number of sites that could be protected with static zones. The 1675–1695 MHz band was not recommended for sharing due to users with mobile or transportable receivers, including receivers supporting emergency management. The Middle Class Tax Relief and Job Creation Act of 2012 then directed the Department of Commerce to identify 15 MHz of Federal-use spectrum in the range 1675–1710 MHz suitable for sharing with commercial wireless carriers. In response to the Presidential direction and Congressional legislation, NOAA redesigned its next-generation geostationary satellite communications to increase the feasibility of shared use in 1695–1710 MHz. In 2015, the FCC completed the AWS-3 auction, selling licenses to commercial LTE wireless services carriers to operate in 1695–1710 MHz. Prior to AWS-3, in 2003, 1670–1675 MHz was sold via FCC Auction 102. The 1670-1675 MHz band was globally allocated for Met-Sat services and was in use by NOAA satellites. OP Corporation, a subsidiary of Crown Castle International Corporation, a cell tower operator, was awarded the 1670–1675 MHz license and soon afterwards leased the band to multiple entities via TVCC One Six Holdings LLC.[5] Through several different entities, including LightSquared (later rebranded as Ligado Networks), a long-term lease covering the continental United States was established, through October 1, 2023.

Considering both the AWS-3 auction of 1695–1710 MHz and the 2003 auction of the 1670–1675 MHz band, NOAA has made available half of the original 1670–1710 MHz Met-Sat allocation (20 MHz of the original 40 MHz) for wireless broadband.

Currently, the FCC is considering an auction of another 5 MHz portion of this meteorological satellite spectrum to share with LTE wireless broadband. In a petition originally filed with the FCC in 2012, the private communications company LightSquared (now Ligado Networks) seeks to open the 1675–1680 MHz band for shared use with mobile wireless.

That 5 MHz band is used by NOAA satellites to transmit crucial, time-sensitive data, primarily to geographically diverse, ground-based users (Figure 2). The current NOAA satellite fleet in geostationary orbit, known as Geostationary Operational Environmental Satellites Series R (GOES-R), relies on the 1675–1695 MHz band to collect and disseminate critical, real-time information on weather, hydrologic and other environmental conditions, and solar activity to a broad range of users in the Federal government, state and local agencies, and the private sector. The GOES-R four-satellite constellation will operate through the year 2035, at which time it is expected to be replaced.

The proposed sharing of the band carries substantial risks. In a shared radio frequency environment, the satellite receivers operated by users of NOAA satellite data could incur radio frequency interference (RFI), resulting in loss or delay of data. The consequences of such interference would be costly. Loss of critical information during a severe weather event would impede the ability of

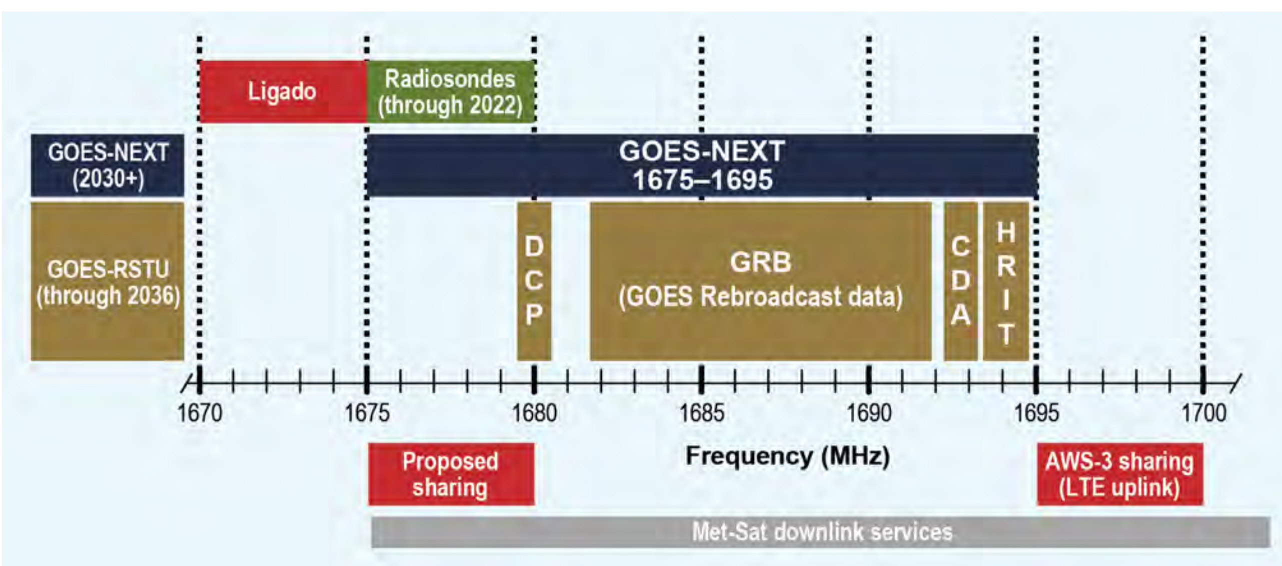


Figure 2. L-band spectrum use. OP Corporation leases the license rights for the 1670–1675 MHz band to Ligado.

NWS, DoD, and other Federal, state, and local organizations to generate advance warnings and could result in significant property damage and loss of human life. In addition, future use of the 1675–1695 MHz band for meteorological satellite development could be severely impacted.

In 2017, the Department of Commerce chartered a comprehensive study to assess the feasibility of shared use of the 1675–1680 MHz band. Because the effort was funded by the Spectrum Relocation Fund—created in 2004 and expanded by the Spectrum Pipeline Act of 2015[6]—the study has been named the Spectrum Pipeline Reallocation Engineering Study (SPRES). In 2019, the FCC issued a Notice of Proposed Rulemaking to reallocate and auction the 1675–1680 MHz band for shared use, further raising the profile of this study.

This study addresses the question of whether, and under what conditions, the 1675–1680 MHz band could be made available for sharing with commercial wireless companies. Information from this report may offer guidance in the development of regulations governing sharing, including the nature, rough order magnitude cost, and necessary measures to ensure that NOAA's mission of providing critical environmental and weather information, necessary for the protection of life and property and the enhancement of the national economy, is not placed at risk.

2. GOES-R Satellite System: An Overview

To develop forecasts, meteorologists rely on both earth-based sensors that measure local weather and environmental conditions, and space-based systems that monitor these conditions on a regional and global basis. GOES satellites have provided imagery and data for weather and environmental monitoring since 1975.

A geostationary satellite orbits in the direction of the earth's rotation on its axis and matches the period of the earth's rotation at the equator. As a result, the satellite always has the same view of the earth's surface, offering a continuous, consistent perspective over a quarter of the planet. NOAA's current generation of geostationary weather satellites, the GOES-R series, operates from two primary locations: GOES-East at 75.2° west longitude and GOES-West at 137.2° west longitude. NOAA also maintains at least one on-orbit spare to serve as backup in the event of problems with a primary satellite. Currently that spare is an older generation of GOES known as the GOES-NOP series.

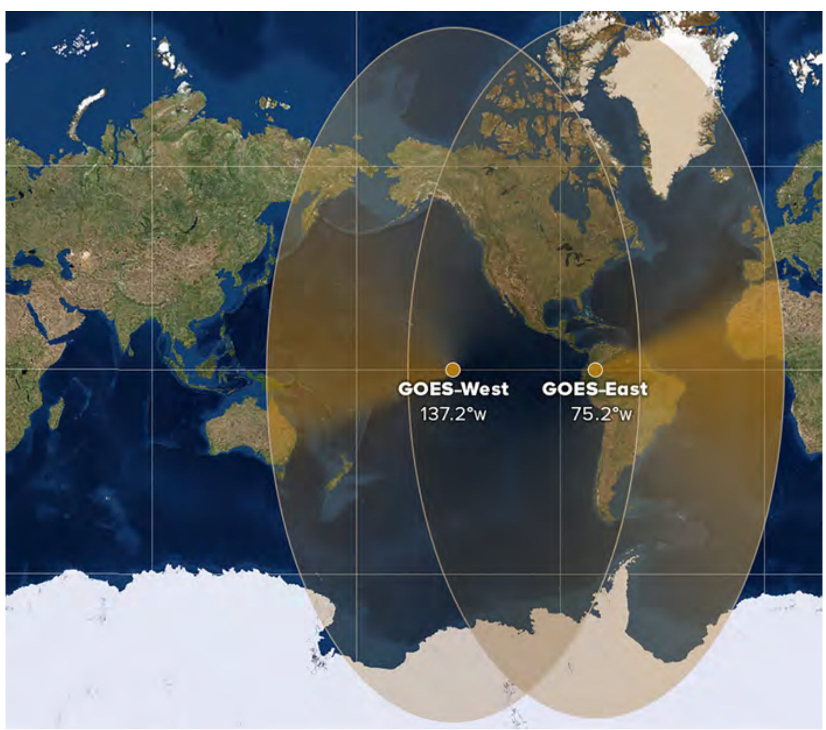


Figure 3. Geographic extent of the GOES-R direct broadcast footprint.
Courtesy of NOAA.

Meteorological and environmental sensors on the GOES-R satellites collect imagery and measurements of earth's atmosphere, oceans, and environment, including real-time mapping of lightning activity. The satellites also monitor solar activity and space weather.

Collecting that information, however, is only part of the task. The raw data must be reliably brought to the ground, processed into calibrated images and other products, and distributed to users in government and the private sector, all in a timely manner. That is the responsibility of the GOES-R ground system, which receives data from the satellites and prepares it for distribution to the NWS and more than 10,000 other Federal and non-Federal users.

The core of the ground system, as shown in Figure 4, is located at three separate sites: the two primary locations are NOAA Satellite Operations Facility in Suitland, Maryland, and Wallops Command and Data Acquisition Station in Wallops Island, Virginia; a third, alternate site is the Consolidated Backup Facility in Fairmont, West Virginia. The primary sites normally receive and process the raw data, but the backup site can perform nearly all critical functions in the event of a primary site failure.

After the ground stations process the raw GOES meteorological data into calibrated images and other products, all results are transmitted in full resolution and in near-real time back to the GOES-R satellites for broadcast to users. This broadcast of processed satellite meteorological information is known as the GOES Rebroadcast (GRB), a 31 Mbps (megabits per second) continuous stream of updated weather and meteorological images and products.

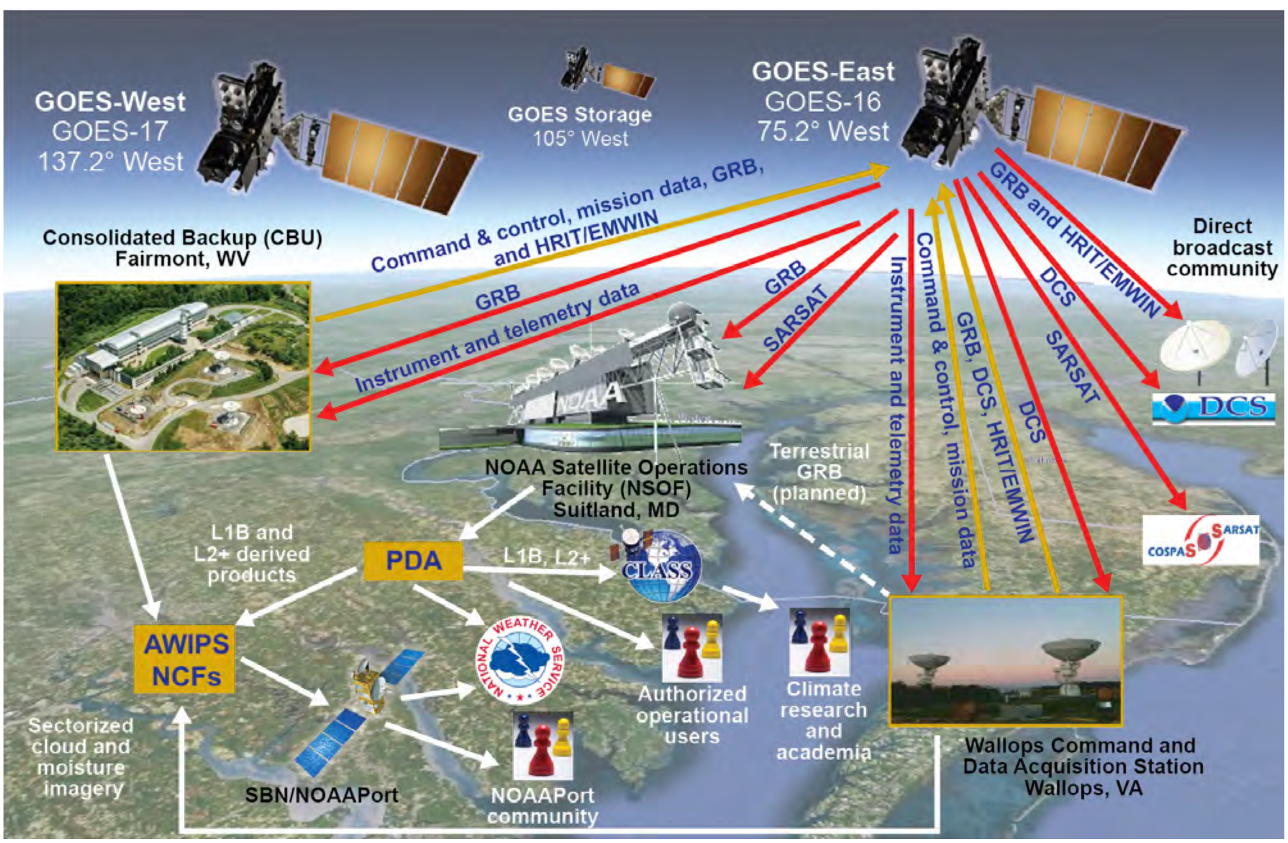


Figure 4. GOES-R system architecture. *Courtesy of NOAA.*

In parallel with the GRB, the GOES-R processed meteorological data is also stored on the ground in the Environmental Satellite Processing and Distribution System (ESPDS). Operated by NOAA, ESPDS is a large weather database supporting near-real-time operational use that consolidates meteorological products from NOAA and international sources.

GOES-R, like previous GOES series, also hosts the Data Collection System (DCS). DCS is a relay system used to collect information from a large number of widely distributed earth-based platforms, which are located primarily in remote areas and operate with minimal human intervention (Figure 5). Sensors on these platforms record information on weather, tides, river and reservoir levels, wildfire, and other conditions and relay it via the GOES-R satellites in the form of short data reports, which are received at ground stations operated by NOAA and other users. Observations and measurements sent by platforms over the DCS relay system are used by government agencies and private companies to manage billions of dollars of critical infrastructure; make critical fire management, natural resource management, and public safety decisions; and enable shipment of more than 600 million tons of cargo per year on inland waterways. DCS information is integrated into a nationwide hydrologic warning system that detects and warns of flood conditions. The DCS network has about 32,000 active platforms that together send an average of 800,000 reports a day. This highly efficient, shared-channel design requires just 400 kHz of communications bandwidth for the service.

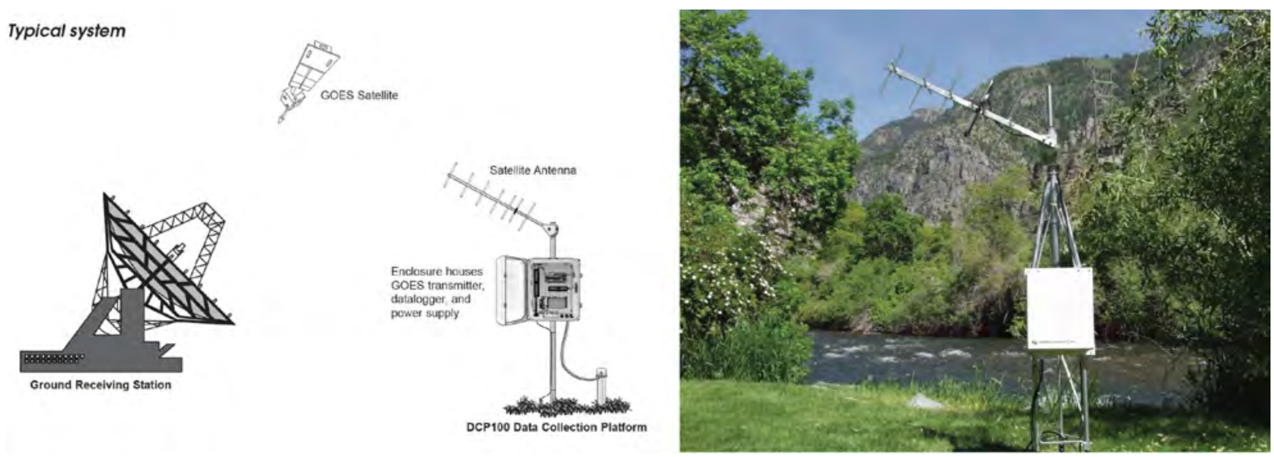


Figure 5. DCS architecture and a typical DCS sensor platform. *Courtesy of Campbell Scientific.*

The GOES-R system provides data that is critical for public safety, economic prosperity, and national security. Compared to earlier systems, the current GOES constellation provides more frequent and higher-resolution data that supports improved forecasts of hurricane intensity and track; earlier warning of tornadoes, severe thunderstorms, and lightning-strike dangers; better detection of heavy rainfall and flash floods; improved air-quality alerts; better fire detection and intensity estimation; and more accurate aviation route planning. In short, the information provided by GOES-R satellites saves both money and lives on a daily basis.

3. How NOAA Shares Weather Information

Once the raw GOES-R meteorological data is received and processed at the NOAA primary ground stations in Maryland and Virginia, information products enter an array of systems for operational use, real-time and near-real-time dissemination, and long-term storage. Although the NWS is the primary user of GOES-R Series products, many other government, public- and private-sector entities retrieve the products directly from NOAA for their own use, perform value-added processing, and further disseminate the original and value-added products to third parties, creating a cascading array of direct and indirect users of the information and allowing for quick response to emergency weather conditions. Depending on their requirements, these users access GOES-R products in different ways, including direct satellite broadcasts and terrestrial networks. SPRES studied the potential impacts of spectrum sharing on each of these users.

Direct satellite broadcast

Immediately after initial processing, GOES-R imagery and related products from the spacecraft instruments are rebroadcast directly to users via the GOES Rebroadcast (GRB), using spectrum adjacent to the band under study. Operators utilize an earth station and processing resources to receive the data relevant to their applications. GRB offers reliable delivery with low latency (i.e., very little delay). The six NWS centers, including the National Hurricane Center (NHC), directly utilize data from GRB antennas (Figure 6).

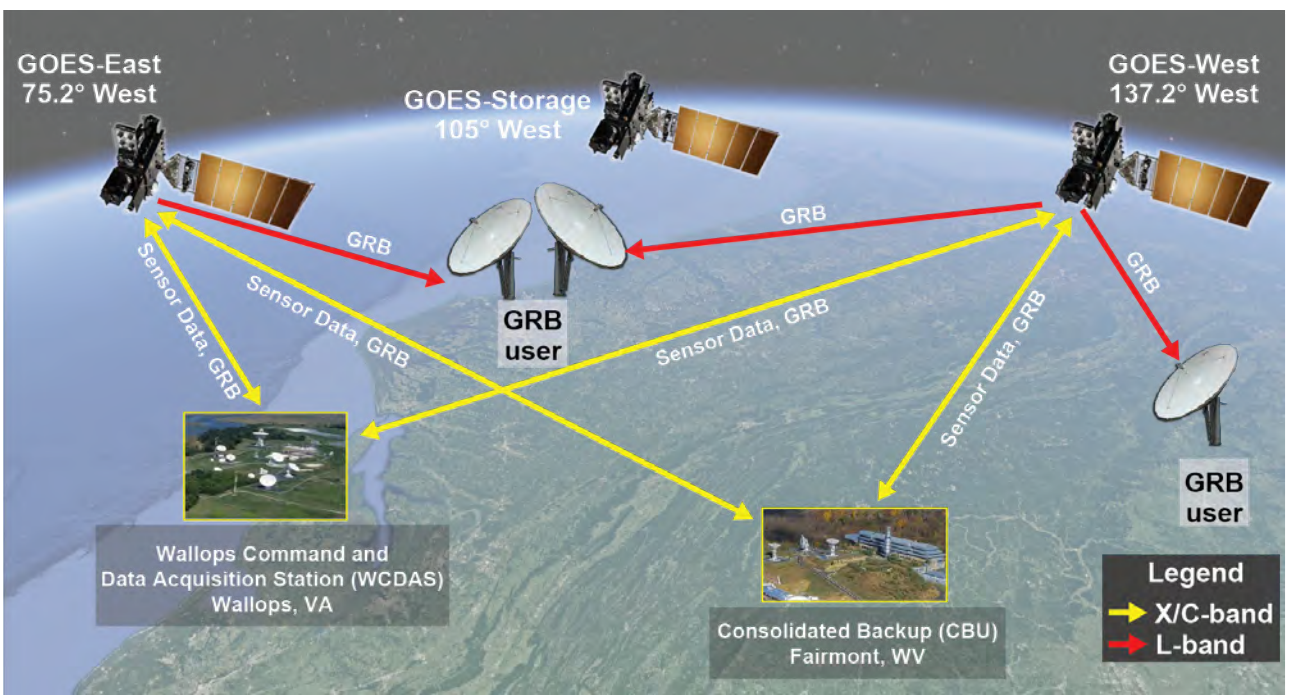


Figure 6. Flow of GOES-R sensor data to NOAA ground processing sites where the GOES Rebroadcast (GRB) is generated, uplinked to the satellite, and broadcast to users. *Courtesy of NOAA.*

As shown in Figure 7, the Data Collection System (DCS), introduced in the previous section, relays information from thousands of remote sensors, many of which are gages measuring hydrological parameters in rivers, streams, reservoirs, and shorelines, or sensors capturing wildfire-weather conditions, to aid water managers and fire managers with localized near-real-time data. The hydrologic sensors, whose data is relayed via DCS, provide an essential input to many hydrometeorological products for warning and forecast. Flood warning and drought products use these sensor results in their formulation. DCS sensor data are also inputs to the numerical weather prediction models and to the U.S. national water model. All Federal and non-Federal sensors on the DCS network provide data for the nation's hydrological products.

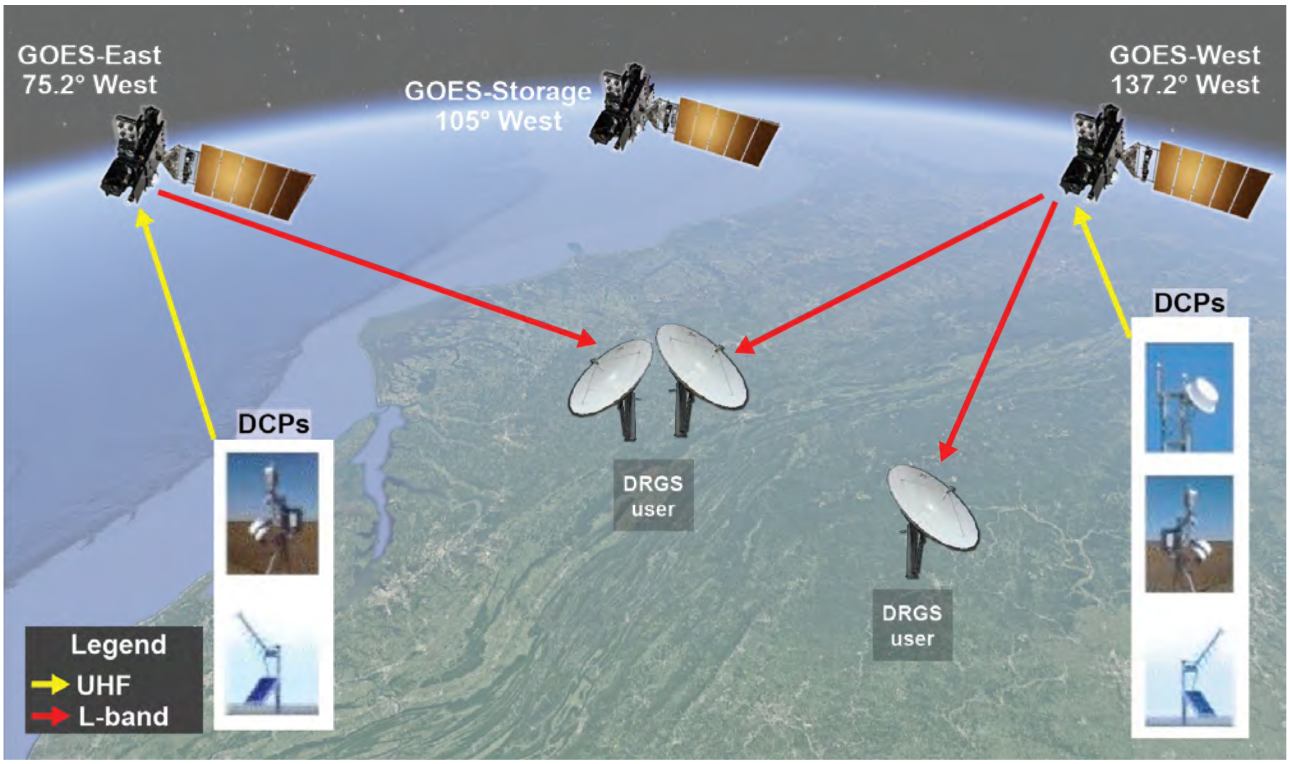


Figure 7. Schematic showing flow of data from Data Collection Platforms (DCPs) to Direct Readout Ground Station (DRGS) users. *Courtesy of NOAA.*

Unlike GRB, DCS is a relay of the original source data rather than a rebroadcast. This means that any interference results in permanent loss of this data. Although there are about 475 DCS registered accounts,[7] many users rely on one of the 34 Federal, state, and local entities that operate DCS receivers in order to receive the data and make it available for third parties. The primary DCS receive sites are operated by NOAA and the U.S. Geological Survey (USGS), who receive all DCS platform reports, store them, and provide retrieval methods for account holders. The NWS does not own or operate any DCS platforms. It obtains gage data used for forecast products and models from the other DCS users.

Many GRB and DCS ground stations exist because of a need for real-time data delivery and resiliency that can be satisfied only by satellite delivery.[8] The high levels of availability required by the GRB (99.988% over a 30-day period) cannot be achieved through terrestrial delivery systems to geographically diverse locations, particularly during severe weather events.

The High Rate Information Transmission/Emergency Managers Weather Information Network (HRIT/EMWIN), another GOES downlink, transmits near-real-time weather forecasts and warnings via satellite in a form well-suited for emergency managers and other decision-makers who may be functioning in an environment where the power grid, wireless networks, and the internet are not in service. The signal incorporates weather event warnings, low-resolution GOES satellite imagery data, DCS messages, and other selected products.

Terrestrial networks

The NWS uses a variety of methods to ingest products and data for its forecast models, and then to distribute weather forecasts and warnings to the national centers and local forecast offices. The Advanced Weather Interactive Processing System (AWIPS) is a computer-based system that ingests and processes GOES data along with other meteorological, hydrological, satellite, and weather radar data and products. AWIPS distributes the results to 135 Weather Forecast Offices and River Forecast Centers, as well as to select Federal Aviation Administration (FAA) locations nationwide. Forecasters and scientists rely on AWIPS to make increasingly accurate weather, water, and climate forecasts. AWIPS information is needed for forecasters to create specialty products for industry segments, such as aviation and maritime, or localized products, such as lake-effect snow forecasts.

ESPDS, introduced in the previous section, makes meteorological information available to select users in near-real time. It is the primary platform for integrating and disseminating near-real-time GOES-R series satellite products, as well as data and products from other NOAA and international sources. ESPDS is not publicly accessible, and users must be approved for both system and product access by NOAA’s National Environmental Satellite, Data, and Information Service (NESDIS). ESPDS is used as a backup option by key customers for access to GOES-R products in the event of GRB receive station outages, and by customers with non-real-time requirements.

NOAA operates the DCS Access and Data Distribution System (DADDS), which processes the DCS data for incorporation into the HRIT broadcast stream, as well as for terrestrial use. USGS operates an independent terrestrial equivalent to the DADDS, known as the Electronic Data Distribution Network (EDDN), which can also serve as a backup to DADDS.

4. The Risk of Radio Frequency Interference

As Hurricane Patricia approached Mexico on October 22, 2015, NOAA scientists studied satellite images in order to predict its track. One important image, however, showed a black band—indicating missing data—that blocked the view of the hurricane (Figure 8). The problem was caused by interference from terrestrial transmission into the Federal GOES stations receiving in 1670–1695 MHz.[9]

Radio frequency interference (RFI) occurs when unwanted signals cause disruptions in reception. It can result from a number of causes. Two signals using the same frequency—for instance, two radio stations broadcasting at 95.1 FM but located in different cities—must transmit at power levels appropriate for the geographical distance and terrain between the cities so that the desired signal

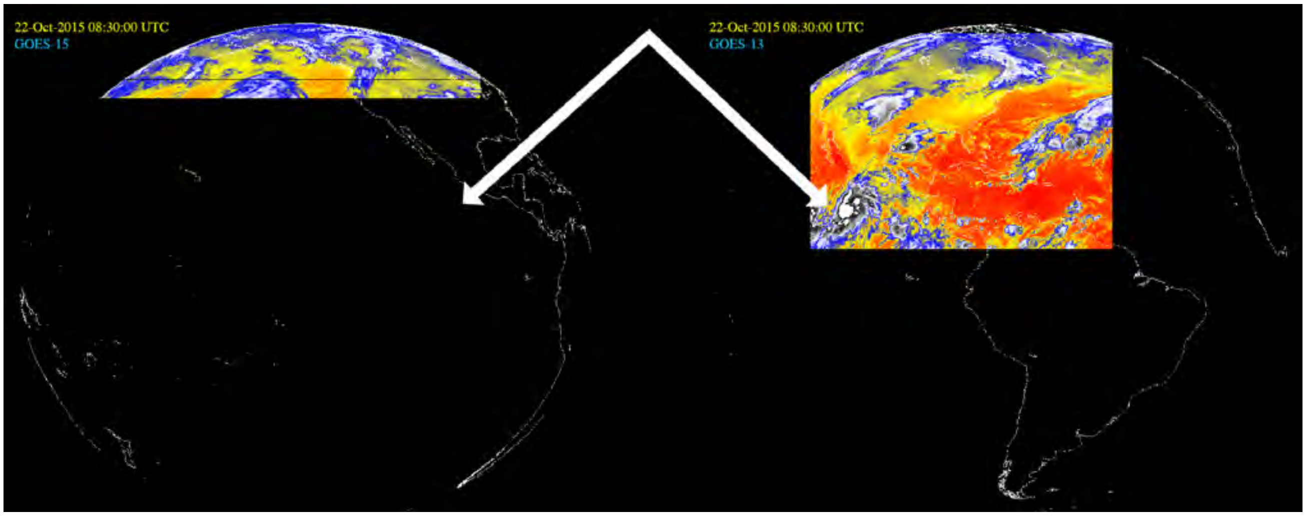


Figure 8. In this GOES-NOP image from October 22, 2015, the black areas indicate satellite weather observations from GOES-West (left) and GOES-East (right) lost due to spectrum interference to the satellite downlink. The arrows point to the location of Hurricane Patricia. *Courtesy of NOAA.*

has significantly greater power within its “coverage area.” If they do not, the desired signal might experience interference, or the radio receiver might switch between stations. In addition, generating a radio signal is never a perfect process, and a signal always includes some energy in frequencies adjacent to the main signal. When a signal is much more powerful than a neighboring one, the power produced incidentally in adjacent frequencies may be enough to unintentionally drown out a lower-powered signal located there.

RFI can also occur under conditions known as anomalous propagation due to atmospheric ducting (Figure 9). This phenomenon, most common in the troposphere, or lowest layer of earth’s

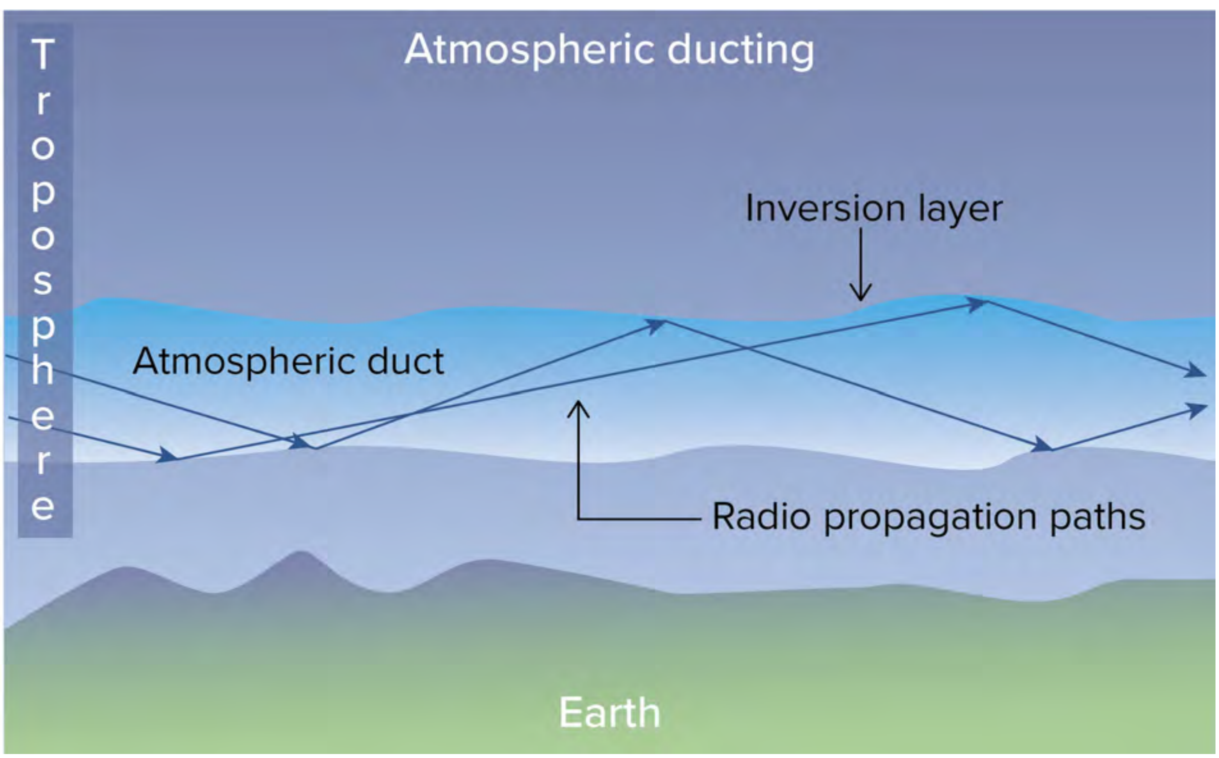


Figure 9. Anomalous propagation due to atmospheric ducting can cause radio frequency interference.

atmosphere, occurs when there are strong temperature and humidity gradients, or significant variation in temperature or humidity in a specific area. The boundaries between these layers can cause a radio signal to refract, or change direction. Rather than dissipating with distance, the radio signal becomes trapped between the layers and propagates within this “duct,” traveling farther and at a higher power level than would normally occur. This phenomenon increases the chances that the signal will interfere with other signals in or near the duct. Ducts, which can remain intact for hours, may extend for hundreds of kilometers and are usually found near coastlines or valleys during periods of calm air.

Successful spectrum sharing requires preventing interference altogether, or reducing it to acceptable levels. Each band that is considered for sharing must be analyzed to determine how to adequately protect incumbent services and to inform, from the start, the rules created to govern the sharing. Prior to the 2015 FCC auction that opened the 1695–1710 MHz portion of the meteorological satellite band to shared use with commercial LTE carriers, rules were put in place to establish protection zones around the at-risk earth stations. NOAA also initiated development of an RFI monitoring system to identify and locate the source of any interference. Those same rules, including specific protection zone sizes, are not directly applicable to the 1675–1680 MHz band, which poses different sharing challenges, for two reasons. First, the Federal satellites that use the 1695–1710 MHz band are in low-earth orbits and fly around the earth in polar orbit. As a result, the communications downlink at each earth station is active in the band only as the satellite passes overhead, which, for a given location, may happen 10 times per day. By contrast, the GOES satellites are in continuous view of the ground stations, sending data seven days a week, 24 hours a day, and therefore presenting many more opportunities for interference to occur at each earth station. Second, the 1695–1710 MHz band is allocated for sharing only with mobile broadband uplinks, or transmissions from handheld equipment to the cell tower. By contrast, mobile downlinks, or tower-to-device communications, are under consideration in the 1675–1680 MHz sharing scenario. Mobile downlinks by design produce much more powerful signals than uplinks and require increased separation to avoid interference. The FCC initially anticipated using the 1675–1680 MHz band for downlinks only, but the agency left open the possibility of a combination of both downlink and uplink, or uplink only.[10]

The GOES-R geosynchronous satellites are located 22,500 miles above the earth. The strength of their signals is greatly reduced upon reaching the earth because, like flashlight beams, their energy spreads across a wide area as they travel a great distance. As a result, highly directional dishes or antennas are required to receive these satellite signals. In comparison, signals from mobile broadband networks travel only a short distance and retain much of their energy. Receiving a satellite signal while a mobile broadband downlink is operating nearby might be compared to attempting to listen to a person whispering from a block away while someone else is shouting in your ear.

The spectrum bands in which GOES-R data and products are transmitted play a large role in determining how they may be affected by spectrum sharing. Reception on the ground of raw, unprocessed instrument data collected by GOES on-board sensors is not directly affected by spectrum sharing in the 1675–1680 MHz band because the data is transmitted to NOAA ground stations in what is known as the X-band, ranging from 8–12 GHz, and is therefore relatively isolated from activities in the 1675–1680 MHz band. In contrast, the HRIT/EMWIN and GRB rebroadcasts and the DCS service operate in the L-band (1–2 GHz), and are adjacent or in-band to the 1675–1680 MHz band being considered for sharing. Because of their placement in the L-band, these signals carry RFI risk and therefore required examination in this study.

As indicated in Table 1, the HRIT/EMWIN broadcast signal is centered at 1694.1 MHz and occupies 1693.5–1694.7 MHz, while the GRB signal is centered at 1686.6 MHz and occupies 1681.15–1692.05 MHz. These are adjacent to or near the 1675–1680 MHz band.[11] The GOES U.S.-based or domestic DCS signal, centered at 1679.9 MHz and occupying the 1679.7–1680.1 MHz band, directly overlaps the 1675–1680 MHz band proposed for sharing.

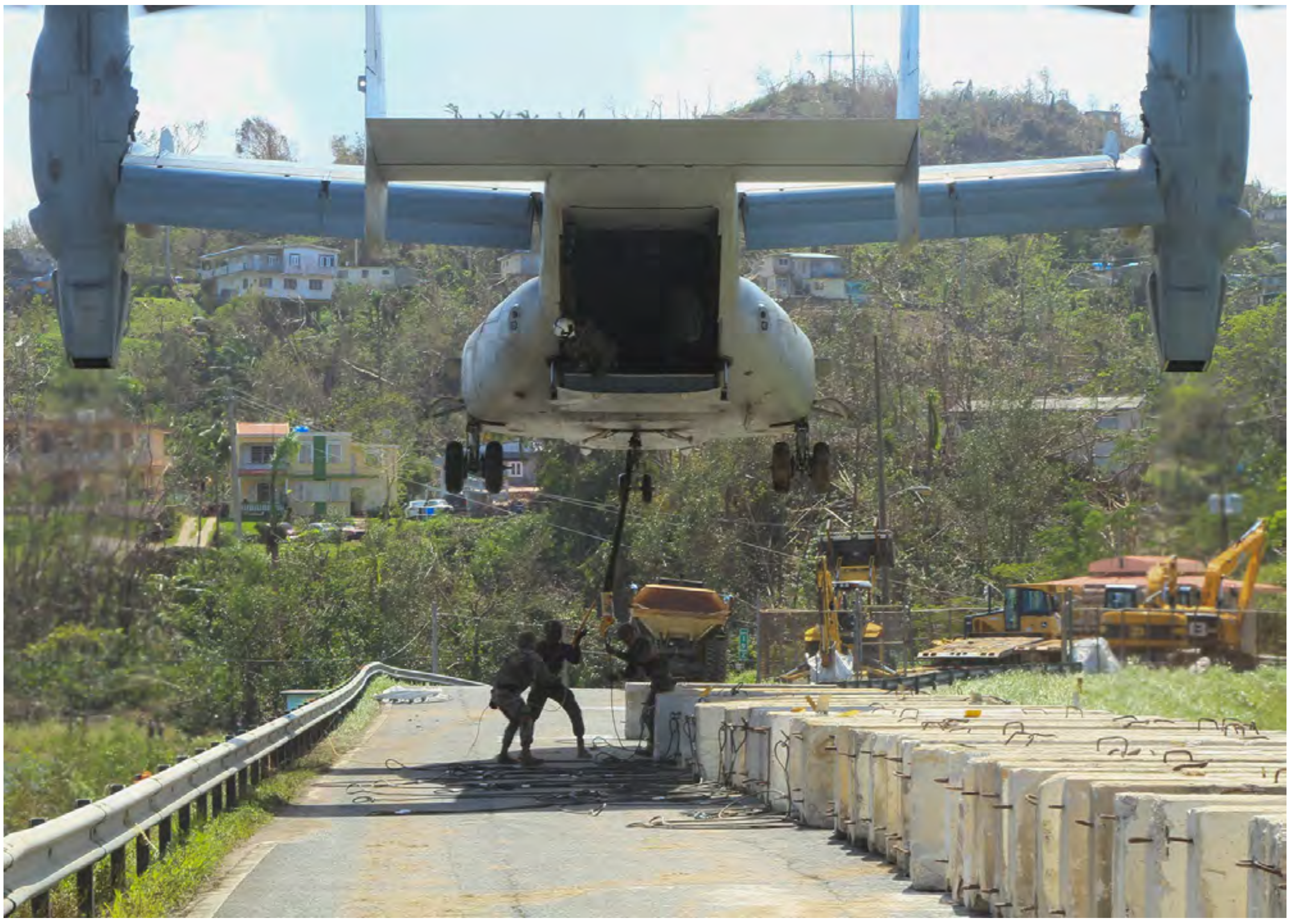
Table 1. Key characteristics of the GOES-R L-band signals.

GOES-R signal	Center frequency	Channel	Data rate
DCS (U.S.-based service)	1679.9 MHz	1679.7–1680.1 MHz (533 signal channels*)	300/1200 baud
GRB	1686.6 MHz	1681.15–1692.05 MHz	31 Mbps
HRIT/EMWIN	1694.1 MHz	1693.5–1694.7 MHz	400 kbps

*Due to internationally agreed channelization of DCS systems, most use of DCS in the Americas falls below 1680 MHz. The GOES satellites support the worldwide DCS spectrum coverage that includes frequencies used by Japan, European countries, and other international users.

5. What's at Stake for Direct Broadcast Users

The GOES Rebroadcast (GRB) and Data Collection System (DCS) services are critical infrastructure to Federal, state, and local government agencies, as well as to private-sector entities, yielding large benefits in terms of public safety and economics. To demonstrate the significance of these broadcast signals, nine use cases are presented here, detailing how specific agencies and offices utilize GOES meteorological data in their daily operations.



Use case 1. *In accordance with U.S. National Space Policy, the Department of Defense (DoD) relies on civil and international satellite-based capabilities for a variety of time-sensitive meteorological, oceanographic, hydrological, and space environmental data and products. The GOES constellation is a primary source of this information. This environmental intelligence optimizes readiness and training, force presentation, and risk management decisions for the Air Force, Army, Coast Guard, Navy, Marine Corps, and Space Force. It also shapes national security planning and force employment activities undertaken by DoD's 11 combatant commands and its combat support agencies. These missions include combat, homeland defense, and non-combat missions across the Air, Space, Land, and Sea domains. Finally, information collected and broadcast by the GOES constellation is essential to DoD's responsibility to issue timely weather watches, warnings, and advisories that safeguard millions of military personnel and their family members, and protect billions of dollars in warfighting capabilities arrayed across the camps, bases, ports, posts, and ranges operated by the armed forces. In the photo, U.S. Marines load a barrier onto a MV-22 Osprey while working to reinforce a dam in Puerto Rico in the aftermath of Hurricane Maria in 2017.* Courtesy of DoD.

GOES Rebroadcast use cases

Use case 2. *The National Hurricane Center (NHC) in Miami, Florida, a component of the NWS National Centers for Environmental Prediction, counts on GRB data to issue forecasts, watches, and warnings that save lives, mitigate property loss, and improve economic efficiency. The NHC has specific responsibilities to generate analyses and forecasts over the tropical and subtropical eastern North and South Pacific and the North Atlantic basins, as well as to forecast storm surges and to coordinate all aerial reconnaissance operations related to hurricanes, cyclones, and other high-impact weather events. A loss of GRB links would force the center to rely on landline retrieval of data from other NWS sites, which may impede or delay its ability to issue time-sensitive forecasts and warnings. Such delays could, for example, damage the ability of state authorities to order timely hurricane evacuations.* *Courtesy of Getty.*

Use case 3. *The NWS Aviation Weather Center (AWC) in Kansas City, Missouri, also part of the NWS National Centers for Environmental Prediction, provides airports and pilots with in-flight weather advisories about hazardous weather, including specific categories of thunderstorms. Some of the products AWC creates require data that is available only through GRB and would be impossible to reproduce in the event of signal loss. GOES data is also delivered directly to FAA centers where embedded NWS forecasters provide detailed outlooks for air routes and airports.* *Courtesy of Getty.*

Use case 4. *Private companies rely on GRB data to serve a wide variety of users. AccuWeather, a major weather company, provides information to railway companies to predict track washouts and ensure that trains avoid the paths of tornadoes. Other weather companies provide lightning forecasts for sports stadiums, closure forecasts for school districts, and specialized forecasts for helicopter transport operations supporting offshore oil production.* *Courtesy of the USAF (top), Utah DOT (above).*

Data Collection System use cases


Use case 5. *The National Interagency Fire Center's (NIFC) specialized DCS platforms, called Remote Automated Weather Stations (RAWS), monitor fire danger by collecting and transmitting data on precipitation, relative humidity, wind, and solar radiation. There are about 2,650 RAWS platforms, including 550 portable units that can be rapidly redeployed to sensitive areas, allowing fire managers to predict fire danger and monitor the behavior of active fires. During a wildfire in New Mexico in 2018, DCS messages allowed firefighters to evacuate in time, even as the platforms were burned over (above right). Interference to DCS signal reception at the NIFC headquarters site, or at NOAA, which serves as backup, would make it much more difficult for officials to assess and manage fire risks and may place firefighters' lives at risk. Courtesy of NIFC.*

Use case 6. *The U.S. Army Corps of Engineers (USACE) relies on DCS data daily to make decisions about flood control, navigation, and wetlands preservation. A delay or loss in the delivery of DCS data during floods could pose dangers to people, property, and critical infrastructure, including water reservoirs.[12] It could also compromise safe navigation of the inland waterways, which annually carry 630 million tons of commodities such as grain, coal, and petroleum. USACE and USGS together operate more than 5,000 platforms and 10 ground stations for this purpose. Courtesy of USACE.*

Use case 7. *DCS data is critical to the U.S. Bureau of Reclamation, which maintains 475 dams and serves as the nation's second-largest producer of hydroelectric power and largest wholesale water supplier, operating 337 reservoirs and delivering 10 trillion gallons of water to more than 31 million people each year. It provides 140,000 farmers in the western U.S. with irrigation water for 10 million acres that produce 60% of the nation's vegetables and one quarter of its fresh fruits and nuts. A delay or outage in the DCS signal, especially during floods, could lead to loss of life, destruction of infrastructure, power failures, and crop losses. Courtesy of USDA.*

Use case 8. *The NWS Alaska Aviation Weather Unit depends on DCS data to fulfill one of its key missions—issuing warnings about volcanic ash to airplanes that overfly the north Pacific, one of the most active volcanic regions on the planet. About 10,000 people per day and up to 50,000 aircraft per year traverse the coverage area, including most flights from the western U.S. to Asia. Interference to the office's reception of DCS data could affect Air Traffic Control's ability to warn planes of hazardous conditions caused by volcanic ash. Courtesy of NASA.*

Use case 9. *To reduce the danger to vehicles in high winds associated with hurricanes and severe weather, the Florida Department of Transportation has placed automated wind-speed monitoring equipment on causeways and coastal bridges to report wind speed via DCS in near-real time. This non-Federal DCS application provides for the safety of life by supporting the decision to close bridges under unsafe high-wind conditions during hurricane evacuations. Failure of DCS due to RFI would force a return to the previous method, where law enforcement officers were dispatched to each bridge to manually take wind speed measurements. This was a costly solution that placed officers in harm's way and prevented them from performing other law enforcement and public assistance duties.* Courtesy of Florida DOT.

6. Study Objectives, Approach, and Methodology

This SPRES study assessed the GOES satellite system and wireless technologies to determine the feasibility of sharing the 1675–1680 MHz band.

Objectives

The study objectives cover three broad areas:

- GOES satellite data use
- Interference risk
- Mitigation options and feasibility

Approach and methodology

The SPRES study consisted of 11 separate projects. Each project addressed at least one of the three study objectives and involved one or more of the following approaches: collecting technical data, performing measurements, and performing system modeling.

The study began with researchers surveying GOES ground station operators and data users to understand their missions and the methods they use to access data, as well as to determine any impacts they would suffer in the event of delay or loss of data. NOAA's records indicated 100 GRB and DCS sites were currently installed and operating, 57 of which were located in the U.S. The site-specific missions and end users were further investigated in the study.

On-site tests and measurements were performed at 32 Federal GOES earth station sites. These sites, which have different combinations of DCS, GRB, and HRIT/EMWIN earth stations, were selected because they currently make vital contributions to the dissemination of time-critical weather information, or are expected to do so in the future. At the same time, representative GOES receivers were evaluated for their susceptibility to interference. The DCS and HRIT receivers were tested in a laboratory environment, and GRB receivers were tested on-site at earth stations in College Park, Maryland, and Wallops Island, Virginia.

A significant part of the study examined the potential for anomalous propagation via atmospheric ducting to cause interference in 1675–1680 MHz from well beyond line-of-site distances. This was prompted by interference events that occurred over the period 2014–2017 at the NOAA Wallops Island site in Virginia, affecting the GOES-NOP Sensor Data (SD) downlink (which operates in the 1670–1680 MHz band). During that period, the 1670–1675 band was being shared with a terrestrial licensee. These interference events led NOAA to install an RF monitoring system at the Wallops Island site that captured spectrum characteristics and source-tower identification numbers associated with the offending signals. Engineers were able to analyze this data and attribute the interference to anomalous propagation of signals from terrestrial installations hundreds of kilometers away, far beyond the protection distance then in place for the terrestrial licensee. As a result, RFI due to anomalous propagation was identified as a risk factor in sharing the 1675–1680 MHz band, and the SPRES study included an assessment of the potential for this source of RFI at all sites.

SPRES quantified both anomalous propagation and local aggregate sources of interference into the GOES earth stations to determine how much protection was necessary. Combined with the earth station receive characteristics, SPRES could then calculate protection distances or protection zones—in which LTE deployments would be controlled or prohibited—around the 32 GOES earth stations. These calculations relied on well-known models for radio frequency propagation, namely the U.S. Navy Advanced Propagation Model (APM), specifically developed to characterize anomalous propagation, and the Longley-Rice Irregular Terrain Model (ITM). Protection ranges were calculated separately for reception of current GOES signals and for expected future use of the band as the volume of weather data increases.

The models used high-resolution data showing the elevation of the terrain surrounding each site, and incorporated measured clutter values where relevant. The modeling evaluated several possible implementations of LTE wireless service, such as various combinations of uplink/downlink and small cells/large cells, and used real-world LTE tower deployment data to model tower heights, typical levels of radiated power, amount of data traffic on the network, and density of tower installations.

Evaluating techniques to mitigate the risk of interference was also a feature of the study. Techniques were considered that could increase the feasibility of sharing by increasing access for LTE carriers while protecting the GOES receivers. The use of RF monitoring, though not specifically an RFI mitigation, was also considered. Mitigation techniques evaluated included alternative dissemination techniques (such as cloud-based solutions and expansion of existing services including ESPDS and DADDS), relocation of satellite data ingest sites to locations less susceptible to RFI, and measures to reduce GOES receive site susceptibility to RFI. Future satellite dissemination architectures—to be implemented post-GOES-R—were also considered.

After gathering information about GOES data users, the importance of data timeliness and availability, and the characteristics of the earth station sites, SPRES integrated this information with data regarding quantifiable risks, mitigation alternatives, and protection zone criteria to develop a comprehensive assessment of sharing potential.

7. Risks and Findings: GOES Satellite Signals are Highly Susceptible to Terrestrial Interference

Risks

The SPRES study results identified that sharing the 1675–1680 MHz band would subject the GOES-R DCS and GRB broadcast signals to an unacceptable level of risk for interference, unless extensive limitations, including power limitations and geographic separation, are imposed. In addition, unless provisions allow for the installation of new earth station receivers when they are required, sharing would impose constraints that could jeopardize future federal missions and spectrum use.

The RFI risks result primarily from three factors:

- the large differences in power levels between LTE signals and satellite signals around receive sites
- the overlap or close proximity of GOES signals with the 1675–1680 MHz band
- the potential for anomalous propagation at many sites

The different GOES-R signals have varying levels of risk:

Extreme Risk: DCS. Sites operating DCS receivers were found to be the most at risk, largely because of overlap between the DCS signal and the 1675–1680 MHz band.

Significant Risk: GRB. The GRB signal, which operates in the adjacent band, also carries a significant risk at the Federal ground stations.

Low Risk: HRIT/EMWIN. The HRIT/EMWIN signal was found to be at low risk in the 1675–1680 MHz sharing scenarios because of the 13 MHz of separation, but it may be at risk from sharing of the 1695–1710 MHz band.

The study also found that current direct broadcast users have requirements for real-time GRB and DCS data, and rely upon the satellite broadcast because of the risk of landline service disruption during severe weather events.

Findings

Finding 1: Anomalous propagation is a significant contributor to RFI risk in this band, particularly in the downlink sharing scenario.

The height and pointing angle of cell towers, combined with the level of radiated power, result in effective transport of energy from towers over many hundreds of kilometers during ducting events. The risk of interference from anomalous propagation was found to be most significant at sites where (1) there are high probabilities of duct formation, particularly along the Atlantic and Gulf coastlines where humidity is high, including at the NOAA Wallops Island, Virginia, site; and (2) there are nearby population centers where high LTE network deployment density is likely.

Finding 2: Spectrum sharing with commercial wireless carriers operating in the *downlink* mode is *not* viable.

The study found that the GOES-R DCS and GRB receive sites would require large physical separation distances from LTE downlink stations—as much as 300 km to protect against 95% of interference events (Figure 10 and Table 2), and as much as 650 km to protect against 100% of

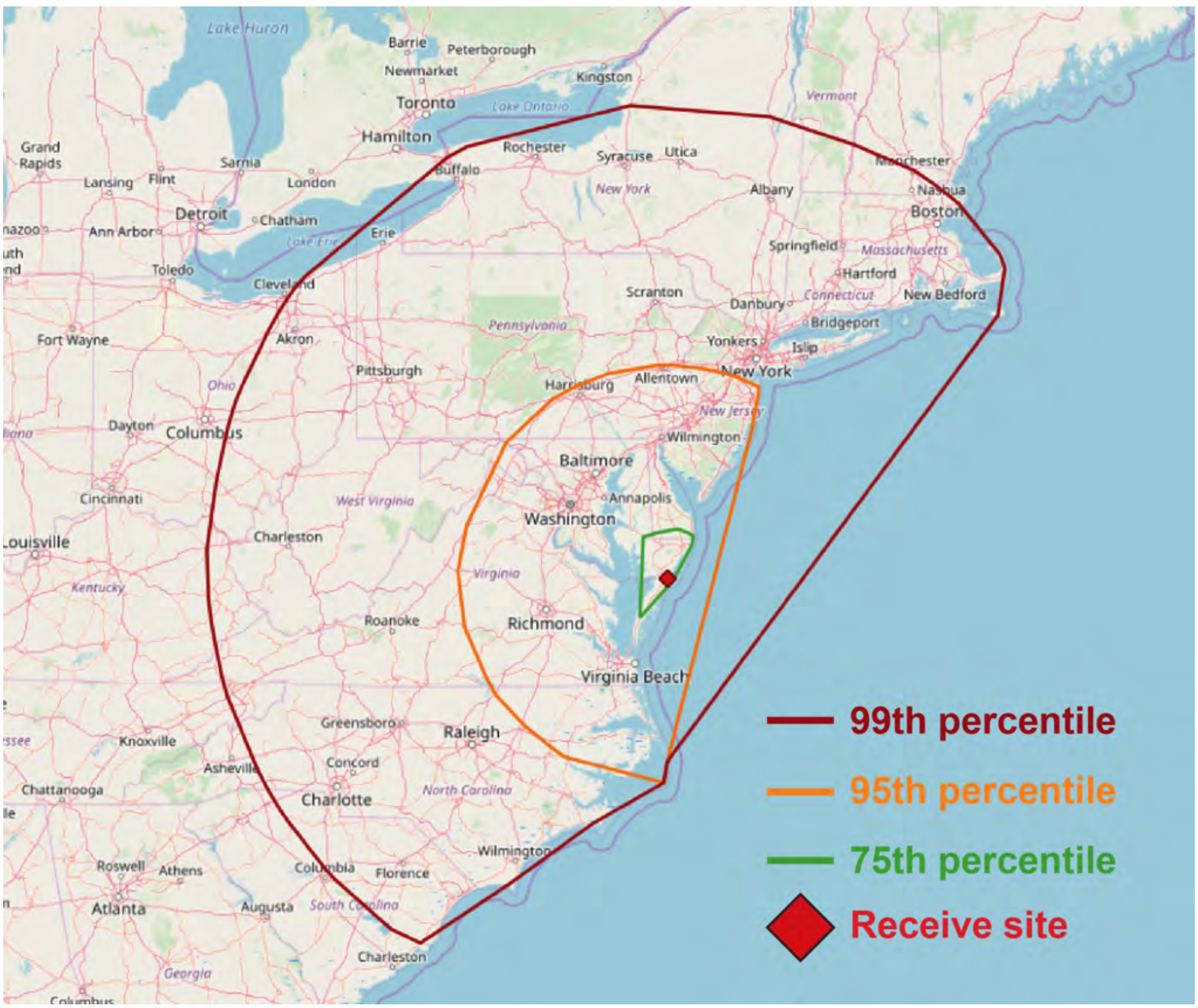


Figure 10. Map showing separation distances for various protection levels around NOAA's Wallops Island site in the event of LTE large-cell downlink deployment. The 95% protection level encompasses much of the Mid-Atlantic region, including Washington, D.C., Baltimore, and Philadelphia.

Table 2. Protection zone sizes for ***downlink*** scenario. Contours provide protection against 95% of RFI events.

GOES receiver	RFI scenario	Maximum separation distance (km)
DCS	LTE downlink	286
GRB	LTE downlink	203
HRIT	LTE downlink	N/A

interference events. This is primarily due to the high (LTE) radiated power levels: at the GOES receivers, downlinks from a cell tower at a distance of 5 km will exceed the power of the GOES satellite signals by more than 30 dB, or 1,000 times. No mitigations were found that were able to significantly reduce the required separation distances or remove the need for the GOES downlink sites.

Finding 3: Spectrum sharing with commercial wireless carriers operating in the *uplink* mode is *potentially* feasible.

The risks to the GOES receive stations are reduced in the LTE uplink mode, because power is reduced, typically by 40 dB or more, compared to LTE downlink signals. Separation distance is still required for DCS and GRB ground stations (Table 3). The study recommends specific mitigation techniques that can reduce separation distances and RFI risk, but these require testing and verification to assess the full benefit and may not eliminate all RFI risk or the need for physical separation.

Table 3. Coordination zone sizes for ***uplink*** scenario. Contours provide protection against 95% of RFI events.

GOES receiver	RFI scenario	Maximum separation distance (km)
DCS	LTE uplink	60
GRB	LTE uplink	20
HRIT	LTE uplink	N/A

Finding 4: Some mitigations may be effective, but only in the *uplink* sharing scenario.

Over two dozen possible mitigation techniques were studied in both the LTE downlink and uplink scenarios. These included GOES antenna and site hardening, GOES receiver improvements, active (RFI) cancellation techniques, RFI monitoring, dynamic protection zones, carrier use of small-cell equipment, and the use of terrestrial rather than satellite dissemination. Most of these proposed mitigations were found to be either incapable of reducing RFI to acceptable levels, excessively expensive to implement, impractical for cellular carriers, or inadequate in meeting the needs of GOES-R product users. The most effective mitigations were those that provided (additional) separation from the GOES signals by moving or truncating the LTE signal below the upper end of the 1675–1680 MHz band. The study found that the mitigations would be effective only for the LTE uplink sharing scenario, and not for the downlink scenario.

Finding 5: The GOES-R direct broadcast signals are essential and must be protected.
The study found that meteorological data collected and disseminated by the GOES satellites and ground system makes significant contributions to public safety and our national water resource management system. GOES-distributed data underpins our national weather infrastructure, including the advance weather warning and forecasting system relied upon by industries including aviation, satellite operations, and maritime shipping, by emergency managers responsible for safeguarding life and property, and by the general public.

Among the 100 DCS and GRB sites, the study found a combination of Federal and non-Federal users, all with compelling missions and business cases. Many of the GRB and DCS earth stations also support other users by distributing downlinked data in near-real time. No viable replacement service was found that could meet the direct broadcast requirements.

The GRB is the primary way that NOAA provides weather and environmental data and products to many of its users. For some extremely time-sensitive applications, such as space weather and lighting maps, distribution via the GRB is the only method that can be used due to the inherent latencies found with other dissemination methods. Overall, L-band direct broadcast provides an efficient means for disseminating large volumes of critical weather data to users in many different locations under most conditions, including severe weather events.

The study further found that DCS is considered critical infrastructure for U.S. Federal agencies including NOAA (including the NWS and National Ocean Service), USGS, DoD, the National Interagency Fire Center, the Bureau of Land Management, the U.S. Army Corps of Engineers, and the U.S. Department of Agriculture's National Forest Service, as well as for international hydrometeorological agencies in Canada, Mexico, Central America, South America, the Pacific, and the Caribbean.

Looking beyond the current GOES-R architecture, any possible sharing scenario may limit existing spectrum use and impact NOAA's ability to design and develop a future satellite communications architecture. Repurposing the 1675–1680 MHz band would restrict the available bandwidth to support next-generation broadcast capabilities.

8. Recommendations

Recommendation 1: Direct broadcast services are vital for the weather enterprise.
As discussed in the Findings, emergency managers, the general public, and many industry segments including aviation, satellite operations, and maritime shipping rely upon meteorological data collected and disseminated by the GOES satellites and ground systems to accomplish their various missions, including safeguarding life and property. The next generation of satellite architectures, including the GEO-XO satellites, should retain the spectrum for direct broadcast L-band services identified in the current filing for 1675–1695 MHz. These services can serve as a benchmark capability as NESDIS considers a broad range of options for sensor acquisition, data processing, and dissemination of data products.

Recommendation 2: Perform testing and verification of mitigations for uplink interference. The risk of radio frequency interference to the satellite receiver stations is reduced in the LTE uplink scenario, as compared to the more powerful LTE downlink signals. Separation distance is still required for DCS and GRB ground stations (Table 3). The report identifies some mitigation techniques and their relative effectiveness to reduce separation distances. These techniques, however, require further testing and verification to assess the full benefit and may not eliminate all RFI risk or the need for separation.

Recommendation 3: Conduct analysis of techniques to establish appropriate frequency separation. The 1675–1680 MHz band proposed for LTE sharing partially overlaps with critical DCS services, and sharing could be improved through frequency separation. Eliminating or reducing the frequency overlap will improve the conditions for sharing, but the amount of separation depends on the GOES receiver design. While frequency separation has potential for implementation in this case, further analysis is needed to assess its feasibility across the various GOES receivers and mobile broadband applications that may be implemented. Therefore, the optimal separation between the shared spectrum band and the lower edge of the DCS signal requires further investigation.

Recommendation 4: Conduct higher-fidelity atmospheric ducting characterization analysis. Further study for characterization of duct size, duration, and variability should be conducted. Existing analyses use duct sizes based on available statistics from current radiosonde locations. While this approach provided a general approximation of duct sizes, higher-fidelity characterizations could be useful to gain a better understanding of interference levels. A possible way to accomplish this analysis is to use a network of ground-based beacons to measure duct characteristics with higher resolution.

9. Summary

Environmental and weather information collected by satellites is crucial to the national security, economic health, and public safety of the United States. This data has a significant impact on the U.S. economy. Economic studies estimate that the benefits and savings attributable to satellite data for aviation, irrigated agriculture, electricity, and natural gas are more than $740 million annually. Satellites perform a number of vital functions, including remote sensing, radio navigation, and communications. These functions involve use of radio frequency spectrum, which is divided into radio frequency bands that are allocated for specific uses. These allocations are designed into the current satellites. Once a satellite is launched into orbit, those radio frequencies cannot be changed. Because radio spectrum is shared by many different users and applications—Federal and non-Federal, television and radio broadcasting, radio astronomy, satellites, GPS equipment, mobile phones, radar, Wi-Fi networks, and dozens more—it is governed by an intricate, apportioned regulatory framework.

Considering both the AWS-3 auction of 1695–1710 MHz and the 2003 auction of the 1670–1675 MHz band, NOAA has already made available half of the original 1670-1710 MHz Met-Sat allocation (20 MHz of the original 40 MHz) for wireless broadband. An additional portion of the remaining essential Met-Sat spectrum (1675–1680 MHz) is being proposed for sharing with LTE wireless broadband. This study examined the feasibility of such sharing, and the results indicate that sharing of the 1675–1680 MHz band without explicit protections for incumbent meteorological satellite services (space-to-earth) in the Federal regulations and implementation of mitigations to reduce RFI risks would subject both Federal and non-Federal users to harmful RFI and loss of data.

A range of mitigations was considered, including alternatives to the GRB and DCS broadcasts. However, there were no terrestrial distribution solutions that met the requirements, functionality, and performance of existing systems. Beyond geographic separation, other mitigations considered require additional assessment and testing.

Spectrum sharing with the commercial wireless carriers operating in the uplink mode is potentially feasible. In this uplink scenario, the risk of radio frequency interference to the satellite receiver stations is reduced, given the far lower transmitter power and height above ground level. However, sharing, even if restricted to uplink mode, may induce unintended risks to incumbent weather data distribution networks, such as a reduction of architecture flexibility (e.g., site expansion or adding sites), and associated costs from indefinite coordination, interference analysis, and interference monitoring.

The volume of weather data is expected to increase in the future as improved instruments are fielded to meet the need for better accuracy and increased warning time. This band has the distinct advantage of resilience in severe weather conditions, even during hurricanes, thunderstorms, and other similar circumstances, when higher-frequency bands perform poorly and terrestrial communication is unreliable. It is in these conditions that direct broadcast transmission would be needed the most.

It is imperative that any proposed changes to the current spectrum allocations carefully consider the findings and recommendations of this study and the measures that must be taken to protect the important incumbent missions from the harmful effects of interference.

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[5]OP license WPYQ831 was originally leased to multiple holders of TVCC One Six Holdings LLC, and subsequently leased in 2010 to One Dot Six LLC, currently owned by Ligado Networks. See lease summary in the FCC's Universal Licensing System, https://wireless2.fcc.gov/UlsApp/UlsSearch/searchLicense.jsp.

[6]U.S. Congress, House, *Bipartisan Budget Act of 2015*, Public Law No: 114-74, 114th Cong., 1st sess., passed November 2, 2015, https://www.congress.gov/bill/114th-congress/house-bill/1314.

[7]U.S. Department of Commerce, National Oceanic and Atmospheric Administration, "GOES DCS Program Update," by Letecia Reeves and Valerie Randall, GOES DCS Technical Working Group (Washington, DC, 2019), https://noaasis.noaa.gov/pdf/docs/TWG2019/0900%20GOES%20DCS%20Program%20Updates.pdf.

[8]Examples include the navigable waterway management mission of the U.S. Army Corps of Engineers (USACE) and the Florida Department of Transportation's causeway bridge wind monitoring application (Randy Pierce, "Comment," "FCC Office of Engineering and Technology Requests Information on Use of 1675–1710 MHz Band," ET Docket 10-123 [June 28, 2010], https://ecfsapi.fcc.gov/file/7020513863.pdf). Both examples are described in Section 3 of the SPRES report.

[9]Alexandra Witze, "Mobile-Phone Expansion Could Disrupt Key Weather Satellites," *Nature* 535 (July 12, 2016): 208-209, https://doi.org/10.1038/535208a.

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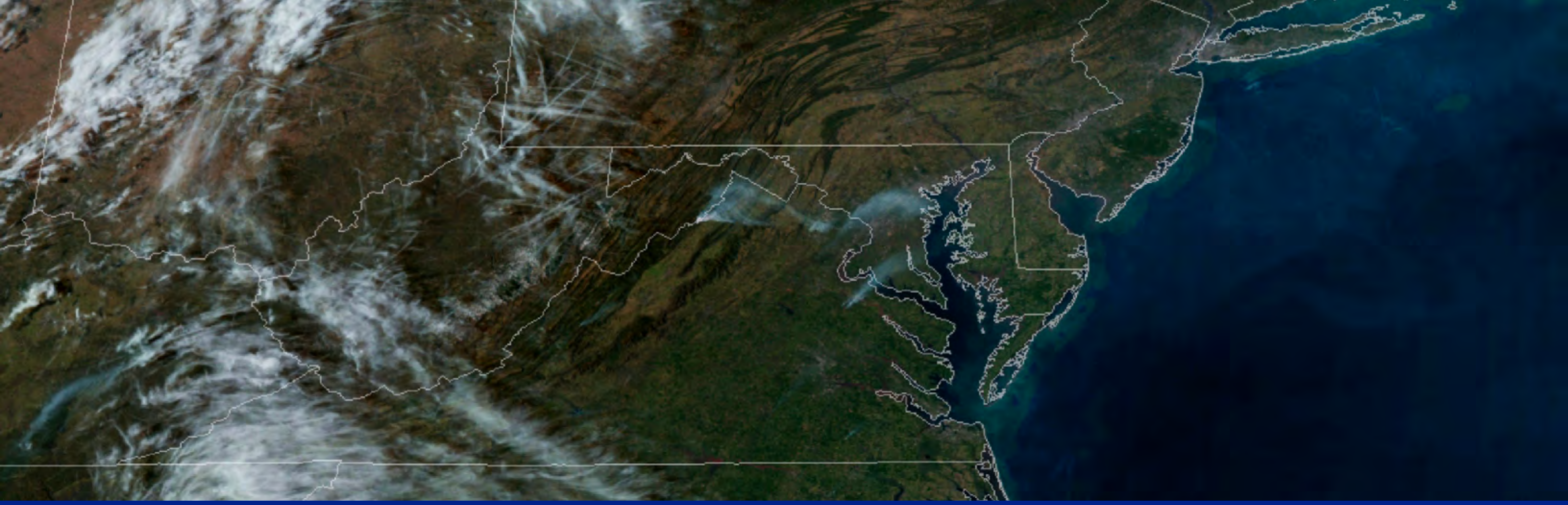

1 Introduction

The Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) are evaluating the reallocation and auction of the 1675–1680 MHz spectrum band to mobile broadband network operators for use on a shared basis with Federal and non-Federal meteorological satellite (Met-Sat) users. The action taken on this particular band is in accordance with both the Spectrum Pipeline Act of 2015[1] and the FCC response proceeding to multiple requests for band access filed by Ligado Networks LLC.[2] Current and future National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellites (GOES) collect and transmit meteorological data and observations in this and the adjacent 1680–1695 MHz band to Federal and non-Federal users. The satellite receivers operated by these users may incur risk of radio frequency interference (RFI) from mobile networks in a shared environment, possibly resulting in data loss or delay. Loss of GOES data, and delays for users in retrieving the data by other means, impedes the ability of numerous agencies to take protective measures based on weather, flood, tidal, and related conditions.

Weather data has a significant impact on the U.S. economy. Although the only comprehensive studies of the economic benefits of weather data date back 11 years, their results can be extrapolated to today. A 2009 economic survey calculated a total value of $31.5 billion per year (in 2007 dollars) to U.S. households for all weather forecast services.[3] Adjusted for 2020 dollars, that would be $39.3 billion annually. A 2007 study estimated the benefits and savings attributable to GOES for the aviation, irrigated agriculture, electricity, and natural gas sectors of the economy to be more than $740 million in forecast 2015 dollars. Those sectors represented about 0.13%

[1]U.S. Congress, House, *Bipartisan Budget Act of 2015*, Public Law No: 114-74, 114th Cong., 1st sess., passed November 2, 2015, https://www.congress.gov/bill/114th-congress/house-bill/1314.

[2]Federal Communications Commission, *Comment Sought to Update the Record on Ligado's Request that the Commision Initiate a Rulemaking to Allocate the 1675-1680 MHz Band for Terrestrial Mobile Use Shared with Federal Use*, DA-16-443, RM-11681, 31 FCC Rcd 3813 (5) (Washington, DC, 2016), accessed May 5, 2020, https://www.fcc.gov/document/ligado-request-allocation-1675-1680-mhz-band.

[3]Jeffrey Lazo, Rebecca Morss, and Julie Demuth, "300 Billion Served: Sources, Perceptions, Uses, and Values of Weather Forecasts," *Bulletin of the American Meteorological Society* 90, no. 6 (2009): 785-798, https://doi.org/10.1175/2008BAMS2604.1.

of value-added 2015 Gross Domestic Product (GDP). Applying these values to the entire U.S. economy in 2020 dollars, the annual value for those sectors of GOES weather data can be estimated at more than $29 billion.[4]

The drive to make Federal spectrum available to mobile Long-Term Evolution (LTE) and 5G networks has already resulted in the clearing of bands where compressing or relocating existing users could be easily implemented. As the costs and complexity of further clearing actions have skyrocketed, and spectrum demand by both government and commercial applications has continued to grow, using spectrum more efficiently has become the only way to satisfy conflicting national goals. Spectrum sharing has become the preferred solution to enable increased commercial use of Federal spectrum and maintain critical Federal operations. Each band considered for sharing requires detailed analysis to ensure that regulations governing the sharing will adequately protect incumbent government functions.

The clear challenge in this case is the enormous difference in signal strength between wireless terrestrial services of any kind and the much fainter—by many orders of magnitude—satellite communications. Satellite signal reception is easily disrupted by interference from ground sources in or near the same frequency band.

In accordance with an NTIA rule governing the procedure to request spectrum relocation funding,[5] the Department of Commerce (DOC) proactively sought and received funding to perform a comprehensive assessment of sharing in the 1675–1680 MHz band. That assessment became the Spectrum Pipeline Reallocation Engineering Study (SPRES). The goals of SPRES are twofold: (1) to quantify the potential impact of sharing to the DOC NOAA meteorological community and users, including those in the Department of Defense (DoD), the Department of Interior (DOI), and the Forest Service and others within the Department of Agriculture (USDA); and (2) to identify possible techniques to facilitate successful spectrum sharing while ensuring the integrity of the NOAA satellite downlink data.

The SPRES program (see organization chart in Appendix C) was initiated in February 2018 to study spectrum sharing between the GOES meteorological satellite service and mobile broadband operations in the United States and its Possessions (US&P).

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[4]Centrec Consulting Group for the National Oceanic and Atmospheric Administration (NOAA), *An Investigation of the Economic and Social Value of Selected NOAA Data and Products for Geostationary Operational Environmental Satellites (GOES)*, report to NOAA's National Climatic Data Center (Savoy, Illinois, 2007), accessed May 5, 2020, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.192.3956&rep=rep1&type=pdf; *Trading Economics*, "United States GDP 1960-2019," accessed May 5, 2020, https://tradingeconomics.com/united-states/gdp.
[5]U.S. Department of Commerce, National Telecommunications and Information Administration, *Implementing Certain Provisions of the Spectrum Pipeline Act with Respect to the Duties of the Technical Panel*, 47 CFR Part 301, Docket No. 160108022–6022–01, RIN 0660–AA31, Document No. 2016-01047, pp. 3337-3338 (Washington, DC, 2016), final rule, accessed May 5, 2020, https://www.federalregister.gov/documents/2016/01/21/2016-01047/implementing-certain-provisions-of-the-spectrum-pipeline-act-with-respect-to-the-duties-of-the.

1.1 Spectrum Sharing Background

In the 225–3700 MHz (low- to mid-band) spectrum range that is preferred for use by commercial wireless networks, 17% of the spectrum was previously allocated for exclusive Federal use.[6] Due to ongoing growth and expansion by the commercial wireless industry, a number of these Federal allocations have been identified for possible reallocation. Complete repurposing of Federal spectrum segments is typically a very difficult process. Most of the straightforward repurposing decisions have already been made, leaving few simple choices for new repurposing efforts. As a result, Federal spectrum is being made available to share with the wireless industry. The 2015 Advanced Wireless Services-3 (commonly known as AWS-3) spectrum reallocation and auction opened the 1695–1710 MHz Met-Sat band to shared use by commercial wireless services providers. Preparations for the auction and sharing found that Federal polar Met-Sat downlink sites could receive RFI from wireless carriers. This RFI risk was mitigated by creating coordination zones around the Federal earth stations (defined in Footnote US88, U.S. Table of Frequency Allocations[7]), and developing coordination processes whereby Federal agencies could study and approve compatible wireless network deployments within the coordination zones. As additional risk reduction, NOAA planned implementation of an RFI monitoring system to quickly identify and locate interference sources. There are two major differences between Federal use of 1695–1710 MHz and 1675–1680 MHz. First, the Federal satellite ground sites utilizing 1695–1710 MHz are actively using the spectrum only when in contact with a site during a satellite pass, which, for most locations, represents less than ten 15-minute intervals per day, per polar orbiting satellite; by contrast, GOES satellites are in contact with the ground sites at all times, and use of the 1675–1680 MHz band is continuous. Second, the 1695–1710 MHz band is allocated for sharing with mobile broadband uplinks, lower-powered transmissions from handheld equipment to a cell tower; by contrast, the proposed sharing for 1675–1680 MHz may involve not only uplinks but also higher-powered downlinks.

Although there is increasing pressure to reallocate government-use spectrum for sharing with commercial users, it is imperative that any proposed changes to the current spectrum allocations be carefully studied to determine the potential for RFI and resulting impacts to important government missions. If shared use of the 1675–1680 MHz band causes RFI to Met-Sat downlinks, the cost to NOAA's mission would be high. Met-Sat data collected and transmitted in this band is used in many industries, from aviation to agriculture, for short- and long-term decision-making, as well as by emergency managers and the general public. Loss of Met-Sat data during a weather event would impede the ability to generate advance warnings and could result in significant loss of property and human life. For these reasons, it is vital to understand the multitude of

[6] Paige R. Atkins, "Understanding Federal Spectrum Use," National Telecommunications and Information Administration, U.S. Department of Commerce, July 30, 2015, https://www.ntia.doc.gov/blog/2015/understanding-federal-spectrum-use.

[7] U.S. Department of Commerce, National Telecommunications and Information Administration, "International Footnotes," section 4.1.3 of the *Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook)*, 47 CFR 300, September 2017 revision of the September 2015 edition (Washington, DC, 2017), pp. 4-131, accessed May 5, 2020, https://www.ntia.doc.gov/files/ntia/publications/ntia_manual_september_2017_revision.pdf. Footnote US88 stated incorrectly that earth stations operating in 1675–1695 MHz are secondary to commercial licensees; in fact, there currently is no such allocation. Also, the zones created for AWS-3 apply only to the provisions set by and interference from AWS-3. The zones and sizes in Footnote US88 are not automatically applicable to this situation.

functions and uses within these bands, along with associated vulnerabilities. The SPRES study was designed to support the decision regarding whether to change the current allocation to shared use or to maintain the status quo, as well as to inform the development of sharing rules in the event of shared use, including assessments of the nature and cost of mitigations to protect incumbent critical functions.

Determining the feasibility of sharing the 1675–1680 MHz band requires in-depth knowledge of the technical characteristics of the Met-Sat systems operating in the band, the proposed LTE-based technology, and the interference mechanisms between the two. SPRES is designed as an objective and comprehensive study on sharing in this band, covering all types of radio frequency (RF) interactions. SPRES also seeks to examine the potential effects of these interactions before any proposed conditions are defined in the next steps of the regulatory process, following the FCC's 2019 Notice of Proposed Rulemaking (NPRM).[8]

Figure 1.1-1 indicates the Met-Sat spectrum band plan with the current (1695–1710 MHz) and proposed (1675–1680 MHz) shared bands.

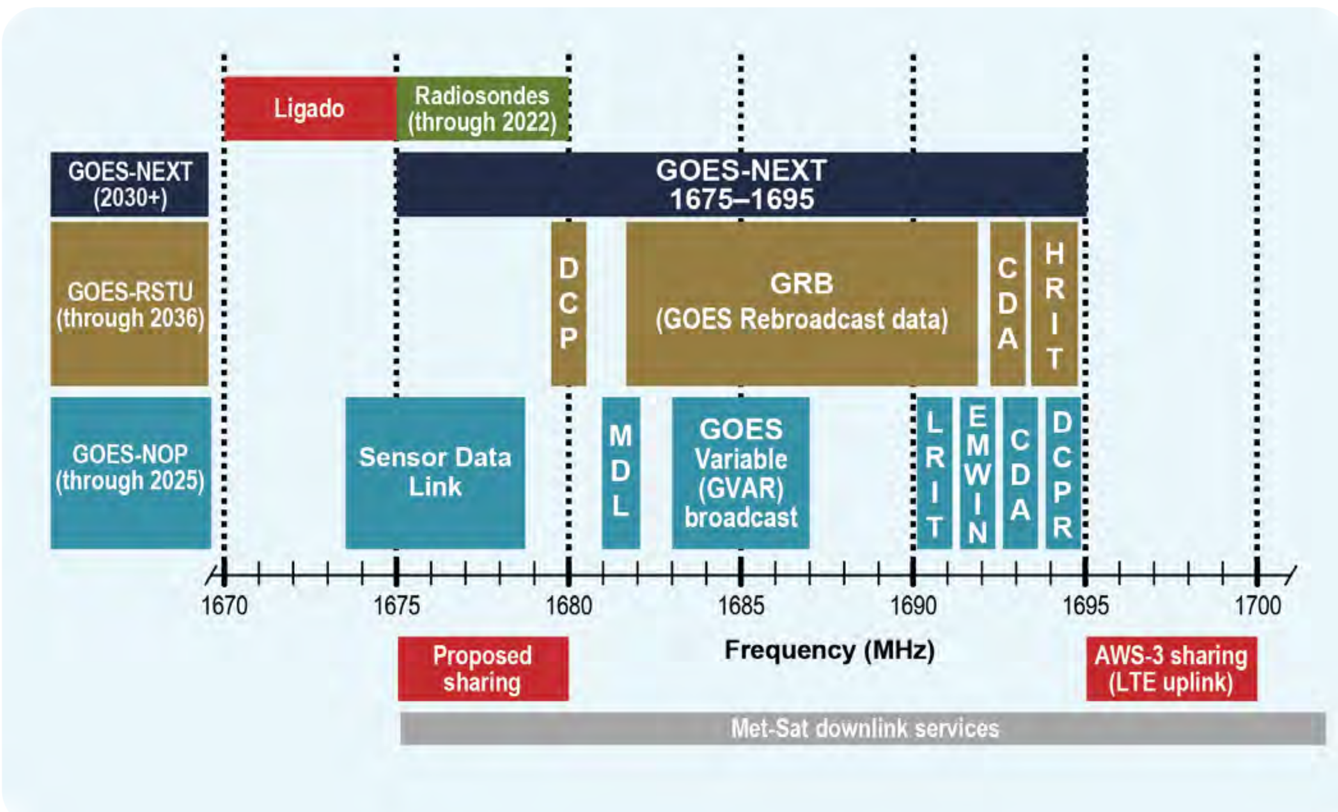


Figure 1.1-1. GOES downlink services bands and current/proposed AWS bands.

[8] U.S. Department of Commerce, National Telecommunications and Information Administration, Allocation and Service Rules for the 1675-1680 MHz Band, 47 CFR 1, 47 CFR 2, 47 CFR 27, WT Docket No. 19-116, FCC 19-43, Document No. 2019-10675, pp. 23508–23519 (Washington, DC, 2019), proposed rule, accessed May 5, 2020, https://www.federalregister.gov/documents/2019/05/22/2019-10675/allocation-and-service-rules-for-the-1675-1680-mhz-band; Federal Communications Commission, *FCC Moves to Open Airwaves for Mobile Services in 1675-1680 MHz Band*, FCC-19-43, RM-19-116, 34 FCC Rcd 3552 (4) (Washington, DC, 2019), accessed May 5, 2020, https://www.fcc.gov/document/fcc-moves-open-airwaves-mobile-services-1675-1680-mhz-band.

1.2 Study Objectives

The overall study objectives are grouped in three broad topic areas:

- GOES data use. Establish a user/customer data flow and user-needs baseline for Federal users; map the flow of GOES data to users and applications and determine the impact of loss or degradation of that data. Using this information, derive user requirements for receiving the data.
- RFI modalities and risks. Characterize any potential RFI modalities to GOES receivers and quantify RFI risks resulting from sharing with terrestrial wireless networks.
- Mitigation options and feasibilities. Identify RFI monitoring and/or mitigation solutions, including exclusion zones, alternative dissemination architectures, and other methods. Assess the feasibility and effectiveness of these solutions.

1.3 Assumptions

The following assumptions about the current and future operating environments and requirements guided the development and execution of this study:

1. One or more Advanced Wireless Services (AWS) operators will deploy a nationwide mobile wireless LTE network in the 1675–1680 MHz band.

2. The LTE wireless carrier(s) may ultimately occupy 1675–1680 MHz only, or may occupy 1670–1680 MHz, as 1670–1675 is already allocated for fixed/mobile terrestrial use. The analysis is different for each case. A 5 MHz carrier in 1675–1680 MHz will have guard bands of 250 kHz on either side, while a 10 MHz carrier signal would have guard bands of 500 kHz on either side. Per the channel bandwidth requirements in the 3GPP standards, the LTE wireless carrier uses 10% of the allocated bandwidth for guard bands (i.e., 9 MHz of transmission bandwidth out of 10 MHz channel bandwidth for the 1670–1680 MHz case), divided such that 5% is placed at each end of the channel.

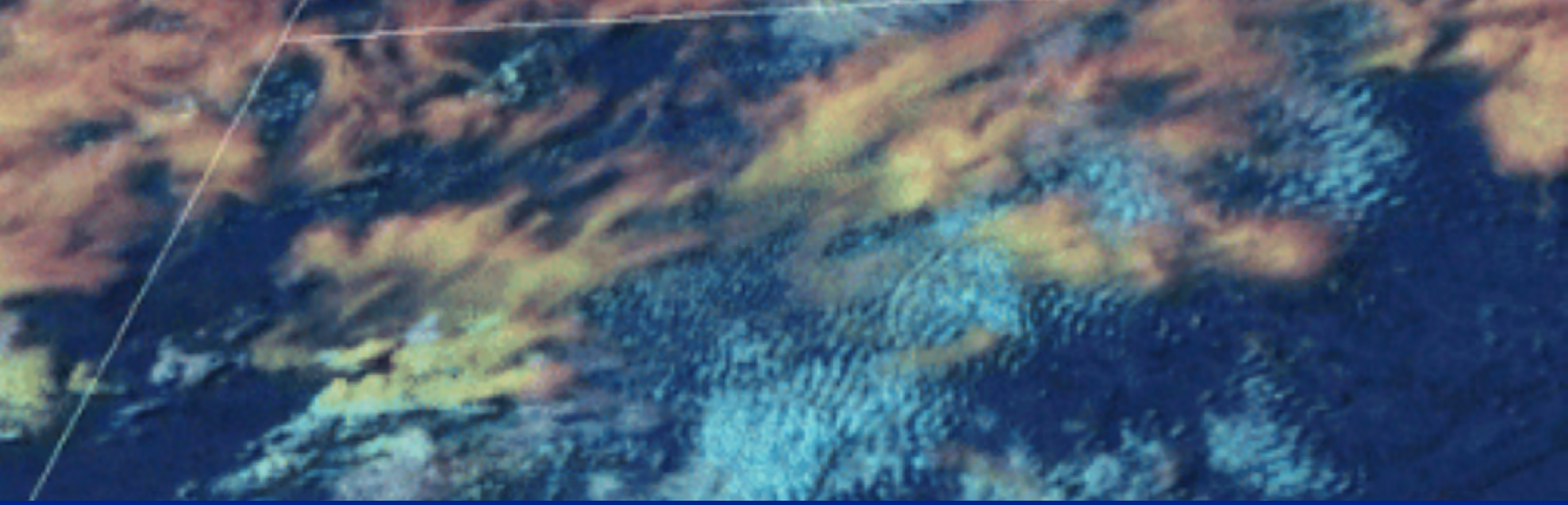
3. LTE can operate in the downlink (base station to user equipment) or uplink direction. If LTE downlinks were to be implemented in the 1675–1680 MHz band, the recommended separation of 50 MHz from the existing AWS uplink services operating in the 1695–1710 and 1710–1755 MHz bands would not be met.[9] However, the study assumes that this will not be a constraint, and that the entrant will resolve potential RFI issues with AWS-3 and AWS-1 incumbent(s) by implementing appropriate filtering and other techniques.

[9] International Telecommunication Union, "Frequency Arrangements for Implementation of the Terrestrial Component of International Mobile Telecommunications (IMT) in the Bands Identified for IMT in the Radio Regulations," Rec. ITU-R M.1036-5 (Geneva, Switzerland, 2015), https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.1036-5-201510-S!!PDF-E.pdf; Bill Alberth, "Duplex Spacing," Federal Communications Commission Technical Advisory Committee, July 2012, accessed May 5, 2020, https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting71612/PANEL2.5-Alberth-Motorola.pdf; Erika Tejedor, "Band Planning: UL-DL Frequency Separation," Federal Communications Commission Technical Advisory Committee, July 16, 2012, accessed May 5, 2020, https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting71612/PANEL2.4-Tejedor-Ericsson.pdf.

4. NOAA’s next-generation weather satellite system, Geostationary and Extended Orbits (GEO-XO), may require 20 MHz (1675–1695 MHz) for L-band broadcast services to ac- commodate higher data throughputs associated with enhanced meteorological sensing instrumentation. An approved Federal certification (under the name GOES-NEXT) exists for such use. Planning for the next generation is underway, but as of the completion of this study, there is no approved system architecture and GEO-XO spectrum requirementsare not yet defined.

5. Different generations of GOES satellites will coexist for continuity of service. Operational overlap exists between the legacy GOES and the GOES-R series, and will occur between the GOES-R series and GEO-XO. Based upon current filings, this implies Met-Sat continuous use of the 1675–1695 MHz band through 2037 and beyond. GOES-14 and GOES-15 legacy satellites will operate until 2025, and GOES-R series satellites will operate through 2036.

6. Per the Pipeline Request Document, the scope of the study was limited to a comprehensive examination of Federal users. However, non-Federal users were identified in some projects because of weather data linkages and interoperability. The results of this study, including any mitigation techniques, will be shared with the non-Federal users for possible implementation. The complex interaction between all parts of the weather enterprise should not be discounted, and the demarcation between Federal and non-Federal operations is not straightforward.



2 | Program Flow, Approach, and Methodology

2.1 Program Flow

The program flow describes the interrelationships and sequencing of the 11 discrete projects, as indicated in Figure 2.1-1. The projects built on each other and led to four specific results, as indicated on the right side of the figure.

- Project 4 created a set of costed alternative terrestrial data distribution architectures for providing reliable and timely data services to GOES users.
- Project 5 produced GOES-NEXT downlink recommendations for increasing throughput and mitigating interference.
- Project 7 established the definitive GOES interference protection criteria and associated spectrum-sharing rules.
- Project 10 generated NOAA ground station interference monitoring requirements and features.

The remaining seven projects collected, analyzed, and developed information required to achieve those results. In meeting the overall program objectives, Projects 1 and 2 were accomplished early in the study in order to support the first objective (GOES data use) and to guide the prioritization of the options identified in the other two objectives (RFI modalities and risks, mitigation options and feasibilities), which were met by Projects 4, 5, 7, and 10. The intervening Projects 3, 6, 8, 9, and 11 were logically sequenced to (1) draw upon results of the initial projects and (2) provide input to the concluding projects.

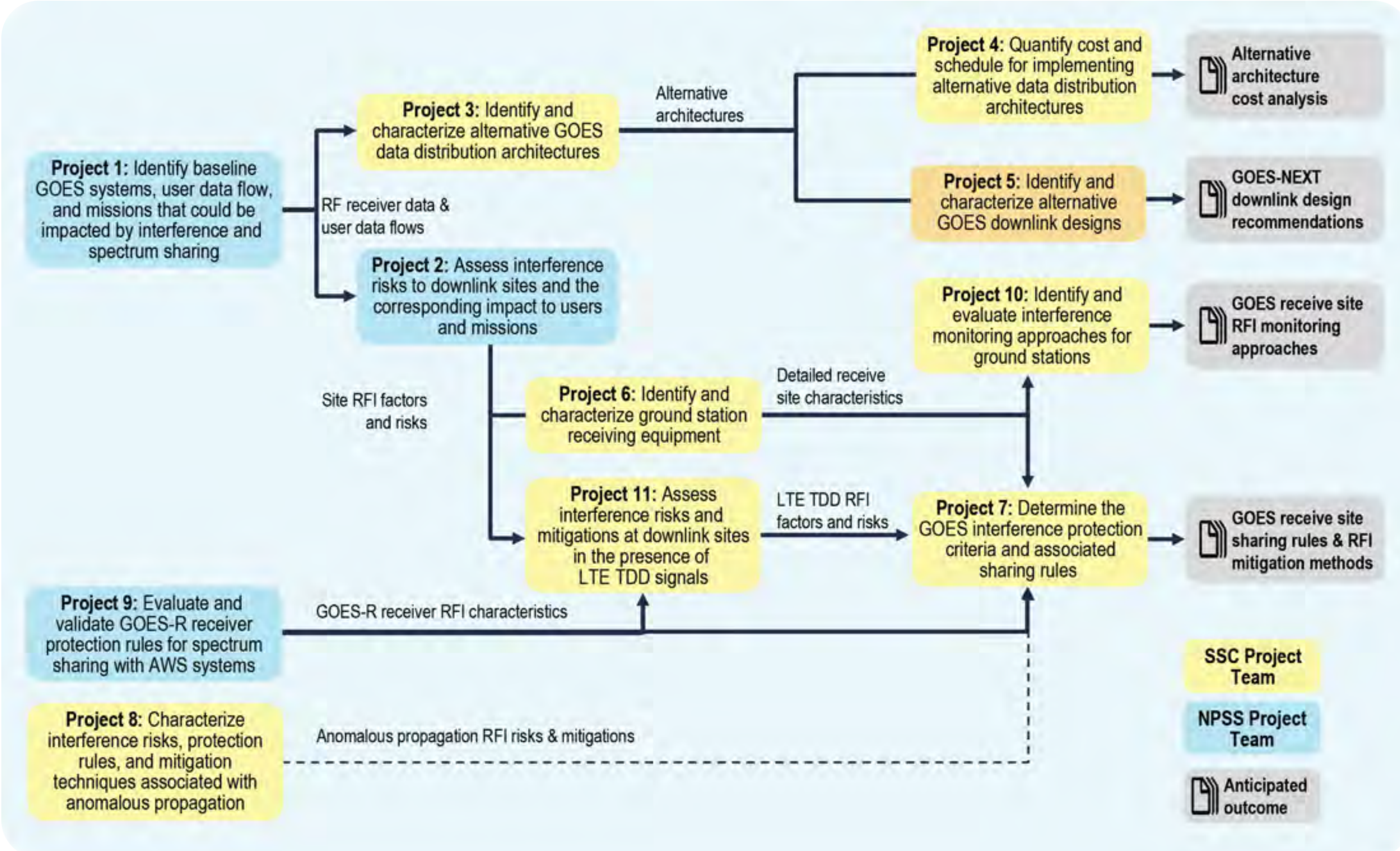


Figure 2.1-1. SPRES project flow.

2.2 Approach and Methodology

Information about end users and Met-Sat related ground systems was gathered by researching existing documentation; conducting mailed, online, and telephone surveys with users; and traveling to numerous Federal ground stations to conduct measurements and testing. The study determined site performance characteristics in nominal as well as potentially interfering environments by performing testing with a combination of radiated and line-injected signals. Due to constraints of time and availability, not all types of GOES receivers could be tested. For environments where RF testing would have been too costly or time-consuming, such as in the case of anomalous propagation (AP), location-specific parametric models and simulations were used. Lastly, in the development of mitigation techniques and future architectures, parametric analysis was done using existing data as well as results gathered from the testing and analysis conducted in this study.

2.3 Study Constraints and Contracting Approach

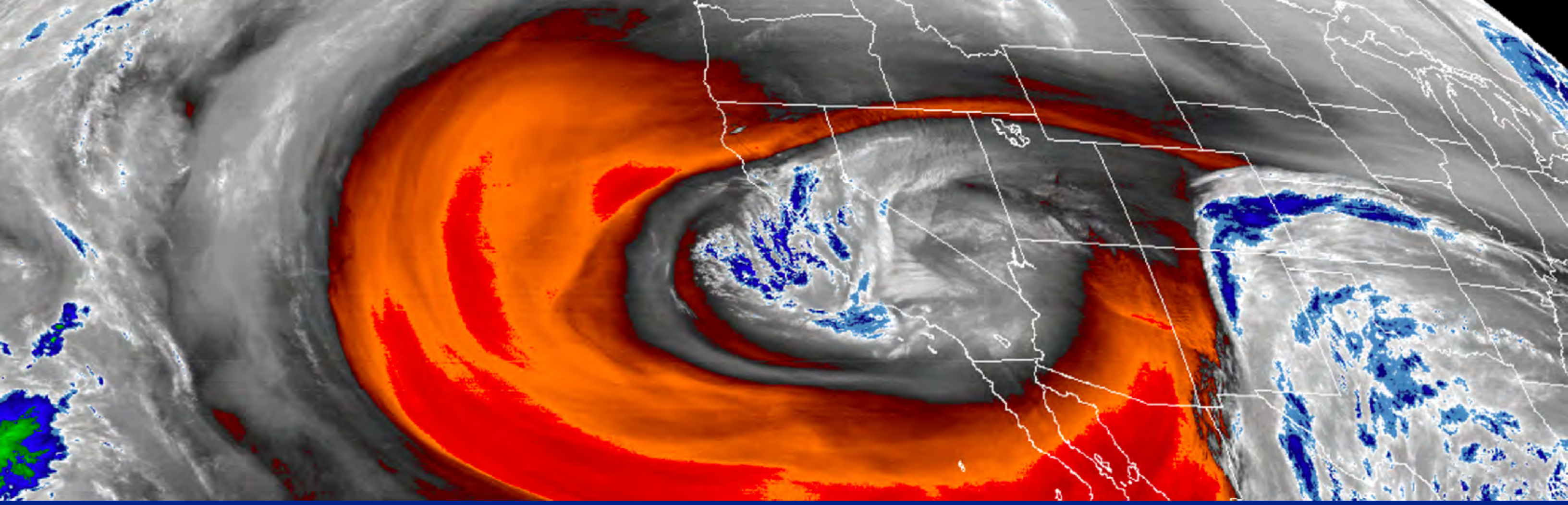
The contracting approach was designed to provide flexibility and the highest-quality study products. This involved multiple acquisition efforts and a longer schedule.

1. The program acquisition strategy was to create a pool of qualified bidders and compete the various projects among them. NOAA therefore began by competitively selecting qualified vendors and awarding them indefinite delivery/indefinite quantity (IDIQ) contracts. Each of the 11 projects within the program was then separately competed and awarded as a task order. As the study encompassed a wide range of technical areas and skillsets, this contracting flexibility allowed NOAA to match task orders to vendors' technical strengths and to evaluate vendor performance on an ongoing basis prior to additional awards. The IDIQ structure also allowed for continuity between studies in a small-business environment.

2. Market research conducted by NOAA acquisition officials indicated the studies could be completed by small businesses, requiring the procurement to follow appropriate procurement rules as defined by the Small Business Administration (SBA).

3. Some individual projects were dependent upon results of other projects, and as a result were impacted by delays in completion of the prerequisite projects.

4. The study was estimated to be completed within two years, assuming no margin or significant changes once underway.



3 | Study Findings

This section summarizes the results and findings of the study according to the overall program objectives.

3.1 GOES Data Use and User Requirements

This section discusses GOES data and mapping of the data flow to Federal users, identifies GOES Federal users and applications, addresses the impact of data loss, and derives data availability requirements, including for latency sensitivity and accessibility.

3.1.1 GOES data flow and mapping

Figure 3.1-1 depicts the current/operational GOES system architecture, which consists of satellites, ground stations, product development facilities, and dissemination infrastructure. The GOES-R series is NOAA's current fleet of geostationary environmental satellites. The "R" refers to the 16th of the series and represents a major upgrade to the previous -N/-O/-P satellite architecture. The four GOES-R class satellites, GOESR/S/T/U, are essentially identical for the purposes of this study.[1]

The GOES-R system utilizes satellites at 75.2° west longitude (GOES-East) and 137.2° west longitude (GOES-West). NOAA also maintains on-orbit spares (GOES-14 and GOES-15, from the previous series) in the event of an anomaly or failure of GOES-East or GOES-West. The GOES-East mission is currently fulfilled by the GOES-16 satellite, and GOES-West by GOES-17.

The GOES-R onboard meteorological sensors provide advanced imagery and atmospheric measurements of earth's weather, oceans, and environment; real-time mapping of total lightning activity; and improved monitoring of solar activity and space weather. Specifically, the GOES-R series was developed to provide:

[1]GOES satellites are denoted by an alphabet letter before they arrive in geostationary orbit, after which they are denoted by a number.

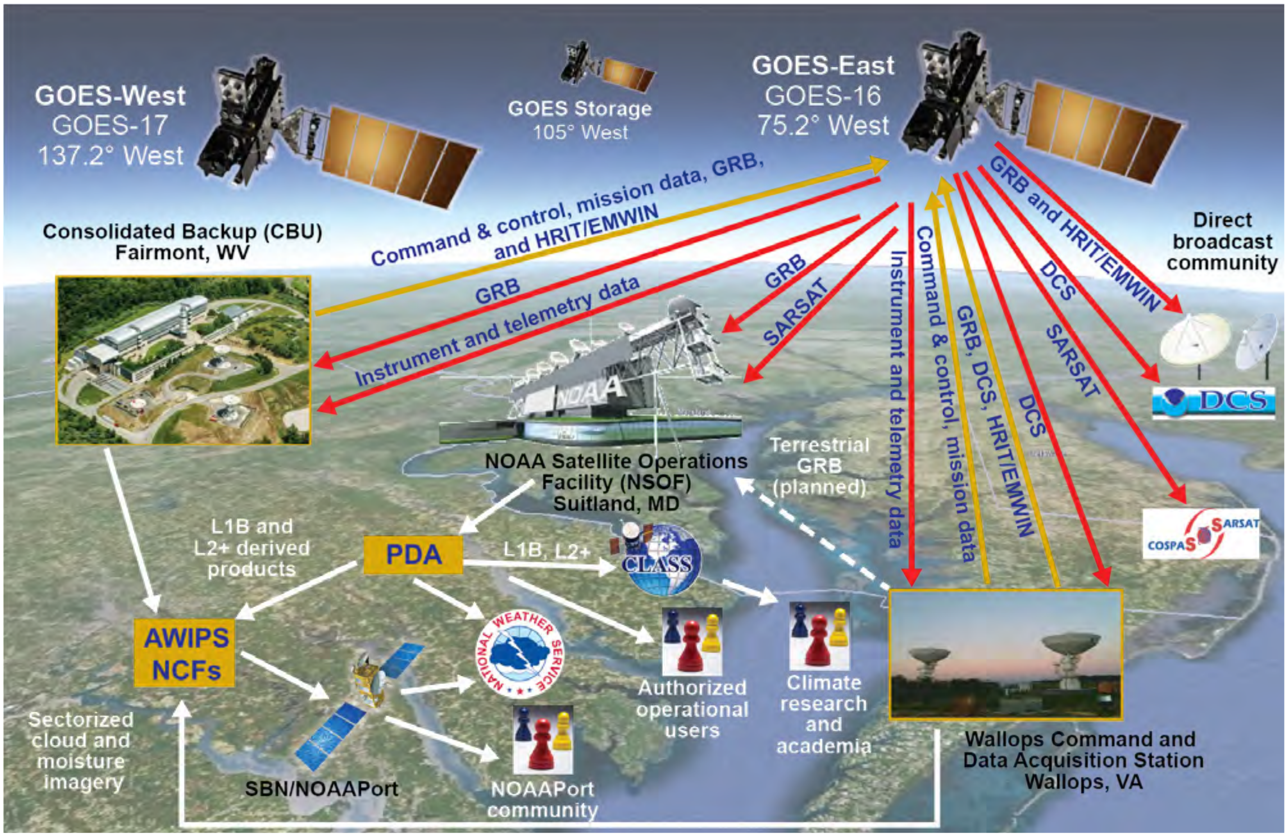


Figure 3.1-1. GOES-R system architecture.

- Improved hurricane track and intensity forecasts
- Increased thunderstorm and tornado warning lead time
- Earlier warning of lightning ground-strike hazards
- Better detection of heavy rainfall and flash flood risks
- Better monitoring of smoke and dust
- Improved air-quality warnings and alerts
- Better fire detection and intensity estimation
- Improved detection of low cloud/fog
- Improved transportation safety and aviation route planning
- Improved warning for communications and navigation disruptions and power blackouts
- More accurate monitoring of energetic particles responsible for radiation hazards

Achieving the performance goals set for GOES-R required the satellites' onboard instruments to provide significantly higher resolution. This led to a corresponding increase in data quantity, with 30 times more data sent to the ground. As a result, GOES-R outgrew previous GOES communication spectrum requirements, which had been met with all data links implemented in L-band. By contrast, GOES-R transmits *unprocessed* (raw) satellite sensor data via a wideband X-band (8220 MHz) channel to the NOAA primary ground sites, and uses the Met-Sat allocation in L-band (1675–1695 MHz) to disseminate *processed* sensor data to users. In particular, GOES-R operates the GOES Rebroadcast (GRB), the High Rate Information Transmission/Emergency Managers Weather Information Network (HRIT/EMWIN) service, and the Data Collection System (DCS) in L-band. The DCS service relays messages primarily from land-based sensor platforms and tsunami buoys deployed around the Western Hemisphere to NOAA and other users' ground stations using transponders on GOES satellites, while the GRB and HRIT/EMWIN broadcasts consist of processed satellite data and imagery. Figure 1.1-1 (Section 1) indicates the Met-Sat spectrum band plan with the current and proposed shared bands, while Table 3.1-1 provides additional detail on the GOES-R signals.

Table 3.1-1. Key characteristics of the GOES-R L-band signals.

GOES-R signal	Center frequency	Channel	Data rate
DCS	1680.1 MHz	1679.7–1680.14 MHz (300+ signal channels*)	300/1200 baud
GRB	1686.6 MHz	1681.15–1692.05 MHz	31 Mbps
HRIT/EMWIN	1694.1 MHz	1693.5–1694.7 MHz	400 kbps

*Due to internationally agreed channelization of DCS systems, most use of DCS in the Americas falls below 1680 MHz. The GOES satellites support the worldwide DCS spectrum coverage that includes frequencies used by Japan, European countries, and other international users, extending to 1680.4 MHz.

L-band spectrum is used to broadcast Met-Sat information because it has robust propagation characteristics, making it generally immune to disruption from weather, and because appropriate ground antennas are readily available and moderately priced. Figure 3.1-2 depicts the ground coverage of the GOES satellites, representing the geographic range of the direct broadcast services for earth stations assuming a 0-degree elevation angle.

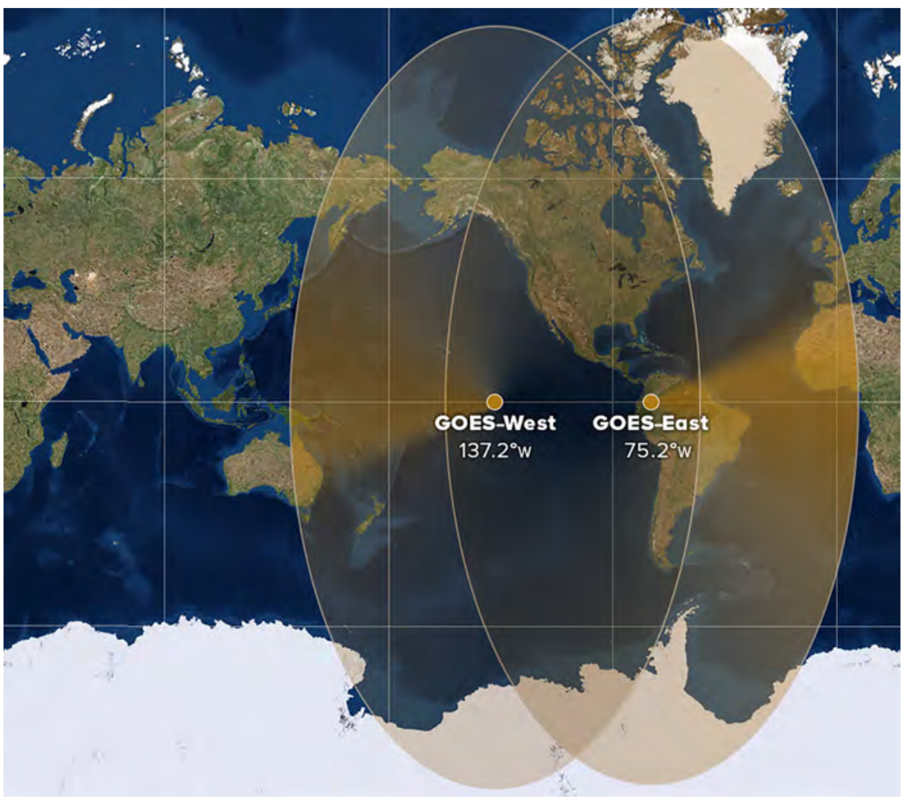


Figure 3.1-2. Geographic extent of the GOES-R direct-broadcast footprint.

As shown in Table 3.1-1, GOES-R spectrum use directly overlaps the study band from 1679.7–1680 MHz, in addition to supporting downlink services in the (upper) adjacent band. GOES-NOP spectrum use has significantly more overlap of the study band (Table 3.1-2). As indicated in Figure 1.1-1 (Section 1), two GOES-NOP satellites, GOES-14 and GOES-15, will be maintained as backups in the event of a GOES-R satellite failure until 2025.

Calculations and measurements taken during Project 6 established that the GOES-R HRIT signal was not at significant risk of RFI from the proposed shared band (1675–1680 MHz) due to a 13 MHz separation. As a result, HRIT users were not specifically studied, although there was significant overlap between HRIT and DCS users. As shown in Table 3.1-3, there are large numbers of users of the GRB and DCS services, who access the services both directly and indirectly. The GRB and DCS data flows and users are discussed in the following sections.

Table 3.1-2. Key characteristics of selected GOES-NOP L-band signals.

GOES-NOP signal	Center frequency	Channel	Data rate
Sensor Data (SD)	1676 MHz	1673.4–1678.6 MHz	5.2 Mbps
Multi-use Data Link (MDL)	1681.478 MHz	1681.278–1681.678 MHz	400 kbps
GOES Variable (GVAR)	1685.7 MHz	1683.59–1687.81 MHz	4.22 Mbps

Table 3.1-3. GOES user statistics.

User type by data access method/GOES signal	GRB	DCS	HRIT
Direct broadcast receivers (owned and operated GRB, DRGS, or direct-receive earth stations)	66	44	N/A
Indirect users (obtain data from a rebroadcast [i.e., HRIT, NOAAPort/SBN, GEONETCast], or terrestrially from databases maintained by NOAA or another entity)	97 known user group members, likely additional users	434+	80
Total:	163+	478+	80
Sources: GRB User Group list and NOAA DCS Program Office as of 2019.			

3.1.1.1 GOES Rebroadcast

GOES Rebroadcast (GRB) is a dissemination service that replaces the GOES Variable (GVAR) service provided by the GOES-NOP series. GRB provides the primary relay of full-resolution, calibrated, near-real-time, direct-broadcast, Level 1b and Level 2+ Geostationary Lightning Mapper (GLM), weather, and meteorological imagery products. The levels refer to the amount of processing applied to the sensor data. GOES-R defines these levels as ranging from Level 0 to Level 2+, as shown in Table 3.1-4. Level 0 represents raw data, while Level 2+ data has had the greatest amount of processing applied. As described in the next sections, the Level 1b and Level 2+ products drive meteorological prediction and research among a wide array of users in the Federal and private sectors.

Table 3.1-4. Categories of GOES-R sensor-derived data.

Product level	Definition	Notes
0	L0 data is the unprocessed instrument data at full resolution.	The Level 0 products are composed of Consultative Committee for Space Data Systems (CCSDS) packets that contain all of the science, housekeeping, engineering, and diagnostic telemetry data from all GOES-R science instruments. The Level 0 product files also contain orbit and attitude/angular rate packets generated by the spacecraft.
1b	L1b data is the L0 data processed with radiometric and geometric correction applied to produce parameters in physical units.	GRB Level 1b image products are produced from Level 0 data files from all GOES-R instruments except the Geostationary Lightning Mapper (GLM).
2+	L2+ data is derived environmental variables generated from L1b data, along with other ancillary source data.	GRB Level 2+ products are created from GLM data files.

3.1.1.1.1 GRB data flow

The GOES-R satellite includes six instruments or instrument suites:

- Advanced Baseline Imager (ABI)
- Geostationary Lightning Mapper (GLM)
- Space Environment In-Situ Suite (SEISS)
- Magnetometer (MAG)
- Extreme Ultraviolet and X-ray Irradiance Sensor Instrument (EXIS)
- Solar Ultraviolet Imager (SUVI)

These instruments are described here and in Table 3.1-5. The main imaging instrument on the GOES-R series is the Advanced Baseline Imager (ABI), which obtains reflected and radiated energy from the earth in 16 spectral bands. The ABI has three modes of operation. The continuous full-disk mode, known as Mode 4, continuously scans the hemisphere visible to the satellite, generating a full-disk image every 5 minutes. In Mode 3, the ABI produces a full-disk image every 15 minutes, a continental United States (CONUS) image (resolution 3000 x 5000 km) every 5 minutes, and two mesoscale domains (resolution 1000 x 1000 km) every minute, or one domain every 30 seconds if it is set to that scanning rate. Mode 6 provides the same CONUS and mesoscale imagery as Mode 3, while reducing the cadence of full-disk imagery from 15 to 10 minutes. Mode 6 (currently the operational “flex” mode) is used to obtain more frequent data associated with localized geographic areas (mesoscale) where critical weather systems are evolving.

The second nadir pointing sensor, the Geostationary Lightning Mapper (GLM), provides semi-hemispherical coverage of lightning events by detecting photon emissions associated with lightning events. GLM is a new sensor on the GOES-R series satellite used to improve prediction of the onset of severe convective weather events.

The four remaining sensors are collectively termed “space weather sensors” and make measurements of the space environment that impact terrestrial and space-based resources. The Space Environment In-Situ Suite (SEISS) consists of five sensors measuring protons, electrons, and ions over a broad range of energy levels. The Magnetometer (MAG) is used to measure and map the magnetic field within the space environment and determine the level of geomagnetic activity. The Extreme Ultraviolet and X-ray Irradiance Sensors (EXIS) measure variability in solar radiation at wavelengths that have been shown to affect the earth’s atmospheric and terrestrial environment. Solar Ultraviolet Imager (SUVI) acquires full-disk images of the sun at a high cadence in the extreme ultraviolet range to predict changes in the earth’s ionospheric and magnetospheric conditions that can have adverse impacts on communication and electrical distribution systems. Some of these space weather sensor products have extremely low latency requirements for reporting, on the order of two to three seconds, and they utilize GRB to meet that latency.

The GRB data stream is generated by the GOES-R ground segment at either the primary site, Wallops Command and Data Acquisition Station (WCDAS) in Wallops Island, Virginia, or at the backup site, the Consolidated Backup Unit (CBU) in Fairmont, West Virginia. These sites continuously downlink Level 0 data in X-band from both the GOES-East and GOES-West satellites. The

L0 data is used to generate Level 1b (L1b) products and the Level 2+ (L2+) GLM products, which are uplinked by the designated primary ground site in X-band to the GRB transponder onboard the spacecraft. The satellite then rebroadcasts that data over the satellite footprint to GRB receivers in L-band. Figure 3.1-3 shows the data flow path from acquisition at the satellite to receipt by the GRB user. The GLM-enabled dissemination of lightning information in near-real time, on a continuous basis with other observable data, provides invaluable data to aid weather forecasters in detecting severe storms in time to give advance warning to the public.

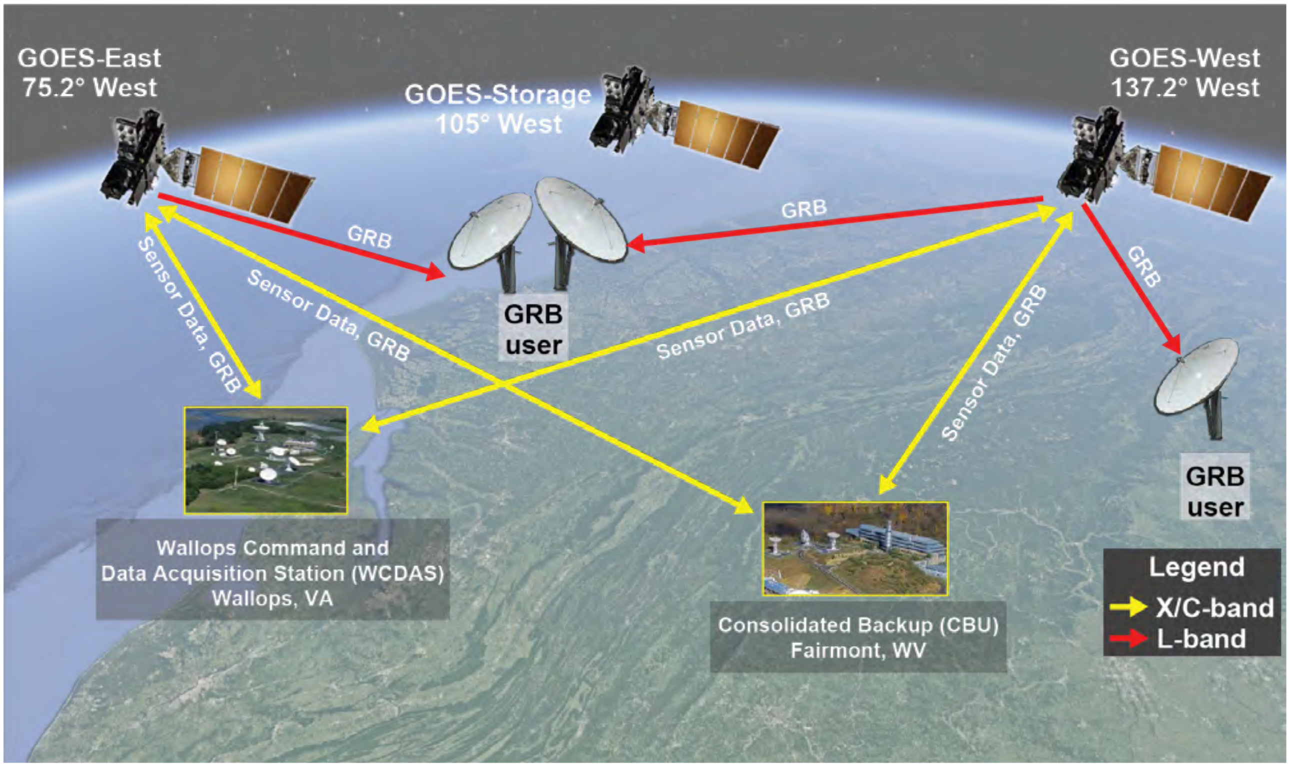


Figure 3.1-3. Flow of GOES-R sensor data to NOAA ground processing sites where GRB is generated, uplinked to the satellite, and broadcast to GRB users.

GRB product scenes, the sensors those products are derived from, and the product refresh rates are shown in Table 3.1-5. In addition to the refresh rates, which are effectively the data acquisition period on the spacecraft, there are latencies induced by the ground processing system to convert L0 products to L1b and L2+ products prior to broadcast over GRB. These quantities are captured in columns 4 and 5 of the table. Understanding the product refresh rates and the time required by the GOES-R ground segment to process GRB products gives an indication of the maximum latency an alternative distribution system can induce. For instance, if GLM products are being distributed every 20 seconds, the distribution system must be capable of distributing products at that cadence; otherwise an ever-growing backlog will accumulate. However, it should be noted that this is the maximum time allocated to the ground processing equipment. Actual processing times are shorter in some cases; for example, an L1b radiance may be used to produce a higher L2+ product with its own latency requirements that drive the L1b product to be produced in a shorter time span.

Table 3.1-5. GOES-R satellite sensors, GRB products, geographic coverage, and product refresh rates.

Sensor	Product name	ABI scene	Product refresh rate/ coverage time	Ground processing time (seconds)
Geostationary Lightning Mapper (GLM)	Lightning Detection: (1) Events (2) Flashes (3) Groups	Full-disk	20 seconds	18
Advanced Baseline Imager (ABI)	Radiances, mode 4	CONUS	5 minutes	55
		Full-disk	5 minutes	55
		Mesoscale	0.5 minute	28
	Radiances, mode 6	CONUS	5 minutes	55
		Full-disk	10 minutes	55
Space Environment In-Situ Suite (SEISS)	Energetic Heavy Ions	—	5 minutes	267
	Magnetospheric Electrons and Protons: Low Energy	—	1 second	51
	Magnetospheric Electrons and Protons: Medium and High Energy	—	1 second	51
	Solar and Galactic Protons	—	1 second	51
Magnetometer (MAG)	Geomagnetic Field	—	1 second	1.8
Extreme Ultraviolet and X-ray Irradiance Sensors (EXIS)	Solar Flux: EUV	—	0.5 minute	28
	Solar Flux: X-ray	—	1 second	1.8
Solar Ultraviolet Imager (SUVI)	Solar Imagery: X-ray	—	10 seconds	54

Note: The Lightning Detection; Solar Flux: X-Ray; Magnetospheric Electrons and Protons: Low Energy; Magnetospheric Electrons and Protons: Medium and High Energy; Solar and Galactic Protons; and Geomagnetic Field products have a refresh rate of 1 second, and have metadata that is aggregated for a set of observations over the immediately preceding time interval, typically at 30 seconds.

3.1.1.1.2 GRB user community

The National Environmental Satellite, Data, and Information Service (NESDIS) has accounted for 66 Federal and non-Federal GRB sites (as of January 2, 2020), as indicated in Table 3.1-6, and an additional 15 sites are planned. Some sites have more than one receive station (antenna). There are 90 receive stations (antennas) in total. Many of the sites use the Community Satellite Processing Package software, developed by the University of Wisconsin–Madison Space Science and Engineering Center (SSEC), which enables the GRB user to process the GOES-16 and GOES-17 GRB data streams and reconstruct the products that were generated in the ground system. It also enables the user to further process the ABI data to generate Level 2+ products.

Table 3.1-6. Summary of the primary users of GRB direct broadcast services.

Summary of GRB users			
User type	Number of users	Percent of total	Planned
Academic	3	4.5	1
Commercial	15	22.7	0
Federal	21	31.8	6
- Department of Commerce	*10*	15.2	1
- Department of Defense	*8*	12.12	5
- National Aeronautics and Space Administration	*3*	4.5	0
International	27	40.9	7
Total	66	99.9	15
Source: NOAA Program Office.			

3.1.1.2 Data Collection System

The Data Collection System (DCS) consists of the three components depicted in Figure 3.1-4. The Data Collection Platform (DCP) uses a sensor to acquire data, which is formatted and uplinked to the GOES-East or GOES-West satellite via a UHF directional antenna. The GOES-R satellite transponder receives the UHF signal and retransmits that data in L-band within its footprint. The data user acquires the L-band signal using a Direct Readout Ground Station (DRGS).

There are 43 installed DCS DRGS direct broadcast receivers known to NOAA. These belong to various user communities, as indicated in Table 3.1-7.

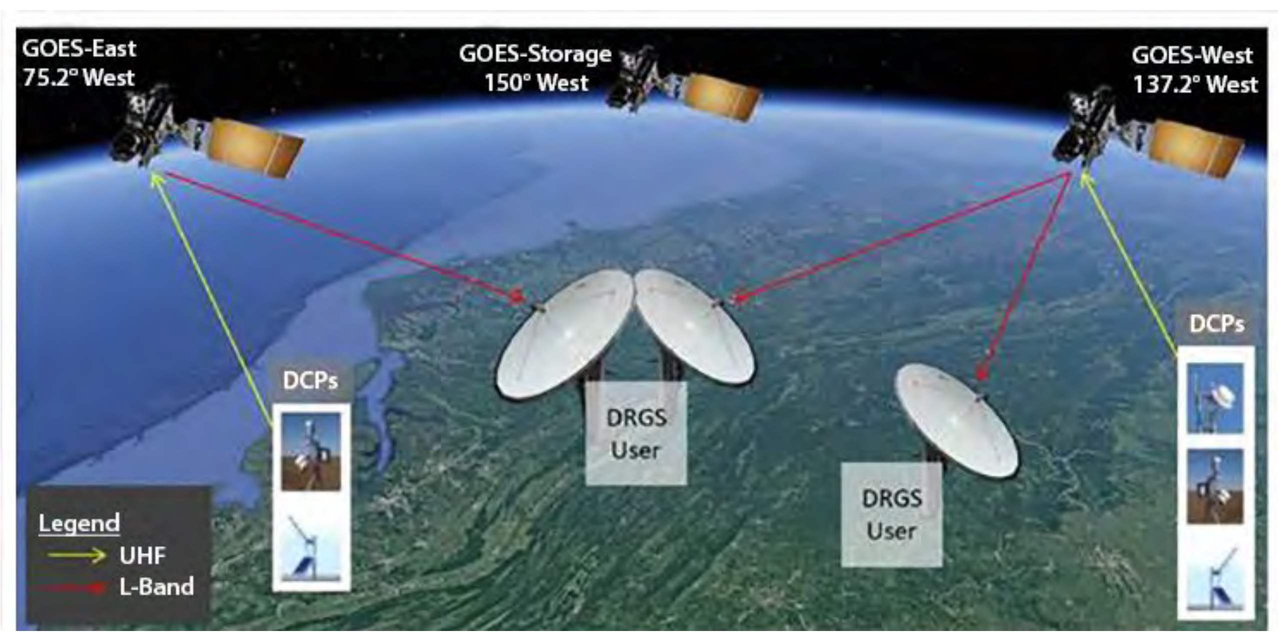


Figure 3.1-4. Schematic showing flow of data from DCPs to DRGS ground stations.

Table 3.1-7. Summary of DCS DCPR/DRGS satellite receiver operators.

Type	Installed receivers	Percent of total
Federal	17	39.5
Commercial	3	7
State	5	11.5
International	18	42
Total	43	100

3.1.1.2.1 Data Collection Platforms

The current Data Collection Platform Radio Certification Standard (DCPRCS) Version 2 was implemented in 2009 by NESDIS, but DCPs are still transitioning to this new standard, with completion planned by 2026. DCPRCS Version 2 specifies up to 532 channels (split equally between two satellites) operating at 300 baud, or up to 177 channels operating at 1200 baud. The DCPs operate in one of two modes, self-timed or random. In self-timed mode, the sensors are configured to report on a specific channel at a specific time. The channel and reporting window allocations are managed by NOAA. In random mode, the sensors have no assigned reporting intervals, but instead typically report based upon an external trigger event such as when a river level gage exceeds a set threshold.

3.1.1.2.2 DCS system use

NESDIS reported in 2019 that there were then approximately 32,000 DCPs actively reporting[2] through the GOES satellites, the vast majority of which are owned and operated by Federal agencies. Surveys taken in Project 1 indicate that approximately 4% of DCPs use event-driven reporting (random mode[3]), while over 95% report in intervals ranging from minutes to one hour. Analysis performed in Project 3, in consideration of alternative terrestrial dissemination architectures, revealed that while the overall volume of data generated by the DCPs is small, the number of messages being sent, on average 800,000 daily, has the capacity to impact the messaging services that are used to manage system internal resources. DCP data is not stored at the origin (platform), so data loss caused by interference at a DCPR receive site is not recoverable.

3.1.1.2.3 DCS data dissemination

Once received in the 1679.7–1680.1 MHz band, DCS data is disseminated by NOAA not only through the DCPR broadcast but also through multiple satellite and terrestrial networks. The next section describes the HRIT/EMWIN downlink service, which is one of the DCS dissemination services. Section 4.3 describes the existing terrestrial dissemination services for DCS data while laying the groundwork for the analysis of alternative DCS distribution service architectures for dissemination.

[2] This does not account for several thousand additional DCPs that are seasonally operated.

[3] Current experiments for DCS operation as relayed from small satellites and any future operational use will also use random mode.

3.1.1.3 High Rate Information Transmission/Emergency Managers Weather Information Network

The combined High Rate Information Transmission/Emergency Managers Weather Information Network (HRIT/EMWIN) rebroadcast signal incorporates weather event warnings, low-resolution GOES satellite imagery data, DCP messages, and other selected products. The HRIT rebroadcast and the Low Rate Information Transmission (LRIT) rebroadcast provide aggregate digitized DCS data and therefore do not require the user to obtain analog demodulators capable of acquiring a specific channel from the DCPR broadcast. Instead, DCS data is packetized and incorporated into the HRIT or LRIT broadcast stream. The LRIT system is incorporated on GOES-N series satellites, while the GOES-R series spacecraft utilize HRIT broadcasts. Although it is expected that LRIT service will be decommissioned (and replaced by HRIT), the current HRIT/EMWIN rebroadcast generation system, which is part of the Environmental Satellite Processing and Distribution System (ESPDS), also has the capability to broadcast in LRIT format should the need arise.

Figure 3.1-5 shows the major components of the HRIT broadcast system. HRIT/EMWIN utilizes NOAA-operated DRGS systems at Wallops Island, Virginia, and Suitland, Maryland, to acquire data from all DCPs reporting over GOES-East and GOES-West satellites. WCDAS and NOAA Satellite Operations Facility (NSOF) in Suitland maintain redundant receivers at both sites. The DCPR data is processed using ground equipment collectively called the DCS Access and Data Distribution System (DADDS), which has redundancies at both WCDAS and NSOF. DADDS sends the data via terrestrial means to NSOF for incorporation into the HRIT broadcast stream (see Figure 4.3-7). That broadcast stream is sent back to WCDAS, where it is uplinked at 2027.1 MHz. The GOES-R satellite transponds the HRIT rebroadcast in L-band at 1694.1 MHz (center frequency [CF]).

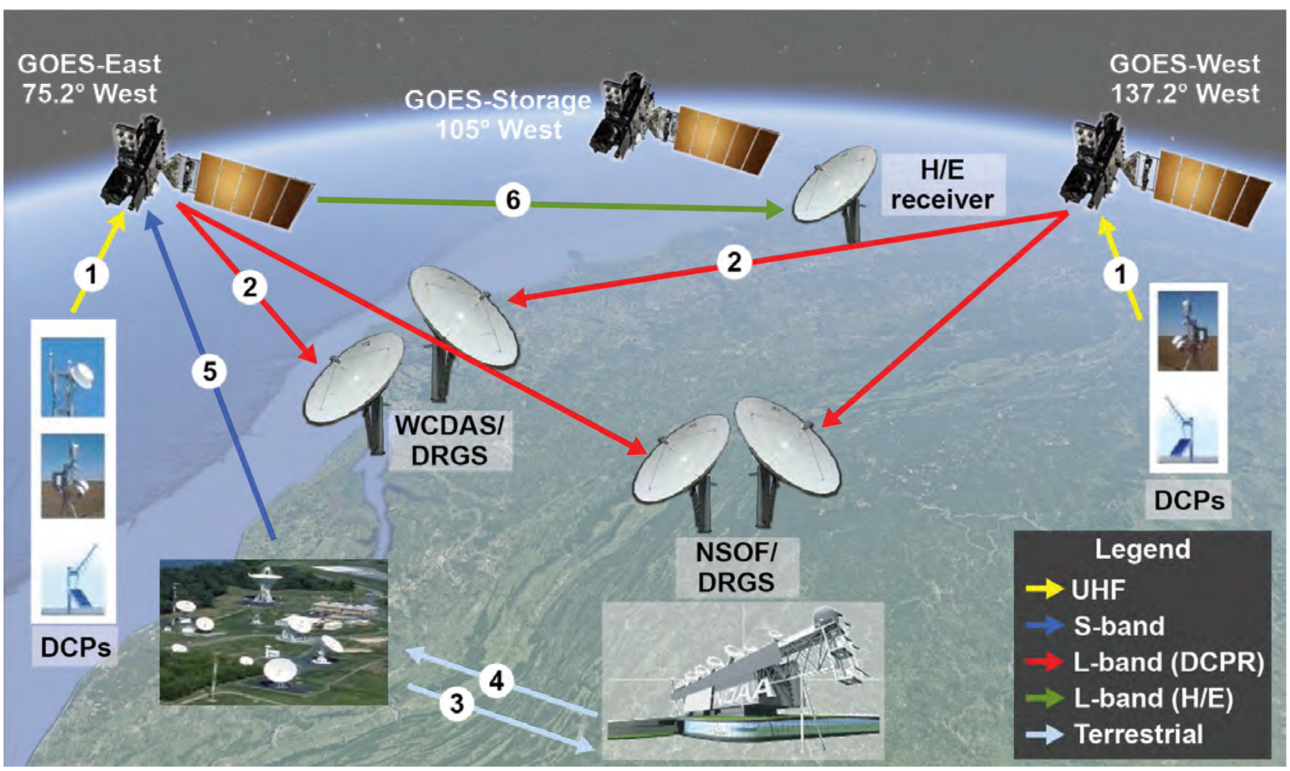


Figure 3.1-5.. HRIT/EMWIN data flow paths.

3.1.1.4 Sensor Data

GOES-NOP satellites are equipped with environmental monitoring sensors that provide horizontal gradient measurements of earth's oceans, land surfaces, clouds, and storm systems. The GOES-NOP Sensor Data (SD) RF link transmits raw instrument data in the 1673.4–1678.6 MHz band, which both overlaps (is co-frequency with) and adjoins (is adjacent to) the 1675–1680 MHz band under consideration. There is only one GOES SD receive site: NOAA WCDAS. WCDAS will continue to support this capability until 2025 and will require protection from RFI until that date.

3.1.1.5 Multi-use Data Link

The GOES-NOP Multi-use Data Link (MDL) has a center frequency of 1681.478 MHz and a bandwidth of 400 kHz. The MDL link may be impacted by adjacent-band interference if 1675–1680 MHz is approved for sharing with a terrestrial mobile broadband provider. The MDL provides WCDAS, the Fairbanks Command and Data Acquisition Station (FCDAS) in Alaska, the Satellite Operations and Control Center (SOCC) located at NSOF, and the Space Weather Prediction Center (SWPC) in Boulder, Colorado, with a medium-rate (400 kbps) downlink of imager and sounder servo error, and imager motion compensation quality-check data. The MDL is received solely at these four locations through the MDL Receive System & Server (MRS&S) ground elements.

Components included in the MDL are Solar X-ray Imager (SXI) telemetry frames, the two spacecraft pulse-code modulation (PCM) telemetry streams, spacecraft dynamics data such as angular displacement velocities and instrument servo error. Use of the MDL by these legacy GOES users helps to meet data latency requirements on selected space weather products of three seconds from detection in space to user notification by SWPC.

3.1.1.6 Command and data acquisition telemetry

For GOES-R series satellites, a housekeeping telemetry downlink is centered at 1693.0 MHz.

For GOES-NOP series satellites, a command and data acquisition (CDA) downlink is centered at 1694.0 MHz. These are received only at NOAA command and data acquisition stations (WCDAS and CBU) into 16.4-meter-diameter earth station antennas. Due to the link margin for those large antennas, interference issues for these particular links were not evaluated in SPRES.

3.1.2 GOES users and applications

The 1675–1680 MHz and adjacent 1680–1695 MHz bands provide downlinked GOES information services to Federal stakeholders. While they are not the primary focus of the SPRES study, several non-Federal stakeholders have nonetheless been identified, including private entities such as the Weather Company (a subsidiary of IBM), AccuWeather, Unisys, Baron Services, and state and local agencies such as the Florida Department of Transportation (FDOT).[4] If these non-Federal

[4] The weather enterprise is a closely knit interaction between public, private, and academic sectors. The traditional view of regulators, which treats Federal users differently than non-Federal users, may not fit the weather enterprise. Federal employees are based at academic sites where NOAA has funded "non-Federal" GRB receiving systems, where products or services directly involved with operations or research utilize those receiving stations.

stakeholders experience RFI, they would be subject to significant economic and safety impacts of their own. These entities use GOES information to protect and safeguard life and property in a variety of areas, and therefore should not be overlooked in this study. An economic report by Irving Leveson,[5] commissioned by NOAA and delivered in 2018, describes several examples of uses and their economic benefits, including loss avoidance, that arise from the use of GOES weather data and its applications. Numerous beneficiaries and applications of GOES data are identified in that report, and they are discussed more extensively in Section 4.1. In the following sections, specific use cases for DCS and GRB are described to give the reader some idea of the extent to which GOES data is integrated into our nation's economy, infrastructure, and public safety systems.

3.1.2.1 DCS usage examples

The following examples will characterize the extent to which data collected from the thousands of DCPs underpins the economy, national security, and public safety of the United States.[6] (See Appendix J, section J.4, for additional information.)

3.1.2.1.1 Inland water management

3.1.2.1.1.1 Economic benefits from DCS usage at Army Corps of Engineers

The U.S. Army Corps of Engineers (USACE) relies heavily on DCS-enabled stream gages for real-time data about river and reservoir levels throughout the United States, information that is used to manage an extensive system of locks and dams. USACE also uses DCS-enabled stream gages to report the water depth in the nation's inland navigation channels,[7] which transport commodities destined for export. This value is described in the USACE Institute for Water Resources report "Value to the Nation," which estimates the average national economic development benefits of USACE programs in the period 2010–2013. Updating these figures to 2016 based on changes in nominal gross domestic product (GDP), the total comes to $129.2 billion. Hydropower accounts for $2.8 billion, and the total excluding hydropower is $126.4 billion (see Table 3.1-8).

Table 3.1-8. National economic benefits of USACE programs, 2016.

Program	Benefits (billions of dollars)
Flood risk management	93.6
Coastal navigation	11.6
Inland navigation	10.4
Water supply	8.9
Hydropower	2.8
Recreation	1.9
Total	129.2

Note: Updated from FY 2010–2013 to 2016 by changes in nominal GDP. Recreation is the average of 2010–2012. The recreation estimate was reduced by $1.5 billion to exclude economic multiplier effects that are not in the other categories.
Source: "Value to the Nation," U.S. Army Corps of Engineers, accessed April 27, 2020, https:/ www.iwr.usace.army.mil/Missions/Value-to-the-Nation/.

[5]Irving Leveson, "Economic and Safety of Life Benefits and Impacts of Loss of GOES Signals," final report to U.S. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service (internal) (Washington, DC, July 2018).
[6]The discussion in Section 3.1.2.1.1 of inland water management does not include the broad topic of hydropower, which is covered elsewhere in the report.
[7]U.S. Army Corps of Engineers, "Rivergages.com," accessed May 18, 2020, http://rivergages.mvr.usace.army.mil/WaterControl/new/layout.cfm. See Economic Benefits of GOES to Inland Navigation later in this section.

Benefits are largely associated with construction that takes place before or after natural disasters, in support of commercial navigation, or in advance of other needs. Projects depend on detailed historical information distributed by GOES DCS. Information that is less accurate, complete, or up-to-date could result in delays and rework of USACE construction projects, worsened flooding, and greater difficulty in navigation.

Methods of measurement used by USACE result in flood damage prevention, transportation cost savings, revenue for water and energy, and visits for recreation. Estimates do not separate contributions of other information and systems from the efforts of USACE.

Assuming the GOES contribution is 1% of the $126.4 billion non-hydropower economic benefits, USACE's economic benefit is $1.26 billion.[8] (The report author notes that this figure is likely understated and should be much higher.)

3.1.2.1.1.2 DCS usage at Bureau of Reclamation

The U.S. Bureau of Reclamation (USBR) uses data distribution via GOES DCS to support its mission of managing water in 17 western states, underpinning the economy of these states by enabling modern agriculture and water-based recreation. Appropriate timing of water availability is critical to many crops, and DCS provides real-time data to support decision-making dependent on water availability.

The USBR is the nation's largest wholesale water supplier, maintaining 475 dams and operating 337 reservoirs with a total storage capacity of 245 million acre-feet. It delivers 10 trillion gallons of water to more than 31 million people each year. It provides 20% of western farmers (140,000) with irrigation water for 10 million farmland acres that produce 60% of the nation's vegetables and 25% of its fresh fruit and nut crops.

USBR, with partners, manages 289 recreation sites that have 90 million visits per year. USBR activities contribute $46 billion to economic output each year and support 312,000 jobs across 17 states, including economic multiplier effects. The real-time monitoring of water levels and availability that DCS provides enables USBR officials to make decisions impacting the accessibility and safety of recreation sites across the West.

The U.S. Department of Interior FY 2016 Economic Report estimates that the irrigation, municipal and industrial water storage and supply, and recreation activities of the USBR had a direct economic contribution of $18.73 billion:

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[8] Leveson, "Economic and Safety of Life Benefits and Impacts of Loss of GOES Signals," 4: "The gross contribution of GOES includes the contributions of data assimilation, models and nowcasts that rely on data collected and/or distributed by GOES since all of this would be compromised if GOES transmissions could not be obtained. ..... Economic multiplier effects which reflect wider impacts on the economy are included in the analysis of broad categories because of the way effects of weather on households and the economy are derived. However, because of limitations on information they are not included for the use cases. This results in an understatement of the benefits and potential losses for those applications." All benefits are on an annual basis based on the year cited in the report.

- USBR irrigation water had a direct economic contribution of $13.09 billion.
- Municipal and industrial water had a direct economic contribution of $4.23 billion.
- Recreation had a direct economic contribution of $1.41 billion.

If GOES data and services contributed 1% of the $18.73 billion value of USBR water services except hydropower, their benefit would be $187.3 million. The combined value of USACE and USBR water services other than hydropower attributed to GOES is on the order of magnitude of $1.28 billion.

3.1.2.1.1.3 Reliance on DCS at the Tennessee Valley Authority

The Tennessee Valley Authority (TVA) uses over 250 DCPs, located throughout the Tennessee Valley watershed, to monitor water levels throughout its 80,000-square-mile service region, which includes 9 million residents and 800 miles of navigable waterways across seven states in the southeastern U.S. TVA provides flood control and navigation for the Tennessee River system through management of its 29 hydropower dams, 17 non-hydropower dams, and reservoirs.

Near-real-time information from DCS provides insight to TVA officials as they manage water resources across numerous water uses in the region, including power, drinking water, agriculture, and industrial uses. The Leveson report noted that in 2010, TVA managed water usage across the region that averaged 11,951 million gallons per day (mgd) for off-stream uses. These uses included:

- Thermoelectric: 10,046 mgd (84.1% of total use)
- Industrial: 1,148 mgd (9.6% of total use)
- Public supply: 723 mgd (6% of total use)
- Irrigation: 34 mgd (less than 1% of total use)

Without DCS, TVA would have less information about changing conditions in river and lake water levels, likely impacting decision-making related to flood control and dam safety, such as opening and closing spillway gates.[9]

3.1.2.1.1.4 Economic benefits of DCS to inland navigation

The USACE is responsible for the maintenance of the channels for the nation's inland waterways. River gages, which relay data via GOES DCS, are the primary means of verifying the width and depth of the waterways. The National Waterways Foundation assessed the economic importance of the current system in a detailed study in November 2014.[10] The inland waterways of the United States comprise over 12,000 miles of navigable waterways that touch 38 states. In 2012, this system accommodated 565 million tons of freight valued at $214 billion. Major river basins include

[9] "Understanding the Drawdown," Tennessee Valley Authority, accessed May 13, 2020, https://www.tva.com/environment/managing-the-river/flood-management/understanding-the-drawdown.

[10] Ted Grossardt, Larry Bray, and Mark Burton, "Inland Navigation in the United States: An Evaluation of Economic Impacts and the Potential Effects of Infrastructure Investment" (National Waterways Foundation: Washington, DC, 2014), http://www.nationalwaterwaysfoundation.org/documents/INLANDNAVIGATIONINTHEUSDECEMBER2014.pdf.

the Upper and Lower Mississippi River, the Ohio River, the Gulf Intercoastal Waterway, and the Pacific Northwest. Any area outside of that was designated as "rest of U.S." The study followed a scenario that compared the current transportation and related supply-chain costs of waterway users to the costs that they would incur if the waterway was no longer available and the next-best transportation alternative had to be used. The added expenses were considered as a loss.

Using this method, the loss during the first year[11] was $124.2 billion, of which $48.8 billion was in the Gulf Intracoastal region. Later years in the National Waterways Foundation scenario showed somewhat higher losses when using this approach.

Table 3.1-9. Output loss from abandonment of U.S. inland waterways, 2012.

Region	First-year loss (billions of dollars)	Percent of total
Ohio River	10.7	8.6
Upper Mississippi	12.2	9.8
Lower Mississippi	19.9	16.0
Gulf Intracoastal	48.8	39.3
Pacific Northwest	0.9	0.8
Rest of U.S.	31.6	25.4
Total	124.2	100.0

Source: T. Grossardt, L. Bray, and M. Burton, "Inland Navigation in the United States: An Evaluation of Economic Impacts and the Potential Effects of Infrastructure Investment," (Washington, D.C.: National Waterways Foundation, 2014), http:/ www.nationalwaterwaysfoundation.org/documents/ INLANDNAVIGATIONINTHEUSDECEMBER2014.pdf.

Traffic on the Mississippi River is dominated by petroleum. The following statistics are from 2011: petroleum (28.7%), farm products (27.3%), coal (~12%), chemicals (~10%), and crude materials (~10%). The Ohio River system carries slightly more than half of what the Mississippi River transports. Major commodities on the Ohio are coal and crude materials, followed by petroleum, chemicals, primary manufactured goods, and farm products. Freight traffic on the Gulf Intracoastal Waterway is concentrated in petroleum products (55.3%), with significant carriage of chemicals (19%) and crude materials (16%). In the western United States, the Columbia and Snake rivers carry farm products (grain) and crude materials.

Existing refineries in the United States are often (though not universally) more easily served by barge than by rail. Most refinery expansion in the U.S. takes place at existing locations. The Department of Energy (DOE) Energy Information Administration (EIA) tracks waterborne crude oil movements on the inland river system. Crude oil shipments from the Midwest to the Gulf Coast have increased tenfold in the period 2009–2013, from roughly 3.7 million barrels to 37 million barrels. The domestic crude oil is sourced from the Bakken region of North Dakota, the Eagle Ford and Permian basins in Texas, and western Canada. While pipelines are the preferred mode for shipping crude oil to refineries, they often are not available or do not have adequate capacity for growth from new sources of production. Waterway shipments help fill that need, with historical volumes shown in Figure 3.1-6.

Without river gage measurements taken by DCS platforms at locks and dams and along the waterways, and without proper data to determine the width and depth of the navigation channels, safe transit by barges would not be possible. Operators consult public sites operated by USACE to learn flood stages and other information that they use to determine the loading of commodities on barges (see Figure 3.1-7).

[11]The SPRES study does not sum up these values for the remaining lifetime of the GOES-R series, nor does it convert these to 2020 dollars, but it is readily apparent they would total a very large number, in the billions of dollars.

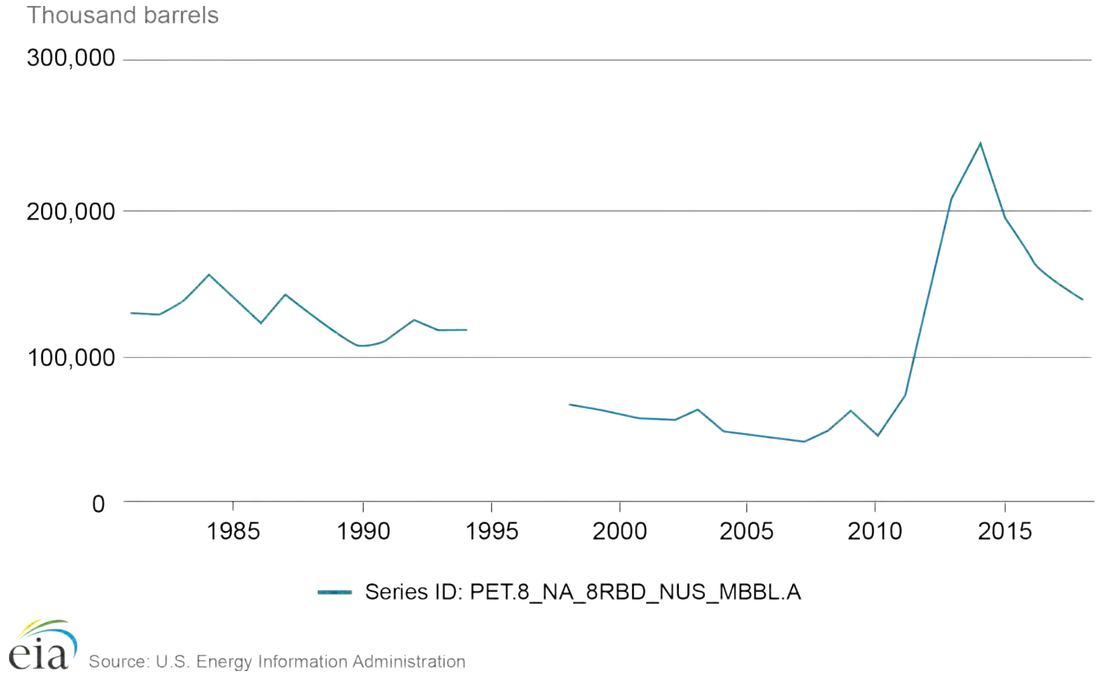
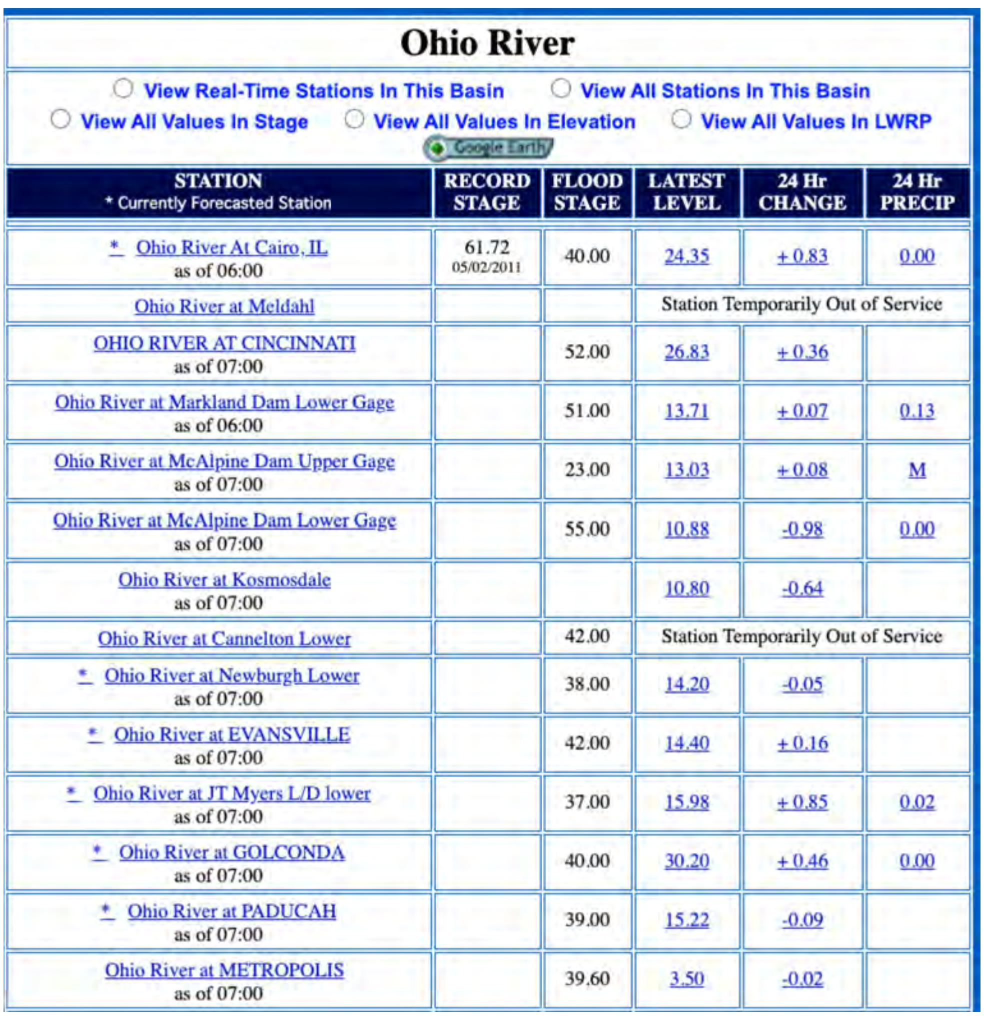


Figure 3.1-6. EIA reports of U.S. domestic crude oil refinery receipts by barge, annually.



Ohio River

○ View Real-Time Stations In This Basin ○ View All Stations In This Basin
○ View All Values In Stage ○ View All Values In Elevation ○ View All Values In LWRP
Google Earth

STATION * Currently Forecasted Station	RECORD STAGE	FLOOD STAGE	LATEST LEVEL	24 Hr CHANGE	24 Hr PRECIP
* Ohio River At Cairo, IL as of 06:00	61.72 05/02/2011	40.00	24.35	+0.83	0.00
Ohio River at Meldahl			Station Temporarily Out of Service		
OHIO RIVER AT CINCINNATI as of 07:00		52.00	26.83	+0.36	
Ohio River at Markland Dam Lower Gage as of 06:00		51.00	13.71	+0.07	0.13
Ohio River at McAlpine Dam Upper Gage as of 07:00		23.00	13.03	+0.08	M
Ohio River at McAlpine Dam Lower Gage as of 07:00		55.00	10.88	-0.98	0.00
Ohio River at Kosmosdale as of 07:00			10.80	-0.64	
Ohio River at Cannelton Lower		42.00	Station Temporarily Out of Service		
* Ohio River at Newburgh Lower as of 07:00		38.00	14.20	-0.05	
* Ohio River at EVANSVILLE as of 07:00		42.00	14.40	+0.16	
* Ohio River at JT Myers L/D lower as of 07:00		37.00	15.98	+0.85	0.02
* Ohio River at GOLCONDA as of 07:00		40.00	30.20	+0.46	0.00
* Ohio River at PADUCAH as of 07:00		39.00	15.22	-0.09	
Ohio River at METROPOLIS as of 07:00		39.60	3.50	-0.02	

Figure 3.1-7. USACE website provides real-time data on river levels relayed by GOES DCS, used for maritime river navigation. Source: rivergages.mvr.usace.army.mil.

GOES serves inland navigation through DCS distribution of data on water levels and flows. If the benefits of information from DCS to inland waterway navigation were 1% of the total value of inland navigation without economic multiplier effects, the value based on 2016 would be $571 million. Benefits of inland waterways include many of the use cases noted in the discussions of the USACE, the USBR, and the TVA. This 1% may not represent the actual contribution to inland navigation from gage measurements relayed by GOES DCS.

3.1.2.1.2 The use of DCS to support safe water access, coastal hazard management, and public safety in Florida

Tampa Bay (Florida) Water, a regional water supply authority serving 2.4 million people in Hillsborough, Pasco, and Pinellas counties, including the cities of New Port Richey, St. Petersburg, and Tampa, uses real-time DCS data from rivers and lakes to plan and manage drinking water for the subject population. These information sources are used in day-to-day water planning and are also critically important to Tampa Bay Water's efforts to adapt to climate change. The transmission of DCS data gives technical staff and consultants near-real-time access to stream-gage data. In a letter to the FCC in June 2010, Tampa Bay Water expressed the importance of DCS as a source of stream-gage data for real-time water level information: "During flood events, stream-gage data is a vital tool for forecasting, warning, planning and emergency response along the Hillsborough River and Alafia River here in our region. (U)sing an Internet vendor (to provide data from USGS and/or NOAA) would greatly diminish the real-time function and reliability of the current stream-gage system. An advantage of having this data transmitted via GOES DCS broadcast is the fact that the data is not impacted by weather events that can interfere with terrestrial communications systems. That advantage is put to good use every year in Florida during the summer and fall hurricane seasons."[12]

In addition, wind-speed monitoring equipment has been installed by the Florida Department of Transportation (FDOT) on causeways and other coastal bridges to monitor for unsafe conditions, especially due to wind, under severe weather conditions, including hurricanes and tropical storms. FDOT has deployed a high-wind alert system, with measured data automatically transmitted using GOES DCS to the FDOT Regional Traffic Management Centers. Historically, when a severe weather event occurred in Florida, local law enforcement personnel would deploy to each bridge in advance of the weather event. The officer would take periodic wind-speed measurements and report them back to their local agencies, which then could make closure decisions regarding specific

Figure 3.1-8. FDOT bridge wind speed monitors and GOES DCS antenna. Courtesy of FHWA/FDOT.

[12]Gerald Seeber to Marlene Dortch, "Re: FCC Office of Engineering and Technology: Use of 1675–1710 MHz Band," Public Notice and ET Docket No. 10-123, June 28, 2010, https://ecfsapi.fcc.gov/file/7020519711.pdf.

bridges. This was a hazardous job for officers in the midst of evacuations from coastal areas. Additionally, officers are needed in other areas during evacuations, when time is limited and traffic tends to be bad as citizens rush to leave evacuation areas. Excessive wind levels could endanger travelers trying to cross a bridge. The increased use of DCS for these purposes and the coordinated management of bridge and causeway closures has enabled communities to more safely evacuate before and during storms, helping to minimize impacts to life and property from such storms. The reduced cost to FDOT of communicating the information from these bridge-mounted wind sensors using Federally-provided GOES DCS relay of the telemetry was a major factor in FDOT's decision to implement this system.[13]

3.1.2.1.3 National Weather Service use of shared gage data

The National Weather Service (NWS) Hydrometeorological Automated Data System (HADS)[14] is a unique use of shared Federal/non-Federal DCS data in support of operational hydrology and meteorology. The HADS system is the most important real-time hydrological data acquisition and data distribution system operated by the NWS. HADS observes more than 17,000 stream-gage locations, which form the basis for all flood and flash-flood warning products issued by the NWS.

NWS does not own any of the DCP platforms used in HADS. Many are operated by the United States Geological Survey (USGS), and the rest by local and state entities. The system exists in support of NWS activities of national scope, specifically the Flood Warning and Flash Flood Warning programs administered by the Weather Forecast Offices (WFO) and the operations performed at River Forecast Centers (RFCs) throughout the United States. Additionally, HADS-created data products bolster several other NWS program areas, including fire-weather support services, local and national analysis of precipitation events, hydrological and meteorological modeling, and the verification of Next-Generation Radar (NEXRAD) precipitation estimates and hydrological models.

HADS pulls data via Local Readout Ground Station (LRGS)—using data received at WCDAS and at the USGS Emergency Data Distribution Network (EDDN) in Sioux Falls, South Dakota—every five to eight seconds, buffers this data, and processes it on two-minute cycles.

DCPs are owned by cooperating agencies and entities. The majority of data acquired and processed by HADS comes from DCPs owned and operated by the Water Resources Division of the USGS, the Bureau of Land Management, the U.S. Forest Service, USBR, and (non-Federal) departments of natural resources at state and local agencies throughout the country.[15] In return, the NWS shares other hydrological and meteorological products and information with these agencies.

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[13]Randy Pierce, "Comment," "FCC Office of Engineering and Technology Requests Information on Use of 1675–1710 MHz Band," ET Docket 10-123 (June 28, 2010), https://ecfsapi.fcc.gov/ le/7020513863.pdf; U.S. Department of Transportation, Federal Highway Administration, "Best Practices for Road Weather Management: Florida DOT Bridge Wind Speed Alerting System," Road Weather Management Program, accessed May 13, 2020, https://ops.fhwa.dot.gov/publications/fhwahop12046/rwm09_florida1.htm.

[14]"HADS: Hydrometeorological Automated Data System," National Oceanic and Atmospheric Administration, National Weather Service, accessed May 13, 2020, https://hads.ncep.noaa.gov.

[15]Any failure of the regulatory structure to protect other Federal or non-Federal DRGS systems may cause those sensors to become unavailable for NWS users via HADS. The Flood Warning and Flash Flood Warning products originate from data collected over GOES DCS in 1675–1680 MHz and then sent via HADS to the NWS.

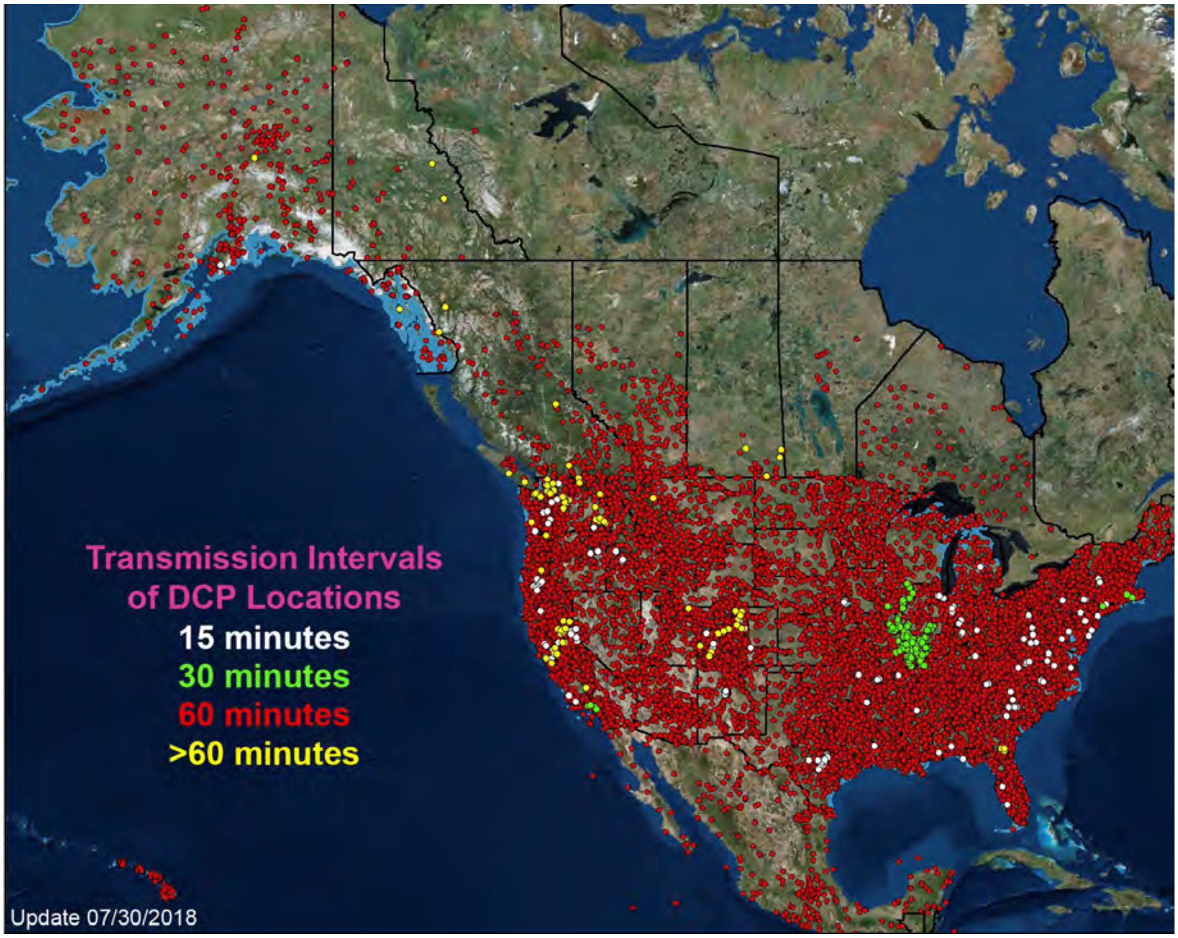

Figure 3.1-9. 17,000 DCP values used by NWS and reported by HADS.

HADS processes and translates the raw DCP data and constructs individual user reports, which are tailored for the needs of each of the NWS WFOs and RFCs. Those HADS data products are disseminated via the NWS Telecommunications Gateway for C-band relay via the NOAAPort/ Satellite Broadcast Network. The end users can downlink the reports via NOAAPort. Additionally, HADS sends some data products via the internet to the RFCs.

HADS is an element of the Meteorological Assimilation Data Ingest System (MADIS)[16] at the NWS. MADIS is a meteorological observational database and data delivery system that provides observations that cover the globe. For an example of products created by NWS from DCPs sourced via HADS, see Section 3.1.2.3.1.

3.1.2.2 GRB usage examples

This section identifies NWS National Centers and other Federal incumbent (e.g. DoD) users that rely on direct broadcast GRB for GOES-R data products. Section 4.1 and Appendix E, Table E-1, provide a comprehensive listing of Federal GRB uses and applications and also capture many non-Federal and academic users of direct broad- cast GRB.

[16] "MADIS: Meteorological Assimilation Data Ingest System," National Oceanic and Atmospheric Administration, National Weather Service, accessed May 13, 2020, https://madis.noaa.gov/index.shtml.

3.1.2.2.1 National Hurricane Center

The National Hurricane Center (NHC), which is part of the NWS National Centers for Environmental Prediction (NCEP), issues forecasts in the form of text advisories and graphical products for tropical cyclones in areas of disturbed weather in the North Atlantic and Eastern North Pacific basins. In addition, on a year-round basis it provides products relating to high seas, offshore waters, and graphical surface and ocean-wave analyses and forecasts for the tropical and subtropical Eastern North and South Pacific and the North Atlantic basins. The storm surge unit forecasts the abnormal rise in sea level accompanying tropical cyclones and prepares storm-surge atlases for use by emergency managers in developing evacuation procedures for coastal areas. The NHC accesses GOES-R products via the GRB direct broadcast dissemination.[17]

The economic value of hurricane forecasts and warnings is the sum of estimates for households and for business and governments. Percentages are applied to estimate the value of NHC forecasts and warnings and the contribution of GOES GRB to the value of NHC hurricane forecasts.

Lazo and Waldman estimated household willingness to pay for improved hurricane forecasts at $340 million, based on responses to a 2008 survey and a 2010 national population survey.[18] This value is updated to 2016 based on changes in median household income between 2008 and 2016 and changes in the number of households between 2010 and 2016, which yields a willingness to pay[19] for improved hurricane forecasts of $383.2 million. The updated estimate for improved forecasts is doubled to obtain a (possibly conservative) estimate of household willingness to pay for existing hurricane forecasts of $766.4 million.

The value of existing forecasts to businesses and governments is obtained by multiplying the value to households by the ratio of benefits of weather forecasts to all sectors of the economy to the benefits of weather forecasts to households. This ratio ranges from 2.41 to 3.25. Multiplying household willingness to pay for existing hurricane forecasts by this ratio results in an estimated value of hurricane forecasts and warnings to the whole economy of $1.85–$2.49 billion in 2016.

The economic value of NHC forecasts and warnings was assumed to be 60%–80% of the value of all hurricane forecasts and warnings, placing it at $1.11–$1.99 billion in 2016. GOES GRB contribution to this value was assumed to be 75%–80%, or $832 million to $1.59 billion.

3.1.2.2.2 GOES-16 fills void caused by destruction of Puerto Rico's weather radar

GOES-16, utilizing the ABI and GLM payloads, and reporting via GRB, helped fill the void when Hurricane Maria destroyed the weather radar in San Juan, Puerto Rico, on September 20, 2017 (Figure 3.1-10). The radar failed at 5:50 a.m. EDT, just before Maria made landfall on the island. Land-based radar is used during storms to provide detailed information on hurricane wind fields,

[17] Leveson, "Economic and Safety of Life Benefits and Impacts of Loss of GOES Signals."
[18] Jeffrey Lazo and Donald Waldman, "Valuing Improved Hurricane Forecasts," *Economics Letters* 111, no. 1 (2011): 43-46, https://doi.org/10.1016/j.econlet.2010.12.012.
[19] Economists often use "willingness to pay" as a measure of value of a public good or service. This does not imply that such data will be sold or that users would be charged for such data.

rain intensity, and storm position and movement. With this critical radar technology disabled and a major hurricane approaching, forecasters in Florida were able to utilize data from GOES-16 to track the storm in real time. In the absence of radar, GOES-16 data allowed forecasters to keep an eye on Maria, which made landfall near Yabucoa, Puerto Rico, about 6:15 a.m. EDT on September 20 as a Category 4 hurricane.[20]

Figure 3.1-10. The remnants of the San Juan WSR-88D radar after its destruction by Hurricane Maria. Courtesy of WFO San Juan.

3.1.2.2.3 Aviation Weather Center

The Aviation Weather Center (AWC) in Kansas City, Missouri, is another component of the NWS National Centers for Environmental Prediction. The AWC provides timely and accurate weather information intended for commercial and private pilots and terminal aerodromes (i.e., airports) in support of the Federal Aviation Administration (FAA) mission and in accordance with International Civil Aviation Organization (ICAO) rules. For example, the AWC issues in-flight aviation weather advisories (e.g., Significant Meteorological Event [SIGMET]) that advises of weather (other than convective activity) that is potentially hazardous to all aircraft. Other products include Convective SIGMETs, which concern specific categories of thunderstorms, and Airmen's Meteorological Information (AIRMETs), which provide concise descriptions of weather that may be hazardous to light aircraft and pilots operating under visual flight rules.

The AWC provides national- and regional-scale satellite images from GOES-West and GOES-East for visible, infrared, water vapor, and visibility/fog in U.S. regional images or in international images via ICAO areas, such as the one shown in Figure 3.1-11. For some satellite products, multiple satellites are necessary to construct images or products needed for aviation. Since imagery products from GOES are in a modified (tiled) format when sent over the Advanced Weather Interactive Processing Systems (AWIPS), these files are not usable for merging with other imagery for the creation of AWC aviation imagery. Therefore, the unmodified Level 1b GRB data is the only source utilized by AWC to construct such products, which are provided for use in aviation operations.

Due to the short-term ("nowcasting") needs of the aviation community, information from GOES-R is essential to the safe conduct of aviation operations. According to the FAA, "Satellite is perhaps the most important source of weather data worldwide, particularly over data-sparse regions, such as countries without organized weather data collection and the oceans. NOAA's GOES imagery

[20] "NOAA's GOES-16 Provides Critical Data on Hurricane Maria," National Oceanic and Atmospheric Administration and National Aeronautics and Space Administration, Geostationary Operational Environmental Satellites—R Series, accessed May 13, 2020, https://www.goes-r.gov/mission/hurricaneMaria.html.

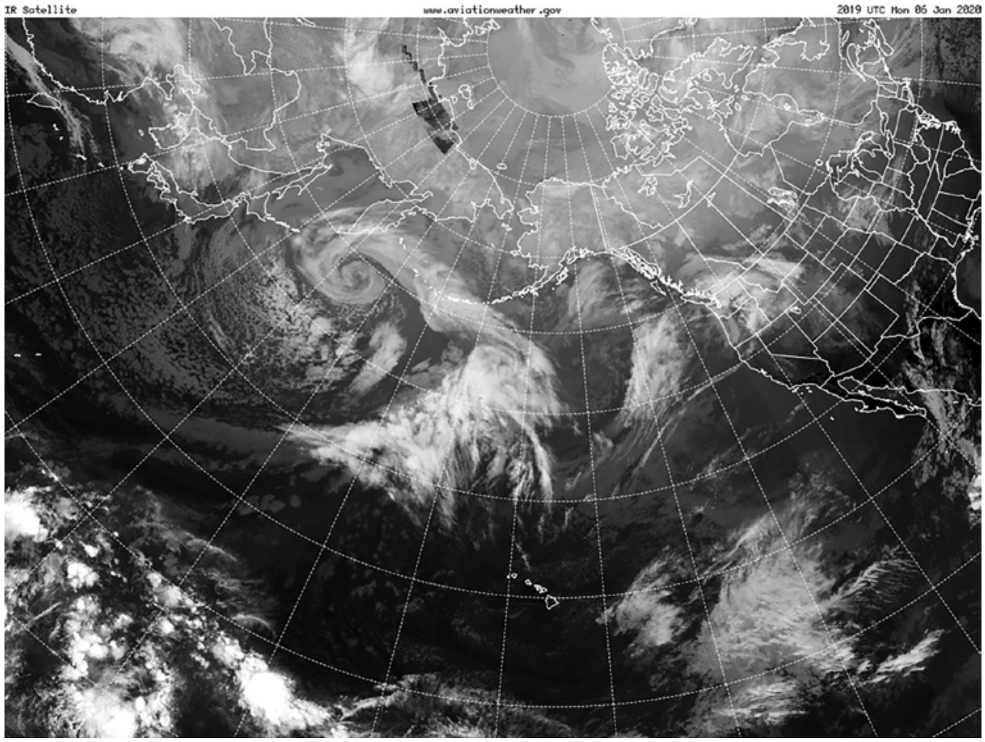

Figure 3.1-11. International Satellite Imagery from AWC, including GOES-R and other satellites, sourced from GRB. Courtesy of www.aviationweather.gov.

can be found on the AWC's website, as well as on all NWS Weather Forecast Office websites. Additional satellite imagery for Alaska can be found on the NWS Alaska Aviation Weather Unit (AAWU) website."[21] GRB receiving installations also support the AAWU and corresponding aviation unit in Honolulu, Hawaii. NWS GRB sites cannot tolerate an availability outage greater than five minutes total over a 30-day period.[22] The service availability requirement is 99.988%.

Weather service to aviation is a joint effort of NOAA, NWS, FAA, and DoD, as well as various private-sector aviation weather service providers.[23] Private-sector aviation products developed from non-Federal GRB-received data are discussed in Section 3.1.2.3.2.

3.1.2.2.4 Fleet Numerical Meteorology and Oceanography Center

As one of many DoD direct-broadcast users, the Fleet Numerical Meteorology and Oceanography Center (FNMOC), located in Monterey, California, is responsible for providing the highest-quality, most relevant, and most timely worldwide meteorological and oceanographic support to U.S. and coalition forces. FNMOC generates weather and ocean prediction products including the Global and Regional Weather Prediction Charts and Global Ensemble Weather Prediction Charts, and performs side-by-side comparisons with NCEP global NWS models.

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[21]U.S. Department of Transportation, Federal Aviation Administration, Aviation Weather Services, Advisory Circular (AC) 00-45-H, November 14, 2016, pp. 3–57, http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_00-45H.pdf.
[22]U.S. Department of Commerce, National Oceanic and Atmospheric Administration, "GOES-R Series: Ground Segment Project Functional and Performance Specification," attachment 2, v.4.9 (Washington, DC, July 8, 2019).
[23]U.S. Department of Transportation, Federal Aviation Administration, *Aeronautical Information Manual* (Washington, DC, 2019), ch. 7, sect. 1, https://www.faa.gov/air_traffic/publications/atpubs/aim_html/chap7_section_1.html.

FNMOC is one of several centers that support the Naval Meteorology and Oceanography Command (NMOC), headquartered at Stennis Space Center in Mississippi. NMOC is responsible for command and management of the Naval Oceanography Program, working in the disciplines of meteorology and oceanography, geospatial information and services, and precise time and astrometry. NMOC serves continuously during peacetime, and, during times of elevated conflict, uses knowledge of the weather environment to enable our forces to make critical and timely strategic, tactical, and operational battle-space decisions. In 2020 NMOC will be installing new GRB earth stations at operating center locations in Monterey, California; Norfolk, Virginia; Stennis Space Center; and Pearl Harbor, Hawaii.

3.1.2.2.5 NOAA Cooperative Institutes

Some receive sites designated as non-Federal in fact are funded by NOAA. These include the University of Wisconsin–Madison Space Science and Engineering Center (SSEC) Cooperative Institute for Meteorological Satellite Studies (CIMSS), Colorado State University's Cooperative Institute for Research in the Atmosphere (CIRA), and the Cooperative Center for Earth System Sciences & Remote Sensing Technologies at City College of New York.

Among these institutes, CIMSS and CIRA rely on their GRB receive stations and the GRB broadcast as the primary source of GOES-R series data products, which are used for decision-making support.

CIMSS uses the GRB data stream to support users in a variety of ways:

- Satellite Data Services (SDS) ingests GOES-16 and GOES-17 GRB data. In addition to local direct access, SDS provides real-time and archived ABI products by limited online access.
- Data is also streamed to external users through a fanout mixer server using multiple antenna inputs to mitigate local RFI. The primary users of GRB data from SSEC are scientists (including NOAA and NASA scientists), educational and commercial users worldwide (including those in the solar power and sport-fishing industries), broadcast media, and the aviation community.
- Real-time GOES visualization packages available from SSEC.
- Interactive Data Access System (McIDAS-X and McIDAS-V).
- RealEarth VM, a web-based and mobile app developed at CIMSS to support outreach and collaboration efforts of scientists.
- Geostationary Satellite Image Browser.
- SSEC-GOES mobile app.
- WxSat mobile app.
- Geo2Grid, an open-source software package designed to create high-resolution images from geostationary satellite data.

CIRA provides access to many products and a variety of advanced visualization tools online.[24]

[24] Visualization tools include RAMM Advanced Meteorological Satellite Demonstration and Interpretation System (RAMSDIS) (http://rammb.cira.colostate.edu/ramsdis/online/) and RAMMB-SLIDER (http://rammb-slider.cira.colostate.edu).

These specialized CIRA-derived products are used by the Federal and non-Federal portions of the weather enterprise. CIRA's global client base includes the U.S. weather research community, the NWS, the Joint Typhoon Warning Center, commercial users including the aviation and fishing communities, satellite researchers in the South Pacific and Asia, educators and media developers (including National Geographic, Public Broadcasting Service, and television networks), and the general public.

NOAA NESDIS does have Federal employees permanently assigned to work at the Cooperative Institute locations, and they do utilize the GRB data.

As an integral part of the weather enterprise, NOAA Cooperative Institutes merit consideration for the same levels of RFI protection as the Federal sites if the FCC decides to reallocate the 1675–1680 MHz band for shared use.

3.1.2.2.6 Other members of the weather enterprise

The Weather Company and AccuWeather both rely on the GRB service, and they have many dedicated industrial customers who benefit from the GRB data. Both of these companies make software and provide data in support of broadcast television weather forecasting, which incorporates GOES satellite imagery derived from non-Federal received GRB products. This is in addition to the general public, which accesses these private-sector companies' data via Internet, smartphone applications, or video channels.

As an example of a private-sector weather service provider, OTT HydroMet (a U.S. subsidiary of OTT HydroMet GmbH) has two GRB receive site installations, one in Denver, Colorado, and another in Round Rock, Texas. OTT HydroMet generates products from the GOES-16 GRB on a continuous basis. Aviation customers including government agencies, airlines, and other private companies use these products for flight planning, flight following, and enhanced product generation such as cloud-top height and determination of convection. Customers also use the data for weather forecasting, weather feature diagnosis, fire detection, and more. Universal Aviation and Weather, a major private flight services and weather organization that supports worldwide flights of private and corporate jets, uses the GRB data received by OTT HydroMet as its weather data source. OTT HydroMet is also one of the sources for weather forecast information supporting helicopters servicing the energy production platforms located off the coast of the United States.

3.1.2.2.7 UCAR/Unidata

The University Corporation for Atmospheric Research (UCAR)/Unidata (Boulder, Colorado) receives GOES-16 and GOES-17 GRB via direct broadcast, as well as a subset of GOES-16 and GOES-17 products on NOAAPort. UCAR/Unidata distributes data products to more than 150 academic institutions.

3.1.2.2.8 International users

Environment and Climate Change Canada (ECCC) has GRB receive systems that process visible and infrared imagery, which is used as "a principal tool for synoptic-scale detection and tracking of weather systems, including severe weather events."[25] All such receive stations are within 50 km (30 miles) of the U.S.-Canada border because that is where population centers and ECCC facilities are located, specifically Dorval, Quebec (including a GVAR station); Toronto, Ontario; and Vancouver, British Columbia. ECCC also has its own DCPs for weather stations, hydrometric monitoring sites, marine data buoys, and geomagnetic observatory stations, many of which are in remote locations without redundant means of communication. The Meteorological Service of Canada (MSC), on behalf of the ECCC, indicated in the referenced letter to the FCC that it "will be reducing reliance on internet-based access to the GOES DCS servers as internet access can be potentially stopped at multiple points in the chain of communications." This indicates that the ECCC is moving more in the direction of utilizing direct broadcast services, rather than having to face increasing risks related to terrestrial access.

As is typical for GEO earth stations at higher latitudes, ECCC's stations have low angles of elevation generally pointed due south (i.e., toward the U.S.), resulting in increased risk of RFI. Similar risks of this type are discussed further in Sections 4.2 and 4.6.

3.1.2.3 Non-Federal users and items outside of SPRES study scope

Although the SPRES study includes many incumbent Federal and non-Federal users, applications of data received by non-Federal users go well beyond those identified in this report. Data received by incumbent non-Federal earth stations have a direct benefit to Federal agencies and critical segments of the economy. Evaluating those interrelationships and impacts generally was beyond the scope of the SPRES study. However, for completeness and to raise awareness that further due diligence may be required, two additional cases are briefly covered here. (See Appendix J, section J.4, for additional information.)

3.1.2.3.1 Hydrographs derived from DCS data used for NWS flood prediction

Federal hydrologists have access to observations from river and stream-gage stations owned and operated by hundreds of Federal, state, and local agencies throughout the U.S. Historical water levels in a river, and future forecast levels, including those at or above flood stage, are shown on hydrographs like the one in Figure 3.1-12.

All DCS river- and stream-gage information is, by agreement with NOAA NWS, aggregated into HADS, which creates a comprehensive picture of national water levels. NWS River Forecast Centers (RFCs) and Weather Forecast Offices (WFOs) use HADS information in their hydrologic models to create displays like the one shown Figure 3.1-12. A dotted vertical line shows the current time, with actual gage measurements on the left and forecasted water levels developed

[25] David Grimes, assistant deputy minister, Meteorological Service of Canada, to Marlene Dortch, secretary, Federal Communications Commission, "Re: FCC Notice of Proposed Rulemaking and Order In the Matter of Allocation and Service Rules for the 1675-1680 MHz Band," Public Notice and ET Docket No. 19-116, May 1, 2019, https://ecfsapi.fcc.gov/file/105013031405442/MSC%20Response%20to%20FCC%20NPRM%20WT19-116.pdf.

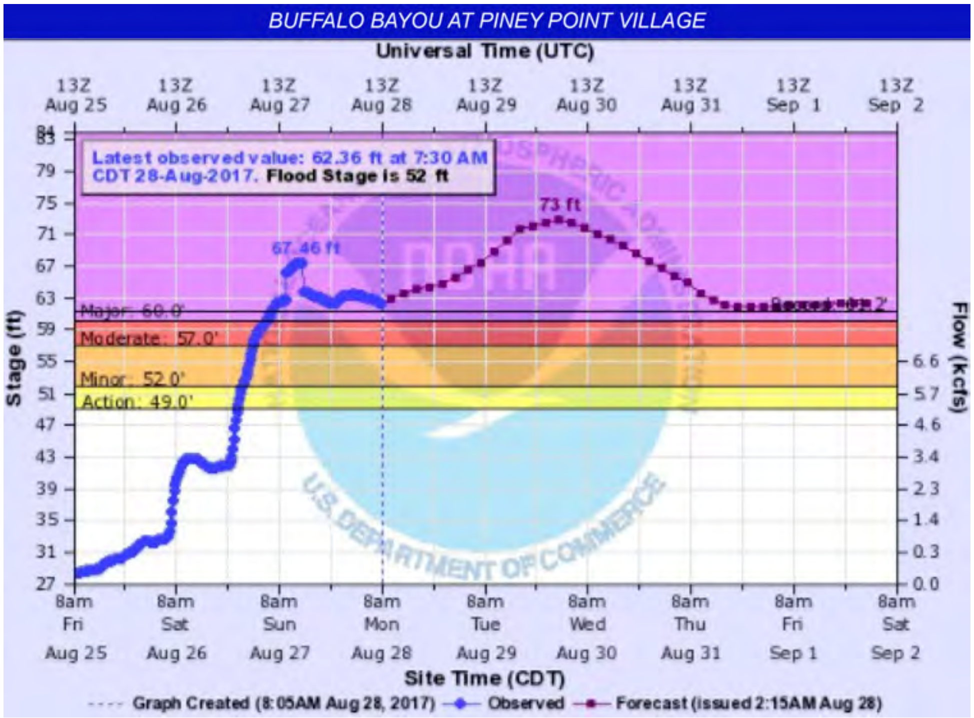

Figure 3.1-12. Hydrograph of DCS gage during Hurricane Harvey in Houston, Texas.

by NWS on the right. There are thousands of gages, all of which may be viewed at http://water.weather.gov. This particular example is on South Piney Point Road in Houston, Texas, gage number PPTT2, owned by the U.S. Geological Survey.

The sharing of DCS user gage data with NOAA allows the NWS to have access to data from thousands of gages that it does not own. Gages from HADS and other sources, once ingested into NOAA's Advanced Hydrologic Prediction Service, are the basis for national and regional products for flood status, long-range river flood risk, and more, as shown at http://water.weather.gov/ahps. It is highly likely that readers of this report can find a gage on the maps that is near their home or work locations, or that protects the route between those two places by providing data used for flood warnings.

3.1.2.3.2 Non-Federal use of GRB data in support of aviation operations

Non-Federal owners of GRB earth stations provide data used for private-sector weather forecasting that is tailored for a given industry or application. The aviation sector provides several such examples. Commercial airlines supplement the NWS aviation products with custom information on airports and products that enhance flight safety, protect ground crews from lightning and hazardous weather, help airlines control costs, and improve efficiency. Nearly all major commercial airlines utilize a third-party weather company to develop specialized products for the cockpit or to alert aviators about turbulence. United Airlines is one of many major aviation companies that are clients of the Weather Company. American Airlines, which for years had GOES GVAR antennas at its offices in Dallas, Texas, now outsources weather forecasting to the Weather Company as well.

Operators of cargo aircraft either have in-house meteorology departments or partner with a private weather company. Kory Gempler, lead meteorologist for Federal Express (FedEx), emphasizes the value of contingency planning for understanding when severe weather is headed for FedEx's hub in Memphis, Tennessee, in a posting from 2013.[26] FedEx uses GRB information as part of the meteorological data necessary to forecast runway visibility when it drops below one-half mile. Precise terminal aerodrome (i.e., airport) forecasts have allowed FedEx planes to be the first ones to arrive or the last ones to depart under severe weather. Cockpits of FedEx airplanes have weather dashboards that provide real-time forecast information. Both FedEx and UPS Air forecast weather conditions as often as 10–15 days in advance and develop critical airport forecasts at least three times per day.

Private jets and helicopter flights that support the energy production segment (see Figure 3.1-13) by flying employees and equipment to offshore oil platforms also require specialized weather products developed by private-sector weather companies. Universal Aviation and Weather in Houston, Texas, is one of several companies that provide flight planning, including weather services. Specialized route-specific products are necessary for flight safety and fuel-burn estimates. Universal is another weather organization that previously had GOES GVAR antennas on site but now procures GRB data from a private-sector third party with antennas in Texas and Colorado.

As is the case for Federal GRB sites, failure to protect these non-Federal sites would have a significant effect on aviation operations, impacting costs, flight safety, and Federal users that rely on this data.

Figure 3.1-13. Bristow Helicopter transport to offshore oil rigs requires custom aviation weather products.

[26]Weather Club, "FedEx Meteorologists Deliver… Rain or Shine," Royal Meteorological Society, last updated December 18, 2013, accessed May 20, 2020, https://www.theweatherclub.org.uk/node/71.

3.1.3 GOES user requirements

GOES users were surveyed to identify the impact of data latency on their applications, and for other factors that might drive them to a reliance on the near-real-time reliability of direct broadcast to obtain the data. A majority of users required less than one minute of delay (from product production for GRB customers and from platform message transmission for DCS customers) for their data. Some users have even more stringent data perishability constraints, especially for lightning and space-weather data, with little or no tolerance for outages or delayed retrieval.

Data assurance requirements across the GOES Federal user community were investigated during Project 1. Federal users have developed safety-of-life and infrastructure management applications around GRB products and DCS platforms, such as for aviation, hurricane and severe storm warning, incident and storm surge flooding, and maritime navigation. Due to the need for data assurance and high reliability, most Federal users have evolved architectures that have two or more backup modes to retrieve messages. This is further explained in Sections 4.1 and 4.3 of this report. The USACE, which relies on the DCS systems to monitor water levels and drive decision-making for managing water levels using dams, spillways, locks, and other infrastructure, typically has three levels of redundancy in its methods of data collection. Direct reception of the DCS DCPR broadcast is preferred because it has the least delay. HRIT serves as a backup, and if the local satellite reception is offline, then LRGS retrieves messages from the USGS EDDN and/or the NOAA LRGS servers. USACE has learned from experience that weather events often take local internet or power access offline, and that satellite broadcast is often more reliable in a crisis. USACE and similar Federal users therefore have a requirement for direct satellite broadcast of GOES data and services to serve their need for reliability.

Federal end-user (and select non-Federal user) latency requirements collected during the DCS and GRB user surveys are grouped into broad categories: low (<1 minute), moderate (1–10 minutes), and high (>10 minutes) system latency. Table 3.1-10 and Table 3.1-11 summarize the DCS and GRB survey responses and show the number of end users by stakeholder affiliation that reported latency usage information. As captured in Table 3.1-10, 37% (64 of 175) of DCS users reported low latency requirements, 45% (79 of 175) reported moderate latency requirements, and 18% (32 of 175) reported high latency requirements. For GRB users who responded to the survey, per Table 3.1-11, 63% (22 of 35) reported low latency requirements, 34% (12 of 35) reported moderate latency requirements, and less than 3% (1 of 35) reported high latency requirements. The GOES direct broadcast user operational availability requirement (for the 1670–1710 MHz band) is taken from the International Telecommunication Union (ITU) interference criteria for service links of stations in the earth exploration-satellite service (EESS) and meteorological-satellite (Met-Sat) services. These criteria are defined in Rec. ITU-R SA.1163-2.

Table 3.1-10. Latency responses from the end users in the DCS user survey.*

End-user stakeholder affiliation	Total number end-user responses	Number that require low system latency (<1 minute)	Number that require moderate system latency (1–10 minutes)	Number that require high system latency (>10 minutes)
Academic	11	5	4	2
Commercial	7	5	1	1
DOC	34	11	18	5
DoD	33	17	13	3
DOI	13	7	5	1
DOS	1	0	1	0
FFRDC	4	2	2	0
Indian Tribe	3	0	2	1
International	29	9	14	6
State or local government	33	8	15	10
USDA	7	0	4	3
Total number of end users	175	64	79	32

*These are not requirements for the DCS community; the data is end-user reported.

Table 3.1-11. Latency responses captured from users in the GRB user survey.*

End-user stakeholder affiliation	Total number of end-user responses	Number that require low system latency (<1 minute)	Number that require moderate system latency (1–10 minutes)	Number that require high system latency (>10 minutes)
Academic	5	3	2	0
Amateur	1	1	0	0
Commercial	7	4	3	0
DOC	12	10	2	0
DoD	2	0	2	0
International	4	1	2	1
NASA	4	3	1	0
Total number of end users	35	22	12	1

*These are not requirements for the GRB community; the data is reported by end users. For the survey, 41 direct broadcast users were identified and contacted, and 35 responded.

3.2 Interference Risks

3.2.1 LTE sharing signal characteristics and network deployment

The SPRES program considered various uses of the 1675–1680 band for existing and emerging types of Long-Term Evolution (LTE) services with varying characteristics. This includes use for uplinks and downlinks, as well as for frequency division duplex (FDD), time division duplex (TDD), and internet of things (IoT) services and waveforms.

The LTE 3GPP standards define channel bandwidth and transmission bandwidth requirements. The channel bandwidth includes transmission bandwidth and a guard band at either end of the signal structure comprising 5% of the total allocated bandwidth. For 1675–1680, this means the 5 MHz channel bandwidth includes 4.5 MHz transmission bandwidth and a 250 kHz guard band at each end of the signal, so that the necessary bandwidth (NB) of the LTE signal extends from 1675.25–1679.75 MHz. If the LTE-allocated signal spectrum extended from 1670–1680 MHz, the NB is 9 MHz and the guard band would be 500 kHz wide on each side of the band. However, even with these standards in place, some of the energy is still present in the adjacent bands in the form of spurs, spurious signals, and a higher noise floor.

Table 3.2-1 identifies the characteristics of the LTE and IoT services that were considered across SPRES. Project 11 determined that use of the band for uplink or downlink produced the major RFI differences, while TDD and IoT had little variance. As a result, only FDD uplink and downlink modeling was carried into other projects. For the simulated interference signal, a broadband noise signal with the effective isotropic radiated power (EIRP) and spectral shape characteristics of the LTE source was used, but other specific characteristics such as modulation were not re-created. For the NB-IoT service deployment, network carriers can choose from three deployment options to suit different network environments: in-band operation, guard-band operation, and stand-alone operation.

Table 3.2-1. LTE/IoT services and signal characteristics used in SPRES analysis.

Signal	EIRP (dBm)	Antenna gain (dBi)	Transmission bandwidth (MHz)	Duty cycle for TDD (percent)	Discussion
LTE large cell: downlink	63	17.23	4.5	60–75	2 kW/5 MHz for 1670-1675 MHz (47 CFR 27.50).
LTE small cell: downlink	40	6	4.5	60–75	GSMA Small-Cell Deployment Guide.
LTE large & small cell: uplink	−37...+23	2.15	1.5	25–40	Max EIRP of 23 dBm per CSMAC Working Groups 1 & 3. Support up to 3 UEs/sector.
LTE-M: downlink	63	17.23	1.08	60–75	1.08 MHz plus guard band for 6 resource blocks (RBs); supports up to 3 LTE-M carriers.
LTE-M: uplink	23	2.15	0.18	25–40	Supports up to 3 LTE-M carriers multiplied by 6 UEs.
NB IoT in-band: downlink	63	17.23	4.5	60–75	One or more of the 25 RBs can be configured.
NB IoT in-band: uplink	23	2.15	0.06	25–40	3 non-IoT UEs plus up to 4 NB IoT UEs (a tone size of 15 kHz) each assigned to 180 kHz RBs.
NB IoT guard-band: downlink	63	17.23	4.68	60–75	One guard-band plus LTE 4.5 MHz.
NB IoT guard-band: uplink	23	2.15	0.06	25–40	Assumed up to 4 NB-IoT tones per sector (a tone size of 15 kHz).
NB IoT stand-alone: downlink	63	17.23	1.08	60–75	Assumed up to 6 NB IoT carriers of 180 kHz each.
NB IoT stand-alone: uplink	23	2.15	0.045	25–40	Up to 4 NB-IoT UEs per sector per NB IoT carrier. Each UE assumed 45 kHz (3 tones).

Note: RB = resource block.

The study sought current, real tower deployments as much as possible for the interference modeling as it was assumed this would best predict future cell locations. Four sources for deployment information were considered: the Commerce Spectrum Management Advisory Group (CSMAC) Working Group 5 (WG 5) tower location and tower characteristics database, CellMapper application tower location data, AWS-3 licensee-provided deployment information, and FCC databases.

The CSMAC WG database of tower locations was sourced from a single carrier network. Tower (transmitter) locations were randomized by a few kilometers to protect competition-sensitive information. In some locations without existing coverage, towers were added using demographic (population density) information; however, coverage gaps, such as in the state of Alaska, persisted. The database includes 68,139 towers. Two tower heights are included (30 m in urban/ suburban areas and 45 m in rural areas). CellMapper is a commercial application that relies on crowd-sourced data. Users install an application on their mobile phone that reports on cell towers encountered in transit.

AWS-3 licensee deployment plans were furnished to the U.S. Government (USG) for Early Entry Portal (EEP) coordination purposes and used by SPRES under nondisclosure agreements (NDAs).

FCC databases were used in Project 2 to research individual tower locations and characteristics because the CellMapper data used to supplement CSMAC data in locations such as Alaska required verification.

The CSMAC tower set was used to produce findings for Projects 8, 11, and 7. Comparison of CSMAC data with CellMapper and the AWS-3 data sets found that:

- CellMapper proved unreliable because it was not possible to completely verify the underlying data. Many towers appeared to be missing, especially in rural areas.
- AWS-3 data is limited to relatively small regions throughout the U.S., and coverage was insufficient to support the analysis.

NOAA’s finding indicated general consistency in relative density of towers between CSMAC and AWS-3 (where AWS-3 data was available), giving confidence that the CSMAC data set could be used. Tower density and distribution relative to the GOES ground station and surrounding terrain is more important to the analysis than exact locations. CSMAC tower locations in Project 7 were randomized and the simulations re-run, and there was no substantial difference in findings.

3.2.2 Measured interference thresholds and standardized interference criteria

SPRES Project 6 measured GOES GRB and DCS (and GVAR at Fairbanks) receiver performance operating on the grounds of the 32 surveyed sites. Measured parameters included frequency-dependent rejection (FDR) and signal margin. FDR is the amount of attenuation offered by a receiver to an adjacent-band transmitted signal via its filtering performance. Signal margin is a key parameter needed to derive FDR (see Table 3.2-2). Measurements showed variation in FDR values among sites, which is attributed to installation and configuration differences. Table 3.2-2 lists the range of results. These are measured results, which are generally lower than the

Table 3.2-2. FDR performance of GOES-R receivers.

Signal	FDR (dB)	Receiver types
DCS	0–10	Signal Engineering (SE) DirectLink DRGS Receiver, Microcom Design DAMS-NT Receiver
GRB	25–30	RT Logic T400RCV, Orbital Quorum GRB-200B

theoretical performance calculated in Project 2, due to non-linearities in the hardware and different LTE spectrum shaping (i.e., 5 MHz versus 10 MHz LTE carrier bandwidth).

It should be noted that the scope of the study included only interference sources in the L-band. Therefore, interference contributions in the DCP uplink (401.7–402.4 MHz) were not considered, although they do detract from the total DCS system interference budget.

For protection requirements, an interference-to-noise (I/N) ratio of −6 dB (i.e., LTE interference [I] power is 6 dB below the noise floor) is used to define LTE energy levels at the GOES antenna. Six dB is consistent with the levels used for fixed-satellite service (FSS) thresholds for Citizens Broadband Radio Service (CBRS) spectrum sharing. For the interference threshold calculation, a value was derived for each signal type. (See Appendix **J**, section **J**.1, and Table **J**-2 for clarifications on the methods used to calculate interference thresholds.)

Table 3.2-3. (Reserved).

3.2.3 Interference modeling

Interference modeling was performed in three SPRES projects using different propagation mod- els and processes. The models and criteria are summarized here.

The Anomalous Propagation Model (APM) is a U.S. Navy (USN) model that explicitly accounts for atmospheric and terrain conditions that affect signal propagation. It uses atmospheric refractivity profiles to calculate how signals propagate through the atmosphere. NOAA used refractivity profiles taken from three years of radiosonde readings to capture actual atmospheric conditions near each ground station in the study. The samples ranged from “standard” atmosphere conditions (no anomalous propagation [AP]) to significant levels of AP. A site-specific statistical analysis of refractivity profiles was created to determine the probabilities of the various AP conditions for each site.

The NTIA-developed Irregular Terrain Model (ITM), also known as the Longley-Rice model, and the Terrain Integrated Rough Earth Model (TIREM) are proven models that can effectively predict aggregate interference scenarios and integrate a variety of clutter data. ITM does not explicitly account for anomalous propagation. It uses an attenuation model that calculates path loss over terrain using a reference attenuation that is varied based on an empirical probability model.

Table 3.2-4. Interference and propagation model characteristics.

Propagation model	Terrain and clutter data	Terrain resolution	Cell tower laydown dB	Receiver antenna pattern	RFI metric	LTE bandwidth (MHz)	LTE guard bands
TIREM	SRTM and, within 2 km, 1 m lidar clutter	30 m (90 m Alaska)	AWS-3	ITU Appendix 8 ES antenna pattern for GSO networks (AP8)	A	1670–1680	500 kHz
APM	SRTM with modified Project 6 (P#6) clutter data	30 m (90 m Alaska)	CSMAC or AWS-3 (partial)	Extrapolated from measured 9 m pattern data	B	1675–1680	250 kHz
ITM (Longley-Rice)	SRTM with modified P#6 clutter data	30 m (90 m Alaska)	CSMAC	Extrapolated from measured 9 m pattern data	B	1675–1680	250 kHz

Notes: A: –128.8 dBm, 1 MHz reference bandwidth. *Source*: ITU Rec. SA.1163-3.
B: I/N = –6 dB (i.e., the interference noise has to be at least 6 dB below the noise floor; the reference link [https:/ www.ntia.doc.gov/files/ntia/publications/ipc_phase_1_report.pdf] recommends an INR of –6 to –10 dB I/N for long-term interfering signals for fixed services (Section 4).

The same shuttle radar terrain model (SRTM) terrain data set was used for all models, while different clutter data were used to observe impact. NOAA's analyses show that ITM and APM are consistent when APM uses a "standard" atmosphere refractivity profile. (See Appendix J, section J.2, for additional information.)

3.2.4 Interference risk findings

Mobile broadband use of the 1675–1680 MHz band can cause RFI to GOES ground stations in two ways: individual and aggregate line-of-site interference from nearby towers, and (anomalous) propagation from distant distributed towers when atmospheric ducting conditions occur. Where and when interference will occur is dependent upon the LTE deployment density, terrain, clutter, atmospheric conditions, and site configuration.

Of the DCS/DCPR, GRB, and HRIT signals, the DCPR signal was expected to have the primary risk of RFI due to partial overlap with the upper edge of the LTE signal (1679.7–1679.75 MHz, just below the guard band) in the 5 MHz-wide interfering LTE signal scenario. DCPR is also an un-coded signal and therefore has no error-correction capabilities or coding gain for added link robustness in the presence of RFI. Harmful interference effects could essentially render the DCS signal useless. DCS platforms have changed little over the years, with the satellite upconverting the UHF transmissions to L-band. If the DCS were not able to function in its current spectrum band, the entire network would have to be redesigned (uplink frequencies, satellite requirement trades, DRGS and DCS platform modifications or replacement) to meet the current DCS mission. Changing modulation techniques on the platforms would not be feasible from an operational or cost point of view, since it would require replacement or upgrade of the thousands of platforms in service. As mentioned in Section 3.1.1.2, the transition to the new DCPRCS Version 2 standard will have been completed over 17 years' time, and it is reasonable to expect another conversion to require a similar timeframe. Although SPRES did not specifically explore alternative satellite-based architectures, consider this rough estimate: for the 40,000 sensors alone, the replacement costs are $20,000–$25,000 per unit, for a total of about $1 billion. This figure does not include any additional sustainment costs or reoccurring commercial access charges. Satellite and DRGS costs would require further study.

The GRB signal risk of RFI is lowered relative to DCS in part due to separation from the 1675–1680 MHz band. How much risk-reduction benefit the separation provides is measured by FDR. Project 6 measured about 25 dB (of FDR) in GRB receivers, meaning that 25 dB more power would be required in the 1675–1680 MHz band to cause interference to the GRB signal. This factor is included in the exclusion-zone calculations. The frequency separation, as well as GRB's inherently robust digital video broadcast satellite 2nd generation (DVB-S2) coding, explains the magnitude of the FDR. The broadcast signal uses forward error correction (FEC), which provides approximately 10 dB of coding gain. In addition, the operating power of the GRB broadcast signal is held constant, and there is enough margin to withstand some interference even at the minimum power level (end-of-life power).

Compared to other services discussed in this study, the HRIT/EMWIN signal has lower risk of RFI from 1675–1680 MHz sharing because of the 13 MHz separation from the 1675–1680 MHz band, although it may suffer degradation from handheld transmitters in the 1695–1710 MHz band.

3.2.4.1 Aggregate interference risks

Aggregate interference modeling was performed using site-specific terrain data, clutter data, ground station configuration and susceptibility data, and LTE network deployment information. Contributions from any LTE tower that exceeded the RFI sensitivity threshold were included.[27] The APM propagation model incorporated SRTM (30 m) terrain data.

Project 11 modeled aggregate interference using ITM (no AP), and Projects 8 and 7 modeled aggregate interference using APM and accounted for a range of atmospheric conditions (from no AP to severe AP) derived from three years of radiosonde measurements.

3.2.4.2 Anomalous propagation interference risk

SPRES analyzed the potential impact of anomalous propagation on LTE downlink spectrum sharing with GOES ground stations in the 1675–1680 MHz band. Specific objectives were as follows: (1) determine the importance of AP interference to the selected GOES stations; (2) develop Federal GOES ground station/downlink protection requirements under AP conditions; and (3) analyze methods to mitigate potential interference under AP conditions.

The project focused on tropospheric ducting effects on RF signal propagation, which is believed to be the dominant anomalous propagation phenomenon. Ducting occurs when temperature and

[27]Although not specifically evaluated, the NPRM for 1675–1680 MHz suggests that if a future licensee in that band has rights in the adjacent band, the FCC could waive the out-of-band emission limit between bands, as is common practice. In this situation, there is a potential for the out-of-band emissions from the adjacent band to impact GOES DCPR, because that is in-band to 1675–1680 MHz. SPRES calculations did not include this case, but any changes such as this that would affect the amount of energy allowed in 1675–1680 MHz would need to be considered when setting emission limits or other regulatory measures to protect incumbent operations.

humidity profiles in the atmosphere have strong gradients, causing RF signals to refract at duct boundaries and become trapped rather than dissipate. As a result, signal energy levels remain stronger across longer distances than occurs under nominal propagation conditions. Propagation loss can be 40–50 dB lower than under normal (standard atmosphere) conditions in a range extending out to the duct edge (up to or exceeding 500 km).

Initially, in Project 8, ducting characteristics were derived for 10 selected GOES ground station sites using historical radiosonde data collected by nearby radiosonde launch locations. The radiosonde data was used to determine the index of refraction versus height at each location. The refractive index profiles were provided as input to the Navy's APM, which accounts for multiple modes of propagation, including tropospheric ducting to predict signal attenuation. APM is a hybrid ray-optic and parabolic equation (PE) model that uses the complementary strengths of both methods to construct a flexible composite model.[28] RFI was characterized statistically to assess the risk of occurrence.

Based on the initial findings of Project 8, and incorporating terrain data, tower laydowns, and improvements in the APM simulations, Project 7 refined the anomalous propagation RFI risks. Table 3.2-5 ranks the impacts of anomalous propagation on the protection criteria for each Federal GOES ground station. The ΔRFI columns rank each location based on the difference in RFI power levels at different percentiles. These rankings essentially indicate the relative impact of the two cases. Column 2 ranks sites based on the difference between the 99th and 95th percentiles, while column 3 provides rankings based on the difference between the 100th (i.e., worst case) and 95th percentiles.

Several factors influence the impacts of anomalous propagation on RFI levels:

1. Occurrence of ducting conditions: In general, coastal and high humidity areas have the most occurrences of ducting, which is a function of temperature inversions and humidity.
2. Strength of ducting conditions: The strongest ducting conditions were found along the East and Gulf coasts, but they are not limited to those regions.
3. Terrain: Flat terrain enables larger duct sizes than areas having moderate-to-significant terrain variations. Areas along the East and Gulf coasts have large stretches of flat terrain, while the West Coast is more mountainous. Similarly, the Midwest has the potential for large ducting due to flat terrain.
4. Proximity to dense population areas: Sites having dense population areas at a moderate distance are affected more than those where dense populations are nearby. As an example, Wallops is highly impacted by anomalous propagation because major populations from Richmond, Virginia, to New York City become significant contributors to RFI under moderate-to-high ducting conditions. While Miami may see similar ducting conditions as Wallops, the population density is highest in close proximity to the GOES ground station and low at moderate-to-long distances.

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[28] Amalia Barrios, "Considerations in the Development of the Advanced Propagation Model (APM) for U.S. Navy Applications," *Proceedings of the International Conference on Radar* (Adelaide, Australia: IEEE, 2003): 77-82, https://doi.org/10.1109/RADAR.2003.1278714.

Table 3.2-5. Anomalous propagation impacts on RFI.

Site	ΔRFI (99%–95%)	ΔRFI (100%–95%)	Average score	Ducting impact on RFI
Wallops Island, VA	1	2	1.5	High
Suitland, MD	3	1	2	High
Vicksburg, MS	2	4	3	High
Rock Island, IL	6	6	6	Moderately high
Sioux Falls, SD	10	3	6.5	Moderately high
Cincinnati, OH	9	5	7	Moderately high
Columbus Lake, MS	5	9	7	Moderately high
Cape Canaveral, FL	4	10	7	Moderately high
St. Louis, MO	8	7	7.5	Moderately high
Norfolk, VA	7	8	7.5	Moderately high
Houston, TX	11	14	12.5	Moderate
Kansas City, MO	13	13	13	Moderate
Sacramento, CA	16	11	13.5	Moderate
Miami, FL	12	15	13.5	Moderate
Fairmont, WV	17	12	14.5	Moderate
Monterey, CA	14	16	15	Moderate
Stennis Space Center, MS	16	16	16	Moderate
Honolulu, HI (Hickam)	18	18	18	Moderately low
Norman, OK	23	20	21.5	Moderately low
Fairbanks, AK	21	23	22	Moderately low
Omaha, NE	26	19	22.5	Moderately low
College Park, MD	24	21	22.5	Moderately low
Honolulu, HI (NOAA)	22	24	23	Moderately low
Boulder, CO	20	26	23	Moderately low
Boise, ID (BOR)	19	27	23	Moderately low
Anchorage, AK	25	22	23.5	Low
Huntsville, AL	29	25	27	Low
Boise, ID (NIFC)	27	28	27.5	Low
Anchorage, AK (Elmendorf)	29	29	29	Low

3.2.4.3 RFI risk to other USG GOES receiver systems

In addition to the Federal locations listed in Table 3.3-3 that were surveyed, SPRES assessed spectrum-sharing risk to USN shipboard AN/SMQ-11 and the U.S. Marine Corps (USMC) mobile meteorological AN/TMQ-56 METMF(R) GOES receiver systems.

3.2.4.3.1 U.S. Navy GOES equipment analysis

USN AN/SMQ-11 shipboard earth stations are installed on certain naval ships. The AN/SMQ-11 receives and processes the GOES-R HRIT signal. To estimate RFI risk, SPRES used the point-to-point link prediction mode of the ITM. The model considers atmospheric changes, terrain profiles, and free-space loss. SRTM terrain data and the CSMAC tower data was used to create terrain profiles that were input into the ITM propagation model. For clutter, the 2016 USGS 30 m resolution land cover data was used for all regions considered in this study. USGS data has 32 different potential clutter categories.

The AN/SMQ-11 antenna mount height was assumed to be 15 m. For the analysis, the ship was placed 10–15 km offshore along the Atlantic, Gulf, and Pacific coasts, and at the following in-port locations: Naval Stations Bremerton, Pearl Harbor, and Norfolk, and Naval Base San Diego, for a total of 349 sites. The CSMAC tower database was determined to be sufficient for aggregate interference analysis in this case and was used for LTE deployment information. An aggregate analysis of all out-of-band emissions from the LTE transmitters around the ship locations was conducted. If initially the aggregate power did not exceed the interference threshold, the ship location would be identified as a point along an exclusion zone indicating no exclusions in that particular direction.

The result of the analysis for the AN/SMQ-11 identified no impact and no appreciable risk due to projected LTE deployments in the 1675–1680 MHz band. The simulation results are consistent with Project 6 measurements that showed an inability to interfere with the HRIT signals at other locations when injecting signals in the 1675–1680 MHz band.

3.2.4.3.2 USMC GOES receiver analysis

The USMC AN/TMQ-56 METMF(R) mobile (truck-mounted) GOES receiver has a 1.2 m dish and receives the (older) GOES-NOP LRIT signal and the (newer) GOES-R HRIT signal. As the system does not receive/process the DCS or GRB signals, and interference risk was determined to be negligible (based upon results from the littoral study described above), no further analysis was completed.

3.3 RFI Mitigation Options and Feasibility

A wide range of mitigation options were examined to improve sharing feasibility and protect GOES data access for the near and long term. *The GOES-R space segment and signal structure is fixed through 2035. As a result, changing frequencies or redesigning GOES signal structure to enhance sharing can be considered only for future architectures (after 2035).* Alterations to LTE deployment and operations, modifications to GOES earth stations, spectrum monitoring, and alternative dissemination techniques were all considered.

The primary goal of finding the most effective RFI mitigation approaches is to reduce the exclusion distance, thus increasing the available coverage area and hence the number of LTE users the carrier can support in the 1675–1680 MHz band, and also allowing the installation of future GOES earth stations with minimal coordination and disruption.

Mitigation approaches were considered in Projects 8 and 11, and the results were used as an input to Project 7, where they were reevaluated. These approaches were identified by examining each parameter in the RFI analysis to determine how the parameter value could be reduced.

The use of dynamic exclusion zones is applicable only to RFI caused by anomalous propagation, and it was assessed for the ability to improve temporal sharing through the use of circular or sectorial exclusion zones in which all LTE sources are switched off during high ducting periods. Other approaches include modifications to the ground station or LTE implementation and operations to improve the spatial spectrum-sharing capability.

The findings indicate that some improvements show promise, and their potential benefits were quantified. Not all would be applicable to a given site, but with several possible approaches, some could be used to reduce the separation distances otherwise required. Those approaches showing the most feasibility are recommended for implementation with *uplink* sharing. No combination of mitigations can realistically make LTE *downlink* sharing feasible.

Mitigation options are ranked by effectiveness and feasibility in Table 3.3-1. Of the mitigations rated the highest, measurable interference benefits that may be used to reduce the size of the exclusion zones are shown in Table 3.3-2.

Table 3.3-1. SPRES RFI mitigation options.

Mitigation	Projects	Applicability				Effectiveness	Feasibility
		Downlink sharing	Uplink sharing	Aggregate interference	Anomalous propagation		
Exclusion zones	7	✓	✓	✓	✓	High	High
GOES receiver improvement	5	✓	✓	✓	✓	High	High
GOES antenna improvements (passive)	11	✓	✓	✓	✓	Medium	Medium
GOES site improvements	11	✓	✓	✓	✓	Medium	Medium
Dynamic exclusion zones	8	–	–	–	✓	High	Low
Terrestrial network substitution	3, 4	✓	✓	✓	✓	High	Low
Small-cell substitution	11, 8, 7	✓	✓	✓	–	Medium	Low
LTE antenna downtilt	11, 7	✓	–	✓	✓	Medium-high	Low
LTE carrier modification	7	✓	✓	✓	✓	Medium-high	*
RF monitoring	10	✓	✓	✓	✓	Low	Medium

*Feasibility is dependent on the carrier’s ability and willingness to reduce resource blocks. See Section 4.7.

Table 3.3-2. Most promising uplink sharing mitigation benefits (other than spatial separation).

Type	Benefit (range) DCS sites (dB)	Benefit (range) GRB sites (dB)	Comments
LTE carrier signal modification	0–10	0	Modify LTE carrier signal width or center frequency to reduce/eliminate overlap with the DCS signal to make RFI adjacent-band and enhance DCS filter performance. Most benefit is contingent on implementing GOES receiver improvements.
GOES antenna Improvements	5–10	5–10	Collar around feed or feed tapering to reduce the GOES antenna sidelobes toward the LTE signals.
GOES site improvements	5–10	5–10	Fences/block wall to antenna feed height to block the LTE signal path. Not for NOAA sites with 16.4 m antenna or other physical restrictions.
GOES antenna electronics and receiver improvements: (1) Amplification (2) Filtering	10–20	10–20	Redesign GOES receivers for operation in a sharing environment. (1) Amplification: Reduce preamplifier gain by 10–20 dB to reduce intermodulation effects and improve preselection filtering. (2) Filtering: Improve LNB (L-band) front-end filtering; reduce bandwidth of preselection (intermediate frequency) filtering.
Total	20–30	10–30	Interaction between mitigation approaches may reduce the cumulative benefit.

3.3.1 Protection contours for GOES receive sites for downlink and uplink sharing scenarios

The studies used a risk-based analysis of RFI to determine exclusion zones. Simulations produced interference predictions for signals from each LTE transmitter in the region surrounding a GOES earth station. Exclusion zones were then found by removing towers within a geographic area surrounding the station until RFI levels fell below the interference threshold. The exclusion zone boundary then encompassed all removed towers.

Exclusion zones were calculated for confidence levels ranging from 50%–100%. The study recommends using a confidence level of 95%, which corresponds to a 5% interference risk. This risk level is consistent with the confidence level used in the CBRS 3.5 GHz spectrum-sharing analysis.

Exclusion zones were calculated using a few methods but generally fall into the categories circular or polygonal zones. Circular zones were found using the distance between the downlink station and furthest removed tower as the radius for the exclusion zone. Polygon zones were found by successively removing towers in order of their interference levels and tracing around the most distant excluded towers.

Table 3.3-3 summarizes the required circular protection distances based upon APM and ITM propagation modeling, accounting for protection against 95% of all ducting occurrences, for both LTE downlink and LTE uplink sharing scenarios. Both scenarios assume a 5 MHz FDD LTE signal. For each site, the GOES signal(s) received and the circular protection distances are shown. Interference thresholds used for these calculations are as follows:

- DCS data link: −128.2 dBm (/400 kHz)
- GRB data link: −113.8 dBm (/10.9 MHz)
- GVAR data link: −124.11 dBm (/4.2 MHz)

Exclusion zones are site-specific and heavily depend on terrain effects and the carrier terrestrial deployment density within the analysis distance. The aggregate RFI originating from the FDD downlink is several orders of magnitude higher compared to the FDD uplink. Analysis shows that vast differences in EIRP between the downlink and uplink signal result in a minimal distinction between FDD and TDD deployments. The primary factors causing the downlink RFI dominance include the following:

- Differences in EIRP between the downlink and uplink
- A larger peak gain of the towers as compared to the UEs
- A lower propagation loss for towers due to their height above terrain clutter, while UEs encounter significantly more clutter loss

Table 3.3-3. Federal GOES earth station calculated RFI protection distances.

Federal site	Data link	LTE sharing	Population impacted	Protection distance (km)***
Anchorage, AK Elmendorf Air Force Base	GRB	Downlink Uplink	260,000 <100	19 1
Anchorage, AK National Weather Service	GRB	Downlink Uplink	240,000 <100	18 1
Boise, ID Bureau of Reclamation	DCS	Downlink Uplink	690,000 200,000	59 8
Boise, ID Bureau of Reclamation	HRIT	Downlink Uplink	<100	0
Boise, ID National Interagency Fire Center	DCS	Downlink Uplink	710,000 470,000	123 32
Boise, ID National Interagency Fire Center	HRIT	Downlink Uplink	<100	0
Boulder, CO Space Weather Prediction Center	GRB	Downlink Uplink	3,500,000 100,000	71 1
Brevard County, FL Cape Canaveral Space Force Station*	GRB	Downlink Uplink	2,400,000 <100	71 1
Chesapeake, VA National Ocean Service	HRIT	Downlink Uplink	<100	0
Cincinnati, OH U.S. Army Corps of Engineers	DCS	Downlink Uplink	2,500,000 900,000	68 15
Cincinnati, OH U.S. Army Corps of Engineers	HRIT	Downlink Uplink	<100	0
College Park, MD Center for Weather and Climate Prediction	GRB	Downlink Uplink	3,000,000 <100	20 1
Columbus Lake, MS U.S. Army Corps of Engineers	DCS	Downlink Uplink	300,000 20,000	55 7
Fairbanks, AK Command and Data Acquisition Center	GVAR	Downlink Uplink	<100	0

Table 3.3-3 cont.

Table 3.3-3. Federal GOES earth station calculated RFI protection distances.

Federal site	Data link	LTE sharing	Population impacted	Protection distance (km)***
Fairmont, WV NOAA Environmental Security Computing Center	GRB	Downlink Uplink	510,000 17,000	59 6
Fairmont, WV NOAA Environmental Security Computing Center	DCS	Downlink Uplink	1,200,000 130,000	103 25
Fairmont, WV NOAA Environmental Security Computing Center	HRIT	Downlink Uplink	<100	0
Hancock County, MS Naval Oceanographic Office John C. Stennis Space Center*	GRB	Downlink Uplink	1,400,000 <100	55 1
Honolulu, HI Joint Base Pearl Harbor-Hickam Air Force Base	GRB	Downlink Uplink	710,000 <100	18 1
Honolulu, HI National Weather Service	GRB	Downlink Uplink	760,000 <100	21 1
Honolulu, HI Joint Typhoon Warning Center*	GRB	Downlink Uplink	—	—
Houston, TX Johnson Space Center	GRB	Downlink Uplink	5,000,000 <100	66 1
Huntsville, AL NASA Short-term Prediction Research and Transition Center	GRB	Downlink Uplink	480,000 <100	24 1
Kansas City, MO Aviation Weather Center	GRB	Downlink Uplink	2,000,000 <100	44 1
Knoxville, TN Tennessee Valley Authority	HRIT	Downlink Uplink	<100	0
Miami, FL National Hurricane Center	GRB	Downlink Uplink	3,800,000 <100	39 1
Monterey, CA Naval Research Laboratory	GRB	Downlink Uplink	810,000 <100	57 1
Monterey, CA Numerical Meteorological and Oceanographic Command*	GRB	Downlink Uplink	—	—
Norfolk, VA Fleet Weather Center*	GRB	Downlink Uplink	2,800,000 33,000	104 4
Norman, OK Storm Prediction Center	GRB	Downlink Uplink	550,000 <100	31 1
Omaha, NE Air Force Weather Agency	GRB	Downlink Uplink	770,000 <100	28 1
Omaha, NE U.S. Army Corps of Engineers	DCS	Downlink Uplink	**	**
Omaha, NE U.S. Army Corps of Engineers	HRIT	Downlink Uplink	**	**

Table 3.3-3 cont.

Table 3.3-3. Federal GOES earth station calculated RFI protection distances.

Federal site	Data link	LTE sharing	Population impacted	Protection distance (km)***
Rock Island, IL U.S. Army Corps of Engineers	DCS	Downlink Uplink	730,000 310,000	81 20
Rock Island, IL U.S. Army Corps of Engineers	HRIT	Downlink Uplink	<100	0
Sacramento, CA U.S. Army Corps of Engineers	DCS	Downlink Uplink	9,200,000 2,100,000	133 54
Sacramento, CA U.S. Army Corps of Engineers	HRIT	Downlink Uplink	<100	0
San Diego, CA Naval Information Warfare Systems Command	HRIT	Downlink Uplink	<100	0
Seattle, WA National Weather Service	HRIT	Downlink Uplink	<100	0
Sioux Falls, SD Earth Resources Observation and Science Center	DCS	Downlink Uplink	480,000 75,000	85 15
Sioux Falls, SD Earth Resources Observation and Science Center	HRIT	Downlink Uplink	<100	0
St. Louis, MO U.S. Army Corps of Engineers	DCS	Downlink Uplink	2,800,000 900,000	81 19
St. Louis, MO U.S. Army Corps of Engineers	HRIT	Downlink Uplink	<100	0
Suitland, MD NOAA Satellite Operations Facility	GRB	Downlink Uplink	7,200,000 10,000	63 3
Suitland, MD NOAA Satellite Operations Facility	DCS	Downlink Uplink	18,000,000 4,000,000	171 39
Suitland, MD NOAA Satellite Operations Facility	HRIT	Downlink Uplink	<100	0
Vicksburg, MS U.S. Army Corps of Engineers	DCS	Downlink Uplink	2,300,000 36,000	154 11
Vicksburg, MS U.S. Army Corps of Engineers	HRIT	Downlink Uplink	<100	0
Wallops Island, VA Wallops Command and Data Acquisition Station	GRB	Downlink Uplink	15,000,000 <100	203 1
Wallops Island, VA Wallops Command and Data Acquisition Station	DCS	Downlink Uplink	24,000,000 15,000	286 8
Wallops Island, VA Wallops Command and Data Acquisition Station	HRIT	Downlink Uplink	<100	0

*GRB sites planned for 2020.
**Omaha, NE (USACE) was not covered in the analysis, but it falls within the Offutt AFB exclusion zone radius.
***HRIT exclusion zones are based only on the 1675–1680 MHz sources, and do not take into account interference that may come from AWS-3 networks or other sources.

Results from the analysis of LTE TDD and FDD deployments reveal that the contour radii are nearly the same for the two and that, with few exceptions, the radius around the GOES ground station has little directional variation between GOES-East and GOES-West.

3.3.2 GOES antenna electronics and receiver improvements

The current GRB and DRGS receivers, including the L-band antenna low-noise block (LNB) electronics, were not designed for sharing spectrum with terrestrial emitters, but rather to manage low levels of adjacent-channel interference primarily coming from the other GOES satellite signals in the 1675–1695 MHz band. Design aspects of GOES receivers affecting susceptibility were assessed through testing and empirical assessment.

During on-site FDR and system-margin testing, SPRES found that the GOES receivers are typically over-driven, resulting in excess amplification of, and increased susceptibility to, unwanted signals (RFI). SPRES found that preamplifier gain could be reduced by 10 dB to yield 10 dB of RFI reduction.

DCS receiver (intermediate frequency [IF]) filtering was empirically reviewed, and it was found that significant improvements could be made to optimize performance in the proposed shared environment.

GOES antenna LNB performance was also assessed during site testing. The GRB LNB readily passes signals from about 1672.6–1700.6 MHz, as can be seen in Figure 3.3-1. This is typical of GOES LNB bandpass equipment designed for the Met-Sat band. LNB design should be further assessed to determine what degree of out-of-band rejection performance can be accomplished.

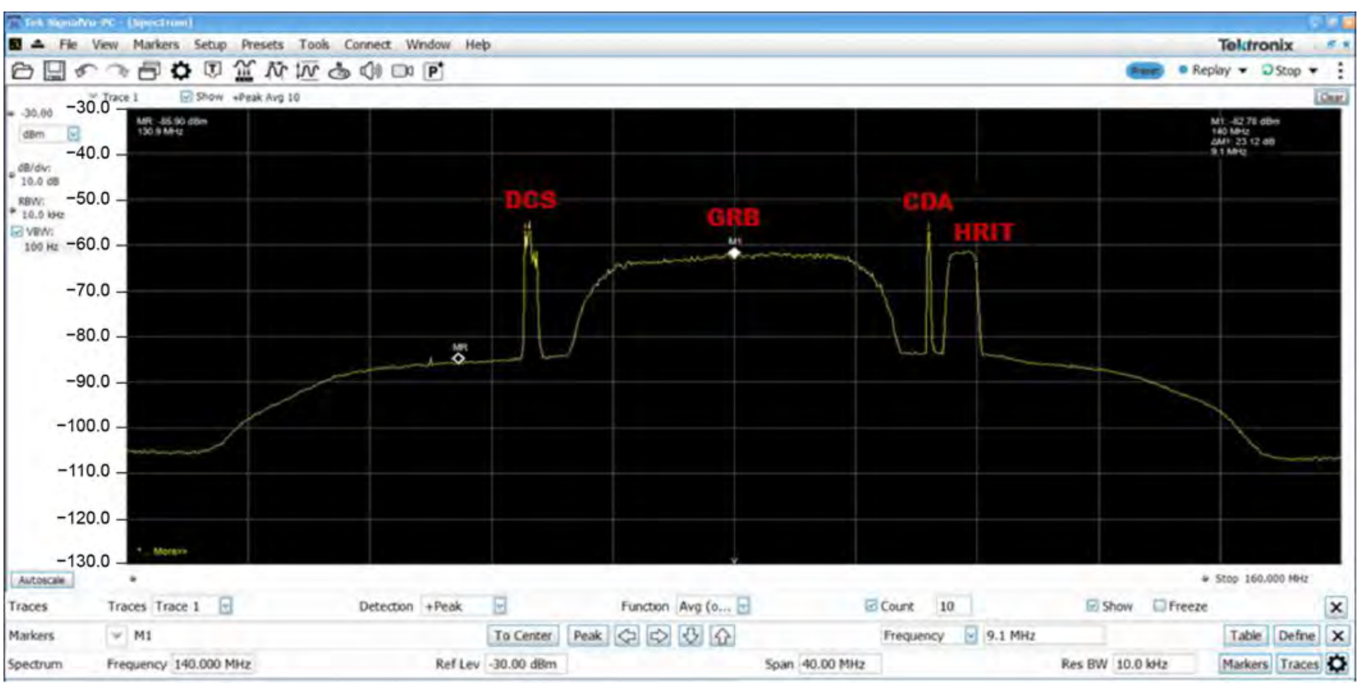


Figure 3.3-1. GOES IF spectrum of a RHCP path from a 6.5 m antenna under normal conditions.

The following are details about the IF spectrum plot:

- Plot center: 140 MHz corresponding to 1686.6 MHz (also center of GRB signal)
- Plot left edge: 120 MHz (or 1666.6 MHz); right edge: 160 MHz (1706.6 MHz)
- Overall plot width: 40 MHz, 4 MHz/division (x-axis)
- Overall plot height: 100 dB, 10 dB per division (y-axis)

A complete conceptual redesign of the GOES receivers from RF to IF is recommended to determine precise obtainable performance in the defined sharing environment. Existing equipment vendors should be engaged. The GRB and DCS cases are further explained here.

3.3.2.1 GRB receiver

The current Harris GRB receivers use a downconverter with very high (55–60 dB) preamplifier gain. This large amount of gain can create large signal levels and adjacent-channel intermodulation of the LTE RFI signal, which would significantly decrease the FDR when attempting to receive a NOAA satellite downlink signal (Figure 3.3-2). The high preamplifier gain maximizes the overall noise figure and maximizes the satellite signal link margin, but the high gain increases RFI susceptibility. If a lower gain were used, then the overall performance (when adjacent-channel RFI is present) can significantly be improved because this avoids creating large signal levels at the amplifier output (large signal levels cause intermodulation noise).

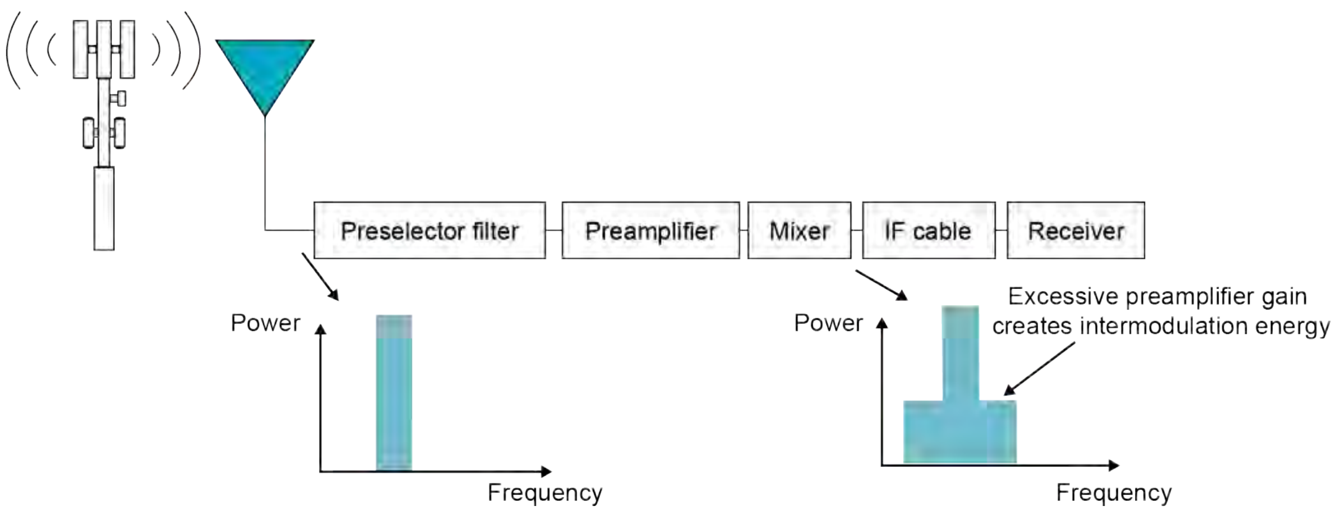


Figure 3.3-2. Improving the preselector amplifier design can reduce undesired intermodulation RFI energy.

Figure 3.3-3 shows the spectrum after a preamp with 45 dB gain (left) and a preamp with 55 dB gain (right) with a −50 dBm input signal. Reducing the preamp gain by 10 dB reduced the intermodulation by 30 dB. As previously discussed, the intermodulation power increases 30 dB when the signal power is increased by 10 dB. Hence, the FDR value would be 10 dB higher with the 45 dB gain preamplifier compared to the FDR value with the 55 dB gain preamplifier.

Figure 3.3-4 shows the spectrum after a preamp with 46 dBm third-order intercept point (IP3) (left) and a preamp with 36 dBm IP3 (right) with a −50 dBm input signal. Increasing the IP3 value by

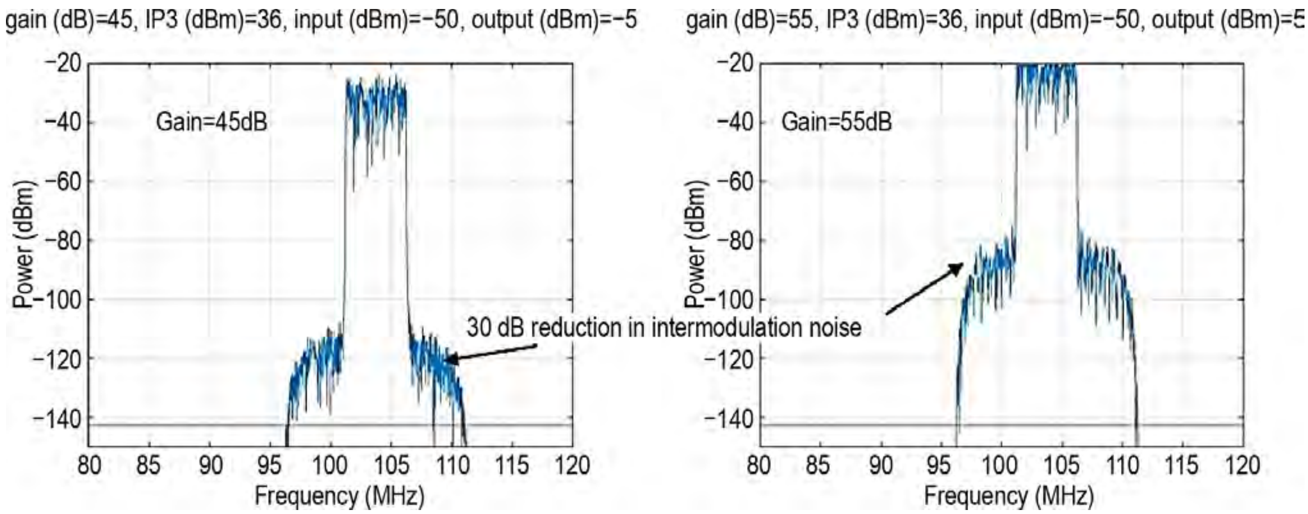


Figure 3.3-3. Spectrum after a preamp with 45 dB gain (left) and a preamp with 55 dB gain (right) with a −50 dBm input signal.

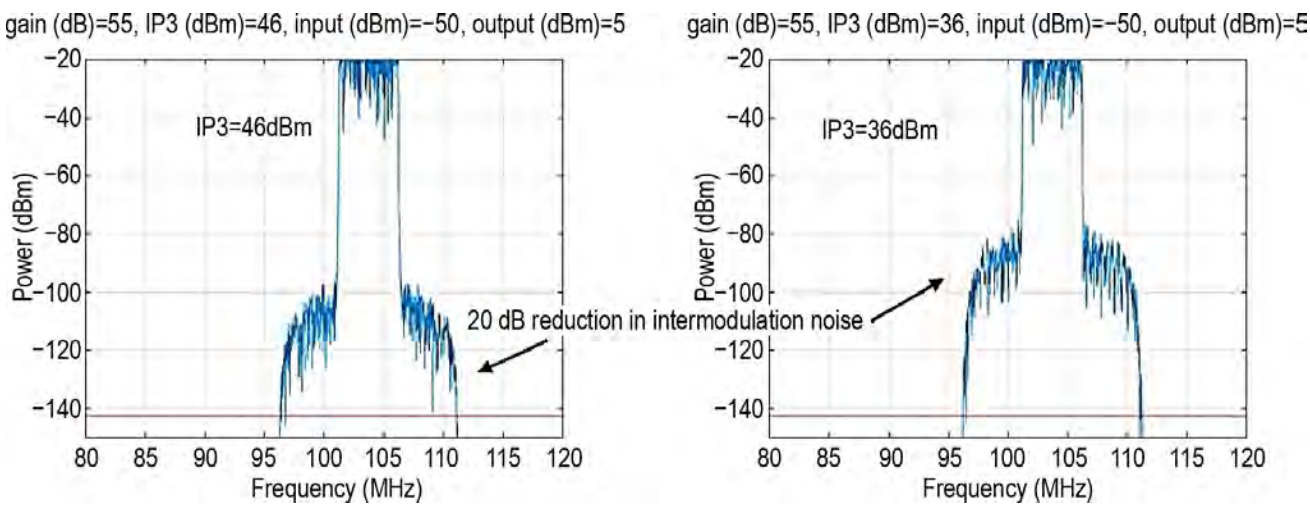


Figure 3.3-4. Spectrum after a preamp with 46 dBm IP3 (left) and a preamp with 36 dB IP3 (right) with a −50 dBm input signal.

10 dB reduced the intermodulation by 20 dB. As previously discussed, the intermodulation power increases 30 dB when the signal power is increased by 10 dB. Hence, the FDR value would be 6.66 dB (10 dB *2/3) higher with the 46 dBm gain preamplifier compared to the FDR value with the 36 dBm gain preamplifier.

The GRB receiver FDR value is limited by intermodulation created at the preamplifier. Using the Harris preamplifier values, this limit is estimated to be 35.6 dB. This is in reasonable agreement with the measured value of approximately 30 dB. The FDR performance can be improved by decreasing the preamp gain or increasing the preamp IP3 value. This demonstrates that, in the presence of a reduced gain setting (or increased IP3), there is still sufficient signal strength for the receiver to operate normally. Further investigation is needed for design considerations.

3.3.2.2 DCS DRGS receiver

The NOAA DCS U.S. signal is made up of 533 channels that operate between 1679.7 MHz and 1680.1 MHz. This was the primary focus for RFI analysis. There is an international DCS signal that extends from 1680.1–1680.4 MHz, yielding a band that fully extends from 1679.7–1680.4 MHz, which was not part of this study. DCS receivers are designed to pass both signals.

Microcom DRGS example

NOAA, USACE (at certain regional centers), National Interagency Fire Center (NIFC), USBR, FDOT, and some other entities utilize the Microcom DRGS for DCS data reception. The current version of the Microcom DRGS was specifically designed to support the transition from GOES-NOP to GOES-R, and to work on both U.S. and international DCS channels.

The Microcom DRGS utilizes a custom Dual Pilot Control Module (DPCM) that finds and locks to the DCS pilots. It is a 160 MHz surface acoustic wave (SAW) filter featuring:

- 1.5 dB passband rating of 1.2 MHz
- 3 dB bandwidth of 1.5 MHz
- 40 dB stop-band rating of +/− 1.25 MHz (2.5 MHz bandwidth)

The filter is centered at 1679.75 MHz (40 dB stop-band extends from 1678.50–1681 MHz). This center frequency was selected for two reasons:

1. It provides some additional rejection to GRB.
2. The SAW filter’s passband is a bit flatter (has less ripple) in the upper portion.

For comparison, the prior generation of the DPCM had two stages of filtering and was higher performance.

- The first stage was a five-pole tuned filter that could have its center between 70 and 80 MHz, a 3 dB passband of approximately 3 MHz, and a 40 dB rejection bandwidth of about 10 MHz.
- The second stage was a seven-pole tuned filter with a 1.5 dB passband of about 600 kHz and a center frequency of 5 MHz. The 40 dB bandwidth was −650 kHz to +850 kHz (i.e., the roll-off was somewhat steeper on the low side).

The prior version of the DPCM also did not include a preamp gain adjustment. This was added to the current (GOES-R) version for two reasons:

1. During the GOES-NOP era, an external, inline preamp or attenuator was needed to get the signal level into the DPCM at the right level due to variations in dish size and front-end gains.
2. GOES-R has a stronger DCS downlink.

The new design included an amplifier at the input, and a step attenuator after the first mix stage and the SAW filter. The amplifier has a fixed gain of about 15 dB, and the step attenuator has a 30 dB range; i.e., the preamp gain could be +15 dB or −15 dB before the pilot automatic gain control stage.

The DRGS internal and front-end (LNB) filtering and gain could be optimized for RFI mitigation. The effort starts with a defined RF (sharing) environment, followed by optimizing the antenna, RF frontend/LNB, and finally the receiver (IF) amplifier and filter stages. Narrower filters are achievable. Once the operating environments are understood and characterized, such improvements could yield benefits of at least 20 dB.

If combined with an LTE carrier modification that removes the LTE carrier from the 40 dB stop-bandwidth of the DCS filter, moving it from in-band to adjacent-band (see Section 3.3.9), additional mitigation would be achieved, resulting in potential reduction of exclusion zone distances. Further investigation is needed for both the single and combined approaches.

3.3.3 Low-sidelobe ground-station antenna mitigation approach

SPRES assessed passive and active measures for GOES antennas to achieve reductions in unwanted RF energy entering the antenna through the sidelobes. To have significant impact, unwanted signals entering the sidelobes need to be reduced by 20–40 dB.

The passive measures consist of modifications to the ground-station antenna to reduce its sidelobe levels. Typical approaches include tapering the feed pattern that illuminates the reflector and the addition of shrouds. These methods are believed to provide 10–20 dB of sidelobe reduction. Design and implementation of shrouds would be subject to the unique requirements of each site.

Active cancellation systems are not common but are used in some applications to eliminate RFI from reflector antennas. For example, the radio astronomy community uses active, digital cancellation as an RFI mitigation approach.[29] This requires extensive narrowband digital filtering and the ability to coherently recombine the signal afterwards. Another approach is to use an array of antennas around the GOES earth station to detect interfering signals, and then process and digitally subtract them from the received GOES signal. NOAA previously investigated such a methodology in a program called Satellite Downlink Interference Filtering and Monitoring System (SDIFMS). SDIFMS simulated an active cancellation approach for L-band spectrum sharing[30] that was designed to mitigate interference signals to NOAA satellite ground stations from wireless user transmitters (such as handheld smartphones and other devices), including aggregate LTE interference from multiple, simultaneous interferers.

The SDIFMS requires a circular array of monitoring antennas (surrounding the NOAA satellite downlink antenna) that continuously sense the interference environment. The number of

[29] Brian D. Jeffs, Richard A. Black, Karl F. Warnick, “Array Processing Methods for Radio Astronomical RFI Mitigation: Assessment of the State of the Art,” presentation at RFI 2016: Coexisting with Radio Frequency Interference, Socorro, NM, October 17–20, 2016.
[30] Shared Spectrum Company, “L-band Radio Frequency Interference Filtering Phase I SBIR Project,” Project 2840, NOAA Contract No. WC-133R-16-CN-0065 (2016).

monitoring antennas (4–20) is scalable depending on the expected environment of interfering signals. The sampled interference signals are then digitally processed to coherently subtract them out of the desired NOAA satellite downlink signal.

While such an approach has considerable theoretical performance, practical implementation of such systems is extremely challenging, and, depending on the size of the antenna array required, may also be costly to install and maintain.

In summary, if NOAA were to pursue a program to reduce antenna sidelobes and antenna susceptibility, only passive measures appear practical at this time, though active measures could be further studied. Passive measures can produce 10–20 dB of improvement, depending upon the antenna type, although additional development, testing, and demonstration would be needed to verify feasibility.

3.3.4 GOES site improvements and RF barriers

SPRES evaluated the sharing benefits of shielding the GOES antennas from RFI by constructing or expanding existing block walls, chain-link fences, or metal-mesh fences used for antenna enclosure.

The term shielding refers to installing artificial barriers or shrouds on or around the earth station dish designed to shield the antenna from radiation outside the main beam (Figure 3.3-5). Since the elevation angle to the satellite is high and interference elevation angle is low, shield walls above feed height could be employed to mitigate interference. The effectiveness of RF shielding to reduce interference at ground stations depends on the sidelobes of the antenna and the diffraction loss sustained by the interferer propagating over the barrier edge. The loss due to the barrier diffracting edge depends on the height and the electromagnetic properties of the material.[31]

[31] Syed A. Bokhari, Mark Keer, and Fred E. Gardiol, "Site Shielding of Earth-Station Antennas," *IEEE Antennas and Propagation Magazine* 37, no. 1 (1995): 7-24, https://doi: 10.1109/74.370577.

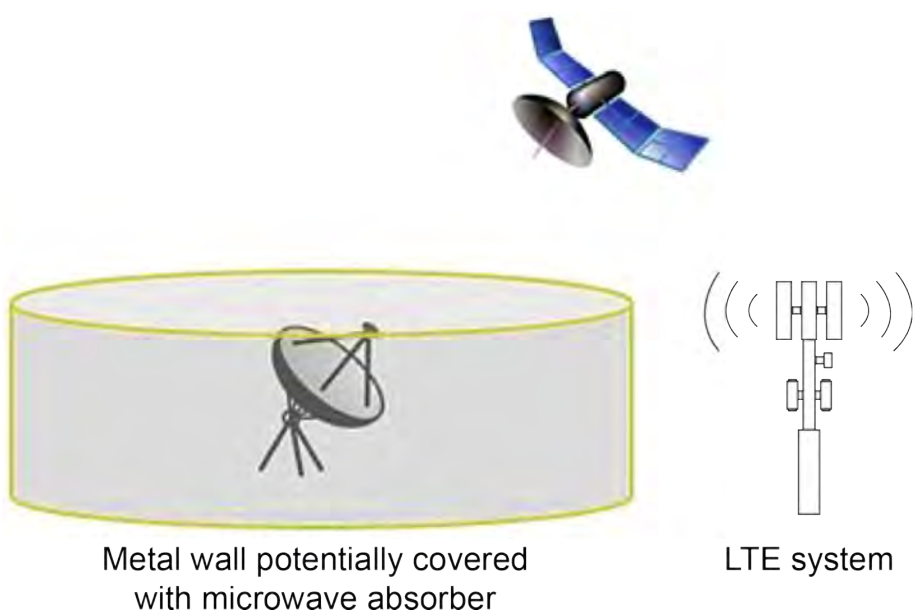


Figure 3.3-5. Satellite ground station shielding blocks the LTE signal.

To be effective, such infrastructure would need to extend to the height of the antenna without obstructing its view of the satellite. Effective shielding requires that the shield be taller than the feed height, which may be prohibitively high for GOES locations with large antennas. For some antenna locations with unusual limitations—such as placement immediately adjacent to a river, or on a rooftop—this technique would be infeasible.

3.3.5 Dynamic mitigation approach

The large static exclusion zones (e.g., 300 km at WCDAS) necessary to protect GOES earth stations from anomalous propagation in the LTE downlink sharing scenario make such sharing infeasible because many of the Federal GOES ground stations with high AP risk and corresponding large exclusion zones are near heavily populated areas.

Dynamic exclusion sectors within a large exclusion zone were considered because when ducting occurs, interference can originate at very large distances. In the dynamic approach, a nominal (e.g., 50 km at Wallops Island) exclusion distance is used until ducting conditions occur. When a ducting event has been detected, the exclusion zone would be extended—up to the calculated protection distance of 300 km distance. To maximize spectrum sharing, the region surrounding a GOES ground station is divided into sectors. For LTE transmissions in a given sector, EIRP reduction or cessation would then be applied in a way that eliminates RFI while impacting the operation of the fewest LTE towers. For example, the area around Wallops Island, Virginia, can be readily divided into three sectors, as shown in Figure 3.3-6.

3.3.5.1 Ducting event detection and localization using beacons

The use of dedicated beacons provides a method to estimate the location and strength of ducting events and thereby select only the affected sector(s) in which to reduce LTE downlink EIRP and prevent an RFI event. The beacons periodically (approximately once per minute) measure the propagation loss from multiple locations in the extended or AP exclusion zone to the Federal ground station, as shown in Figure 3.3-7. A centralized monitor at a NOAA site or some other location measures the received signal level of multiple RF signals. These measurements are used to infer the ducting conditions in each signal path direction toward major LTE transmitter locations. The system would use increased signal amplitude to estimate ducting enhancement. During ducting events, the system would then determine which LTE towers should modify operation.

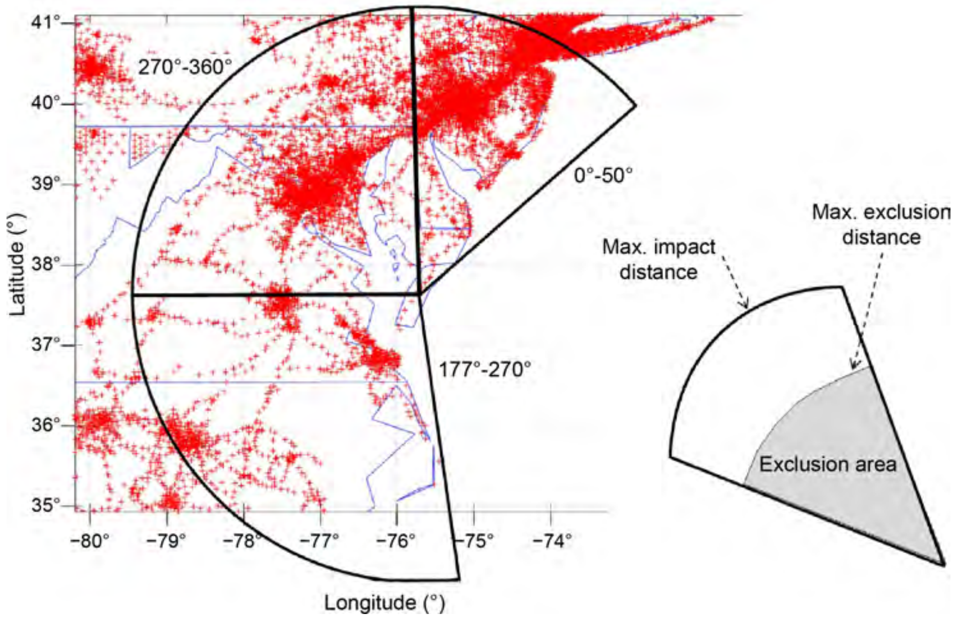


Figure 3.3-6. Potential dynamic exclusion zones defined by sectors.

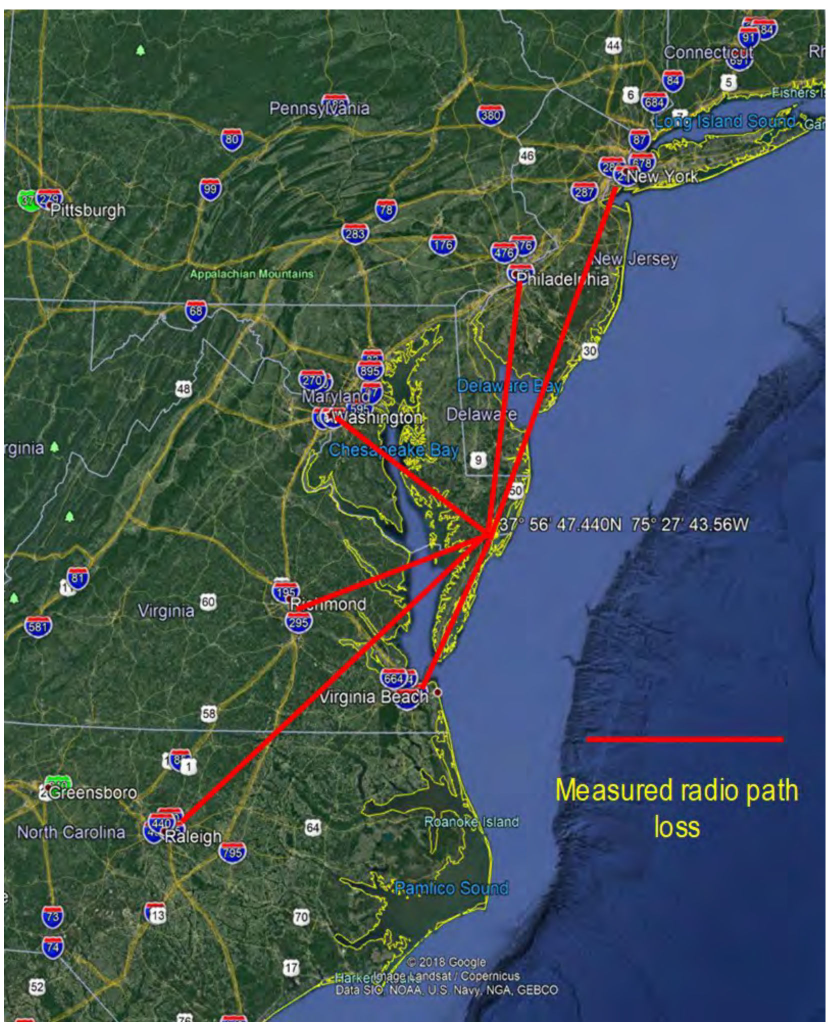


Figure 3.3-7. Use of beacons to measure the path loss from multiple locations to the ground station at Wallops Island, Virginia.

There are several beacon architectures:

- The beacons' dedicated transmitters are located at multiple locations within the exclusion zone, and the receiver is near the NOAA ground station.
- A dedicated transmitter beacon could be located at the NOAA ground station and receivers located at multiple locations within the exclusion zone.
- The beacons could be supplemented (or replaced) by measurements of existing off-air signals.

The beacon design depends on several factors. Because of spectrum availability limitations, the beacons should be narrow bandwidth. However, the beacons should have multiple frequencies to provide greater propagation loss estimation accuracy (which would require more spectrum). The reason is that many types of ducts produce frequency-selective variations in propagation loss with distance.

3.3.5.2 Using off-the-air signals to act as beacons

Ducting events can also be readily observed by measuring off-the-air signals. Ducting tends to impact a wide range of RF signal frequencies, and this provides a method for recognizing ducting events in measured data. Previous projects that involved monitoring the signals from local television stations over multiple days detected 10 dB variations in signal strength, and these were correlated with ducting events. A network of ground sensors, such as the system mentioned above, measuring television and other fixed transmitters with known locations could be used to determine when ducting events are occurring and the ducting location.

Another important feature of ducting is that the ducts can form rapidly, in less than one hour. An adaptive RFI mitigation approach needs to recognize and mitigate the interference effects within tens of minutes. This time period is a critical RFI mitigation approach parameter, and additional measurements are required to better quantify this time period.

3.3.5.3 Findings: Dynamic mitigation approach

Anomalous propagation due to tropospheric ducting has received limited consideration in previous spectrum sharing studies in part due to limited sharing scenarios where it would be a significant factor and lack of accepted prediction and modeling tools. The GOES receiver sites at or near the Atlantic and Gulf coasts, where the terrain is relatively flat, are at the most risk for atmospheric ducting and AP conditions. As a result, WCDAS and NSOF have the largest exclusion zone requirements of the sites considered, with zones of 300 km and 200 km, respectively, for DCS reception in the LTE downlink sharing scenario (at 95% protection). Exclusion zones for uplink sharing at these two sites are much smaller but still significant, at 15 and 40 km, respectively. While these are among the most susceptible sites, all sites require protection in the LTE downlink sharing case, and even in the LTE uplink case most still require protection. The need for large, permanent (static) exclusion zones for all or most receivers, including future ones, would make sharing infeasible. Mitigating AP is challenging, requiring cooperation on the part of the LTE carriers across distances much greater than the normal exclusion zones, complex and expensive physical measures on the affected GOES earth station antenna hardware, or expensive monitoring and notification systems. As in the findings discussed in Section 3.3.5.3, LTE carriers would also have to extend a high level of cooperation and accept potential lost services if they are identified as having the offending towers. A regulatory solution may be needed to obtain the necessary high level of cooperation.

3.3.6 Alternative dissemination architectures

SPRES Projects 3, 4, and 5 considered whether alternative means, specifically using terrestrial networks, of disseminating DCS and GRB data could feasibly reduce or replace the need for the L-band data relay or broadcast for some or all end users. The projects identified the DCP and GRB users' data and performance needs, then evaluated a combination of existing NOAA assets and new distribution/dissemination technologies that may be capable of fulfilling those needs. The projects found that while some improvement was possible in dissemination techniques, *a subset of users remain dependent, due to unique requirements, upon the real-time L-band broadcast for mission-critical, safety-of-life, and property missions.* For example, certain Level 1b products—such as Solar Flux: X-Ray and Geomagnetic Field, with a perishability metric known as Vendor-Allocated Ground Latency (VAGL) of 1.8 seconds—were found to be so latency-sensitive that only the GRB broadcast could deliver them to users while they were still relevant.

Project 3 evaluated several alternate distribution systems, including: ESPDS; an ESPDS/cloud service provider (CSP) hybrid service; DADDS; and a remote downlink site placed in a location free from AWS interference. Each of these alternatives was evaluated using a decision analysis and resolution (DAR) process that combined qualitative and quantitative evaluation techniques to rank the alternatives. The DAR process is described in greater detail in Section 4.3.5. Each option would have implications for users, depending on factors including the availability and reliability of internet connections.

NOAA currently provides multiple dissemination capabilities geared toward specific user groups, over both satellite and internet. Each of these has limitations and unique characteristics, including the selection of a subset of data, data format, and amount of data delay. SPRES specifically considered architectures that provided performance similar to that of the direct broadcast.

HRIT, which receives DCS and other data from ESPDS, may be able to serve as a fully viable alternative for all or most users. However, three key requirements need further investigation: (1) possible further reductions in message latency to meet user needs, (2) acceptable uptime/availability performance, and (3) assessment of RFI (and potential mitigation solutions for RFI) from the adjacent 1695–1710 MHz band.

3.3.6.1 GRB alternative access methods

Table 3.3-4 provides DAR form scores for the existing near-real-time GRB data access methods and the three alternative architectures explored in the study. It depicts a quantified summary of results based on an evaluation of the criteria for each alternative. The results of the evaluation showed ESPDS as the highest-scoring alternative GRB data distribution architecture; using base

Table 3.3-4. DAR form scores for GRB alternative architectures.

		Alt. 1: Cloud			Alt. 2: ESPDS			Alt. 3: Remote GRB receiver		
Evaluation criteria	***Weight (percent)***	***Base***	***Low***	***High***	***Base***	***Low***	***High***	***Base***	***Low***	***High***
Technical	20	2.75	2.53	2.75	2.5	2.5	2.50	2	1.85	2
Schedule	10	2.33	2.33	2.33	2.67	2.57	2.77	1.67	1.67	1.87
Operational	10	2.5	2.43	2.50	2.75	2.60	2.75	2.75	2.75	2.83
Security	20	2.50	2.50	2.50	3.0	3.0	3.0	3.0	2.93	3.0
Cost	20	2.25	2.1	2.33	2.75	2.6	2.83	1.5	1.35	1.65
Scalability	10	2.5	2.5	2.5	2.50	2.50	2.65	2.00	2.00	2.15
Performance	10	2.75	2.68	2.75	2.50	2.43	2.50	2.50	2.43	2.50
Total weighted score		2.51	2.42	2.52	2.69	2.63	2.73	2.19	2.11	2.26

scores, it led the cloud alternative by a margin of 9.5% and the remote receiver by a margin of 46.2%. See Section 4.3.5.1 for details of the GRB alternative architecture scoring.

3.3.6.2 DCS alternative access methods

Several effective methods exist for users to retrieve DCS platform messages, including multiple satellite broadcast and terrestrial/internet options. Table 3.3-5 lists the DCS message delivery and retrieval options and the average delay associated with each. Delays are induced by file processing, storage, and transfer over terrestrial networks. Delays associated with transfers can vary depending on the quality of the internet service available to a user at a given location. As shown in Table 3.3-5, each option has the drawback of higher latency, and none fully meets all users' requirements for low latency and high availability. Terrestrial retrieval options require internet access, which may not be available during severe weather events, when they are most needed. Most customers have implemented two or more modes of access in order to prepare for an outage on one mode.

One potential alternative, the GOES HRIT rebroadcast, is used as a backup to the DCPR by many customers. While reliable and cost effective—requiring only a small 1.2 m antenna and a simple receiver—HRIT was assessed as not yet a fully capable replacement for DCPR reception due to latency. It has been under improvement by NOAA, and is continuing to be improved, such that at some point it may be able to meet latency requirements. In the event of its widespread deployment around the U.S., it would have to be protected from adjacent-band RFI coming from 1695–1710 MHz. Fully assessing HRIT for future performance capability and acceptable RFI risk (from 1695–1710 MHz) was not part of SPRES. As a result, further investigation will be required to assess HRIT's viability as a full replacement for DCPR reception by customers. The service, however, is promising.

Whatever terrestrial retrieval options are selected, it is important to note that DCS is a communications relay and all solutions require initial satellite downlink signal reception as a data source. DCS data, uplinked at 401–402.4 MHz (and currently transponded down in 1679–1680.4 MHz) is not a rebroadcast, but a primary relay of raw data.

Table 3.3-5. DCS message delivery/retrieval methods.

DCS data access method	Definition	Terrestrial/ satellite	Average delay
NWSTG-HADS	The National Weather Service Telecommunication Gateway (NWSTG) is the central communication facility of the NWS and the primary acquisition and distribution center for NWS data and products. The NWSTG supports a range of protocols (IP-based) and speeds and is mostly used by high-volume users. The NWSTG obtains DCS data from DADDS and then sends it to HADS for processing and production of DCS products. HADS products are used to create local Flood Warnings and Flash Flood Warnings by the NWS, and also are input into NWP models.	Terrestrial	2.5 min.
LRGS	High-volume LRGS servers at NESDIS sites and the USGS EDDN use the DCP Data Service to distribute data to client LRGS processes. Users have "LRGS appliances"—universal store-and-forward devices for GOES-DCP messages that can be configured to receive multiple simultaneous data streams from DRGS, HRIT, NOAAPort, Iridium, and other satellite links. LRGS also allows the user to configure "network backup" options to receive lost data from other LRGSs; usually these are internet connections to the NOAA/USGS LRGS servers. The LRGS appliance merges data from the streams, keeping the best (i.e., those with the fewest parity errors) and longest version of each message and discarding others. All configured ports are always active. The LRGS appliance stores the raw DCP data efficiently for a month or until automatic deletion of the oldest data when pre-set storage limits are met.	Terrestrial	5 sec.
HRIT	The HRIT/EMWIN broadcast service forwards all DCS messages. Users identify their own messages from the stream. Most DCS messages experience just 5–20 seconds of delay over HRIT, but about 0.5% will be delayed by several minutes.	Satellite broadcast	11 sec.
NOAAPort/ SBN	NOAAPort/SBN provides broadcast service of NOAA environmental data and information in near-real time to NOAA and external users. Only 85% of DCS messages are broadcast due to a WMO packet-header incompatibility.	Satellite broadcast	variable
Alt. 1: Cloud	This alternative has the advantage of offloading any scaling requirements that may be necessary for ESPDS, and implements a cloud distribution service to fulfill the end-user requirements. ESPDS can send the data using an existing secure FTP protocol in which data would be pushed to the CSP storage upon inventory in ESPDS. If existing FTP distribution protocols are used, changes to ESPDS would be minor for this alternative and would likely require only integration of a new data consumer interface (i.e., the cloud provider).	Terrestrial	14+ sec.
Alt. 2: ESPDS	Implementing ESPDS into the GRB and DCS alternative architectures can have impacts to system components that may require scaling of existing ESPDS hardware and software as well as integration with direct broadcast users that do not have existing interfaces to ESPDS/PDA.	Terrestrial	9+ sec.
Alt. 3: Remote DCS receiver	Installation of a remote receiver at a geographically diverse site that would be unlikely to experience simultaneous interference with a GRB DRGS receiver at NSOF or WCDAS.	Satellite broadcast	0 sec.
Alt. 4: DADDS (already operating)	DADDS is the primary processing system used at NESDIS ground stations for DCS platform and message data dissemination; supports direct message retrieval for users via the DCP Data Service (DDS).	Terrestrial	5 sec.

Table 3.3-6 provides DAR form scores for existing, and four alternative, terrestrial architectures for disseminating DCS data. The results show that the DADDS system is the lowest-risk alternative distribution architecture. It outperformed the ESPDS alternative by a 14.4% margin, the cloud alternative by a 23.9% margin, and the remote antenna site by a 59.6% margin. It is important to note, however, that the DADDS architecture still relies on the L-band downlink from GOES to receive the DCS data before distributing it. In order to reduce the probability of RFI impacting DCS data availability on the DADDS distribution system, consideration should be given to moving the DCPR downlink reception, processing, and distribution from NSOF to CBU. The CBU provides a

Table 3.3-6. DAR form scores for DCS alternative architectures.

		Alt. 1: Cloud			Alt. 2: ESPDS			Alt. 3: Remote DCS receiver			DADDS		
Evaluation criteria	***Weight (percent)***	***Base***	***Low***	***High***	***Base***	***Low***	***High***	***Base***	***Low***	***High***	***Base***	***Low***	***High***
Technical	20	2.25	2.18	2.25	2.25	2.25	2.25	1.50	1.50	1.58	2.50	2.50	2.50
Schedule	10	2.33	2.13	2.33	2.33	2.33	2.33	1.33	1.33	1.33	3.00	3.00	3.00
Operational	10	2.50	2.43	2.58	2.50	2.35	2.50	2.25	2.10	2.33	2.75	2.75	2.83
Security	20	2.50	2.50	2.58	3.00	3.00	3.00	1.75	1.68	1.83	3.00	3.00	3.00
Cost	20	2.25	2.10	2.33	2.75	2.68	2.83	1.50	1.35	1.50	3.00	2.78	3.00
Scalability	10	3.00	3.00	3.00	2.50	2.35	2.65	2.50	2.35	2.50	3.00	2.70	3.00
Performance	10	2.50	2.43	2.65	2.75	2.60	2.75	2.00	2.00	2.15	3.00	2.85	3.00
Total weighted score		2.43	2.35	2.49	2.61	2.55	2.64	1.76	1.68	1.81	2.88	2.79	2.88

geographically diverse option as it is located far from the WCDAS/NSOF area. This would reduce the likelihood that interference would simultaneously impact the primary and backup DADDS systems, a situation that would lead to a loss of NOAA capability to distribute any DCS data. CBU may require a review of the exclusion zone size if it assumes this new critical role.

3.3.6.3 Alternative architectures: Findings

Two SPRES projects were devoted to the examination of alternative terrestrial architectures to ascertain if they could reduce the reliance on direct broadcast signals in the L-band by replacing them with terrestrial-based access to the same data after collection by NOAA. Alternatives do exist for environmental data users who can tolerate the additional latencies or different availabilities, the different risks associated with the added ground-based nodes and internet, and the acquisition and operating costs associated with these adaptations. Quantitative analyses favor enhanced ESPDS-based and DADDS-based architectures over the other alternatives to support GRB and DCS, respectively. However, these do not present definitive solutions, as other parts of the study show that a significant number of Federal and non-Federal users will continue to have operational needs for the ultra-high reliability and low latency of direct broadcast services.

Table 3.3-7. Availabilities specified for each alternative.

Dissemination method	Availability (percent)
ESPDS–Product Distribution and Access (PDA)*	99.98
High Rate Information Transfer (HRIT)**	99.90
DCS Administrative and Data Distribution System (DADDS)	99.90
Local Readout Ground Station (LRGS)	99.90
GOES-R Rebroadcast (GRB)	99.96
Direct Readout Ground Station (DRGS)	99.96
*Actuals = 99.44% **Actuals = 99.33%	

Table 3.3-7 presents a summary of the availability of the different space- and ground-based architectures. Of particular note are Federal users such as the USACE, non-Federal users such as the Florida DOT (examined in Section 3.1), and other agencies in locations where above-ground telecommunication lines are prominent and exposed to severe weather damage; their reliance on direct broadcast is most critical precisely during times of severe weather. The NHC, a Federal user, relies on direct

broadcast services, in this case Level 1b GRB data, to carry out marine forecasting responsibilities through severe weather conditions. This forecasting ability would be put at risk if NHC had to rely on above-ground internet connections.

If the ESPDS or ESPDS/cloud alternative is to be implemented, consideration should be given to remediating the lack of GRB data availability at CBU in a continuity-of-operations scenario. This would require that ESPDS at CBU interface directly with the GOES-R ground station. Furthermore, operationalizing the terrestrial network between CBU, WCDAS, and NSOF would eliminate the reliance upon direct downlink reception at the NSOF site. The GRB downlink at NSOF is currently an essential RF downlink because it enables ESPDS to distribute GOES-R data to hundreds of users. Furthermore, the GRB downlink at NSOF enables production of GOES-R Level 2+ products. There is only one L2+ product production system that GOES-R feeds, and it is located at NSOF and relies on Level 1b data from the GRB downlink.

Currently, CBU has the capability to receive all of the GOES L-band downlink signals, including DCPR, GRB, telemetry, and HRIT, but it cannot process or distribute the DCPR data to users. In order to reduce the probability of RFI impacting DCS data availability on the DADDS system, consideration should be given to moving the DCPR downlink reception, processing, and distribution from NSOF to CBU. This would reduce the likelihood that interference would simultaneously impact the primary (WCDAS) and backup (NSOF) DADDS systems, leading to a loss of NOAA capability to distribute any DCS data.

3.3.7 Small-cell substitutions

Another RFI mitigation approach considered was the replacement of some large cells within a given radius of the GOES ground stations by lower-powered small cells. This mitigation approach would be expected to have the most impact and be the most feasible for protecting the GOES earth stations situated in urban regions, typically where the density of towers is the highest. Table 3.3-8 indicates that this mitigation approach initially demonstrated reductions in RFI and the required protection distance at the Federal sites at Wallops Island, Virginia, and Miami, Florida, due to the distribution of cell towers. The influence of a small-cell substitution ultimately depends on the locations' morphologies,[32] as explained in Section 4.11.4.1. Due to the potential beneficial RFI reduction achieved, in Project 7 an evaluation of benefits from this mitigation was carried out for all the earth stations in the study. However, when detailed GOES antenna and receiver characteristics and enhanced propagation modeling were used, small-cell substitution did not demonstrate useful reductions in RFI risk or exclusion-zone sizing.

As described in Table 3.3-8, the small cells utilize an EIRP of 40 dBm, an omnidirectional antenna with 6 dBi gain, and a height of 6–10 m. Three UEs were considered per small cell (8 RBs per UE) and were randomly placed at a distance from the center of the small cell. The maximum distanceof UE placements depends on the coverage area of the small cell.

[32]Morphology in this context is the classification/grouping of terrain features (e.g., dense urban versus urban versus suburban versus rural).

Table 3.3-8. LTE small-cell downlink system parameters.

Parameter	Value	Discussion	Data source
eNB coordinates	Latitude, longitude	Coordinates determined based on population density of regions	—
eNB transmitter (EIRP) (dBm)	40	Lower EIRP compared to large cell to account for smaller coverage area	GSMA Small-Cell Deployment Guide
eNB antenna gain (dBi)	6	Antenna gain from an omnidirectional antenna pattern	—
eNB antenna height (m)	6–10	—	GSMA Small-Cell Deployment Guide
Transmission bandwidth (MHz)	5	—	—
Number of sectors/small cell	1	—	—
Downlink loading (%)	100	Assumed worst-case scenarios	—

Summary

Small-cell substitution was modeled for potential mitigation benefits and initially showed promise at some sites. However, since carriers deploy small cells based only upon demographic factors (i.e., in urban areas), it cannot be considered feasible and is not recommended as a mitigation technique.

3.3.8 LTE cell tower antenna downtilt

A potential RFI mitigation approach was examined involving simulations adjusting the LTE evolved NodeB (eNB) antenna downtilt in one degree increments from 2° to 6° below the horizon. An eNB can be adjusted electronically on most installations. Typically, dense urban areas have the highest site density and hence the highest signal coverage overlap. This results in the greatest downtilts for dense urban areas (as much as −8°). In rural areas, sites are farther apart and therefore require minimal downtilt (about −2° to point the main vertical lobe of antenna toward ground). In urban and suburban areas, −3° to −4° is common.

SPRES Project 11 found that applying a mechanical downtilt in a large-cell downlink deployment effectively mitigates the exclusion zones required. This process included the application of 2°, 3°, 4°, 5°, and 6° downtilts. Project 7 controlled the footprint of the large cells based on the classification of the tower (rural, suburban, etc.). In the Monte Carlo simulations, the downtilt was randomized based on the classification of the tower. The effectiveness of applying an additional downtilt to offending antennas proved to be an effective mitigation in Project 7 for many locations, even under anomalous propagation conditions. For example, the protection distance needed to protect the DCS data link at WCDAS was reduced by approximately 110 km (from 300 km to 190 km) under ducting conditions that occur 5% of the time.

Despite the potential effectiveness of mitigating RFI by increasing downtilt, analysis in Projects 7 and 10 indicates that it is infeasible. Commercial users may have the ability to adapt downtilt, but doing so reduces their coverage area and results in large-scale reductions in service that affect millions of users. Those users would need to be migrated to alternative services and risk overall reductions in user service (e.g., data rate throttling). It is unlikely that commercial carriers would be willing to accept such disruptions and take on the responsibility to carry them out in a suitable timeline. Furthermore, developing, deploying, and maintaining a monitoring system that is able to accurately determine which commercial transmitters need to cease operation is infeasible. At best, all transmitters within a predefined protection area would be required to cease operations during heightened RFI conditions.

Summary

Antenna downtilt was modeled as a potential mitigation option. Dynamic antenna downtilting has technical benefits, but discussions with carriers indicate that operational network mitigation would not be feasible for them. Therefore, it cannot be recommended as a mitigation.

3.3.9 LTE carrier modification

SPRES evaluated the sharing benefits of reducing LTE signal overlap with GOES signals through the reservation (non-use) of the upper resource blocks (RB) in the LTE signal for LTE downlink and LTE uplink sharing. Each RB is 180 kHz wide, and SPRES considered reserving up to 3 RBs. Creating frequency separation by reservation of the upper RBs may eliminate or reduce co-channel and possibly adjacent-channel interference, as the DCS receivers have limited rejection from signals below DCS frequencies.

The intermodulation noise caused by high-gain amplification, 5 MHz and 10 MHz LTE interfering signals, DCS traffic, and pilot channels was examined. In addition, an FDR analysis was completed using the microcomputer spectrum analysis models (MSAM) tool developed by the NTIA. This analysis did not consider narrowband internet of things or 5G technologies.

3.3.9.1 DCS and LTE signals analyzed

3.3.9.1.1 DCS signal description

The majority of DCS users have moved to DCPRS Certification Standard 2 (CS2) with a data rate of 300 bps. For this analysis, a single 300 bps CS2 channel with a bandwidth of 750 Hz operating at the lowest DCS frequency, 1679.701 MHz, was analyzed. In addition, DCS has two pilots that are critical to DCS operation, operating at 1679.7 MHz and 1679.85 MHz. An analysis on these pilots was conducted because the majority of the field DCS receivers have limited rejection from signals below DCS frequencies.

3.3.9.1.2 LTE signal description

A standard 5 MHz LTE signal is made up of 25 180kHz LTE resource blocks within a 3 dB bandwidth of 4.5 MHz, and has a 0.25 MHz guard band located at either end. This is the case for both uplink and downlinks signals. Using a center frequency of 1677.5, the upper edge of this signal is 1679.75 MHz. This results in a 50 kHz overlap of the lower DCS channels starting at 1679.7 MHz. These overlapping DCS channels are impacted by direct co-channel interference, as well as by adjacent-channel interference. Figure 3.3-8 illustrates a 5 MHz LTE signal centered at 1677.5 MHz

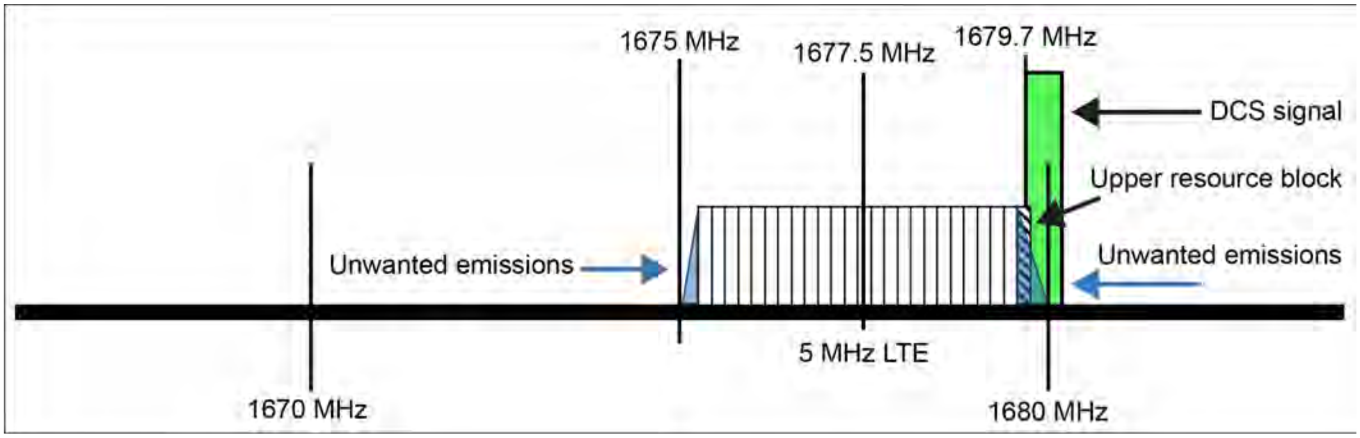


Figure 3.3-8. DCS and 5 MHz LTE signals.

with the upper resource block highlighted. This figure represents unwanted emissions in the upper and lower guard bands, following FCC and 3GPP guidelines. The lower guard band represents a normal 5 MHz emission mask, and the upper guard band is a visual representation of the roll-off if the upper resource block were removed.

A standard 10 MHz LTE signal comprises 50 180 kHz LTE resource blocks within a 3 dB bandwidth of 9 MHz, as well as a 0.5 MHz guard band at either end. A center frequency of 1675 MHz and 3 dB upper frequency edge of 1679.5 MHz were used. Unwanted emissions that slope to 1670 and 1680 MHz according to FCC and 3GPP guidelines were applied. Figure 3.3-9 displays a 10 MHz LTE signal with resource blocks and unwanted emission mask with respect to the 400 kHz DCS receive signal.

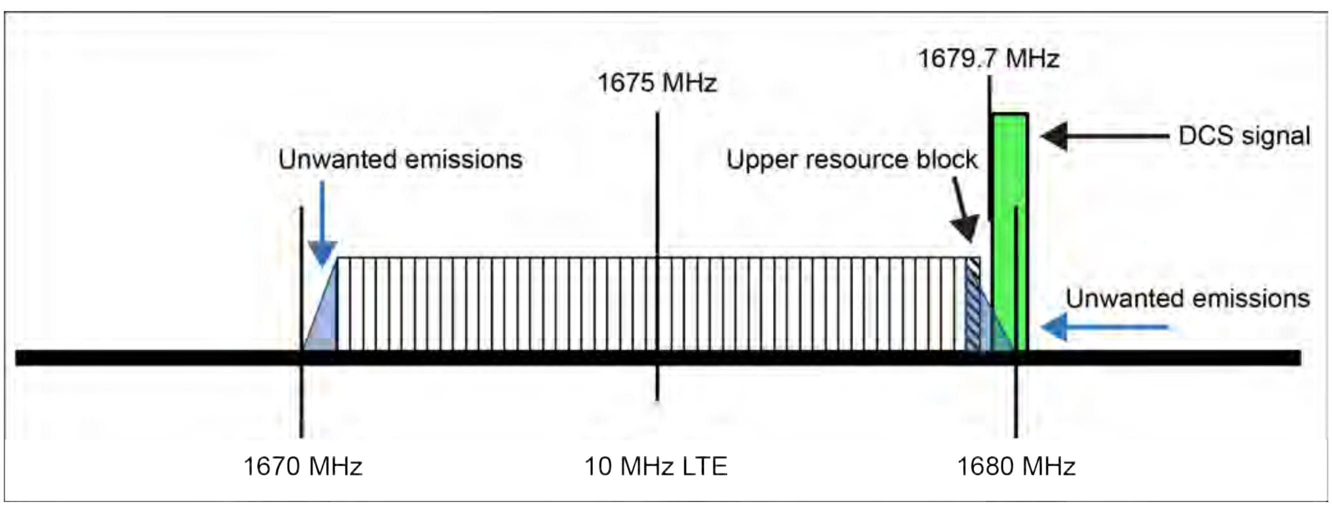


Figure 3.3-9. DCS and 10 MHz LTE signals.

3.3.9.2 Findings of the LTE resource block adjustment

3.3.9.2.1 LTE downlink sharing

As discussed in Section 3.3.2, the DCS IF receiver passband is about 2.5 MHz wide on the observed fielded receivers, and the amplifier chain provides 10–20 dB of excess gain. If these conditions are not remedied, removal of the upper resource block(s) provides only a 3 dB FDR improvement. This was true if the LTE signal was 40 W or 2000 W, or if the DCS receiver was in a non-linear condition. For a 10 MHz signal, expect a 9–15 dB improvement in FDR if the upper resource block is removed.

3.3.9.2.2 LTE uplink sharing

As observed in the results of the 10 MHz LTE downlink preliminary analysis described in Section 3.3.9.1, creating adequate frequency separation between the LTE carrier and the DCS channel can yield significant reduction of RFI to the DCS signal. The amount of frequency separation required to achieve the maximum benefit, perhaps 20 dB, is partly dependent upon receiver design parameters. Projects 6 and 7 identified excess amplifier gain and receiver IF bandwidth as contributors to intermodulation products that significantly increased the amount of frequency separation required. Optimizing GOES receiver performance in a shared environment should be considered first to minimize the amount of frequency separation through resource block non-use needed to achieve desired mitigation levels. This is recommended for further study.

3.3.10 RF monitoring and carrier identification

RF monitoring does not prevent RFI, but it can mitigate the effects of such events through (1) rapid detection of interfering signal levels, (2) isolation of the interfering signals to a source, (3) notification of the offending (source) carrier, and (4) timely action by the carrier.

SPRES Project 10 conducted a trade study of current and future radio frequency monitoring capabilities, including the potential use and availability of carrier (base station) identification numbers (carrier ID or CID) to expedite identification of sources of interference. In addition, discussions were held with industry experts to understand current industry practices and experiences. RF monitoring to identify RFI events and sources requires a system with high sensitivity, directionality, and extensive processing resources. SPRES Project 10 looked at commercial solutions but ultimately proposed a custom solution to meet protection requirements.

The ability to obtain CID information from an interfering RF signal during an RFI event can, in principle, dramatically shorten the time required to isolate the source of (LTE) RFI and resolve the interference. It can be implemented in an automated RFI mitigation solution, eliminating or minimizing the need for human interaction. Based on RFI events occurring at NOAA WCDAS, CID decoding was demonstrated to work effectively in the presence of individual received signals.

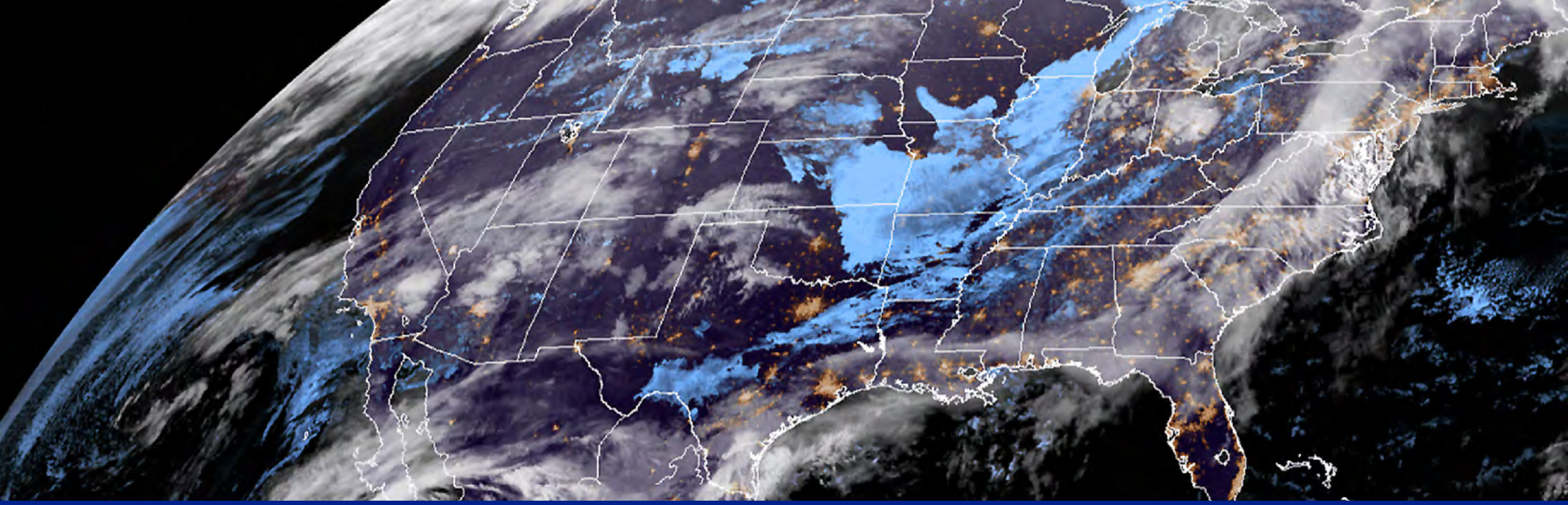
However, limitations to making practical use of CID information render it of minimal use in many of the RFI modalities expected in the LTE sharing environment predicted for NOAA. In a common scenario where multiple interfering signals are received simultaneously, the process can decode the CID for only one signal at a time and only when there is a sufficiently large differential (delta) of power levels among the aggregation of signals. If there are multiple signals present, only the strongest signal will be decoded. Furthermore, in the most likely scenario of aggregate interference, where multiple signals with similar power levels are present at the receiver at the same time, no CIDs would be decoded.

Finally, CID information is directly available only for LTE downlinks, not for LTE uplinks, further limiting its usefulness.

Summary

A trade study and assessment was performed of RF monitoring to examine potential benefits and capabilities. SPRES found that RF monitoring can be beneficial for the detection and recording of interference events, both to reduce the time to resolve such events and to support post-event enforcement actions. RF monitoring may also be able to provide early warning of interference conditions, such as changes in the noise floor prior to an RFI event and coarse directional information for troubleshooting resolution.

SPRES recommends that a cost-benefit analysis be performed on each approach.



4 | Summary of Individual Projects

This section describes the more detailed findings of the individual projects. Each project had discrete tasks and objectives, the results of which were integrated back into the overall program objectives. It is important to note, when reviewing individual projects, that some assumptions evolved or changed during the program, and that completion of projects by different vendors resulted in different factors, such as radio frequency (RF) thresholds, being used. With regard to site protection requirements and measures, these issues were resolved in Project 7, where relevant outputs of earlier projects were integrated or, as needed, re-created using standardized assumptions.

4.1 Project 1. Spacecraft-to-End-User Data Flows and User Needs

Project 1 supported the overall program objective of GOES Data Use. It examined the different types of users who rely on NOAA's geostationary environmental satellite services, within and adjacent to the 1675–1680 MHz band, including how they receive, process, utilize, and, in some cases, further disseminate their data. Project 1 also examined some of the potential consequences of GOES users experiencing RFI that results in data loss and/or delayed arrival of data.

Study objective

The objective of Project 1 was to map the flow of GOES data from the satellite to the receive sites operated by customers, and from the receive site to other intermediate or end users. Included in this is an examination of customers' applications or uses of the data and any data processing they perform. With this information, the impact to customers of untimely or missing data can be better understood. GOES information services have Federal (and non-Federal) stakeholders, as seen in Table 4.1-1.

Table 4.1-1. Federal users and critical next-tier users of GOES information services.

Federal agencies	Agency departments that are critical next-tier users
Department of Commerce (DOC)	• National Weather Service (NWS) Storm Prediction Center (SPC) • National Hurricane Center (NHC) • Aviation Weather Center (AWC) • Space Weather Prediction Center (SWPC) • Ocean Prediction Center (OPC) • Weather Prediction Center (WPC) • Central Pacific Hurricane Center (CPHC) • Alaska Aviation Weather Unit (AAWU) • National Ocean Service (NOS) • Air Route Traffic Control Centers (FAA, supported by DOC Staff) (DOT)
Department of Interior (DOI)	• Bureau of Land Management (BLM) • National Interagency Fire Center (NIFC) • Bureau of Reclamation (USBR) • U.S. Geological Survey (USGS)
Department of Defense (DoD)	• Joint Typhoon Warning Center (JTWC) • U.S. Army Corps of Engineers (USACE)
Federal Aviation Administration (FAA)	• Air Route Traffic Control Centers (FAA, supported by DOC Staff) (DOT)
Department of Agriculture (USDA)	• Forest Service (USFS) • National Interagency Fire Center (NIFC)
Department of State (DOS)	• U.S. International Boundary and Water Commission
National Aeronautics and Space Administration (NASA)	• Spaceflight Meteorology Group (SMG) (NASA, staffed by NWS)

Methodology

The main approach consisted of data collection from, and research into, the users of the GOES data services that are transmitted in or adjacent to 1675–1680 MHz. A survey, primarily focused on Federal users, was developed and distributed. Upon completion of the surveys, follow-up interviews were conducted with a sample of respondents from a variety of agencies. In addition, existing documentation made available by NESDIS was reviewed, validated with survey and interview responses, and incorporated into the report. Third-party reports, system description documents, and impact studies were also reviewed. An extensive search was conducted of the Defense Information Systems Agency's (DISA) Global Electromagnetic Spectrum Information System (GEMSIS), Spectrum XXI, and Integrated Spectrum Desktop to identify any other government users who may be impacted by spectrum sharing in this frequency band.

A supplemental effort (Project 1A) was added to provide additional research regarding GOES applications, users, and customers. For each Federal GOES satellite receive site, information was solicited in the form of an interview and paired questionnaire. Information was then composed into a site narrative that references site webpages, specifically site mission statements, for further description of on-site user requirements.

Findings

The major results of this project include a quantification of the numbers and descriptions of receive sites and users of GOES information services, including, for example, numbers of Data Collection Platforms (DCPs) and High-Rate Information Transmission (HRIT) terminals and the resulting number of direct users of such services. Project 1A discovered multiple GOES data services in this band that are utilized by Federal and non-Federal users. It also uncovered a wide variety of applications across multiple economic sectors that have varying tolerances for data latency and loss, and quantifiable impacts when data is delayed or lost. Furthermore, this project revealed an intricate web of non-Federal users with varying data requirements that would be disrupted by any reconfiguration of GOES spectrum for the purposes of sharing spectrum bands.

Some services provided in this spectrum provide primary sources of the data not originally sourced elsewhere in the radio spectrum (e.g., GOES DCS, MDL, or SD). Other services are dissemination or rebroadcast of information originally acquired by a Federal agency (e.g., HRIT/EMWIN) or data modified from raw data for dissemination to users (e.g., GRB or GVAR).

The accepted practice of subdividing users between Federal and non-Federal is not always clear for some of the services in this band. As an example, many of the DCPs, whose signals are acquired and then relayed by the GOES DCS system, are owned in full or in part by non-Federal entities, but have their results reported by tools or services of Federal agencies. For example, the NWS Office of Dissemination operates the Hydrometeorological Automated Data System (HADS),[1] which uses more than 17,000 DCP sensors to gather real-time information on water

[1] HADS is an element of the NWS Meteorological Assimilation Data Ingest System (MADIS), which ingests data from NOAA and non-NOAA data sources for use by all of the National Centers for Environmental Prediction, as well as by the following NOAA entities: National Centers for Environmental Information (NCEI), Office of Oceanic and Atmospheric Research (OAR), Earth System Research Laboratory (ESRL), and Global Systems Division (GSD).

flow and levels, but none of these platforms are owned by the NWS. This is the source data for the National Water Model, as well as for water information that goes into the nation's numerical weather prediction models. In addition, U.S. Geological Survey (USGS) often consolidates DCP information from sensors that are funded and supplied by non-Federal organizations (state, local, tribal, or private), some of whom also operate their own DRGS receiving systems.

This situation arises from the requirements that (1) all users of the GOES DCS system must freely share their data among all other DCS users, and (2) all users must have a Federal agency sponsor in order to use the Direct Readout Ground Station (DRGS) system.

The results of this project provide important information about the number and nature of users of GOES information services in and adjoining this band. While the quantification of users in this study is informative, representative, and reliable, the results provided regarding non-Federal users cannot be deemed fully comprehensive given that not all are required to register. Especially among users of GRB systems, such data could be deemed proprietary due to business competition concerns.

4.1.1 Data Collection System

The GOES Data Collection System (DCS) is a data collection and transmission subsystem that automatically collects environmental information from remote sensors (such as radio-connected stream and tide gages) and transmits it to ground-based receive sites via GOES satellite. Users include many Federal, state, and local agencies as well as non-Federal entities required to monitor environmental and earth resources for a variety of purposes. These purposes include meteorological analysis and forecasting, river forecast, tsunami warnings, flood warnings, reservoir management, dam monitoring, water quality monitoring, fire potential, maritime navigation (including inland river, coastal, and port), irrigation control, seismic monitoring, air quality monitoring, and other highly variable applications that require observations to be collected frequently and transmitted immediately. DCS, which provides near-real-time access to data, is used by state, local, and emergency managers in the U.S. and nearby nations to provide early warning of natural and manmade disasters that threaten life and property, including floods, fires, tsunamis, hurricanes, tornadoes, dam breaches, and many others. DCS is considered critical infrastructure for NOAA (NWS and National Ocean Service), USGS, DoD, the NIFC, the Bureau of Land Management, the Forest Service, and international hydrometeorological agencies in Canada, Mexico, Central America, South America, the Pacific, and the Caribbean.

DCS has more than 40,000 DCPs deployed from Africa westward to eastern Australia and from the edges of the Arctic to the tip of South America. More than 750 organizations, government agencies, and representatives of government agencies have DCPs that are reported via DCS.

It is very important to point out that DCS is not a rebroadcast but a dedicated relay link of *original* sensor data. The real-time reporting from DCP devices via DCS is the primary method of obtaining this sensor data from the wide geographic region described earlier. If a DCP transmission fails to be acquired at a receive earth station, that data is not retransmitted by the original platform; it is permanently lost.

DCS is vital to the operation of several Federal agencies whose mission is to reduce loss of life and minimize property damage, and its information is critical to several sectors of the economy. The USGS uses DCS to transmit stream-gage information for flood warning and obtains seismic observations to warn the aviation industry and other affected parties of volcanic eruptions. These observations are critical for air traffic safety. In addition, USGS obtains data on earthquake location, size, and strength. The Pacific Tsunami Warning Center uses this data to provide tsunami information to countries and islands of the Pacific basin and the Caribbean.

NOAA operates a ground system at WCDAS in Virginia and has a backup site in Suitland, Maryland. USGS operates a ground system for the Emergency Data Dissemination Network (EDDN) in South Dakota. Data from these sites are distributed to users in various ways, including rebroadcast to a satellite (via HRIT or other relay) and distribution through the internet (via LRGS). Due to the critical nature of their responsibilities, many users who access DCS data for emergency warnings and emergency management also receive data directly from NOAA satellites, with some users requiring multiple redundancy to provide needed availability.

The Data Collection Platform Report (DCPR) transponder is a bent pipe—i.e., it receives signals from DCPs in 401.7–402.4 MHz and then translates the data to downlink frequencies of 1694.5 and 1694.8 MHz (GOES-N series) and in the 1679.7–1680.1 MHz band (GOES-R series). The GOES satellites do not perform any operations on this data; they simply acquire it from the very broad geographic coverage area and relay it to ground stations in the translated spectrum.[2] The frequency scheme and subdivision into transmission slots of the GOES DCS system follow internationally agreed-upon channelization. Although the downlink capability is from 1679.7–1680.4 MHz, all but 36 kHz of spectrum in use in the Americas falls below 1680 MHz, placing those signals in-band to the proposed shared band. (See Appendix J, section J.4, for additional information.)

HRIT/EMWIN: This broadcast signal combines the NWS-originated Emergency Managers Weather Information Network (EMWIN) with low-resolution GOES satellite imagery data, DCP messages, and other selected products. HRIT/EMWIN occupies 1694.1 MHz center frequency (bandwidth 1.2 MHz). The flow of data originating from the DCPs to the GOES ground segment and ultimately to the users is depicted in Figure 4.1-1. To ensure availability, the data is dual-redundant over three sites. As the figure shows, the downlinked DCP data is received at WCDAS and transferred by terrestrial means (using Product Dissemination and Access [PDA]) to NSOF (primary) and CBU (backup) for processing into the HRIT format. EMWIN data is folded into the same stream and then returned over PDA to WCDAS (primary) and uplinked to the spacecraft via S-band and then downlinked via L-band to the user community on the HRIT/EMWIN band. In the backup mode, CBU combines the data and uplinks the stream in the same way.

Some users operate HRIT receivers in order to obtain GOES DCS information, which is why it is included in this section. Other users benefit from being able to obtain a reduced resolution set of imagery from NOAA satellites. HRIT complies with a global specification that may be found on the website of the World Meteorological Organization (WMO).

[2] Microcom Design Inc., "DCS DRGS Overview," presentation to the National Oceanic and Atmospheric Administration, March 2018, https://noaasis.noaa.gov/pdf/DRGS_Overview.pdf.

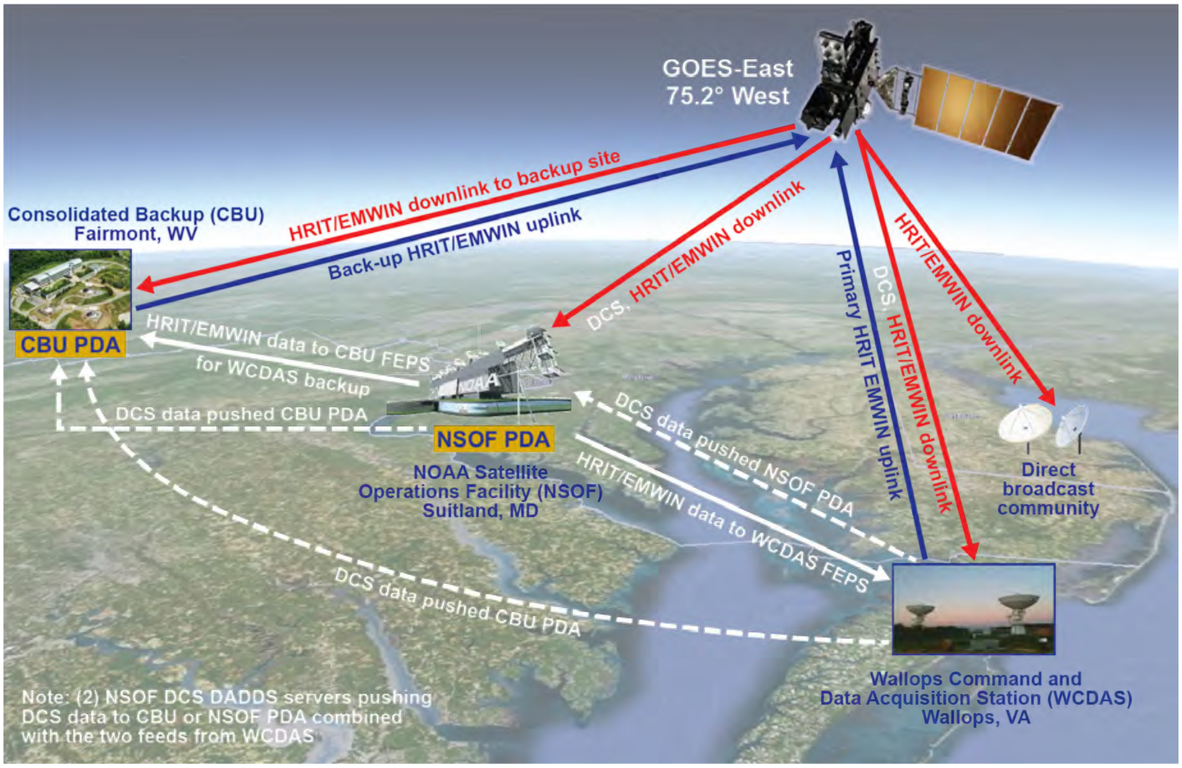


Figure 4.1-1. HRIT data flows from DCS through ground and space segments to users.

Direct Readout Ground Station (DRGS): DCS users with critical missions—such as monitoring critical infrastructure or forest fires, or otherwise detecting hazardous conditions, such as unsafe wind conditions on causeway bridges—operate their own primary DCS Direct Readout Ground Stations (DRGS), due to the critical nature of their responsibilities and need for extremely high reliability. The number and types of users and platforms, as estimated through the survey and government-provided information, are summarized in Table 4.1-2. NOAA identified 34 DRGS receivers, 23 of which are in the U.S. According to the results of Projects 2 and 6, these receivers, which include the ingest sites at Wallops Island and Sioux Falls and the many users who rely upon them, are the most vulnerable to potential RFI impact from sharing 1675–1680 MHz.

Emergency Data Distribution Network (EDDN): As mentioned in Section 3.1.1.2, DCS data is also received using the EDDN. The USGS Earth Resource Observation and Science (EROS) Center in Sioux Falls, South Dakota, one of the critical direct-broadcast users of GOES DCS, developed the EDDN in cooperation with NESDIS and other DCS users to provide a backup for data reception and distribution. The data flow from the DCPR to the EDDN user is shown in Figure 4.1-2. The EDDN ground network serves as an emergency backup to DCS reception at NOAA, although some users obtain their original DCP information directly from servers in the EDDN.

4.1.2 In-band Sensor Data for GOES-NOP

The GOES-14 and GOES-15 legacy satellites, currently placed into orbital storage, are available for reactivation if the need arises. Given those circumstances, these satellites are given due consideration for potential impacts in this report. The satellites are equipped with environmental monitoring sensors that provide horizontal gradient measurements of earth's oceans, land

Table 4.1-2. U.S. users with DRGS receivers.

User	Receiver	Location
Bureau of Reclamation	DRGS/HRIT/LRGS	Boise, ID
National Interagency Fire Center	DRGS/HRIT/LRIT	Boise, ID
Great Lakes and Ohio River Division (USACE)	DRGS	Cincinnati, OH
Mobile District (USACE)	DRGS	Columbus Lake, MS
State of New Hampshire Dam Bureau (two DRGS sites)	DRGS	Concord, NH
International Boundary and Water Commission, U.S. and Mexico (U.S. Department of State)	DRGS	El Paso, TX
NOAA Consolidated Backup Unit (NESDIS)	DRGS/HRIT	Fairmont, WV
Microcom Test and Development Site (Federal partner site)	DRGS/HRIT	Hunt Valley, MD
Tennessee Valley Authority (TVA) River Forecast Center	DRGS/HRIT	Knoxville, TN
South Atlantic Division (USACE)	DRGS	Mobile, AL
Omaha District (USACE)	DRGS/HRIT/EMWIN	Omaha, NE
Mississippi Valley Division (USACE)	DRGS/HRIT	Rock Island, IL
South Pacific Division (USACE)	DRGS/HRIT	Sacramento, CA
SeaSpace Corporation	DRGS/HRIT	San Diego, CA
EDDN–EROS (USGS)	DRGS/HRIT	Sioux Falls, SD
Mississippi Valley Division (USACE)	DRGS/HRIT	St. Louis, MO
National Buoy Data Center (NOAA NWS)	DRGS/HRIT	Stennis Space Center, MS
NOAA Satellite Operations Facility (NESDIS)	DRGS/HRIT	Suitland, MD
Florida Department of Transportation (two DRGS sites)	DRGS	Tallahassee, FL
NOAA National Water Center	DRGS	Tuscaloosa, AL
Mississippi Valley Division (USACE)	DRGS/HRIT	Vicksburg, MS
Wallops Command and Data Acquisition Station (NESDIS)	DRGS/HRIT	Wallops Island, VA

surfaces, clouds, and storm systems. The ground segment receivers for the low-resolution raw instrument and Sensor Data (SD) are located at Wallops Island, Virginia. As noted in Table 3.1-2, the GOES-NOP SD RF link transmits information in the 1673.4–1678.6 MHz band, which is within and adjoining the 1675–1680 MHz band under consideration for sharing. Figure 1.11 illustrates the electromagnetic spectral neighborhood of the GOES-NOP L-band frequency assignments along with the 1670–1680 MHz potential LTE downlink. If interference from spectrum sharing within 1675–1680 MHz occurs with GOES-NOP SD receivers, the raw SD data and subsequently all processed products could be lost or corrupted.

The raw instrument data collected on the Operations Ground Equipment (OGE) at the NOAA earth stations from the SD link is processed into the GVAR format and retransmitted to ground users through other RF links (including dissemination via GVAR). The Wallops Island site will continue to support this capability even with the GOES-R Series satellites operational.

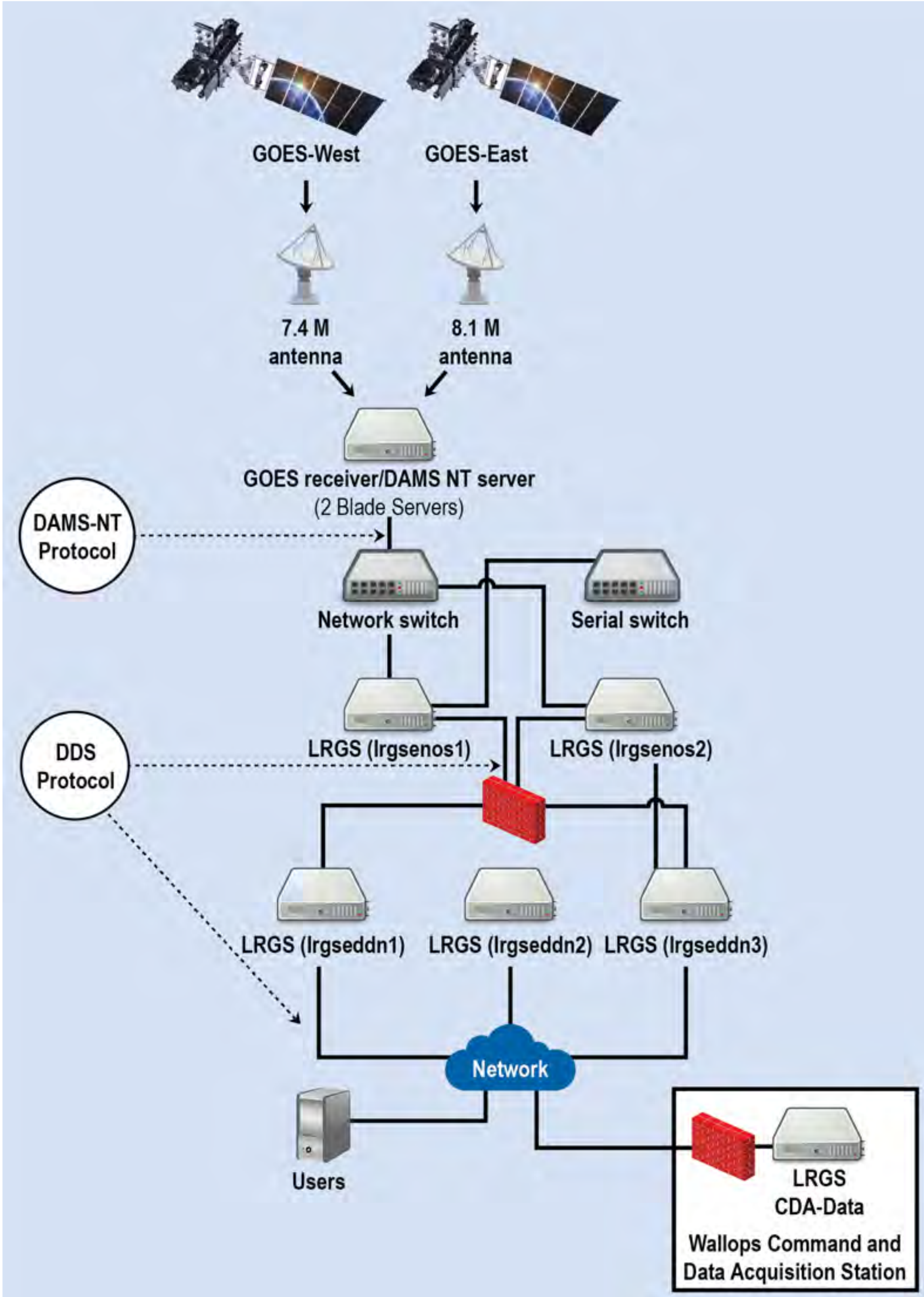


Figure 4.1-2. EDDN data flow.

4.1.3 GOES Rebroadcast

GOES Rebroadcast (GRB) is a dissemination service on the GOES-R series satellites. GRB replaces the GOES Variable (GVAR) service of legacy GOES. The GRB signal, centered at 1686.6 MHz and occupying 1681.15–1692.05 MHz, is adjacent to the 1675–1680 MHz band in consideration for shared use with commercial carriers.

GRB provides the primary relay of full-resolution, calibrated, near-real-time direct broadcast space relay of Level 1b data from each instrument and Level 2 data from the Geostationary Lightning Mapper (GLM). The GRB contains the Advanced Baseline Imager (ABI), GLM, space environment data, and solar data that drive data flow in the NOAA space and earth environment research and operational framework. Table 4.1-3 identifies a sample of Federal users and the types of sensor data they receive by direct broadcast for further processing, analysis, and distribution. Many GRB user sites have three receive antennas, with one for GOES-East, one for GOES-West, and a hot spare antenna. Some GRB users require local GRB reception for either data latency or availability, or to obtain unmodified Level 1b data. Information about the specific sensor data and their volumes and rates are explained in further detail in Section 4.3.

Table 4.1-3. Selected Federal GRB receive sites with data applications and products.

Site	Site mission and related GOES requirements	Products enabled by site
NWS Storm Prediction Center (SPC), Norman, OK	SPC collects GRB (ABI/GLM) directly and DCS data indirectly via AWIPS to create watch and forecast products for tornadoes, severe thunderstorms, lightning, wildfire, and winter weather. The mission of SPC is to protect lives and property from hazardous weather events by providing timely and accurate watch and forecast information to the public. GOES data is continuously collected, with ABI and GLM data coming in as frequently as every minute. GLM data at SPC is used by civilian scientists/meteorologists. Often the jump rate of lightning observed by GLM is an indicator of convective interaction and severe-storm formation. SPC maintains its mission of product creation by processing the continuous feed of ABI and GLM data and combining it with AWIPS data. Scientists use all 16 ABI bands to evaluate weather conditions. They monitor ABI full-disk scales every 10–15 minutes when they come in, contiguous U.S. scales every 5 minutes, and various mesoscales every minute.	SPC creates an entire suite of products. All products are made on-site by Federal civilian scientists/meteorologists. The product list includes: • Storm and tornado watches and warnings • Mesoscale discussions • Convective outlooks • Storm reports • Fire weather outlook • Atmospheric moisture • Tornado convective weather outlooks • Mesoscale convective discussions • Hazardous weather watches and warnings
NOAA Space Weather Prediction Center (SWPC), Boulder, CO	The mission of SWPC is to generate space weather products and services to meet the needs of the U.S. The GRB data collected is part of the gateway for GOES data collections. The data is continuously collected and processed on site into files that are compatible with downstream data ingestion. As a backup for the GOES data collections, SWPC cross-feeds the data stream with NOAA Center for Weather and Climate Prediction (NCWCP) in LDM format protocol. SWPC has the same GRB setup, so all of the data files are the same. In cases when NCWCP loses GRB direct broadcast reception, the data backup is provided from the LDM data stream connection with the SWPC servers. SWPC requires low latency for receipt of space weather data from the GOES-R series satellites. There are some SWPC products that require three-second latency from when conditions are sensed on orbit to when potentially affected end users are notified.	Data is processed on-site into files that are compatible with data ingestion downstream, where they are turned into visualizations by AWIPS, supercomputer modeling, Panoply (free visualization of GRB files), and the University of Wisconsin's McIDAS GRB processing software. SWPC provides numerous tools, graphics, and data sets to help both the casual user and research scientists understand and make use of the vast array of space weather information. Forecasts of several types are available to give warning of upcoming space activity, and models provide longer-term outlooks for future events. The products generated by SWPC are developed from GOES observations as well as from other NOAA data collection sources and include: forecasts, reports, models, observations, alerts, watches, and warnings. Applications include protection of the U.S. power grid, protection from excessive natural radiation of aircraft crew and passengers on over-the-pole flights, maintaining accuracy of GPS signals, and protection of orbiting satellites.

Table 4.1-3. cont.

Table 4.1-3. Selected Federal GRB receive sites with data applications and products.

Site	Site mission and related GOES requirements	Products enabled by site
NOAA National Center for Weather and Climate Prediction (NCWCP), College Park, MD	NCWCP is the home of NOAA's Weather Prediction Center (WPC), Ocean Prediction Center (OPC), and Climate Prediction Center (CPC), as well as units of OAR. WPC provides nationwide analysis and forecast guidance products for seven days into the future. The OPC issues weather warnings and forecasts out to five days for the Atlantic and Pacific Oceans above 30° north latitude, and it serves as a backup to the National Hurricane Center. CPC monitors and forecasts short-term climate fluctuations and provides information on the effects climate patterns can have on the nation. The NCWCP is also a major node in the NWS Integrated Dissemination Program, which also uses the GRB antennas located at College Park.	WPC is the source of the National Forecast Chart, often seen on broadcast television. It issues forecasts from a half-day day through about seven days for the continental U.S. and Alaska. WPC also develops flood outlooks, excessive rainfall products, storm summaries, tropical products, winter weather forecasts, and precipitation forecasts. OPC develops products on maritime weather, ice, wind, waves, and sea state and surface. The CPC issues the Winter Outlook as well as outlooks from six days to three months. CPC also prepares a seasonal drought outlook and a U.S. and Global Tropics hazards outlook.
NOAA Aviation Weather Center (AWC), Kansas City, MO	The Aviation Weather Center (AWC), an ICAO-certified Meteorological Watch Office, provides aviation warnings and forecasts of hazardous flight conditions at all levels within domestic and international airspace. The AWC is a major user of GOES-R data via GRB. Tiled data format issues prevent AWC from using GOES-R images sent via the NOAAPort/SBN to construct aviation products. They must have GRB data.	The AWC provides forecasts for convection, turbulence, icing, and winds, and also provides specialized warnings to pilots for hazards to aviation. The center combines data from multiple satellite imagery products to support air routes.
NOAA National Hurricane Center (NHC), Miami, FL	The NHC is co-located with the Miami/South Florida WFO in leased space at Florida International University. The NHC issues watches, warnings, and forecasts of hazardous tropical weather such as hurricanes in order to save lives, mitigate property loss, and improve economic efficiency. The GRB earth stations at NHC are the center's primary method of receiving GOES-R data in support of the hurricane forecasting mission.	The Hurricane Specialist Unit (HSU) within NHC prepares and issues analysis and forecasts on tropical cyclones and areas of disturbed weather for the U.S. and the Caribbean. The Tropical Analysis and Forecast Branch generates analyses and forecasts for the North and South Pacific basins and the North Atlantic basin on a year-round basis. The Storm Surge Unit forecasts abnormal rise in sea level accompanying hurricanes and prepares information used by emergency managers to develop evacuation procedures.
Air Force Weather, Mark IV-B Sites: Joint Base Pearl Harbor–Hickam, Honolulu, HI	The MARK IV-B meteorological data stations were designed to support the Defense Meteorological Satellite Program (DMSP). MARK IV-B stations currently operate continuously to receive GOES-R series GRB data in support of the Air Force Weather Web Services (AFW-WEBS), Worldwide Merged Cloud Analysis, USAF Land Information Systems, and numerical models.	Data files remains resident on-site, and users (military forecasters and research entities) use the MARK IV-B Forecaster desktop application to pull data from appropriate sites. The ABI data collected by the MARK IV-B sites are exported to the 557th Weather Wing, where it is used to produce weather products.
Joint Base Elmendorf-Richardson, Anchorage, AK Offutt AFB, Omaha, NE	MARK IV-B data stations at Hickam, Elmendorf, and Offutt AFBs collect GOES-17 ABI data and provide it to Air Force weather stations as needed to support DoD tactical operations. ABI data provides a view of the earth's surface and is used to monitor weather and meteorological events. MARK IV-B stations make it possible to receive full earth disk scans every 10–15 minutes, contiguous United States area scans every 5 minutes, and mesoscale scans every minute. ABI ABI & GLM data streams is collected 24/7/365 and ingested by the Real- time Software Telemetry Processing System (RT-STPS).	The 557th Weather Wing is a unit of the Air Combat Command. The 557th Weather Wing creates worldwide weather products such as weather models, analysis, and forecast development, and also issues weather advisories, watches, and warnings, available via the internet.

Table 4.1-3. cont.

Table 4.1-3. Selected Federal GRB receive sites with data applications and products.

Site	Site mission and related GOES requirements	Products enabled by site
NOAA Inouye Regional Center (IRC), Ford Island, HI	The IRC consolidates many of the NOAA offices in the Pacific Region, including the Pacific Tsunami Warning Center. GRB reception supports weather forecasting needs for the NOAA Pacific Region functions in Hawaii. In the event of terrestrial internet failure in Oahu, GRB reception would be a major source for Pacific Region forecasting activities.	Forecast responsibilities for the Honolulu WFO, which benefits from the GRB information, include aviation in the North Central Pacific, Marine forecasts in the central North and South Pacific, and support for the Central Pacific Hurricane Center. PTWC issues watches for the Caribbean Sea, Hawaii, and portions of the Pacific.
USAF 45th Space Wing, 45th Weather Squadron, Cape Canaveral, FL	45th Weather Squadron performs weather assessments for air and space operations such as weather observations, forecasts, advisories, and warnings in support of space launches. The GRB receive system is planned to provide critical information necessary to confirm lightning launch commit criteria and relevant space weather information in support of every Federal and private launch from Kennedy Space Center or Cape Canaveral Space Force Station.	Monitoring of conditions for local lightning and severe weather to comply with launch commit criteria; receiving space weather information.
NASA Spaceflight Meteorology Group (SMG), Houston, TX	SMG provides current and expected state of the atmosphere information during human spaceflight operations. The data is ingested and displayed into the Johnson Space Center Meteorological Information Data Display System (MIDDS), which uses McIDAS as the core software. Beyond standard imagery and GLM data, SMG creates a few specialized products from the GOES data.	Products issued in support of human spaceflight or for missions in checkout intended for future human spaceflight use.

4.1.4 Multi-use Data Link for GOES-NOP

The GOES-NOP Multi-use Data Link (MDL) has a center frequency of 1681.478 MHz and a bandwidth of 400 kHz. If 1675–1680 MHz is approved for sharing with a terrestrial mobile broadband provider, the MDL link may be impacted by adjacent-band interference. If the need arises to return to operation, MDL would provide WCDAS, FCDAS, Satellite Operations and Control Center (SOCC) at NSOF, and the Space Weather Prediction Center (SWPC) in Boulder, Colorado, with a medium-rate (400 kbps) downlink of imager and sounder servo error, and imager motion compensation quality-check data. The MDL is received through the MDL Receive System & Server (MRS&S), which resides at each of these four locations. GOES-NOP space weather sensors are reported via the MDL.

4.1.5 Other adjacent-band Federal services considered to be at risk

4.1.5.1 Overview and approach

To identify the RF systems registered for use within and adjacent to the 1675–1680 MHz spectrum, the services of the Defense Information Systems Agency (DISA) Global Electromagnetic Spectrum Information System (GEMSIS) Spectrum Operations Support Center (SOSC) in the Joint Spectrum Center (JSC) located in Annapolis, Maryland, were used. The SOSC/JSC provides government agencies with access to the following GEMSIS databases that contain license, assignment, certification, and parametric information for RF systems:

- End-to-End Spectrum Supportability (E2ESS)
- Coalition Joint Spectrum Management Planning Tool (CJSMPT)
- Joint Spectrum Data Repository (JSDR)
- Integrated Spectrum Desktop (ISD)
- Spectrum XXI (SXXI)

Additional queries were made in the following GEMSIS databases:

- Spectrum Certification System (SCS)
- FCC Government Master File (GMF)
- International Telecommunications Union (ITU)
- Canadian Master File (CMF)
- Frequency Resources Records System (FRRS)
- JSC Equipment Tactical & Space (JETS)
- Radio astronomy databases

The GEMSIS database was queried to identify systems operating within or overlapping with 1665–1695 MHz. All of the non-meteorological system records queried in the JETS database were identified as having wideband frequency operations outside of the 1665–1695 MHz band. Each of the system records identified as having potential interference issues with 1675–1680 MHz spectrum sharing are listed in Table 4.1-4.

Table 4.1-4. Non-GOES Federal users potentially impacted by 1675–1680 MHz spectrum sharing (unclassified list).

Agency	Number of records overlapping 1665–1695 MHz	Brief description of spectrum use	Summary of system functions
NASA	2	Eastern Range Timing Distribution System (ERTDS). Distribute time and frequency standards to eastern range mainland sites, in support of space launches.	Communications data, telemetry, radar.
NSA	9	Digitally controlled microwave receiving and analysis system.	Electronic warfare, communications monitoring.
U.S. Army	3614	Countermeasure detection system, identification of enemy radio frequency signals and their point of origin, direction finding monitoring systems, low-power communications telemetry system, land and air radar, handheld detection system for anti-tank and anti-personnel mines, radio line-of-sight communications system, meteorological measuring set, meteorological data collection processing and communication systems for upper atmosphere data.	Meteorological aid, communications telemetry and data, navigation, electronic warfare, direction finding, radiosonde, secure communications, satellite communications, emergency communications, electronic warfare jamming, radar.
U.S. Air Force	797	Pulsed radar, RATSCAT, radar and communications countermeasures, high-performance receive system, microsatellite technology, electronic warfare simulator systems, ground-based telemetry tracking system, direction-finding monitoring system, jamming source, tactical weather analysis receiver set, transportable weather satellite terminal.	Navigation, direction finding, electronic warfare, electronic warfare interception, satellite telemetry and SD, EW jamming, radar, velocity and height measurements, Doppler measurements, meteorological aid.
U.S. Coast Guard	158	Over-the-horizon countermeasures for targeting, area surveillance, and threat warning, direction-finding systems, surface search radar.	Electronic warfare, radar, navigation, direction finder.
U.S. Marine Corps	765	Command and control warfare communications and jamming system, electronic attack and jamming system, secure digital communication system, line-of-sight digital communications system, transportable radio direction-finding system, meteorological data collection system.	Electronic warfare intercept and jamming, radar, navigation, direction finder, communications monitor, air traffic control, satellite communications, secure voice, meteorological aid, radiosonde.
U.S. Navy	7244	Radar detection system, small-ship electronic support measures, radar threat warning system, over-the-horizon detection, classification, targeting, area surveillance, and threat warning systems, small ground and aerial radio jammer platforms, electronic counter-countermeasures, hostile integrated targeting system for aircraft and ships, telemetry communications system, communication and emitter sensing and attacking system, battle group horizon system acquisition receive system, electromagnetic detection beyond a ship's line-of-sight range, meteorological data collection and processing system, transportable weather satellite terminal, complex meteorological data receiver, airborne countermeasure receiver system.	Direction finder, navigation, search and tracking, communications monitoring system, equipment monitor, satellite communications, emergency communications, secure voice communications, electronic warfare, electronic warfare jamming, radar, video/data link, network communications, radar warning receiver, intercept, air traffic control, radiosonde, satellite tracking, meteorological aid, maritime mobile satellite services.

4.1.5.2 Results

The GEMSIS database search for systems in the 1665–1695 MHz found 3,428 RF systems used by Federal and U.S. commercial entities for receive and transmit operations of various modulated signal types. Of these systems, 2,263 (60%) are classified and were tallied but not considered in this analysis.

Outside of NOAA, the unclassified systems identified in GEMSIS include information for systems used by each of the services as well as the private sector (non-Federal). The systems have various purposes, ranging from RF components used in radar and spectrum-monitoring direction finding systems, to RF countermeasures and jamming devices.

4.1.6 Impact to end users if data is not available or not timely

4.1.6.1 GOES data end users and applications: Overview

Direct broadcast users play a significant role in the distribution of GOES data to additional, particularly indirect, users of environmental information. Referred to as "end users" in this report, they may be directly associated or indirect beneficiaries of the satellite downlink; the category includes both public and private organizations. Airlines and other ground or maritime transportation companies may require private-sector forecast products that are more specific or limited in location than the products provided by the NWS. For example, the Weather Company (IBM) supports several major commercial airlines, including United Airlines, with forecast products and information. AccuWeather provides specialty products in support of railway transportation, forecasting track washouts and ensuring trains avoid the paths of tornados. Small meteorological companies provide lightning forecasts for professional or collegiate sports stadiums or closure forecasts for school districts. Private meteorological companies use GRB imagery in developing products and forecasts in support of helicopter transport operations in the Gulf of Mexico supporting oil exploration and production. NOAA cooperative institutes associated with academic campuses, but employing both Federal employees and students, often have secured funding for GRB antenna installations via NOAA grants. The ultimate beneficiaries are governments (local, state, and Federal), businesses, and households that use these services provided by intermediaries. End users include large Federal service facilities like the NWS National Hurricane Center; smaller government entities supporting flood forecasting, hydroelectric power generation, and reservoir operations; and businesses and households served by the public- and private-sector weather industry. GOES satellite images shown on broadcast television by local meteorologists are often received by private-sector GRB antennas and disseminated via weather servers for television weather programs. The services that the GOES data end users provide our nation yield large economic and safety-of-life benefits.[3] Representative use cases are described in Table 4.1-5.

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[3] Irving Leveson, "The GOES Program: Features, Capabilities and Applications of NOAA's Geostationary Observational Environmental Satellites," final report to the National Oceanic and Atmospheric Administration, National Environmental Satellites, Data, and Information Service (Alion Science and Technology, Inc., July 2018); Jeffrey K. Lazo, Rebecca E. Morss, and Julie L. Demuth, "300 Billion Served: Sources, Perceptions, Uses, and Values of Weather Forecasts," *Bulletin of the American Meteorological Society* 90, no. 6 (2009): 785-798, https://journals.ametsoc.org/doi/pdf/10.1175/2008BAMS2604.1.

Table 4.1-5. Selected Federal end users, use cases, and impacts of data delays.

High-level end user	Use cases by lower-level organization or agency end user	Adverse end-user impact
DOC	NWS: The Alaska Aviation Weather Unit is the only International Civil Aviation Organization (ICAO) meteorological office in the world that is both a Volcanic Ash Advisory Center and a Meteorological Watch Office (MWO). This unit is responsible for issuing Volcanic Ash Significant Meteorological Information Statements (SIGMET), the primary warning product to the aviation community in this region of the hazard of volcanic ash.	The Anchorage VAAC covers North Pacific air routes that overfly one of the most active volcanic regions on the planet. Approximately 10,000 people per day and up to 50,000 aircraft per year traverse the Anchorage VAAC coverage area, including most flights from the western United States to Asia. Interference to the Anchorage office will impact information provided to Air Traffic Control of inflight hazardous weather conditions. All air traffic (commercial, cargo, and general aviation) and parties impacted on the ground by volcanic ash benefit from these products.
	NWS: Pacific Region offices provide products for aviation, maritime, flooding/hydrology, and public forecast services. The Central Pacific Hurricane Center (CPHC) issues tropical cyclone watches, warnings, advisories, discussions, and statements for all tropical cyclones in the Central Pacific.	The NWS Pacific Region offices or service locations include Honolulu, HI; Tiyan, Guam; Pago Pago, American Samoa; Majuro, Republic of the Marshall Islands; Pohnpei, Chuuk, and Yap in the Federated States of Micronesia; and Koror, Republic of Palau. Interference at any of the Pacific Region offices will impact the weather forecast products provided to these locations. Relay of GOES data to regions out of GOES-17 GRB coverage occurs from the antennas located in Hawaii.
	NWS: Tsunami warning and hurricane-related storm surge warnings for coastlines and islands within the U.S. and Possessions (Pacific Tsunami Warning Center).	Interference will impact the weather forecast products provided. EMWIN in many cases is the sole source of tsunami or storm-surge data for remote island nations and territories.
	Ocean Prediction Center (OPC): Marine charts and text forecasts, lightning strike density, unified surface analysis, product loops, volcanic ash information.	OPC, which backs up some of the NHC services if necessary, requires the same direct broadcast reception capability as the NHC. This backup capability to the NHC would be adversely impacted if interference occurs. According to the OPC website, “Hazards from thunderstorms include reduced visibility, saturation of collision avoidance radar due to attenuation from heavy rain, rapidly increasing and shifting winds, building waves, and lightning. Sailing vessels and small fishing vessels are particularly vulnerable to rapidly degrading conditions associated with thunderstorms, especially those (ships) operating beyond the WSR-88D (radar) detection volume and cell coverage over the open ocean.” Interference will impact the OPC’s Lightning Strike Density product, which benefits many maritime communities. GLM data is providing information not previously available to maritime or transoceanic aviation users.
	Physical Oceanographic Real-Time System (PORTS): Real-time tide and current data to promote safety of maritime navigation. Harbors where systems are installed are: Cape Cod, Charleston, Cherry Point, Chesapeake Bay, Corpus Christi, Cuyahoga, Delaware River, Houston/Galveston, Humboldt, Jacksonville, Lake Charles, Los Angeles/Long Beach, Columbia River, Lower Mississippi River, Matagorda Bay, Miami, Mobile, Morgan City, Narragansett, New Haven, New London, New York/New Jersey, Pascagoula, Port Everglades, Port Fourchon, Anchorage, Sabine Neches, San Francisco, Savannah, Soo Locks, Tacoma, Tampa Bay, and Toledo.	The up-to-date nautical information contained in PORTS has the potential to save the maritime insurance industry from multimillion-dollar claims resulting from shipping accidents. Inland waterway management of the navigation channel and information surrounding locks and dams is necessary for the safe transportation of commodities via the inland waterways, including the Great Lakes. The PORTS products will be adversely impacted if interference occurs to the GOES DCS direct broadcast receivers. Maritime users include cargo vessels, cruise ships, yachts, and tugboats.

Table 4.1-5. cont.

Table 4.1-5. Selected Federal end users, use cases, and impacts of data delays.

High-level end user	Use cases by lower-level organization or agency end user	Adverse end-user impact
DoD	Joint Typhoon Warning Center (JTWC): Responsible for tropical cyclone/typhoon forecasting and warning in the Western Pacific Ocean. JTWC is located in Pearl Harbor, HI, and is jointly operated by the Navy and Air Force.	Interference will impact the weather forecast products provided: tropical cyclone and tsunami products including warnings and advisories.
	USACE: River navigation. Data relayed by GOES DCS, providing updated information on the nation's inland waterways, where USACE is responsible for maintaining channel depth and width. Tugboat and barge companies need this data to establish loading of commodity cargo for exports in major river basins. See RiverGages.com.	Capacity of barges carrying goods down major rivers, generally for export, are established by water levels and draft for such maritime vessels. It is essential that the navigation channels comply with minimum depths and widths.
DOT/ FAA	Air Route Traffic Control Centers (ARTCC): 21 locations house Center Weather Service Units (CWSU) that are staffed by NWS. Each CWSU provides weather information by computer products and standup briefings to air traffic control area managers.	CWSUs issue Center Weather Advisories (CWA) and Meteorological Impact Statements (MIS). Interference will impact these products, which provide weather forecasts to ensure safety of flight operations and ground personnel at airports.
	International Civil Aviation Organization (ICAO): Has created nine Volcanic Ash Advisory Centers (VAAC) to support aviation. Two of these VAAC locations operate in the United States (College Park, MD, and Anchorage, AK) and generate products used by the AWC and NOAA to provide warnings of volcanic ash events.	Volcanic ash plumes present a hazard to aviation. The material in a volcanic ash cloud hardens like cement when ingested into jet turbine engines, causing the engines to lose power or stall in flight. Ash clouds can also damage aircraft lift surfaces and wind screens, resulting in potential loss of lift, reduction in engine power, impacts to crew visibility, and potential impacts to aircraft communications. Interference to the GOES-R direct broadcast receivers will affect these warning products.
	NWS: Meteorological Watch Offices (MWOs) operated by the NWS are responsible for providing en-route domestic and international weather information and services to the FAA. MWOs create customized aviation product mosaic forecast of GOES GVAR and GRB data sources.	The MWO aviation forecasts produce localized aviation weather products, which are mosaics of NOAA GOES processed data. Any interference to the direct reception and ingest of the GOES/GOES-R data that affects receipt or quality would adversely impact the creation of the critical use-case displays and most likely make the mosaics useless.
	Offshore Precipitation Capability (OPC): Combined products using GOES-R imagery and GLM data were developed from work for the FAA by MIT/Lincoln Labs for the OPC. OPC is a system that helps compensate for the fact that there are no land-based radars over the ocean. Air traffic controllers work to keep aircraft away from severe storms and conditions that are hazardous to air transportation.	Customized aviation forecast products produced by the WMO will be impacted if interference occurs at the GOES GRB direct broadcast locations that are used as the WMO data source for these FAA aviation products.

Table 4.1-5. cont.

Table 4.1-5. Selected Federal end users, use cases, and impacts of data delays.

High-level end user	Use cases by lower-level organization or agency end user	Adverse end-user impact
DOI	USGS: Water Data for the Nation, program for disseminating water data within USGS, to USGS cooperators, and to the general public.	USGS National Water Information System (NWIS): Many types of data are stored in NWIS, including comprehensive information for site characteristics, well-construction details, time-series data for gage height, streamflow, groundwater level, precipitation, physical and chemical properties of water, and water-use data. Additionally, peak flows and chemical analyses for discrete samples of water, sediment, and biological media are accessible within NWIS. Interference may corrupt the NWIS data.
	USGS: Tsunami warning and hurricane-related storm surge warnings for coastlines and islands within the U.S. and Possessions.	Interference will impact the weather forecast products provided.
BLM	National Interagency Fire Center (NIFC): The Remote Automated Weather Stations (RAWS) are deployed in about 4,000 strategic locations throughout the United States and are packaged for rapid deployment in areas where data needs to be collected to monitor changing conditions. These remote weather sensors are primarily owned by wildland fire agencies and used for monitoring fire danger by collecting, storing, and forwarding precipitation, relative humidity, wind, solar radiation, and other data.	The data provided from remote stations allows fire managers to predict fire behavior and monitor fuels and resource managers (including those managing wildfire firefighting operations) to monitor environmental conditions. Interference will impact the ability of fire managers to make decisions, and missing information will place wildfire firefighter lives at risk. NIFC indicates that when RAWS stations have been deployed and in use, no firefighter lives are at risk.

Delay and outage liabilities vary for intermediate and end users of GOES data products originating from critical and important Federal GOES sites. Intermediate and end users for this study are identified as those relying on GOES data for decision support or additional product creation. Table 4.1-6 is a representative set of users and impacts.

Table 4.1-6. Representative users and impacts.

Site	Intermediate/end user of GOES data	Uses of GOES data and impacts of delays/outages
NOAA National Ocean Service (NOS) GOES earth station	First responders	Delays or outages would critically impact the ability to respond to potentially hazardous situations and delay the ability to effectively and accurately disseminate public warnings and implement other emergency actions such as evacuations. Lack of real-time data could result in a larger response than necessary (wasting emergency funds) or inadequate responses (risking lives).
	Port managers, general public	An outage of DCS data would negatively impact maritime navigation, potentially closing ports to larger commercial vessels.
	Tourism industry, general public, emergency management	A delay in DCS data could critically impact the ability of end users (both public and private) to respond to potentially hazardous situations and delay NOS's ability to effectively and accurately disseminate public warnings, potentially resulting in delayed response to hazardous weather events.
	Ship Operators: VanEnkevort Tug & Barge Inc. (VTB) (example from Great Lakes)	VTB is a privately owned, U.S.-flag, bulk transport company serving the mining, steel, and construction industries on the Great Lakes. Real-time weather and oceanographic information has a significant bearing on achieving safe and efficient Great Lakes navigation for VTB's industrial clients. VTB relies on information from NOAA and USACE, much of it reliant on DCS. Ship operators depend on these products every day to bring ships safely between Great Lakes ports and through a complex array of locks, and that need is rapidly increasing. Products produced by two Federal programs (that are reliant on information that is monitored and quality-controlled at the NOS Chesapeake site) are critical for safe and efficient navigation on the Great Lakes. National Water Level Observation Network (NWLON): Reliant on DCS to transmit information in real time from its sensors, NOAA's NWLON program is a coastal observing network of more than 200 stations nationwide that collects continuous long-term water level observations to a known vertical reference, as well as other oceanographic and meteorological parameters that support navigation and safety. Physical Oceanographic Real Time System (PORTS): See previous table.
Department of the Interior (DOI), Bureau of Reclamation (BOR), Boise, ID	Federal, state and local agencies	Users of BOR data monitor flood events, assess and plan irrigation, manage hydropower dams, and control water distribution during droughts. Data is as mission-critical to stakeholders as it is to BOR. Data is distributed as soon as it is received. A delay or outage in DCS collection would result in loss of potentially critical data during flooding events, increasing the potential loss of life and property. A data delay at certain times of the year could be catastrophic.
	Public and private utilities, irrigation districts	BOR is the largest wholesaler of water in the country, controlling water supply to 17 western states. BOR brings water to 31 million people and provides irrigation water for 10 million acres of farmland, allowing the production of 60% of the nation's vegetables and 25% of its fruits and nuts. DCS data is used to properly manage water throughout droughts, floods, and varying seasonal demands. An outage of DCS data would result in uninformed management of water.
	Hydropower utilities	BOR is the second-largest producer of hydroelectric power in the U.S. DCS data from BOR is used to manage hydropower dams. Outages or delays would result in uninformed management of hydroelectric dams, creating the potential for interrupted power service to users.

Table 4.1-6. cont.

Table 4.1-6. Representative users and impacts.

Site	Intermediate/end user of GOES data	Uses of GOES data and impacts of delays/outages
U.S. Army Corps of Engineers (USACE). Rock Island, IL; St Louis, MO; Cincinnati, OH; Sacramento, CA; Columbus Lake, MS; Vicksburg, MS; Omaha,NE	General public	Residents living along rivers, lakes, and streams rely on the information for purposes ranging from recreation to evacuation during floods; data unavailability places lives and property in danger.
	Hydropower plants operators	Hydropower plants rely on GOES data provided by USACE for power generation purposes; outages can adversely impact their operations.
	Academia	Academia uses the data for studies and modeling in their systems; missing data will disrupt that flow of information into their systems.
	USACE scientists and water project managers	Internally, USACE relies on GOES data daily, and disruptions in the reception of data incapacitates USACE's ability to run hydrologic models that provide guidance in determining how to operate USACE flood-control and navigation projects, considering downstream constraints, preserving wetland areas and biodiversity, and more. A delay in DCS data, especially during floods, would place people, property, and critical infrastructure at risk; in particular, barge traffic would be at risk of running aground. An outage of DCS data would adversely impact end users across various sectors, as well as fish and other wildlife that live in and near rivers, lakes, and streams.
NWS Storm Prediction Center (SPC), Norman, OK	SPC scientists/ meteorologists	A delay in GOES GRB data would delay watches and warnings, particularly for severe thunderstorm and tornado outbreaks, where lead time is crucial to ensure people can find stable shelter to minimize loss of life. An outage in GOES GRB data would result in reliance upon landline retrieval of the data. While it is possible to use a landline connection from other NWS sites (NWS National Hurricane Center, Aviation Weather Center, Space Weather Prediction Center, etc.), the latency of landline connections is not as fast as required; in addition, there is concern about cost and increased risk of a full data outage due to a lack of a redundant landline paths on site. SPC is located in an area that is intentionally remote. NOAA leases the building from the University of Oklahoma, and the building lacks a redundant landline within the last mile of the site. Several years ago, a telecommunication contractor accidentally cut the landline during construction, leaving the site with no redundancies for data collection. Fortunately, during that event, GRB data continued to be received, and no data outage occurred. A full data outage would severely impact the ability to produce watches and warnings in a timely way for severe weather outbreaks across the country, threatening accuracy and the lead times to ensure those affected can get to shelter in advance of severe weather.
	Private weather services	Private-sector companies in the weather industry rely on SPC for content and analysis. Often this means that weather forecasters at television and radio stations across the country rely on information from private weather companies as well as the government to inform their public communications.
	General public	Products produced at SPC are first and foremost for the general public to support decision-making in the midst of hazardous weather. An outage could delay information to communities of people, leaving them in danger during hazardous weather events.
	Emergency managers	Emergency managers at the state and county level use SPC data to plan rescue missions, evacuations, and mitigation efforts. These groups require the most up-to-date information during hazardous weather events.
	Hospital staff	A delay in GRB data would delay tornado protection efforts. Hospitals need as much time as possible to respond to a tornado watch or warning. Hurricane protocol in a hospital is to move all patients away from windows. Hospitals have limited staff, and complying with this protocol takes time. A delay in tornado watches/warnings would limit the amount of time hospitals have to move patients and all medical equipment to safety.

Table 4.1-6. cont.

Table 4.1-6. Representative users and impacts.

Site	Intermediate/end user of GOES data	Uses of GOES data and impacts of delays/outages
NOAA Space Weather Prediction Center (SWPC), Boulder, CO	General public	A delay in GOES GRB data would could have negative life and property impacts, especially during and leading up to critical weather and emergencies when the data sets from GOES observations are used to develop advanced forecasts, reports, models, alerts, watches, and warnings of the inclement weather.
	Commercial service providers: global positioning systems (GPS), radio, satellite, aviation	While data redundancy protocols are currently in place with NCWCP, if the SWPC GRB products are delayed or lost, the end users that require the GRB data products to be continuously available (in real time) will be negatively impacted. These users require the SWPC products to assist in their operations by having knowledge of space weather's impact on our climate, GPS systems, electric power transmissions, HF radio communications, satellite drag, and communications.
	Cooperative Institute for Research in Environmental Sciences (CIRES)	CIRES was created in 1967 as a partnership of the University of Colorado and NOAA. It is NOAA's oldest and largest cooperative institute. About half of CIRES' researchers work in NOAA's David Skaggs Research Center in the Earth System Research Laboratory (ESRL), the Space Weather Prediction Center (SWPC), and the National Centers for Environmental Information (NCEI). The researchers participate in many aspects of NOAA's mission-critical work. The NOAA-based research is guided and sustained by a cooperative agreement, reviewed every five years and funded by Congress through NOAA. CIRES's Boulder-based researchers are affiliated with departments across the campus and are dedicated to the university's academic mission, including training the next generation of scientists. These CIRES scientists support their research with external funding from diverse sources: the Department of Energy, the National Science Foundation, NASA, and many more. The partnership with SWPC fosters fundamental and applied research on the atmosphere, biosphere, geosphere, oceans, hydrosphere, cryosphere, and more. It provides NOAA with access to the university's intellectual depth and resources while giving students direct experience in operational and mission-focused research. (*Source*: https://cires.colorado.edu/about/partners)
Air Force Weather: JB Pearl Harbor-Hickam, Honolulu, HI; JB Elmendorf-Richardson, Anchorage, AK; Offutt AFB, Omaha, NE	Air Force and Army warfighters, unified commands, national programs, and the national command authorities	A delay in GRB ABI data could potentially delay or degrade weather modeling and research. Delays in weather modeling could negatively impact Air Force operations, causing delays, less accurate planning, or inadequate preparation for hazardous weather. An outage of GRB ABI data could result in DoD resources being damaged or lost to hazardous weather. DoD personnel would be at risk of injury or death. Timely weather information is critical for military users to prepare for missions and respond to immediate situations. MARK IV-B systems currently use GOES-R GLM Geostationary Lightning Mapper data. Requirements for GLM data will mimic that of ABI data.
	University research groups	MARK IV-B data is used to develop, evaluate, test, and transition new technologies to weather teams around the world. A delay or outage could mean a gap in important research data.

4.1.6.2 Survey methodology and approach

A key objective of Project 1 was to document the impact of missing or delayed data to the GOES users through survey questions and email/phone interviews. In some instances, a point of contact provided a single impact relevant to several GOES receive sites he or she operates. If data were not available to identify the operational availability requirements for each user, a similar process for generating the impact to end users was used in that case.

4.1.6.3 Survey results

The end user's latency information was collected during the DCS and GRB user surveys and is grouped by low (<1 minute), moderate (1–10 minutes), and high (>10 minutes) system latency. Table 4.1-7 and Table 4.1-8 summarize the DCS and GRB survey responses and show the number of end users, by stakeholder affiliation, that reported latency usage information. While the period of operations for some of the GOES direct broadcast users is not consistent, the data requirements during their operations is, since they all require 99.988% data availability per GOES-R Series Ground Segment (GS) project Functional and Performance Specification (F&PS) (2017).

Table 4.1-7. Latency responses from the end users in the DCS user survey.*

End-user stakeholder affiliation	Total number of end-user responses	Low system latency (<1 minute)	Moderate system latency (1–10 minutes)	High system latency (>10 minutes)
Academic	11	5	4	2
Commercial	7	5	1	1
DOC	34	11	18	5
DoD	33	17	13	3
DOI	13	7	5	1
DOS	1	0	1	0
FFRDC	4	2	2	0
Indian Tribe	3	0	2	1
International	29	9	14	6
State/local government	33	8	15	10
USDA	7	0	4	3
Total number of end users	175	64	79	32

*These are not requirements for the DCS community; the data is end-user reported.

Table 4.1-8. Latency responses captured from users in the GRB user survey.*

End-user stakeholder affiliation	Total number end-user responses	Low system latency (<1 minute)	Moderate system latency (1–10 minutes)	High system latency (>10 minutes)
Academic	5	3	2	0
Amateur	1	1	0	0
Commercial	7	4	3	0
DOC	12	10	2	0
DoD	2	0	2	0
International	4	1	2	1
NASA	4	3	1	0
Total number of end users	35	22	12	1
*These are not requirements for the GRB community; the data is end-user reported.				

4.1.7 Considerations for way forward

If 1675–1680 MHz is approved for spectrum sharing with a terrestrial mobile broadband provider, NOAA may consider incorporating the following general engineering considerations for the way forward, based on the findings of Project 1:

- Long-term: Require future GOES receive sites to register with the NOAA Program Office, possibly through manufacturer reporting upon device sale, with allowances for proprietary submissions that are not reported publicly. This will ensure all future receive sites are considered during coordination and protection analysis.
- Long-term: Implement coordination efforts with commercial carriers so that the geographical placement of future receive sites is not impacted by spectrum sharing. Future GOES-R receive sites will continue to be installed as the next generation of GOES-R satellites becomes operational. Geographical placement of any future GOES direct broadcast receiver will become an issue due to RFI concerns and will need to be thoroughly analyzed and coordinated to ensure the operational integrity within an overlapping shared spectrum environment.
    - Implementing this recommendation is challenging due to proprietary concerns of terrestrial mobile broadband providers.

Subtask 1: DCS considerations

- Long-term: Expand and provide data redundancies in the GOES DCS backup architecture by expanding the network interface to include other Federal agencies' direct-broadcast DCS identified in the user list. SPRES Project 3 analyzes and provides insight into alternative data distribution architectures.
- Long-term: Research a method to provide a backup DCS RF link outside of L-band. If possible, utilize the 468.8 MHz transmitter aboard the GOES-R Series satellites for two-way DCS communications.[4] Utilizing the 468.8 MHz transmitter for DCS backup communications may be a good method for DCS users to:

[4]Brian Kopp, Duane Preble, and Brett Betsill, "An Interference Avoidance Waveform for the UHF Downlink on the New NOAA GOES-R satellite," presentation at IEEE SoutheastCon, Charlotte, North Carolina (March–April 2017), https://www.noaasis.noaa.gov/docs/IEEE%202017%202%20wayPres.pdf.

  - Send commands and configuration changes to DCPs
  - Switch DCS receiver and DCP channel data collections to an ultra-high frequency (UHF) link to receive DCS message data via an alternative backup RF link.
- Long-term: Conduct electromagnetic compatibility test scenarios with new antenna hardware that integrates narrowband filtration specific to the DCPR downlink frequency/channel, to determine if new hardware can further mitigate the interference the DCS receivers encounter because of spectrum sharing.

Subtask 2: SD considerations

- Long-term: The direct frequency overlap with the GOES-NOP SD RF link, regardless of the size of any exclusion zones implemented, presents a risk of potential data loss (which is further assessed in other SPRES projects). The team recommends that the one NOAA SD site be included in future spectrum-sharing coordination analysis.

Subtask 3: GRB considerations

- Short-term: Conduct electromagnetic compatibility test scenarios with new antenna hardware that integrate narrowband filtering specific to the GRB downlink to determine if new hardware can provide protection to the GRB receivers from adjacent-channel interference.
- Long-term: Expand and provide data redundancies in the GOES GRB data distribution and backup architecture by expanding the network interface to include other Federal agencies' direct broadcast data collections. Implement the designs for a system similar to that of the NWS AWIPS structure, to ensure if regional interference is observed at the NESDIS receive sites, redundancy in data collection will mitigate lost or corrupted data.

Subtask 4: MDL considerations

- Long-term: The close spectrum proximity of the 1675–1680 MHz band to the MDL link poses a high risk for adjacent-channel interference (ACI) with the GOES-NOP MDL receive sites. This needs to be factored in for any sites that could receive MDL through 2025.

Subtask 5: Adjacent-band considerations

- Short-term: At the classified project level, it would be prudent to understand whether any of these systems are at an elevated risk for RFI from AWS LTE operations in this band.

Subtask 6: End-user impact considerations

- Long-term: Given that the NESDIS definition of operational availability requirements is applicable for all GOES direct broadcast users, grouping all user data requirements (that are the same), regardless of the user's period of operations, is recommended. The users' period of operations is defined not by a specific schedule but rather by the environmental conditions that drive the users' operational requirements.

4.2 Project 2. Analysis of Potential Interference to GOES Users

The scope of Project 2 spanned two of the SPRES program topic areas, GOES Data Use and RFI Modalities and Risks. In doing so, it sought to confirm the site configuration, classify sites in terms of preliminary risk of RFI, and model sites for expected RFI. The classification of each site fell into one of the following risk categories: negligible, low, medium, or high.

Earth stations classified as high risk for RFI were further examined for impacts that interference could have to NOAA and consumers of NOAA data. The impact of interference could be the loss or delay of GOES meteorological data, which may in turn have safety of life and other socioeconomic consequences, which are covered in more detail in sections 3.1 and 4.1.

Study objectives

The specific objectives of this project were to provide:

- Survey and analysis of respective sites and capabilities, including a listing of ground-station equipment part numbers and characteristics for antennas, receivers, and filtering.
- Identification and documentation of associated environmental factors (topography, proximity to existing or likely network terrestrial buildout/population centers) for each site that could be pertinent to successful spectrum sharing with AWS carriers.
- A list of sites and associated users grouped by common site characteristics.
- A first-order line-of-sight interference analysis of all sites using the worst-case antenna characteristics in relation to well-defined cell tower locations.

The expected outcome of this project was a first-order classification of the susceptibility of GOES ground stations to RFI as negligible, low, medium, or high risk. Of equal importance, this study sought to identify sites with a negligible-to-low chance of RFI to streamline the analyses to bring more focus to the higher-risk sites.

Methodology

Project 2 took a dual approach of performing qualitative assessments of equipment and GOES signals, along with quantitative assessments of the susceptibility of the GOES signals at each site to RFI.

Quantitative assessments were accomplished using the U.S. Army's Radio Frequency Processing Tool (RFPT). This analysis tool, operated by Alion, simulated two scenarios for LTE interference with the GOES downlink signals: (1) uplink from LTE user equipment (UE) to base station, and (2) downlink from LTE base station to LTE UE. The propagation model used in RFPT is the Terrain Integrated Rough Earth Model (TIREM).

Site risk analysis required information on cell tower placement to better understand those risks. Two sources of cell tower laydowns were available.

1. Results of a study commissioned by the NTIA's Commerce Spectrum Management advisory Committee (CSMAC), herein referred to as the CSMAC laydown.
2. CellMapper, a crowd-sourced database based on the participation of users running the app on their cell phones. While the user is driving, the app automatically uploads information on cell towers detected using GPS-based triangulation techniques.

The cell tower information consists of the following parameters: (1) tower location, (2) tower height, (3) antenna downtilt, (4) number of sectors, and (5) sector angle, etc. For uplink analysis, the UE transmitters were assumed to comprise three per sector, in a radial pattern around the tower location. Two radiation pattern types for the antennas were used: (1) omnidirectional and (2) antenna pattern. The omnidirectional type radiates at full power in all directions and is considered the worst case. The use of an antenna pattern is considered more realistic. In terms of simulating RFI, RFPT assesses the contribution of the interfering transmitter(s) in each sector, of each tower, to the power of the interfering signal at the ground station antenna. Any sector found to contribute to the interfering signal is referred to as a “denied sector.” The presence of one or more denied sectors represents the presence of RFI in the scenario in question.

When a reference is made to an omnidirectional antenna pattern, this simply means the simulation was run assuming both the GOES earth station and LTE interferer were set to simulate an omnidirectional pattern. In the case of simulations that are run using the nominal antenna pattern, the interferer (LTE base station) is set with the appropriate downtilt, radiation pattern (in the case of an earth station), azimuth, and elevation angle. This methodology was decided upon because future links may be available and the antenna pointing angle of the earth station may change. With simulations resulting in zero denied sectors after both the victim and interferer are set to an omnidirectional antenna pattern, the likelihood of interference is negligible.

The following three conditions define how the earth stations are classified according to susceptibility to RFI:

- Low-risk site: When results show zero denied sectors in the RFPT analysis with bare earth cartography and relief, using an omnidirectional pattern with the appropriate gains, then the site risk is classified as low.
- Medium-risk site: When results show zero denied sectors when antenna pattern is applied in the RFPT analysis, then the site risk is classified as medium.
- High-risk site: When results show denied sectors from the RFPT analysis described for the medium-risk case, then the site risk is classified as high.

It is possible to further distinguish high-risk sites with additional study. Clutter (e.g., buildings or foliage) would tend to attenuate interfering signals and could cause some sites classified as high risk to have zero denied sectors if clutter data were included in the model. This scenario would allow sites classified as high risk to be reclassified in a lower risk category.

A follow-up analysis of the receive sites used a newly available AWS laydown of mobile carrier antennas and incorporated lidar clutter data of 1 m resolution within 1 km of the earth station, and 30 m or 90 m resolution beyond 1 km. The goal was to obtain a worst-case look at RFI risk, which meant using the smallest DRGS antenna in all cases. This set the stage for a potential future addition of a DRGS antenna where none are present today, in that wider exclusion zones may be needed in those instances. Project 7 addresses the protection and coordination zones for the existing ground assets.

Findings

This project undertook a first-order assessment of risks associated with spectrum sharing on a site-by-site basis. While some sites were found to be high risk, this assignment was based on ITU-R thresholds, which are considered to be conservative. The recent field testing and measurement of actual thresholds as part of SPRES Project 9 indicated all tested earth stations used for GOES reception have a higher threshold than what was predicted in the ITU recommendation. It should be noted that not all fielded receivers were tested due to time limitations, including models from Dartcom, Sutron, and commonly available software defined radios (SDRs).

The outcome of this study clearly shows more RFI potential with ***downlink*** operations in 1675–1680 MHz than with ***uplink*** operations. This is because base stations transmit with a muchhigher effective isotropic radiated power (EIRP) than UEs, and the antennas are typically located above the clutter. For base stations that pose an adjacent-band interference potential (i.e., for GRB receivers), the sites that are classified high risk are unable to achieve a high enough FDR to mitigate the potential of interference. Risks assigned to each site were assessed, first by proximity of their primary GOES signal bands to the potentially interfering downlink bands, and then by cell tower placement. The two cell tower laydowns, CSMAC and CellMapper database, demonstrated in principle that the degree of RFI risk is reduced by tower placement and orientation. But the results had their shortcomings. For proprietary reasons on the part of the commercial carriers, the tower locations were purposely "randomized" (randomly displaced by an agreed-upon margin) to allow the CSMAC laydown to be publicly available. CellMapper was found to have inherent limitations due to both user participation (in certain areas) and the geographical (physical) layouts of the roadways. Since both databases had their own issues of accuracy and completeness, a more definitive laydown was used in Project 7 for the final contour calculations.

4.2.1 Analysis of users' RF equipment configuration

Using the data from Project 1, a comparison was made of information provided versus information still outstanding. Any identified gaps were resolved in part by a review of the Frequency Resource Record System (FRRS) and the Defense Information Systems Agency (DISA) Spectrum XXI databases. These databases contain information on spectrum use from DD-1494s, the Government Master File (GMF), International Telecommunication Union (ITU) filings, and the North Atlantic Treaty Organization (NATO) spectrum management repository.

The ground station data obtained from the surveys conducted in Project 1 was reviewed, and follow-ups were performed where necessary. This included a listing of the hardware and equipment at each of the earth stations and also a description of the operating environment and conditions at each ground station. Specifications not clear from the survey results were supplemented by an online search. This third verification step was crucial in obtaining a set of valid data, including a list of receiver manufacturers, for the RFI analysis performed later in Project 2 and testing in Project 9.

4.2.2 Preliminary analysis of both in-band and adjacent-band emissions based on available government databases

SPRES completed a review of the NTIA GMF database, as well as a query of the Defense Information Systems Agency (DISA) Joint Frequency Equipment Allocation Process (J/F-12 Process) database. The searches ascertained that there were no other government users in or near the band that may become collateral RFI victims. A secondary output of this analysis was the creation of a comprehensive spreadsheet to include the data elements depicted in Table 4.2-1 for subsequent RFI analysis using RFPT and as an input resource for Project 6.

Table 4.2-1. Data elements for Project 6 input.

Basic information	Additional information
Site locations	Receiver datasheet available
Supported mission	LNA/LNB type and model, etc.
Supported receive frequencies	Noise figure
Latitude/longitude	Receiver 3 dB intermediate frequency bandwidth
Dish diameter	Elevation
Height above the ground	Azimuth
Gain	Address
System temperature	Comments
G/T	—
Receiver type and model	—

4.2.3 Federal systems/sites that are most likely to be at risk for interference from LTE sharing

The following documents formed the basis for establishing methods for determining risk:

- NTIA report: "An Assessment of Near-Term Viability of Accommodating Wireless Broadband Systems in the 1675–1710 MHz, 1755–1780 MHz, 3500-3650 MHz, and 4380-4400 MHz band"[5]
- ALION preliminary protection study for DCPR and GRB, funded by LightSquared[6]
- ITU-R SA.1160[7]
- ITU-R SA. 1163[8]
- Propagation Loss P.452 Model[9]

Project 2 did not consider the impact of AP, nor detailed terrain/clutter data. These were considered in later projects. For LTE tower deployment and characteristics, the CSMAC database was used.

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[5]U.S. Department of Commerce, National Telecommunications and Information Administration, "An Assessment of the Near-Term Viability of Accommodating Wireless Broadband Systems in the 1675-1710 MHz, 1755-1780 MHz, 3500-3650 MHz, and 4200-4220 MHz, 4380-4400 MHz Bands," October 2010, https://www.ntia.doc.gov/files/ntia/publications/fasttrackevaluation_11152010.pdf.

[6]Gerard J. Waldron and Paul Swain, counsel to New LightSquared, to Marlene Dortch, secretary, Federal Communications Commission, "Re: RM-11681; IB Docket No. 12-340; IBFS File Nos. SAT- MOD-20120928-00160; SAT-MOD-20120928-00161; SES-MOD-20121001-00872," December 16, 2015, https://ecfsapi.fcc.gov/file/60001387484.pdf.

[7]International Telecommunication Union, "Interference Criteria for Data Dissemination and Direct Data Readout Systems in the Earth Exploration-Satellite and Meteorological-Satellite Services Using Satellites in the Geostationary Orbit," SA.1160 (July 2017), https://www.itu.int/rec/R-REC-SA.1160/en.

[8]International Telecommunication Union, "Aggregate Interference Criteria for Service Links in Data Collection Systems for GSO Satellites in the Earth Exploration-Satellite and Meteorological-Satellite Services," SA.1163 (December 2018), https://www.itu.int/rec/R-REC-SA.1163/en.

[9]International Telecommunication Union, "Prediction Procedure for the Evaluation of Interference Between Stations on the Surface of the Earth at Frequencies Above About 0.1 GHz," P.452 (July 2015), https://www.itu.int/rec/R-REC-P.452/en.

As this was still early in the SPRES study, a first-order risk assessment was performed regarding impacts RFI could have on the NOAA earth stations. This consisted of using available information to address whether there was a direct frequency overlap, or if the link in question would be subject to adjacent frequency interference. In the case of direct frequency overlap into the Met-Sat band, the classification was high risk. Where adjacent-band interference was determined to be a mode of RFI, those sites were classified as medium risk. All other sites were classified as low risk. As will be shown in subsequent sections, further refinements were made to the risk categorizations.

4.2.4 LTE tower configurations at at-risk system and facilities

Further investigation was then conducted to determine what parameters would have to be calculated or understood in order to proceed with RFPT analysis.

1. Areas found to be at risk would be further analyzed using LTE tower laydown information.
    a. CSMAC data was used to find LTE base stations where the sites were believed to be at risk.
    b. Where CSMAC data returned no results around the Met-Sat receiver, tools such as CellMapper and Antenna Search database were used.
2. Risks were further refined using actual system performance interference characteristics.
    a. Calculate the undesired user equipment/base station (UE/BS) transmitter energy at the Met-Sat receiver input.
    b. Calculate frequency-dependent rejection (FDR) using Microcomputer Spectrum Analysis Models (MSAM) and MATLAB.
    c. Import actual antenna gains using Antenna Pattern Tool (APT).
    d. Incorporate actual antenna pointing angles (azimuth/elevation).
    e. Interferer selectivity to include:
        i. User equipment (UE) and base station (BS) power levels in EIRP.
        ii. Emission occupied bandwidth of the interferer.
        iii. Out-of-band emissions and far out spurious emission domain.
    f. Receiver selectivity of the Met-Sat earth station.
    g. Interferer selectivity of both UE and BS.
    h. Implementation of ITU-R thresholds scaled to Met-Sat link bandwidth.

In areas where the Met-Sat earth station was deemed to be at risk, CSMAC laydowns were originally used. However, in three cases, an insufficient number of towers were found near the earth station locations due to the fact that the laydown consisted of only one commercial carrier. This affected all sites in the state of Alaska, as well as the sites in Rock Island, Illinois, and Fairmont, West Virginia. This was resolved by the use of a combination of CellMapper and CSMAC data to develop the laydown.

To compute values for the parameters required for RFPT analysis, a calculation was performed of the interferers' transmitted energy at the Met-Sat receiver input (after the antenna). A combination of MATLAB and MSAM was used to define the FDR parameter. The roll-off curves found from these tools were then verified against recorded Ligado transmitter spectral plots to ensure accuracy (see Figure 4.2-1).

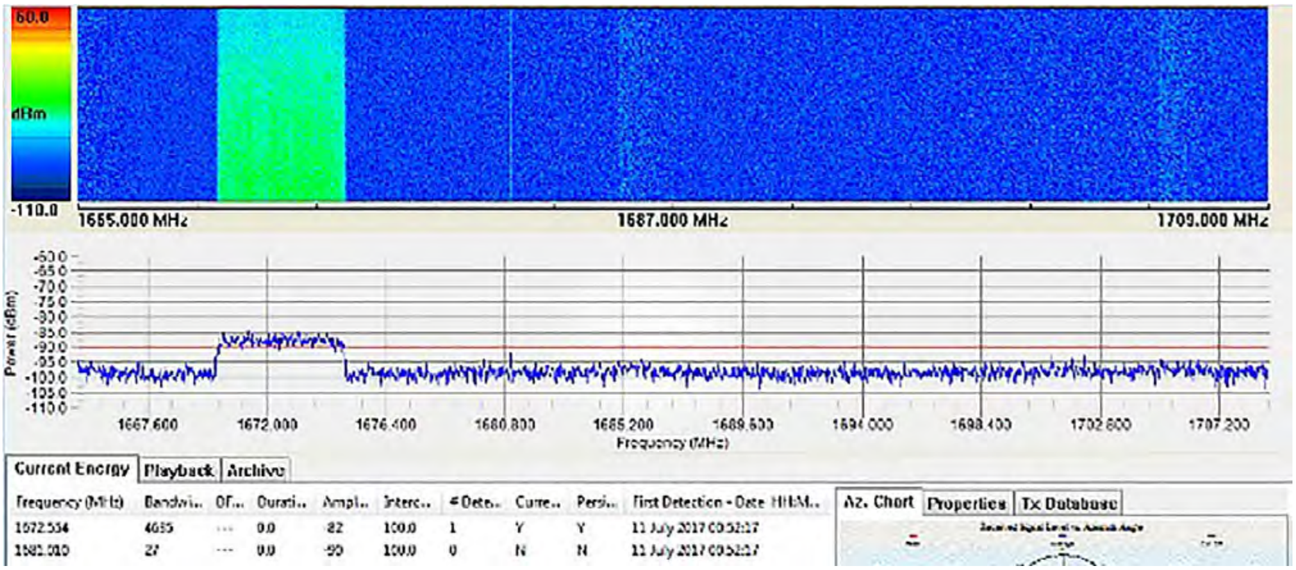


Figure 4.2-1. Spectral plot of a Ligado transmission in 1670–1675 MHz. EIRP not given.
Note: At the time this plot was captured, Ligado was transmitting at a much lower power level than proposed by the petitioner. Tower distance from the earth station was not noted.

Using the earth station parameters for RFPT analysis, a tool called Antenna Pattern Tool was utilized. This tool produces a file that can readily be used by RFPT. Such parameters consist of gain, EIRP, and azimuth and elevation pointing angles for each earth station. This approach moved the analysis from a worst-case scenario to a more real-world simulation.

In the cases where Project 9 had captured measured interference threshold results, these values were used in the analysis in addition to ITU-R thresholds values. It should be noted that the measured data was preliminary at this phase of the program, but added more realism in understanding the comparison between ITU-R thresholds and real receiver performance characteristics.

The ITU-R SA.1160 and ITU-R SA.1163 recommendations (see Table 3.2-4 in Section 3.2.3) were used to calculate the interference thresholds for each NOAA link, as shown in Table 4.2-2. ITU specifies a long-term and a short-term threshold per link. The interference thresholds used are referred to as *long-term thresholds* because it is assumed that the interfering signal levels are present most of the time.

Table 4.2-2. Interference thresholds in dBm per signal bandwidth.

Data link	Signal BW (MHz)	Long-term threshold (dBm)
SD	5.2	−120.8
DCPR (GOES-R)	0.475	−125.5
DCPR (GOES-NOP)*	0.475	−116.8
HRIT/EMWIN	1.205	−123.19
GRB	10.9	−114.088
*Note: GOES-NOP was in the GOES-WEST orbital slot at the time of the Project 2 study.		

The site tests of Project 9 also permitted the first calculations of FDR, as shown in Table 4.2-3. FDR includes many variables but in essence is a figure of merit indicating how well a receiver is isolated from potential interference sources as a function of frequency. To calculate the FDR, the receiver and interferer selectivity must be well understood.

Table 4.2-3. FDR 1670–1680 MHz and 1695–1710 MHz.

FDR (NOAA RX/BS Tx - Downlink [1670–1680 MHz])		
Link	Freq.* (MHz)	FDR (dB)
SD	1676	6.9
DCPR-R	1680	69
GRB	1686.6	51.7
HRIT	1694.1	61.1

FDR (NOAA RX/BS Tx - Uplink [1670–1680 MHz])		
Link	Freq.* (MHz)	FDR (dB)
SD	1676	4.3
DCPR-R	1680	88.4
GRB	1686.6	43.2
HRIT	1694.1	48.5

FDR (NOAA RX/UE Tx - Uplink [1695–1710 MHz])		
Link	Freq.* (MHz)	FDR (dB)
SD	1676	50.5
DCPR-R	1680	95.8
DCPR	1694.8	90.9
GRB	1686.6	46.6
HRIT	1694.1	48

*Frequencies refer to the center frequency of the link.

4.2.5 Sites unlikely to be affected by RFI from LTE spectrum sharing

A second analysis run using RFPT further assessed sites deemed low or medium risk to further validate those assessments. In the RFPT analysis, a combination of ITU-recommended and measured thresholds were utilized. In the case of measured thresholds, these numbers were incorporated into the simulation upon completion of threshold measurements obtained from Project 9. At the time Project 2 was completed, the threshold numbers had not yet been finalized, but they are included here to show the anticipated increase in threshold values based on real-world measurement. At this stage in the analysis, TIREM data was utilized for terrain modeling.

In all models, aggregation of signal power scenario was used. In addition, the maximum power density allowed was incorporated into the RFPT model. This worst-case-scenario approach allowed for sites to be safely ruled out, where applicable.

4.2.6 In-band/adjacent-band effects of LTE uplink and downlink to NOAA earth stations

Following up on the previous section, a preliminary level analysis was completed for both uplinks and downlinks. Using data obtained from research, calculations, and computer simulation, FDR and off-tune rejection (OTR) figures were entered into the RFPT simulation. Multiple sources were used to verify the adjacent-band interference found in the RFI scenario. These included recorded downlink transmissions, MATLAB, and MSAM. Cross-verifying these responses confirmed that our understanding of the LTE downlink transmitter frequency response was correct.

In the context of effects on the ground sites, downlink signals are very different from uplink. While there is no complete overlap (other than the legacy SD) to any of the Met-Sat links, there is a risk of interference due to the amount of power the base stations can produce. While the FDR value is greater, this can be overcome by the fact that the EIRP of the base station is higher, and that the antennas are typically located above the clutter.

Two factors contributed to the classification of risk: (1) link direction and (2) direction and density of population centers. The first order exercise was useful; however, additional factors were taken into account in subsequent projects to achieve higher fidelity results.

4.2.7 Possible RFI and impacts to Met-Sat downlinks

A follow-up survey was conducted supplementing the Project 1 findings outlined in Table 4.1-5. Selected impact statements based on the relative site risks noted in the table above are provided here:

- Cincinnati, Ohio, and Sacramento, California. "A delay in DCS data, especially during floods when people, property, and critical infrastructure are at risk, barge traffic is at risk of running aground or other casualties due to high flow conditions. Residents living along rivers, lakes, and streams rely on the information for purposes ranging from recreation to evacuation during floods; data unavailability places lives and property in danger. Hydropower plants rely on GOES data USACE provides for power generation purposes; outages can adversely impact their operations. Academia uses the data we provide for studies and modeling in their systems; missing data will disrupt that flow of information into their systems. Internally, USACE relies on GOES data daily and disruptions in the reception of data incapacitates USACE's ability to run hydrologic models providing guidance determining how to operate the USACE flood control and navigation projects; considering downstream constraints, preserving wetland areas and biodiversity, etc."
- Ford Island, Hawaii. "Critical hurricane and marine-hazard products could be degraded, increasing the risk of loss of life and property. GOES-17 data and products are used to continuously monitor the tropics including the Central, South, and Eastern Pacific for tropical cyclones and other hazardous marine weather. The delay or outage of this data would hinder Central Pacific Hurricane Center (CPHC) and National Hurricane Centers (NHC) ability to analyze the position, motion, and intensity of tropical storms and hurricanes, which would increase the errors in our forecasts and watches/warnings that the public and emergency managers rely on for mitigation activities. This could lead to reduced

lead times for preparation activities, including coastal evacuations, and to over-warning of surrounding areas, with very large economic costs."

- Omaha, Nebraska, and Honolulu, Hawaii. "A delay in GOES GRB ABI data would cause (meteorological) mission degradation. A delay could potentially delay or degrade weather modeling and research. Delays in weather modeling could negatively impact Air Force operations, causing delays, less accurate planning, or inadequate preparation for hazardous weather."

4.2.8 Users with related mission functions that may be affected by spectrum sharing in the 1675–1680 MHz band

No additional, non-Met-Sat users were found to have systems or assignments in the 1675–1680 MHz band. While it was noted that there are users in the nearby adjacent frequencies, these search results were deemed out of scope of this project.

4.2.9 CellMapper laydown in RFPT simulations

Directionality (i.e., placement relative to the ground station, particularly where line-of-sight to the satellite was clearly affected) is an important factor in further refinements to assessing risk. Since the CSMAC-provided LTE tower location data set provided "randomized real" tower locations (for proprietary reasons) in a given area, it presented the shortcoming of not having any fidelity in modeling line-of-sight interference. Therefore, CellMapper data was selected for inclusion in the analysis.

CellMapper data is crowd-sourced from volunteers who download an app to their mobile phones, which reports the location and other data for towers to which the phone has connected. This data is then stored in a database and available for download. As with any crowd-sourced product, CellMapper does not guarantee that all towers in a given area are captured, or that locations are 100% accurate, as it relies on the accuracy of reporting and the geolocation device used by the data contributor.

For some locations, the CellMapper data did offer the advantage of more precise (but with some corrections) tower locations of the top four carriers (by subscriber count): AT&T, Verizon, Sprint, and T-Mobile. These four providers are estimated to represent more than 90% of total subscribers. This was considered sufficient because the time and effort needed to find the remaining locations was too high for the small improvement it would have yielded. It should be noted that most providers lease space on towers from a third party rather than erecting and populating their own towers.

All scenarios that were run through the RFPT simulator using the CSMAC laydown data set were then rerun using CellMapper laydown data to provide a comparison. All sites were then reclassified using the methodology outlined.

4.2.10 Recommendations and areas of further study

These recommendations were identified in Project 2 and carried forward to Project 7 for further investigation:

- LTE spectrum notching. This is a carrier-implemented RFI mitigation technique in which the control frequency is moved and resource blocks at the band edge are turned off. From a frequency domain perspective, the output of the LTE transmitter appears to have a steep notch at the lower band edge that will introduce more FDR between the interferer and the victim receiver. There is great potential in this technique if supported by the LTE carriers.
- Using more precise laydowns and incorporating lidar data with 5 m resolution has the potential of yielding more accurate separation distances of LTE transmitters to Met-Sat earth-station locations. This would increase the confidence in the identification of sites having potential adverse impact from spectrum sharing.
- Use of a tool such as the AWS-3 Early Entry Portal (EEP) to approve or disapprove deployment plans within coordination zones by commercial LTE carriers.

4.3 Project 3. Identification of Alternative Architectures

Objectives

The scope of Project 3 spanned two of the SPRES program topic areas: GOES Data Use and Mitigation Options and Feasibilities. The project's objective was to seek alternate methods of distributing NOAA satellite data that could increase the feasibility of spectrum sharing. The goal of Project 3 was to identify, develop, and evaluate the risks associated with alternative methods of distributing DCP and GRB data to users currently receiving it via direct broadcast from the GOES satellite. These alternative architectures were then further developed with sufficient detail to identify system components needed to replicate the broadcast distribution functions.

Method

To accomplish this goal, Project 3 identified the DCP and GRB users' data and performance needs, then evaluated a combination of existing NOAA assets and new distribution technologies capable of fulfilling some or all of those needs. Project 3 evaluated several alternate distribution systems, including: the Environmental Satellite Processing and Distribution System (ESPDS), an ESPDS/cloud service provider (CSP) hybrid service, the DCS Administration and Data Distribution System (DADDS), and a remote downlink site placed in a location free from AWS interference.

Each of these alternatives were evaluated using a decision analysis and resolution (DAR) process that combined qualitative and quantitative evaluation techniques to rank the alternatives in order of implementation preference. The alternatives were scored and ranked from the perspective of NOAA needing to identify a secondary distribution service due to LTE-caused degradation in DCP and GRB direct broadcast quality of service (QoS). It should be noted that cost and performance were evaluated qualitatively in Project 3; these criteria were evaluated quantitatively in SPRES Project 4 (cost) and Project 5 (performance).

Findings

The analysis covered 41 GRB users and 76 DCP direct broadcast users, along with their data performance requirements, using survey data from SPRES Project 1. The existing NOAA DCP and GRB data distribution architectures were documented to understand the flow of data to end users and opportunities to leverage existing assets. This resulted in a set of architectural drawings that identify existing system assets, as well as the changes required to implement the alternate distribution system in order to deliver data from existing sources to end users.

It should be noted that terrestrial alternatives have an implicit dependence on terrestrial internet service to access data. All alternatives evaluated here, as well as in applicable parts of Projects 4 and 5, are independent of any "last-mile" considerations for internet availability and cybersecurity, since those considerations would always be the same at the termination point for each user. Both availability and cybersecurity depend on the internet provider, and these factors could present intolerable conditions to the end user, no matter how good the proposed alternatives are.

The DCP alternative distribution architecture that scored highest overall was DADDS, which relies on direct broadcast downlinks operated by NOAA. Based on the outcome of the DAR process, DADDS outperformed other alternatives investigated by a 14%–60% margin. It is an existing, operational NOAA system with functional and performance capabilities enabling it to meet the existing needs of the DCP user base. It has redundant systems at both the primary location (WCDAS in Wallops Island, Virginia) and the backup location (NSOF in Suitland, Maryland). These systems rely on Direct Readout Ground Stations, which operate in the 1679.7–1680.1 MHz band, as will any DCP alternative using the GOES satellite, and must be protected from interference at those locations.

The highest-scoring GRB alternative distribution architecture is the ESPDS. This is also an existing NOAA asset, built to fulfill the NESDIS ground enterprise satellite data distribution requirement. Based on the DAR process, it outperformed other alternatives by a 10%–46% margin. The cloud was the second-highest-scoring alternative, and if the uncertainty in quantifying risk is accounted for, the margin may be as low as 1%. It is expected that cost and performance evaluations resulting from SPRES Projects 4 and 5 will reduce uncertainty and help clarify the preferential GRB alternative architecture. Both ESPDS and the cloud alternatives rely on the GRB downlink located at NSOF, which is planned to be in place until 2022 and then moved to Fairmont, with the data routed terrestrially back to NSOF. NSOF will remain a backup and will require protection from sources of interference.

4.3.1 Existing direct broadcast distribution architectures

In order to develop a set of constraints that would be used to help evaluate the risks associated with an alternative architecture, the existing DCS and GRB distribution systems were analyzed to identify data characteristics and usage.

4.3.1.1 GRB distribution architecture

This section describes the data acquisition and ground processing timelines, GRB broadcast contents, GRB data users, the satellites from which data is obtained, and the products used to accomplish this mission. Table 4.3-1 describes the existing near-real-time GRB data access methods and the three alternative architectures explored in the study. Notwithstanding the unmet stringent latency requirements of some users, as discussed in earlier sections, the results of the evaluation showed ESPDS as the highest-scoring alternative GRB data distribution architecture. Using base scores, it led the cloud alternative by a margin of 9.5% and the remote receiver by a margin of 46.2%.

Table 4.3-1. Near-real-time GRB data access methods and description.

Acronym	System name	Description	Direct/ indirect	Federal/non-Federal users
GRB	GOES Rebroadcast	All Level 1b ABI data products, space weather and solar data, and GLM (L2). This data is available to any user with a GRB receiver.	Direct	Fed and non-Fed
Alt. 1	ESPDS	Implementing ESPDS into the GRB and DCS alternative architectures can have impacts to system components that may require scaling of existing ESPDS hardware and software as well as integration with direct broadcast users that do not have existing interfaces to ESPDS/PDA. PDA is the distribution portion of ESPDS. ESPDS* is responsible for receiving and storing real-time environmental satellite data and products and making them available in near-real time to authorized users (ABI L1b & L2+, space weather L1b, GLM L2).	Indirect	Any
Alt. 2	ESPDS/commercial cloud hybrid	Has the advantage of off-loading any scaling requirements that may be necessary for ESPDS, and implements a cloud distribution service to fulfill the end-user requirements.	Indirect	Any
Alt. 3	Remote receiver	Installation of a remote receiver at a geographically diverse site that would be unlikely to experience interference simultaneously with a GRB receiver at NSOF.	Indirect	Any

Source: NOAA
*ESPDS was built to be the enterprise meteorological data distribution system for NESDIS satellites. It serves as the product generation system for JPSS and produces some L2+ products for the GOES-R program. PDA may not have adequate site redundancy to meet all requirements in lieu of direct broadcast. PDA's data latency can be significantly affected by the inputs from polar satellite data and by use of push notifications.

Table 4.3-2 indicates the large amount of data transferred over the GRB broadcast daily, indicating the challenge involved in recreating the GRB broadcast over the internet to multiple users. Not all aspects of implementing internet-based data flow have been explored, and internet dissemination may not be suitable for some users. The volume of data shown here is derived from measured GOES-16 GRB data flows, and it shows the contrast between a current GRB satellite broadcast and the likely dissemination requirements of

Table 4.3-2. Typical GRB daily data products and volume.

Service	Products per day	Volume of data per day
G-16/G-17 GRB direct broadcast	87,300	390 GB
Calculated maximum number and volume of data products if distributed terrestrially	~3.4 million	~14.9 TB
Calculated nominal number and volume of data products if distributed terrestrially	~917,000	~8.1 TB

the same GRB data using the ESPDS or ESPDS/cloud terrestrial alternatives. These estimates are further explained in the following subsections.

4.3.1.1.1 GRB users

In order to determine suitable alternative architectures that are capable of meeting user requirements, it was necessary to estimate the number, geographic location, and product use requirements of existing GRB users. This would determine the geographic service area, network throughput requirements, and system distribution performance requirements for meeting existing user needs. SPRES Project 1 survey data, which captured about 50% of GRB receiver operators, was used as the source for product use requirements and receiver locations. Note that a large population of secondary users, more than 100, also make use of GRB data collected by these primary users/GRB receiver operators. A summary of the survey data has since been updated for this report, and is presented in the previous section in Table 3.1-6. The geographic location of the same users is shown in Figure 4.3-1. Of the 41 users identified, 10 stated that they did not currently have a GRB receiver but would procure one in the future. Those users planning for future installations were included in this trade study to obtain a conservative estimate of near-term data distribution needs.

Figure 4.3-1. Map showing geographic distribution of GRB users by type.

Table 4.3-3 shows GRB usage statistics from the surveyed users, including the number of users who access specific product types from—or the entirety of—the GRB broadcast, the number of receivers they operate (on GOES-East and/or GOES-West), and the total number of products and associated volume received daily. The daily volume numbers and the number of files associated with a product type were acquired from statistics obtained from ESPDS/PDA. The data obtained from PDA was averaged over a two-day period for both GOES-16 and GOES-17. Both satellites produce roughly the same amount of data when operating in the same mode.

Table 4.3-3. Surveyed GRB users and their specific product needs responses.

Summary of GOES-R product use					
Product types used	Number of users	Number of receivers	Percent of total users	Number of products*	Daily volume* (GB)
ABI (L1b)	1	2	2.4	6,079	103.5
ABI (L1b), GLM (L2)	2	4	4.9	10,399	104.8
ABI (L1b), GLM (L2), SEISS (L1b), EXIS (L1b)	1	2	2.4	23,637	116.3
All GRB products	13	21	31.7	42,279	196.6
Not specified	24	32	58.6	—	—
Total	41	61	—	1,321,655**	8,341.0**

*Based on daily averages of GOES-16 products received by PDA over a 48-hour period.
**Assumes users that did not specify a "product type used" received ABI and GLM data.

Knowing which users access GOES-16 and/or GOES-17 GRB, as well as the products they use, enables an estimate of the total expected volume of data and number of files that an alternative GRB distribution system would need to handle over the course of a 24-hour period. That data is shown in Table 4.3-3. A significant portion of users did not specify the products used to fulfill their mission, and it was assumed that they would obtain data from nadir-pointing ABI and GLM sensors. Given this assumption, the alternate GRB system would distribute a total of approximately 1.322 million files totaling 8,341 GB per day.

4.3.1.1.2 GRB distribution risk

The GRB downlink operating at 1686.6 MHz is at risk for RFI, as shown in Figure 4.3-2. The proposed GRB alternative architectures could replace this portion of the direct broadcast downlink, and are evaluated in this section.

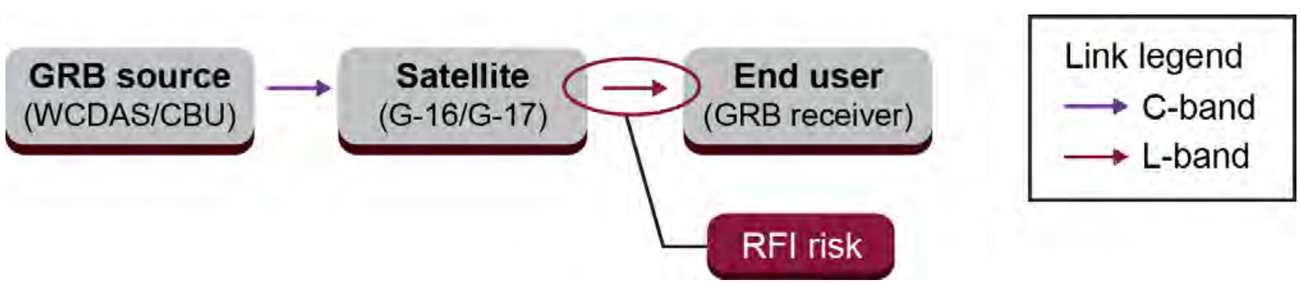


Figure 4.3-2. GRB distribution system RFI risk that exists in the L-band downlink to end-user GRB receivers.

4.3.1.2 DCS distribution

DCS data is distributed using several different distribution services. However, all of them are contingent on a Direct Readout Ground Station (DRGS), and in fact this is the only way to obtain data from DCPs that report data through the GOES DCPR service. The DRGS may be either located at the user's site or operated by NOAA, which extracts the DCP messages for distribution through the HRIT or NOAAPort satellite broadcast services, or through the DADDS or LRGS terrestrial services.

As noted in the mitigation options discussion in Section 3.3, users can retrieve DCS platform messages in several ways, including multiple satellite broadcast and terrestrial internet options. Each of these alternative architectures was analyzed, and the terrestrial alternatives are scored using the DAR process, as shown in Table 3.3-6. However, each option has the drawback of higher latency and does not fully meet user requirements for low latency and high availability. Terrestrial retrieval options require internet access, which may not be present during severe weather events, when data products are most needed. Most customers have implemented two or more modes of access in case of an outage of one mode.

4.3.1.2.1 DCS data by terrestrial means

In addition to distribution through DRGS and HRIT/EMWIN, DCS data is distributed by NOAA using terrestrial broadcast means. The DADDS system, which assembles the DCS data for HRIT/EMWIN transmission (see Section 3.1.1.2), is also accessible over the internet. Users must obtain an account through NESDIS, but accessing their sensors over DCS enables them to view administrative and sensor messages. DADDS systems operate in a hot backup mode, and a user connects through a single proxy to access any one of the four distribution systems available. The DADDS system was designed with sufficient capacity to disseminate DCS messages to all registered users.

The DADDS system also sends data to a Local Readout Ground Station (LRGS), also known as an Open-DCS web server. This system also has primary and hot backups located at WCDAS and NSOF. In addition, LRGS webservers are located at U.S. Geological Survey (USGS) Earth Resource Observation and Science (EROS) Center in Sioux Falls, South Dakota, where all DCP data is downlinked from GOES-East and GOES-West satellites and made available to LRGS users who are registered with NESDIS.

Another satellite broadcast that carries DCS data is NOAAPort/SBN. NOAAPort obtains DCS data from the DADDS at WCDAS or NSOF. It then further processes that data using an NWS system called Hydrometeorological Automated Data System (HADS). HADS has specific data requirements in order to process DCS data and therefore does not disseminate data from all DCPs reporting through GOES satellites. In addition, HADS induces approximately 2–3 minutes of processing latency to DCS data and therefore is not an option for users with low latency needs. Figure 4.3-3 shows the HADS ground processing chain prior to transmission to the NOAAPort master ground station, where it is uplinked for broadcast using Intelsat’s Galaxy-28 satellite located at 89° west longitude.

Table 4.3-4 shows (1) a summary of the distribution services used by the surveyed sample of 79 DCS users identified in Project 1, and (2) the percentage by user type.

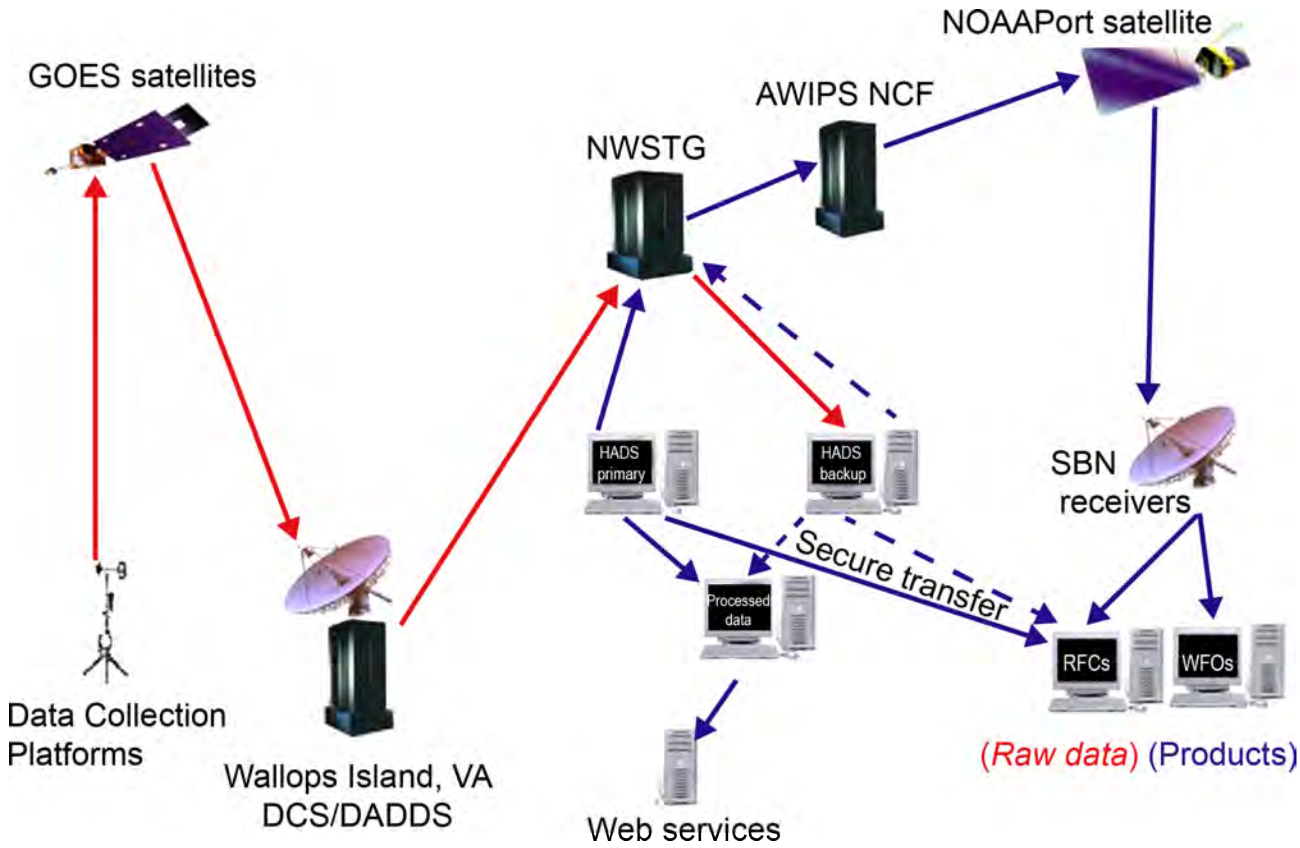


Figure 4.3-3. Flow of DCP data into the NWS NOAAPort broadcast.

Table 4.3-4. Distribution of services by user and type.

(1) Distribution services used by 79 DCS users identified in Project 1.

DCS distribution services		
Service	Number of users	Percent of total
DRGS	24	30.4
DADDS	1	1.3
HRIT	45	57.0
LRGS	2	2.5
LRIT	1	1.3
NOAAPort	6	7.6
Total	79	—

(2) Types of DCS users identified in Project 1.

DCS user summary		
User type	Number of users	Percent of total
Academic	1	1.3
Commercial	4	5.1
Federal	63	79.7
- DOC	*17*	21.5
- DoD	*40*	50.6
- DOI	*6*	7.6
International	6	7.6
State/Local	4	5.1
Tribe	1	1.3
Total	79	—

4.3.2 DCS distribution risks

The DCS distribution services at risk for RFI are shown in Figure 4.3-4. As can be seen in the figure, all the DCS distribution services previously discussed depend on a DRGS downlink at either WCDAS or NSOF. Note that the EDDN, which is a USGS entity, also exists as an alternative for terrestrial DCS services via LRGS, and would share the same risks. However, for the purposes of this project, EDDN was not evaluated for distribution risk because it is not a NOAA-owned and -operated DCS distribution system. The proposed DCS alternative architectures are expected to replace this portion of the direct broadcast downlink.

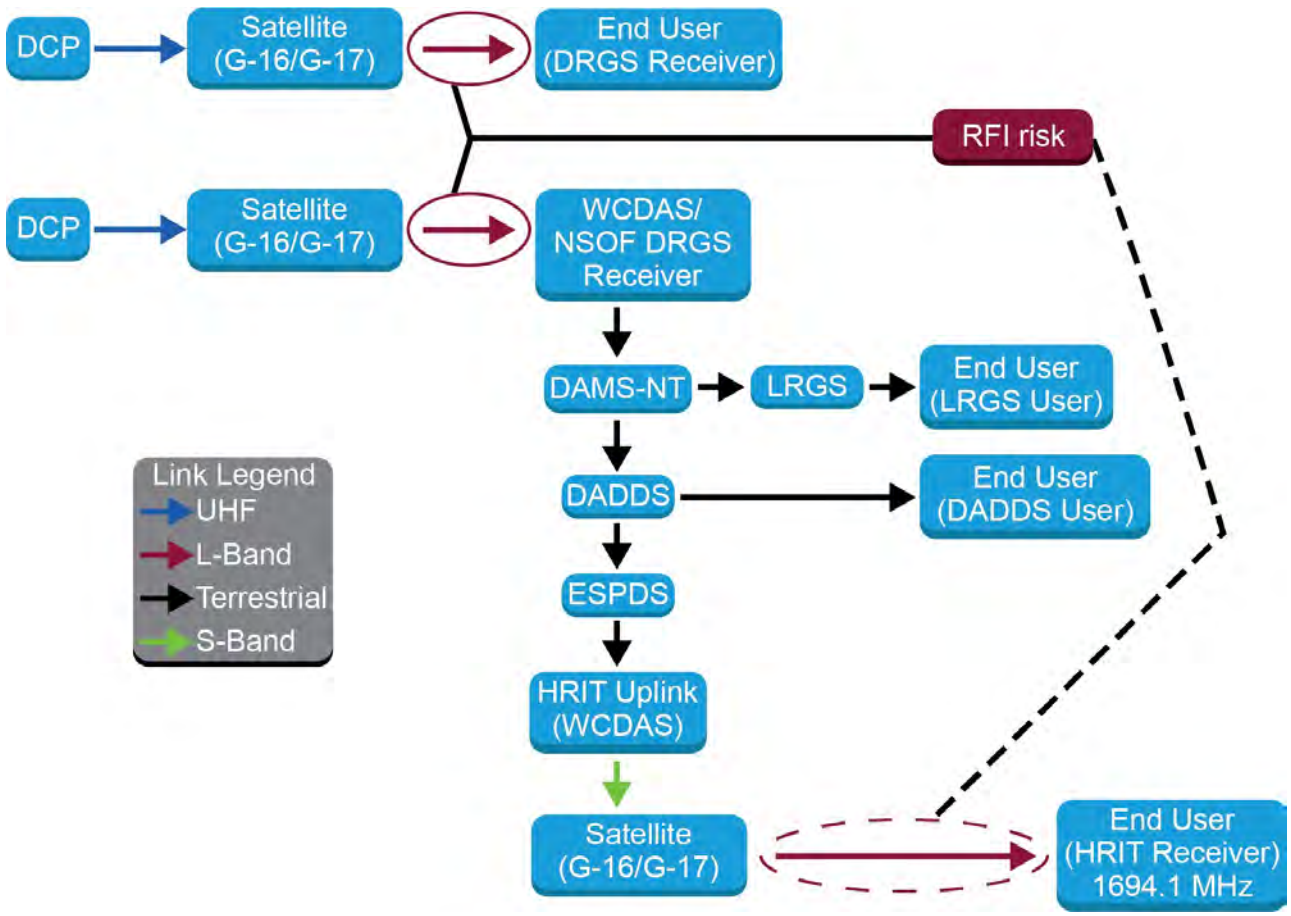


Figure 4.3-4. DCS broadcast services and the potential for interference to impact those services.

4.3.3 Alternative architectures

This section describes the GRB and DCS data distribution alternative architectures to mitigate L-band RFI risks, as shown in Figure 4.3-2 and Figure 4.3-4. The alternative architectures are first described by a set of functional flow drawings that identify the new or modified system components used to mitigate RFI. Those discrete structural components are then described in terms of their functional elements. These components are viewed as discrete objects in this report that may be applicable to multiple alternative architectures. The components are then assembled to create an end-to-end alternative distribution system that mitigates the identified risks. The common components that are present in multiple GRB and/or DCS alternative architectures are described in Section 3.1. The components that are required for a specific alternative are described in the appropriate subsections.

4.3.3.1 Common structural components

There were two common components that appear in the GRB and DCS data distribution alternatives. These components, ESPDS and cloud service provider (CSP), are described in the following subsections.

4.3.3.1.1 ESPDS

ESPDS is the primary platform for processing and disseminating Joint Polar Satellite System (JPSS) and GOES-R series satellite data. It is a subsystem of the Environmental Satellite Processing Center (ESPC), residing within the ESPC's information network security boundary as defined in NOAA document NOAA5045. Defining this boundary is required by the Federal Information Security Management Act of 2014 (FISMA).[10] In addition to providing processing and distribution services for the latest generation of NOAA geostationary and polar orbiting satellites, ESPDS is consolidating processing and distribution functions within the ESPC. In effect, ESPDS is functioning as the interface for all ESPC external data communications as well as ESPC processing. ESPDS has been operated by the Office of Satellite and Product Operations (OSPO) since 2017, when it became the operational processing and distribution system for the Suomi National Polar-orbiting Partnership (SNPP) satellite. The system was designed to distribute approximately 48 TB per day (PDA office reported actual performance slightly over 40 TB per day). Figure 4.3-5 shows the ESPDS system architecture along with major external data providers and consumers. ESPDS is not publicly accessible, and users must be approved for both system and product access by OSPO. In addition, OSPO limits the daily volume each data user is able to transfer as well as the number of simultaneous connections that can be established by each user, effectively limiting the maximum transfer rates to specific users.

ESPDS was designed to provide 99.98% operational availability averaged over a 30-day period. However, over the past year actual availability has averaged 99.44%. The ESPDS primary system is located at NSOF in Suitland, Maryland. There is a backup system located at CBU in Fairmont, West Virginia. Failover to the backup is determined by personnel in OSPO.

CBU is not a hot-backup capability, meaning that the system's product/data inventory is not actively replicated at CBU for immediate transition of product generation and distribution functions. Users whose systems are functioning in the client role, and initiating data transfers, must make the necessary changes within their environment to obtain products from the active site during a failover to CBU, and failback to NSOF, or they will experience a loss of data. It is

[10] U.S. Congress, Senate, *Federal Information Security Modernization Act of 2014*, Public Law No: 113-283, 113th Congress, became law December 18, 2014, https://www.congress.gov/bill/113th-congress/senate-bill/2521. The act requires each Federal agency to develop, document, and implement an agency-wide program to provide information security for the information and information systems that support the operations and assets of the agency, including those provided or managed by another agency, contractor, or other source. FISMA requires agency program officials, chief information officers, and inspectors general to conduct annual reviews of the agency's information security program and report the results to the Office of Management and Budget (OMB).

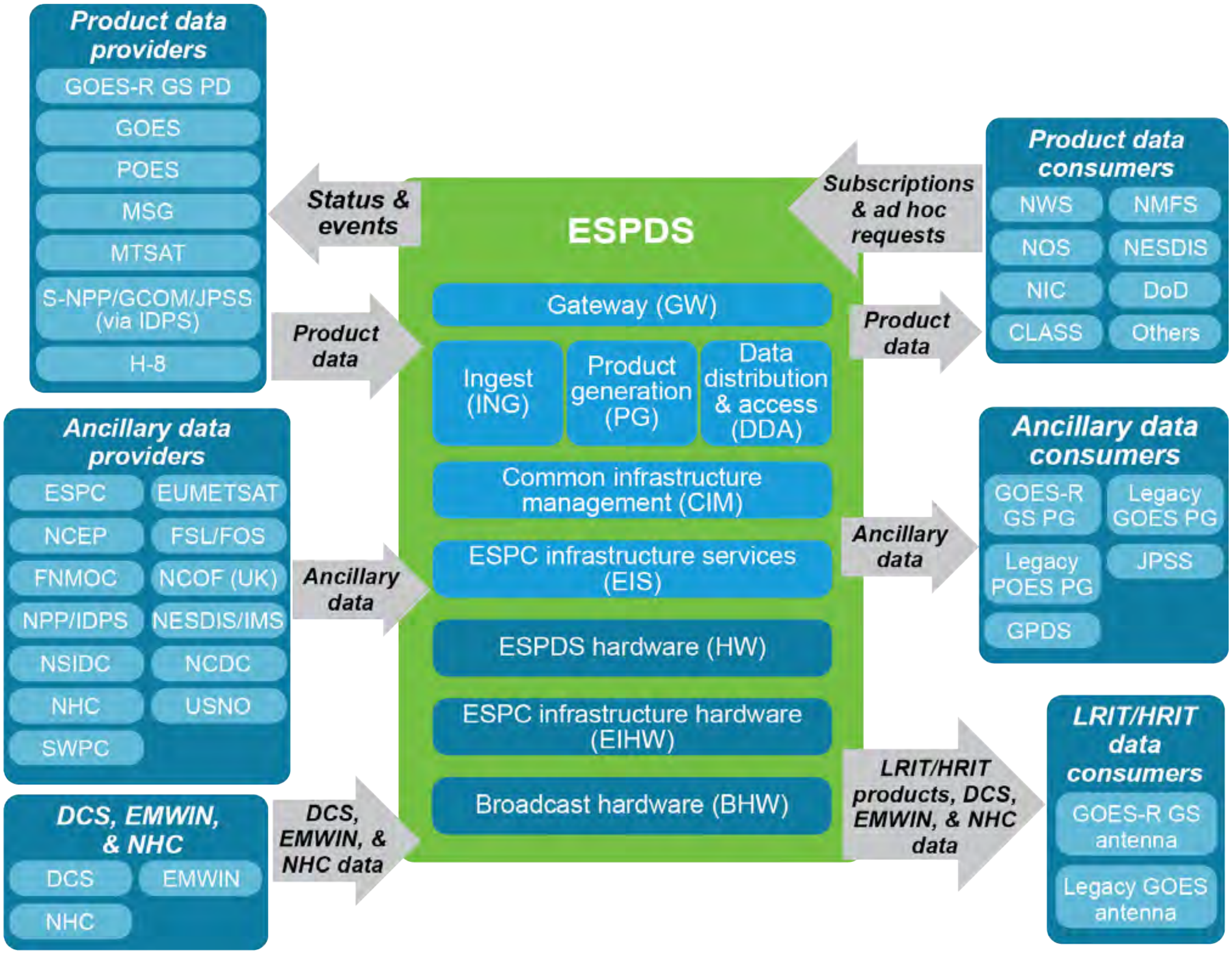


Figure 4.3-5. ESPDS system architecture and major external interfaces.

important to keep in mind that a failover has never been declared during normal operations and that ESPDS at CBU has been activated only in test scenarios. Another important consideration is that ESPDS currently has no interface to GOES-R at CBU. Therefore, in the event of a failover to CBU, no GRB data will be available from ESPDS. As configured, ESPDS has a single point of failure and therefore would not meet the redundancy and data continuity requirements necessary for operational use.

DADDS has connectivity between CBU and both NSOF and WCDAS. Therefore, ESPDS and the HRIT broadcast stream will contain DCS data. There is also the possibility of a partial failover, in which ESPDS operates from both NSOF and CBU simultaneously to permit continuity of operations if JPSS were to failover to CBU while other interfacing systems remain operational at NSOF. ESPDS has processed and distributed JPSS data from CBU while simultaneously distributing GOES-R and HRIT data from NSOF during previous continuity of operations (COOP) test events.

The flow of data from the satellite to the ESPDS ingest point is shown in Figure 4.3-6. Raw data is downlinked at both WCDAS and CBU, where the Level 1b and Level 2 (including GLM) products are generated by the GOES-R ground segment. That data is uplinked by the primary CDA site, downlinked at NSOF via GRB receivers, then provided to ESPDS over its interface with

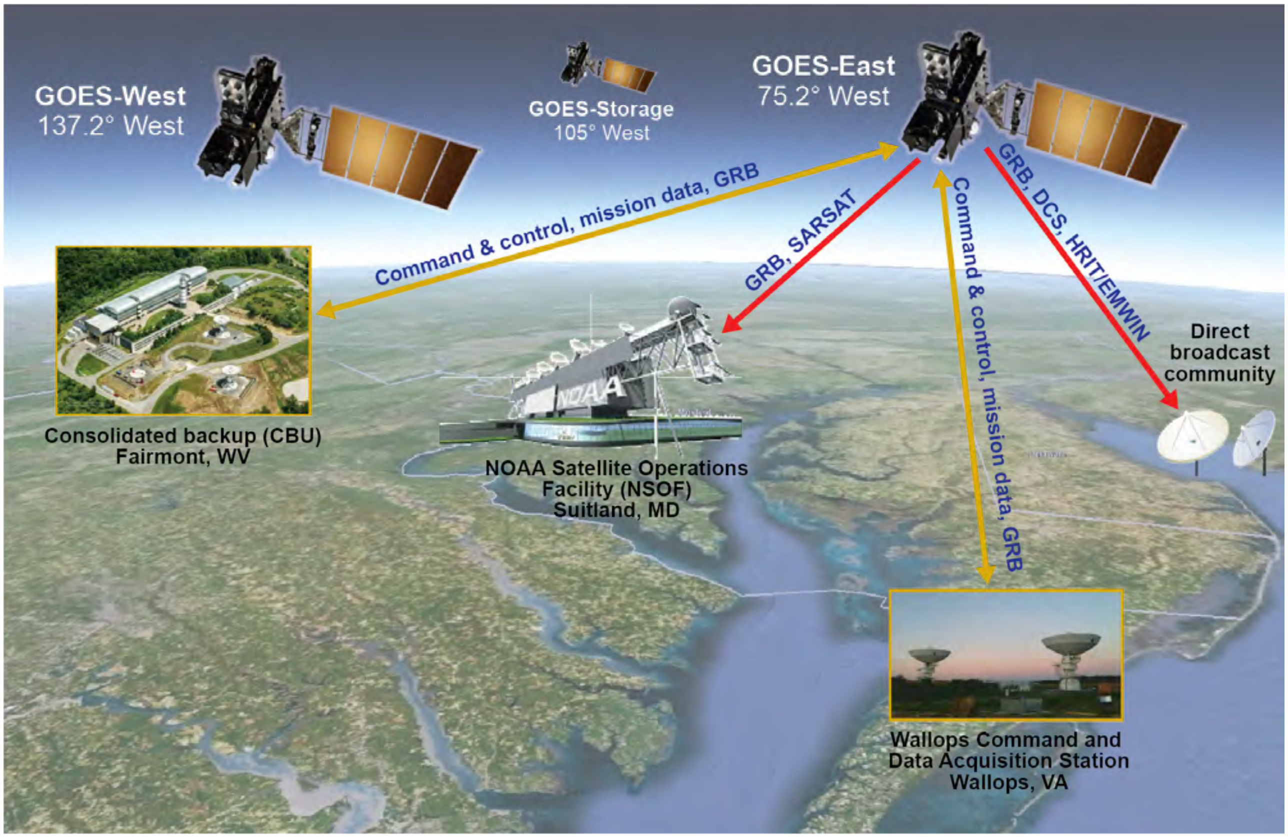


Figure 4.3-6. Flow of GRB data to ESPDS/PDA.

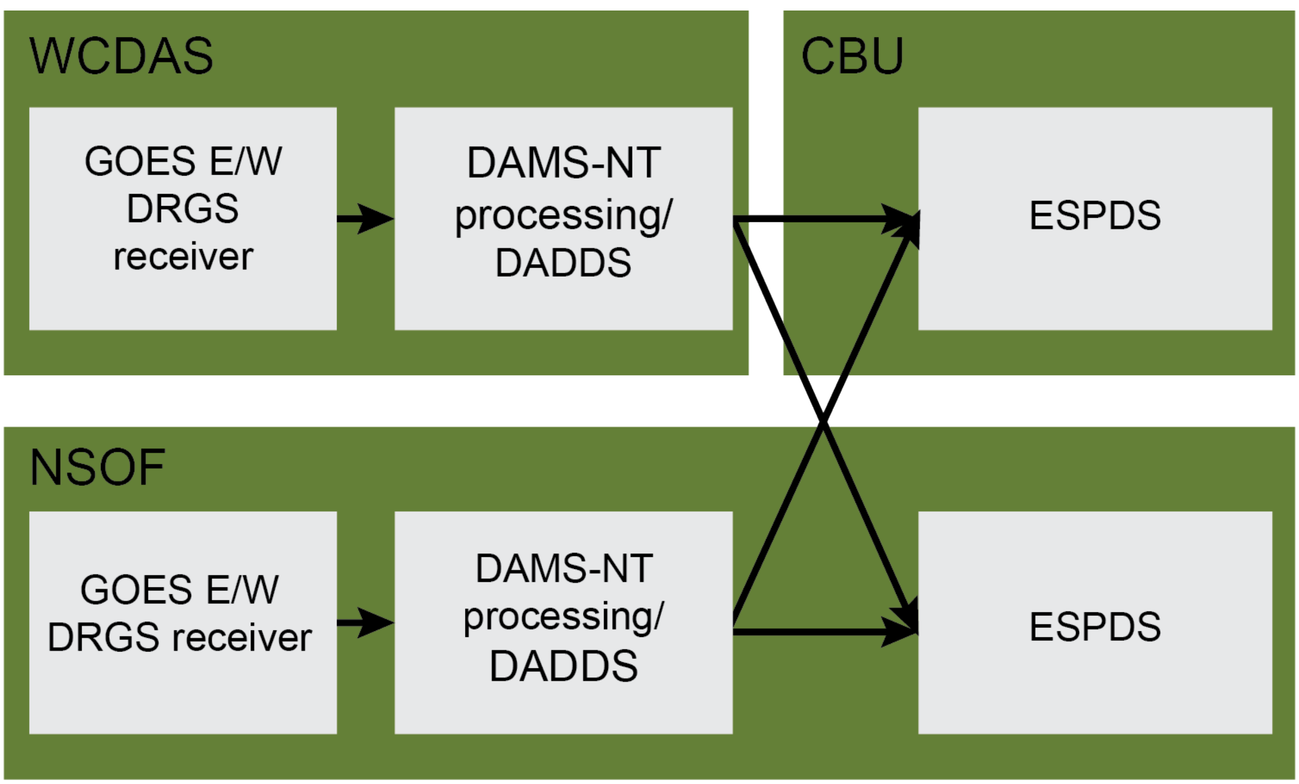


Figure 4.3-7. DADDS interface to ESPDS used to transfer DCS data.

the GOES-R GS product production zone (PPZ) interface. ESPDS will then transfer that data to users based on approved subscriptions. DCS data is acquired by ESPDS through its interface with DADDS. That interface configuration is shown in Figure 4.3-7. It has redundant interfaces to diverse locations at both the NSOF and CBU instances of ESPDS.

Implementing ESPDS into the GRB and DCS alternative architectures can have impacts to system components that may require scaling of existing ESPDS hardware and software as well as integration with direct broadcast users that do not have existing interfaces to ESPDS/PDA. Figure 4.3-8 is a view of the ESPDS system functions that will likely be impacted by the additional data transfers and user interfaces.

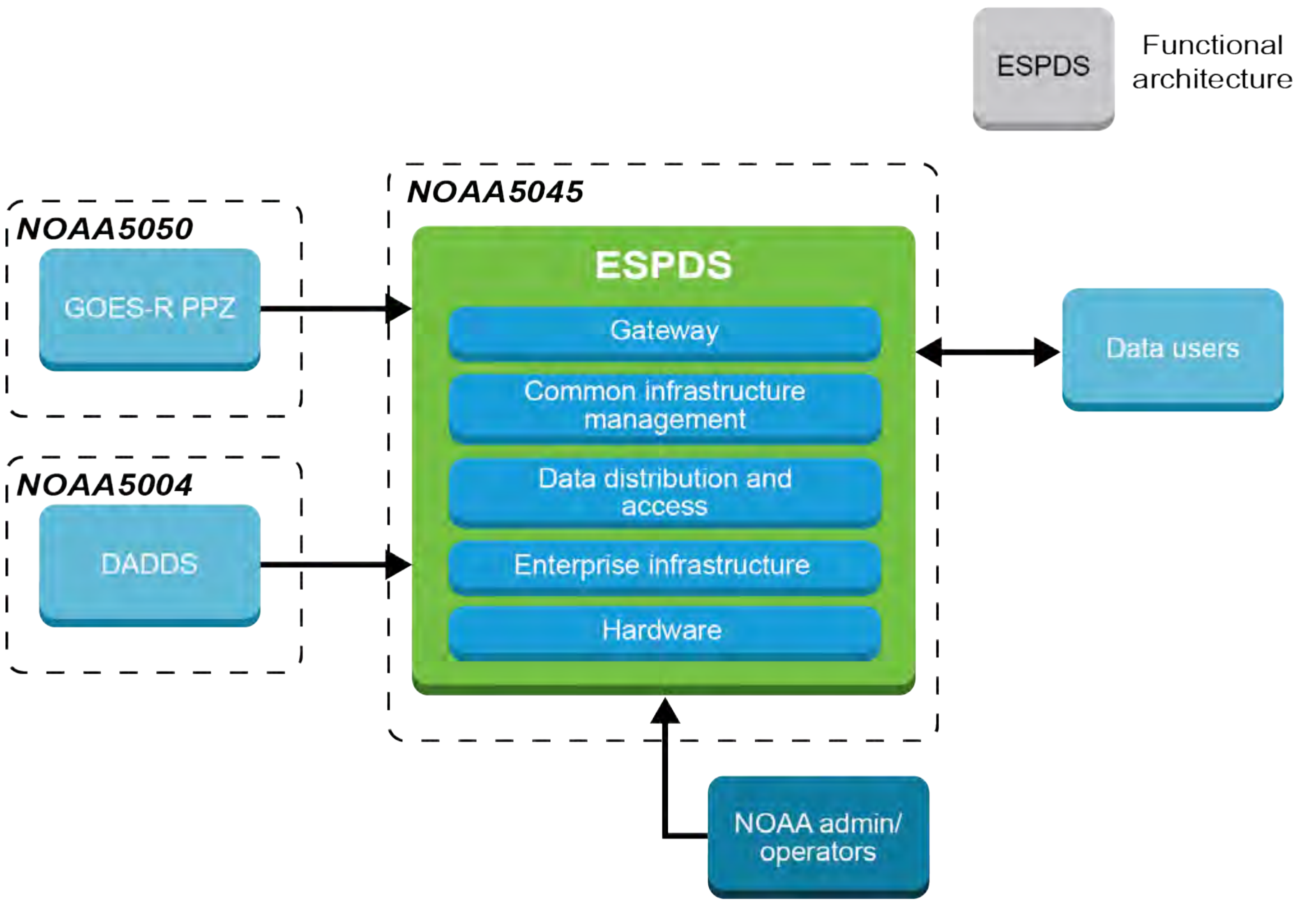


Figure 4.3-8. Functional elements of the ESPDS component (blue fill) and NOAA personnel (green fill) likely to be impacted if implemented in alternative architecture systems.

The following is a general description of the flow of information to users:

- Gateway services provide a portal through which the data users and system administrators access the system and manage their accounts, including which products they are subscribed to and how products are transferred.
- Common infrastructure management (CIM) refers to the system components that manage hardware and software resources, create the communication framework, and manage task scheduling, user profiles, and data transmission.
- Data distribution and access (DDA) manages user subscriptions and system data inventories.

- Enterprise infrastructure (EI) includes many of the security functions, including identity management, continuous monitoring, logging, and reporting functions. It also includes networking hardware and services as well as common storage.
- Hardware refers to the additional ESPDS compute, storage, and network resources that may be impacted due to increased data use.

It is important to note that although this architecture appears to have a straightforward implementation, it does have some inherent limitations. The ESPDS/PDA program office reported that during times of ingest of data from the polar orbiting JPSS satellite, ESPDS must create a queue as it pushes out both JPSS and GOES data to users. This creates a spike in latency for users waiting for data to be pushed to them. As a result, the program office implemented a freeze on the account limit. Adding more user accounts (the current estimate is 24), some of whom may have a push requirement, would therefore not be feasible without significant modification to the DDA and possibly other elements of ESPDS.

As will be shown in the DAR tradeoffs, the data push capability becomes a key limitation to this terrestrial alternative.

4.3.3.1.2 Cloud service provider

There are a number of different cloud service providers that are currently being investigated by NOAA to meet future data processing, distribution, and archival needs. These include Amazon

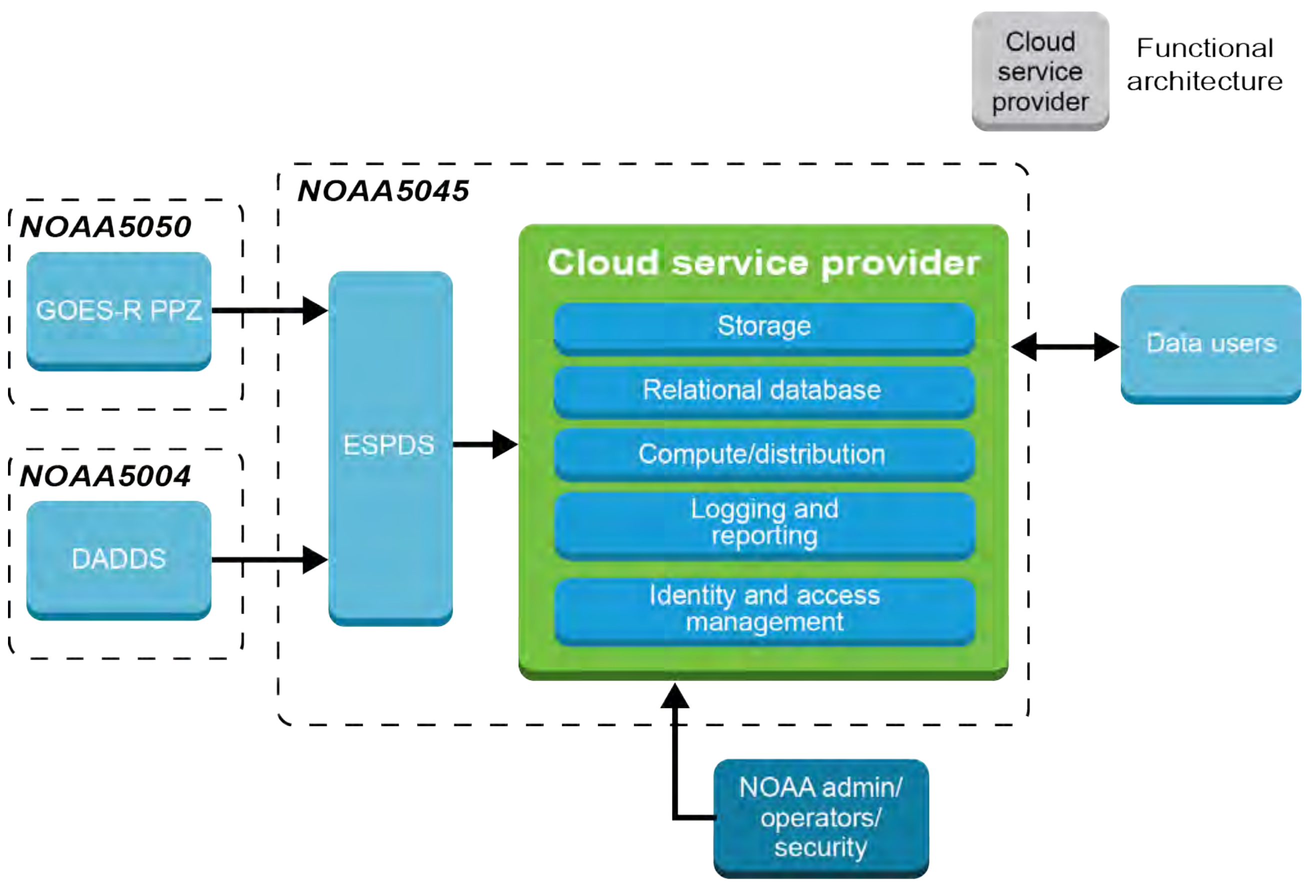


Figure 4.3-9. Functional elements of the cloud provider component (blue fill) likely to be required to distribute products to users with low latency and NOAA personnel (green fill) that may be impacted.

Web Services, Microsoft Azure, Google Cloud Platform (GCP), and IBM Cloud. In general, these providers offer similar infrastructure, platform, and software services. Figure 4.3-9 is a view of the cloud services that are expected to be utilized to facilitate low-latency data transfers to users.

- The CSP storage service would provide a location for GRB and DCP data to be written for subsequent distribution to data users.
- The relational database would be used to initiate data transfers to users when the desired file is written to storage.
- The compute service would host the data transfer client to push products to the data users.
- Logging and reporting functions are required for system security audits and to track system performance.
- Identity and access management is used to control access to resources within the virtual private cloud (VPC).

The data provider, shown as ESPDS, will transfer data to the cloud provider using secure file transfer protocol (FTP) or file gateway virtual machines (VMs) deployed on the ESPDS VMWare to transfer files to the CSP storage via network file system (NFS) mount points. The ESPDS system interface can use a direct-connect service, which can be coordinated with local network providers that establish direct routes for data transfers rather than using public internet routes. In order to minimize latency, files would be pushed to the data users on arrival in cloud storage. Direct connect is also an option for the data user interfaces to minimize latency and potentially reduce costs associated with internet data transfers.

The cloud services would reside on a NOAA VPC that would be inside the FISMA boundary. NOAA would be responsible for configuring and managing that virtual network, including establishing subnets, IP address space, gateways, firewall and other network services, and virtual devices. Figure 4.3-9 shows the cloud services as being a part of the NOAA5045 boundary, effectively an extension of the existing ESPC system boundary, currently rated a FISMA High. CSPs provide a range of FedRAMP-compliant services that set continuous security monitoring and auditing standards in an attempt to minimize the effort required to obtain an authorization to operate (ATO) when implementing cloud services. Amazon Web Services Simple Storage Service (S3), Elastic Compute Cloud (EC2), Virtual Private Cloud (VPC), Cloud Watch, Identity and Access Management, and Relational Database Services (RDS) are a subset of the Amazon cloud services that are currently approved at FedRAMP High.

4.3.3.2 GRB alternative architectures

Figure 4.3-10 is a block diagram showing the existing GRB data distribution system. The broadcast is generated from L0 data, which is downlinked from the satellite in X-band (8220 MHz) at WCDAS and CBU and then uplinked to the satellite by the designated primary site in C-band (7216.6 MHz).[11] The data is rebroadcast by the satellite in L-band at a center frequency of 1686.6 MHz and a channel bandwidth of 12 MHz. This downlink is adjacent to the 1675–1680 MHz channel being considered for auction and is at risk for interference.

[11]Using IEEE 521-1984 definitions for C-band and X-band; see "IEEE Frequency Bands," Citizendium, accessed May 18, 2020, http://en.citizendium.org/wiki/IEEE_frequency_bands.

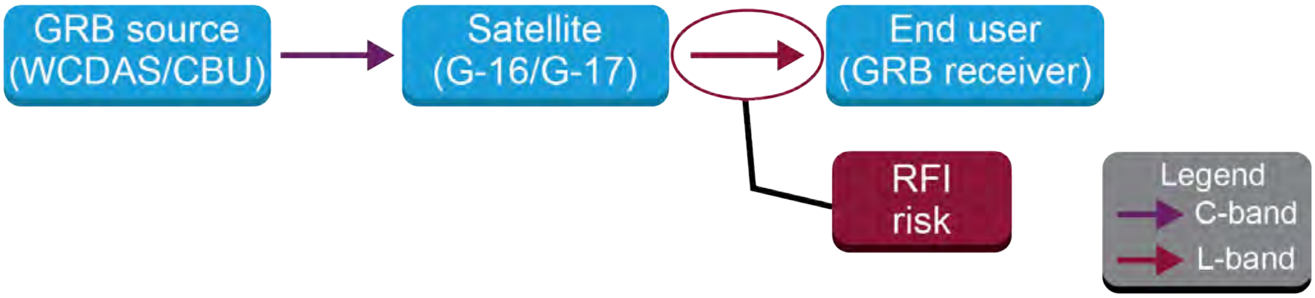


Figure 4.3-10. Existing GRB data distribution block diagram showing the portion of the direct broadcast system at risk for RFI.

In order to be considered as a feasible alternative distribution system to the GRB direct broadcast, the alternative has to meet a basic set of requirements: it must be capable of (1) providing the same meteorological data, (2) servicing the same geographic areas within the GOES-R satellite footprint, and (3) meeting user data performance requirements. Five different alternative architectures were considered as a replacement for GRB satellite distribution. Two of the five, NOAAPort and GEONETCast-Americas, were eliminated from consideration because of their inability to meet the feasibility criteria. However, they are discussed at the end of this section because they are listed as existing backup GRB data sources for two users and may provide an alternative data source, depending on the users' missions and how interference occurs at their locations.

The three different architectures that were considered as a replacement for GRB satellite distribution are ESPDS, ESPDS/cloud, and a remote downlink site. ESPDS and ESPDS/cloud solutions are alternative data distribution systems, while the remote downlink site provides a redundant source of data to one of these distribution systems and effectively mitigates L-band interference at the NOAA Satellite Operations Facility in Suitland, Maryland.

4.3.3.2.1 GRB ESPDS alternative

ESPDS was built to be the enterprise meteorological data distribution system for NESDIS satellites. It serves as the product-generation system for JPSS and produces some L2+ products for the GOES-R program. In addition, ESPDS has been integrated with numerous meteorological agencies throughout the world to acquire and disseminate global meteorological data to NOAA and its partners. Because of its inextricable link with the GOES-R ground segment data distribution system, ESPDS is a linchpin in each of the alternatives considered in this project. Figure 4.3-11 shows the implementation of ESPDS to mitigate the RFI risk to end users. GRB would be downlinked and ingested by the GOES-R satellite operations zone (SOZ),[12] sent to the PPZ,[13] and then passed through the existing interface to ESPDS. No changes to the GOES-R components would be required in this alternative. However, ESPDS components may need to be modified, as discussed in Section 4.3.1.1. The ESPDS interface changes highlighted in Figure 4.3-11 are referring to the 28 existing GRB users that do not currently have an account on ESPDS.

[12]Satellite operations zone (SOZ): self-contained architecture consisting of the Satellite Operations Control Center and related enterprise systems, performing product generation and distribution within the architecture.
[13]Product production zone (PPZ): secondary processing architecture that receives data from the SOZ and interfaces with ESPDS and external users.

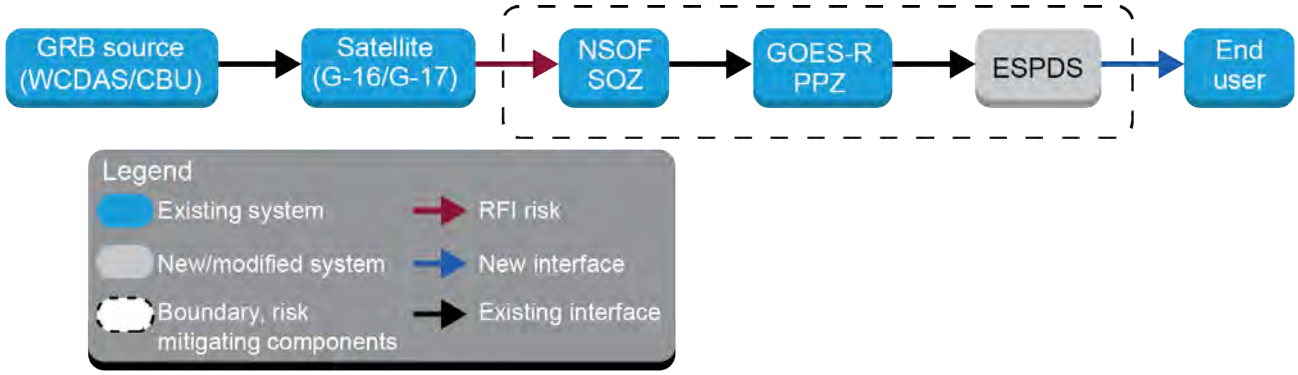


Figure 4.3-11. ESPDS alternative architecture functional flow diagram, showing existing and new distribution system components added to mitigate end-user L-band downlink RFI risk.

This scenario would require protecting the GRB downlink at NSOF to ensure data is still available from the GOES-R GS PPZ for distribution by the ESPDS system. Primary GRB reception is anticipated to move to CBU in 2022; however, Suitland will remain a backup site. This option would also require end users to obtain authorization from the OSPO to subscribe to the required products, and they would have to integrate with the system located at NSOF (primary) and CBU (backup) and accept advertised system reliability numbers.

4.3.3.2.2 GRB ESPDS/cloud alternative

The ESPDS/cloud alternative is shown in Figure 4.3-12. It has the advantage of offloading any scaling requirements that may be necessary for ESPDS, and implements a cloud distribution service to fulfill the end-user requirements. This alternative shows two interfaces to ESPDS. The existing interface, denoted by the black line, services GRB users who currently have an account on ESPDS. Those without an account, approximately 68% of GRB users, will access GRB data through a cloud service provider. ESPDS can send the data using an existing secure-FTP protocol where data would be pushed to the CSP storage upon inventory in ESPDS. Alternatively, a capability does exist to use file gateway VMs deployed within the ESPDS virtual environment that will transfer data to CSP storage using NFS mount points.

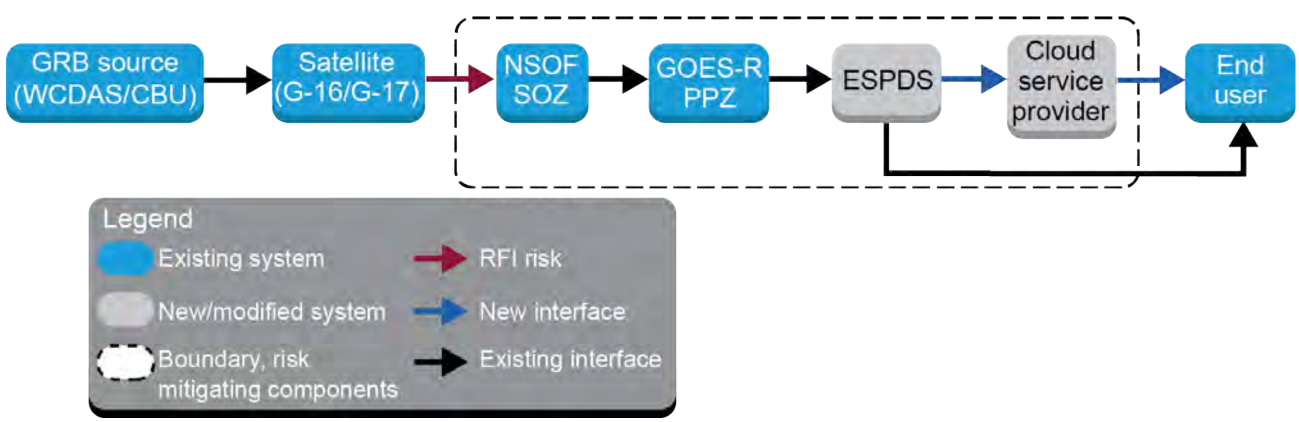


Figure 4.3-12. ESPDS/cloud alternative functional flow diagram, showing the new distribution components that are added to mitigate end-user L-band downlink RFI risk.

If existing FTP distribution protocols are used, changes to ESPDS would be minor for this alternative and would likely only require integration of a new data consumer interface (i.e., the cloud provider). However, extending the NOAA system boundary to include a CSP may be a difficult change to implement, especially since ESPDS is considered a high-security Federal Information System under FISMA. In addition, administrators and operators will need to be trained to effectively manage cloud services, a new paradigm in NESDIS satellite data management.

Further due diligence is needed to determine if the connectivity from the termination of cloud services to a user's location (i.e., the "last mile" of connectivity) could impact data availability or latency.

It should be noted that NOAA has a pilot program called the Big Data Project (BDP) that is intended to show the feasibility of utilizing cloud distribution services to make NOAA Met-Sat data publicly available. The current data set includes all GOES-16 L1b data and is publicly available via Amazon Web Services to anyone with internet access. Currently the L1b products are sent from PDA to the North Carolina Institute for Climate Studies (NCICS), which sends the data to Amazon Web Services S3 storage. NCICS utilizes native simple notification services (SNS) that are provided with S3 to notify users of new product arrivals. Unfortunately, there is significant latency associated with the data upload segment from PDA to S3, amounting to more than 50 seconds on average. This latency may be caused by an NCICS client scheduler used to initiate data pulls. The actual time to transfer a file, based on measurements gathered by ESPDS, is less than two seconds. NCICS reported that the time required to receive notification and pull a file from S3 was on the order of a few seconds. This indicates that if the upload latency problems were corrected, the BDP may be a viable solution for all GRB users and would meet their latency requirements. Based on current performance of the BDP, this solution would meet the latency requirements of approximately 27% of GRB users who do not have low latency requirements (<1 minute).

4.3.3.2.3 Remote GRB receiver alternative

A third alternative that was investigated as part of the SPRES program was the installation of a remote receiver at a geographically diverse site that would be unlikely to experience simultaneous interference with a GRB receiver at NSOF. That remote site would forward the data to a NOAA distribution system that would be capable of distributing data to GRB users. It was assumed that the system would be the ESPDS distribution system. It is possible that this alternative could easily support an ESPDS/cloud distribution alternative, and since the trade study demonstrated a slight difference between the two, it was assumed that ESPDS would be used for analysis purposes. The functional flow diagram for this alternative is shown in Figure 4.3-13.

The remote receiver site was expected to be incorporated at an existing NOAA site in an effort to reduce the cost of managing another facility along with the security burden that would be imposed by physical access control management. Therefore, WCDAS and CBU were analyzed to determine their suitability of meeting the requirement of geographical diversity. SSC used modeling results from SPRES Project 11, "LTE TDD Simulations and Passive Site Surveys," to assess overlapping exclusion zones indicating a probability of simultaneous interference. Figure 4.3-14 shows the results of that study. There is a likelihood that simultaneous interference may

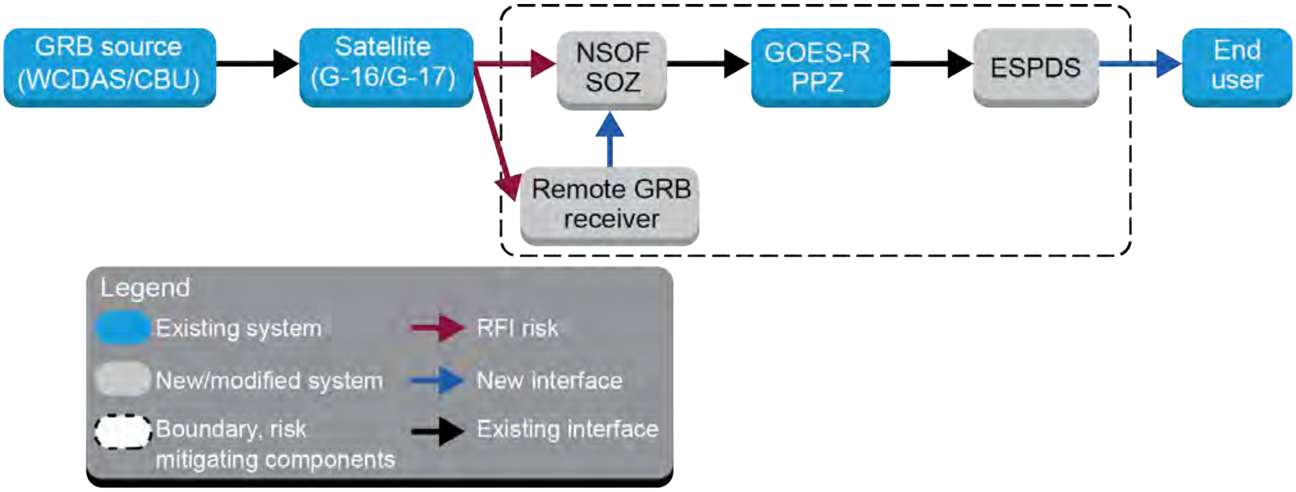


Figure 4.3-13. GRB remote receiver alternative functional flow diagram, showing the new distribution components that were added to mitigate the L-band interference risk.

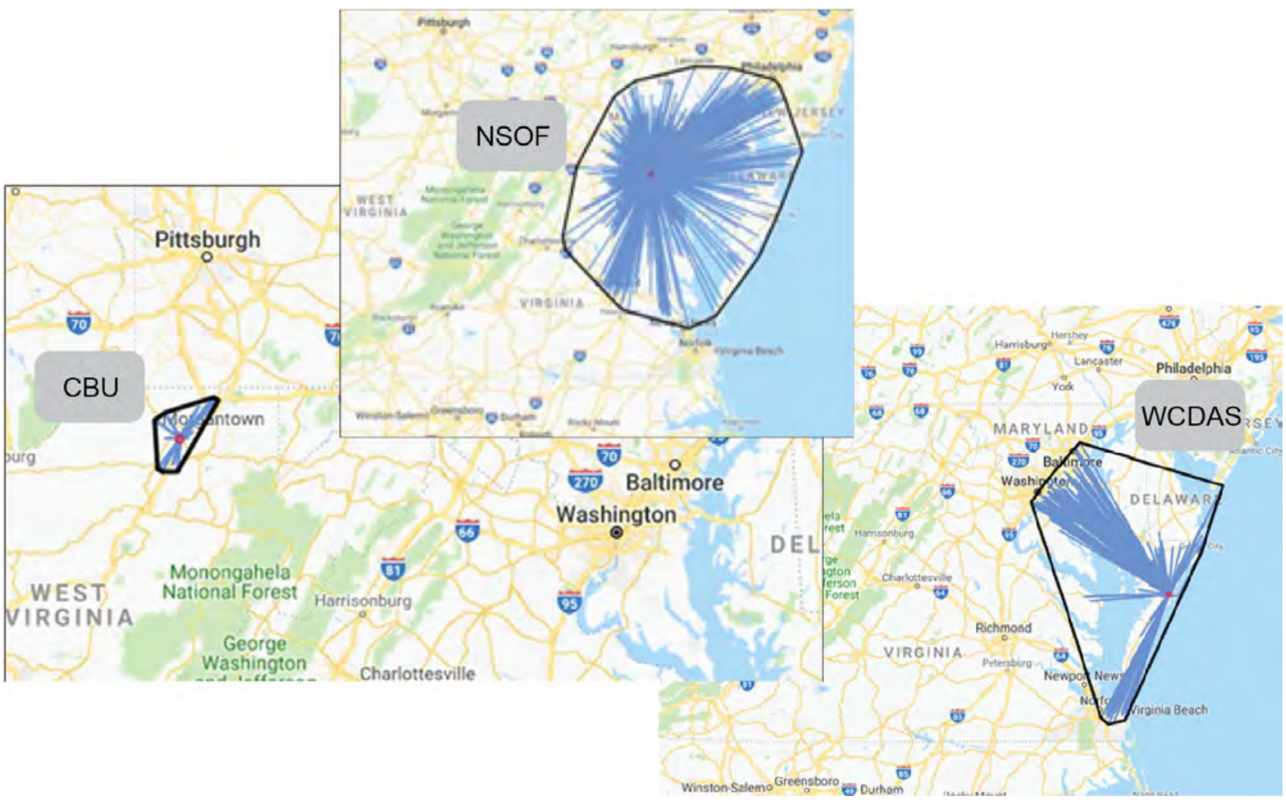


Figure 4.3-14. Map showing significant overlap of exclusion zones for WCDAS and NSOF based on results from Project 11. CBU is considered geographically diverse relative to the other zones.

be experienced at WCDAS and NSOF; therefore, the most likely candidate site would be CBU. The advantage of using this site is that it already continuously generates GRB data from both GOES-East and GOES-West. Using CBU would require only distributing that data via terrestrial network to the NSOF SOZ for subsequent transfer to the PPZ and ultimately ESPDS for distribution to end users. In fact, this scenario would reduce the dependency on L-band at Suitland. However, Suitland would remain a backup GRB downlink site in the event of failures at WCDAS or CBU.

The remote receiver alternative includes three modified components. It is expected that the interface between the GOES-R PPZ and ESPDS would remain unchanged. ESPDS changes required would be the same as those covered in the ESPDS alternative discussion in Section 4.3.3.2.1, meaning the addition of more user external interfaces and a higher data throughput. It should be noted that prior to GRB initiation, during post-launch testing, the GOES-R ground segment supports transmission of data over terrestrial networks to NSOF for the purposes of disseminating test data to a select group of users that assist with product calibration and validation. Therefore, the ability to send data over that terrestrial link exists, but it would need to be operationalized with adequate redundancy for reliability.

In this case, the remote GRB receiver is the CBU SOZ. The affected components of the NSOF PPZ and CBU SOZ are shown in Figure 4.3-15. All affected components would lie within the NOAA5050 (GOES-R) boundary and interface with elements of the NSOF SOZ and ESPDS. The existing antenna and receiver components at CBU would downlink raw sensor data and generate GRB in the product generation (PG) element. But in addition to sending GRB data back to the mission management component for uplink, that data stream would be sent to the product distribution (PD) element for transfer to the NSOF PPZ. This PD function will need to be configured to

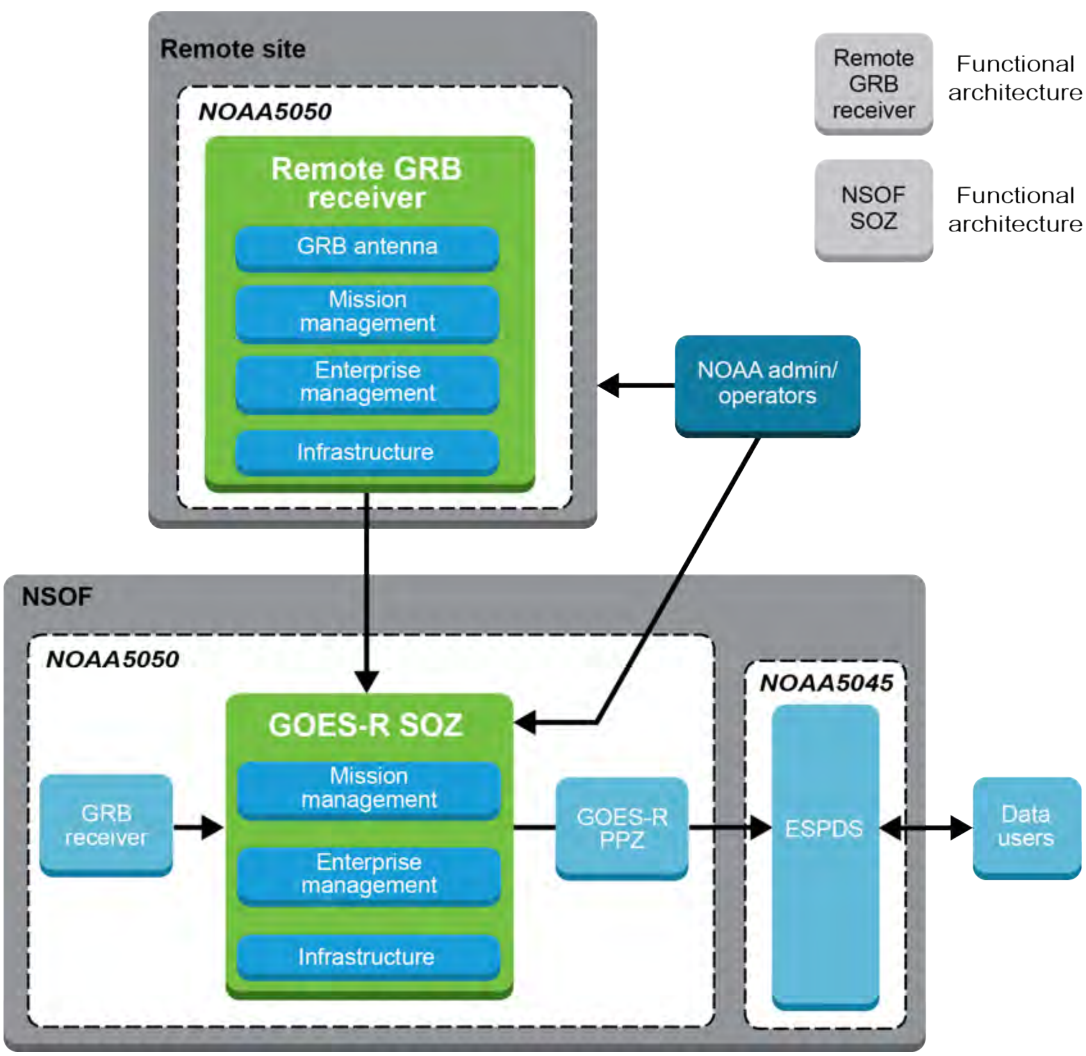


Figure 4.3-15. Diagram showing functional architecture of the remote GRB receiver and NSOF SOZ objects.

accept data from PD at CBU and pass GRB data through to ESPDS. The enterprise management and infrastructure elements are expected to support central management of the remote site resources, as well as NOAA-required logging, reporting, and monitoring functions.

4.3.3.2.4 Additional GRB alternatives considered

There were two alternatives that were considered initially as being possible replacements for existing GRB direct broadcast service: GEONETCast-Americas (GNC-A) and NOAAPort, also known as the Satellite Broadcast Network (SBN). Ultimately, these services were not considered viable alternatives because they did not meet the feasibility constraints that alternatives must provide the same data and distribute within the United States. That being said, NOAAPort is a satellite broadcast distribution service, operating at a downlink frequency of 4040 MHz, and is in fact used by some GRB users as a backup source of data when their GRB receivers are nonfunctional. NOAAPort/SBN is fed by a direct terrestrial feed from WCDAS of sectorized, tiled imagery, which is a different format than the Level 1b data sent via GRB. Not all locations and users can utilize the sectorized, tiled format. The Aviation Weather Center (AWC) has made it clear that it cannot use the GOES-R imagery sent in sectorized, tiled format to generate aviation imagery products.

However, as with NOAAPort, some users rely on GNC-A[14] as a backup to GRB broadcast. It utilizes Intelsat-21 at 58° west. Future impacts, if any, to reliable data reception via C-band commercial satellite after proposed repurposing of portions of the 3.7–4.2 GHz spectrum were not considered in this study. A third alternative, the Comprehensive Large Array-data Stewardship System (CLASS), was briefly considered, but its primary function as an archive database makes it inherently unviable. All three alternatives are listed in Table 4.3-5. None were found to be suitable replacements for GRB.

Table 4.3-5. Non-real-time GOES data access methods and description.

Acronym	System name	Description	Direct/ indirect	Federal/non-Federal users
CLASS	Comprehensive Large Array-data Stewardship System	Web-based data archive and distribution system for NOAA's environmental data. CLASS provides retrospective data access and distribution services of GOES-R data to all users. It is for archived data and is not intended as a near-real-time data source.	Indirect	Federal and other approved users
GNC-A	GEONETCast Americas	A NOAA-supported international commercial satellite broadcast system. Consists of selected cloud and moisture image products.	Direct	Non-Federal users
SBN	Satellite Broadcast Network	Sectorized cloud and moisture imagery (NOAAPort).	Direct	Primarily Federal users
Source: NOAA				

[14]Determining whether GNC-A or NOAAPort SBN receive terminals in the 3.7–4.2 GHz band would be adequately protected from interference due to potential sharing of part of the FSS downlink band is beyond the scope of this study. GNC-A or NOAAPort/SBN performance could be affected in the presence of downlink interference if mitigations are not adequate.

Another issue that users may want to consider is how RFI may manifest at their particular locations. The selection of an alternative data source may depend upon how their operations are impacted. For instance, intermittent data interruptions that cause infrequent product loss or partial product loss may allow for looser constraints on the alternate source, in which an alternate source may be used in conjunction with the existing direct readout system. By contrast, users who experience complete loss of data, or data loss that may extend for significant periods of time, may want to find an alternate source to be used as the primary method of obtaining direct broadcast data.

4.3.3.3 DCS alternative architectures

This section describes the DCS alternative architectures intended to mitigate the risk to L-band RFI identified in Figure 4.3-16.

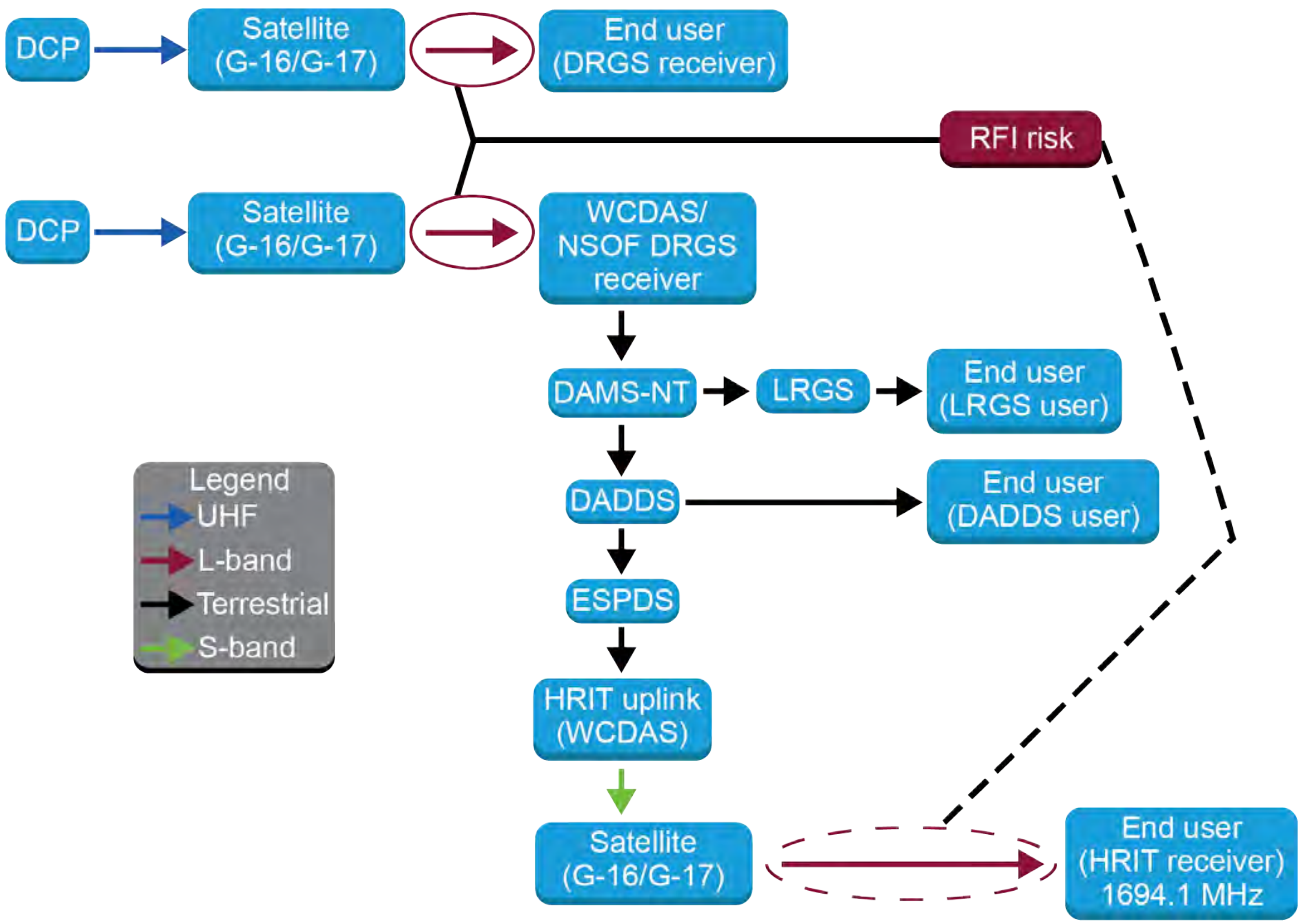


Figure 4.3-16. Schematic showing DCS distribution services and risks associated with L-band downlinks.

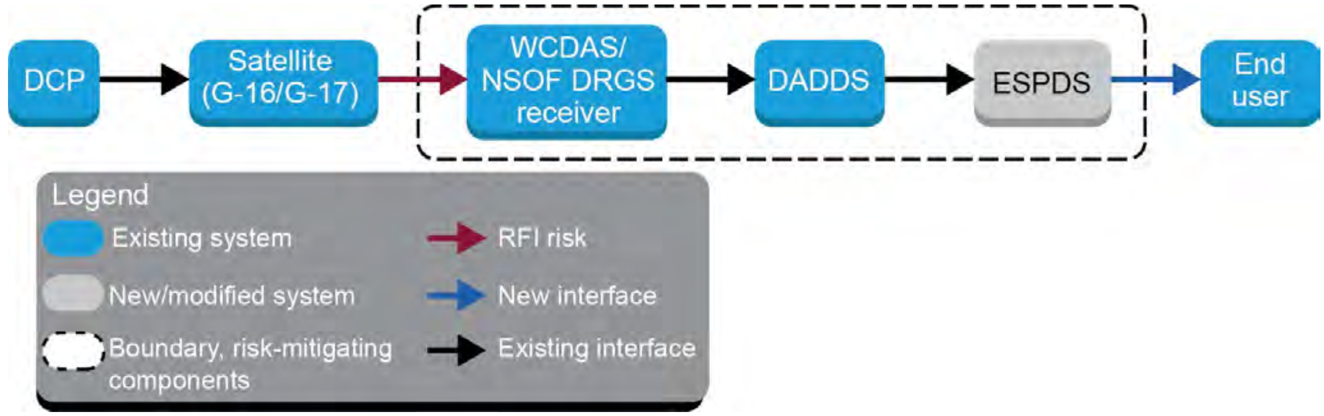


Figure 4.3-17. ESPDS alternative architecture functional flow diagram to mitigate end-user interference.

4.3.3.3.1 DCS ESPDS alternative architectures

Figure 4.3-17 shows the new distribution components required to mitigate L-band interference at end-user locations. This alternative assumes that the DRGS downlinks at NSOF and WCDAS are protected from interference and ESPDS is still able to obtain data through the DADDS interface. In this scenario, all NOAA distribution services, both terrestrial and satellite broadcast, should continue operations. ESPDS would provide an alternative distribution service for specific DRGS users that may be experiencing interference. This may not be suitable for all DRGS users.

There could be up to 79 user interfaces that would need to be integrated with ESPDS. The impacts due to data volume increases are likely to be negligible, but the common infrastructure management components may be impacted due to an increase in the number of internal system messages.

ESPDS aggregates DCS messages into 8 KB files for insertion into the HRIT/EMWIN broadcast stream. However, users do not typically subscribe to DCS data through ESPDS.

4.3.3.3.2 DCS ESPDS/cloud alternative architecture

The ESPDS/cloud alternative DCS distribution system is shown in Figure 4.3-18. This system would send a single set of DCS messages, aggregated into 8 KB files, from ESPDS to the cloud

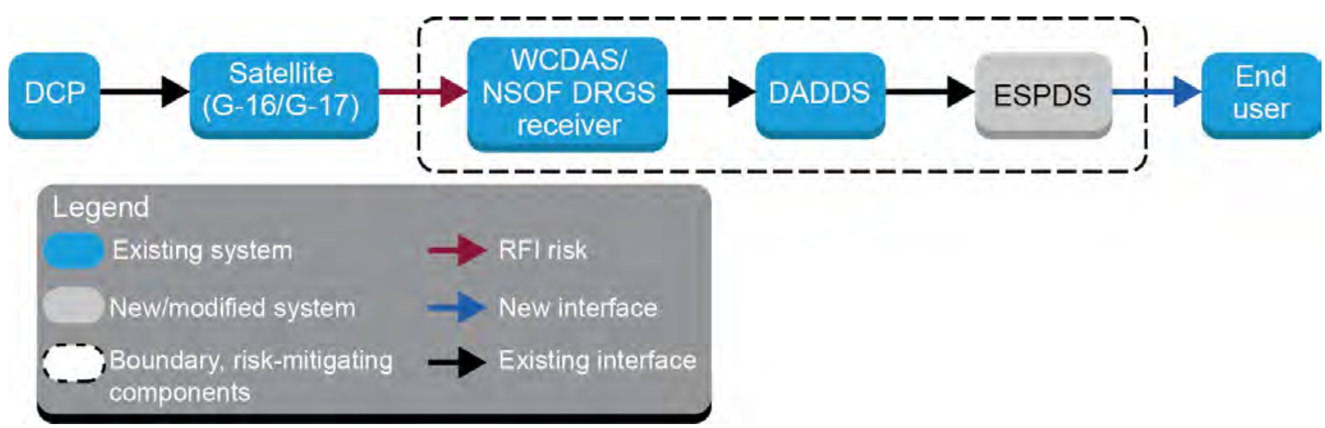


Figure 4.3-18. ESPDS/cloud alternative architecture functional flow diagram.

provider for subsequent distribution. As with the ESPDS alternative, this solution mitigates interference that occurs at a user's DRGS receiver and requires that the downlink at WCDAS and/or NSOF remain protected and that all other distribution services are available. This solution may not be suitable for all users.

4.3.3.3.3 Remote DCS receiver alternative

Figure 4.3-19 shows the functional flow diagram of a remote receiver integrated with the DADDS distribution system at NSOF and/or WCDAS, which can then distribute products using HRIT/EMWIN satellite broadcast, DADDS, or LRGS webservers. Initially, ESPDS was going to be used for distribution, but sending the data from a remote receiver to DADDS enables NOAA to continue operating three existing distribution services, leaving nearly 70% of the users unaffected by this RFI event at WCDAS/NSOF. In addition, LRGS and DADDS have lower latencies than ESPDS. They also allow users to select the DCS data they receive, allowing for more efficient use of network resources.

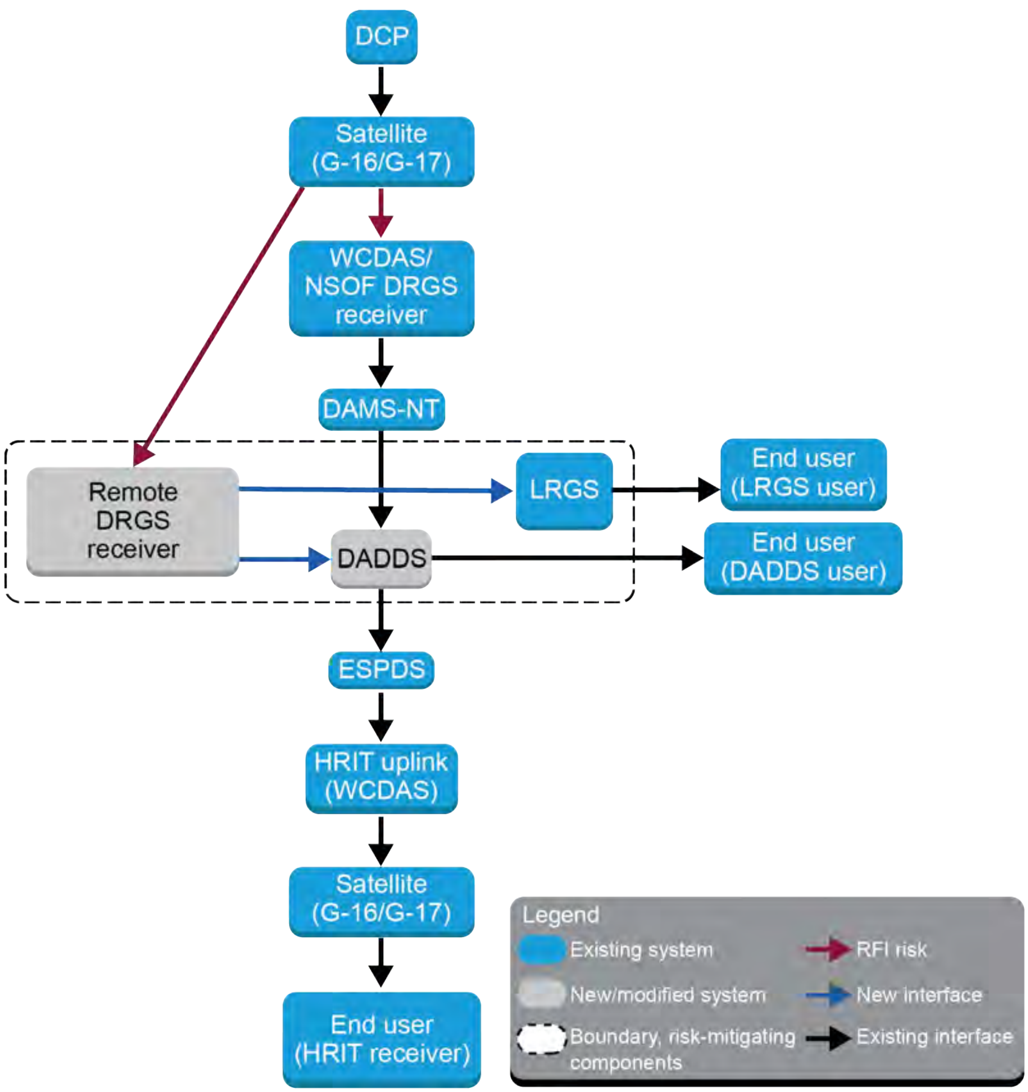


Figure 4.3-19. Remote receiver alternative architecture.

The remote receiver alternative includes two modified components. The functions within those components that are likely to be affected are shown in Figure 4.3-19. It is expected that the interface between the remote DRGS receiver and the LRGS system at WCDAS or NSOF will require minor configuration changes due to the ability of Open-DCS to accept data from multiple sources.

The NOAA5004 (DCS) boundary could be extended to include the remote receiver components. These are expected to include a DRGS antenna, demodulators, and data acquisition and monitoring systems–new technology (DAMS-NT) servers to process DCP messages and send that data to the NSOF and/or WCDAS DADDS and LRGS systems.

At WCDAS and NSOF, the DADDS system would need to be configured to accept data from a secondary receiver source. The remote site will also require installation of network infrastructure and enterprise management functions to enable access management, remote operation, and continuous monitoring, logging, and reporting functions.

Since the results from Project 8 imply that a duct affecting WCDAS will also affect NSOF, there may be a justification for relocating the DCS equipment located at NSOF or WCDAS to CBU in Fairmont, West Virginia. The network throughput to provide DCS data between those locations would likely have no impact on the existing N-Wave private terrestrial network infrastructure linking WCDAS, NSOF, and CBU.

4.3.3.3.4 DCS DADDS alternative architecture

The final DCS distribution alternative examined as part of Project 3 was migrating users at risk for RFI to the DADDS systems located at WCDAS and NSOF or to the LRGS systems located at WCDAS, NSOF, and USGS EROS. Discussions with the DCS program manager indicated that the DADDS system was built to easily accommodate all registered DCP users being investigated as part of this study and that it offers high availability with primary and hot backups located at both NSOF and CBU, totaling four available servers (one primary and three redundant). This alternative assumes that adequate protection has been implemented at both NSOF and CBU to prevent DRGS RFI leading to product loss. The DADDS system is shown in Figure 4.3-7 (and expanded in Figure 4.3-20) and would not require modification to any of its components.

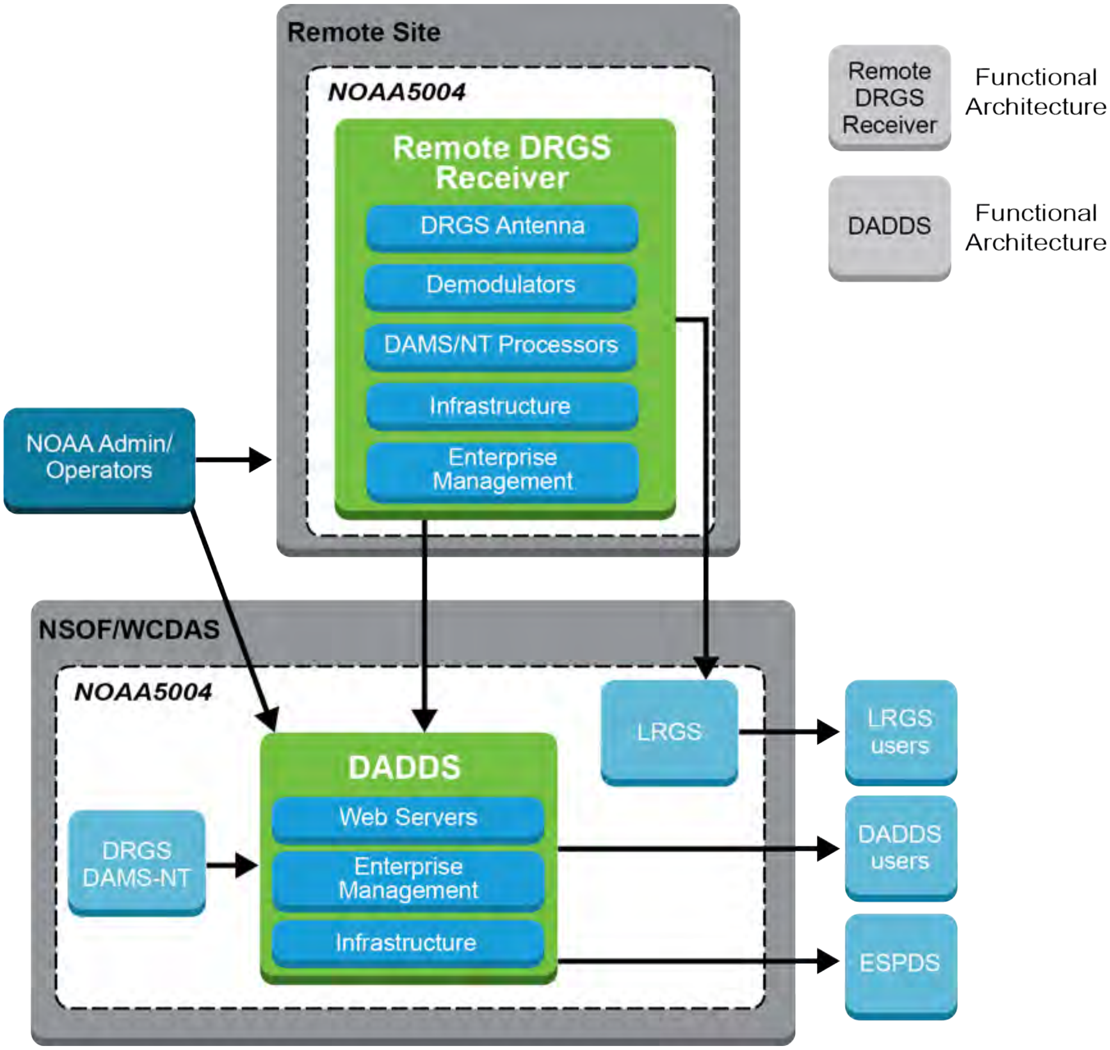


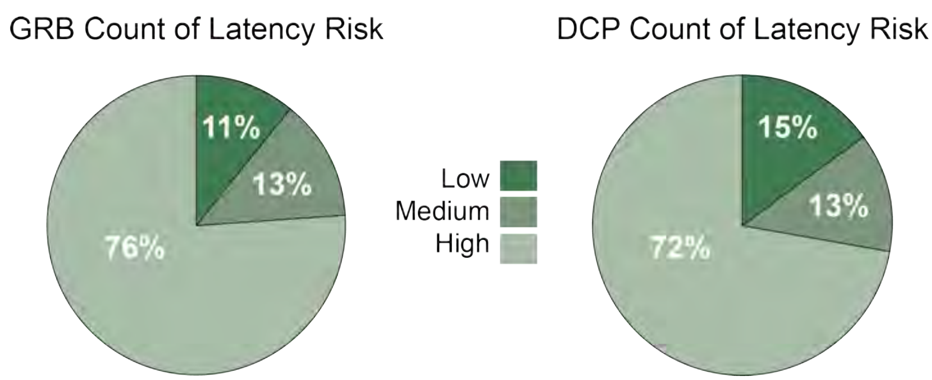
Figure 4.3-20. Remote receiver components interfacing with DRGS and DADDS.

4.3.4 User risk evaluation

Project 1 grouped user data performance requirements into three categories: period of operations, latency, and operational availability. The operational availability for all DCS users was stated to be 99.988%; however, there was no period specified over which the availability percentage applied. Since the operational availability was derived from the GOES-R F&PS, it is assumed the operational availability spanned a period of 30 days. This correlates to 5 minutes over a 30-day period. However, it is important to note that users did not specify their operational availability requirement during the Project 1 survey, and the requirement was assumed to be the limitation of the GOES-R GRB ground system (0.99988 over 30 days). Latency is the data delay induced by the data distribution system. Users indicated they had low (less than 1 minute), moderate (between 1 and 10 minutes), or high (greater than 10 minutes) latency requirements. Period of operations was defined as year-round (24/7/365), periodic (daily/weekly), or intermittent (seasonal/as needed). Table 4.3-6 shows the number of DCS users, taken from a total of 175 respondents, and GRB users, taken from a total of 41 respondents, grouped by data requirements.

Table 4.3-6. Percentage of total DCS and GRB users, grouped by data requirements.

Data requirements		DCS users (percent)	GRB users (percent)
Period of operations	Continuous	92.68	89
	Periodic	1.22	0.00
	Intermittent	2,44	0.00
	No response	3.66	10.53
Latency	Low	71.95	76.32
	Moderate	13.41	13.16
	High	9.76	0.00
	No response	4.88	10.53
Operational availability	99.988%	100	89.47
	No response	0.00	10.53



Another concern for users is the dependency on terrestrial internet service to access data. All the alternatives were evaluated independent of any "last-mile" considerations for internet availability and cybersecurity, since such considerations would be the same in all cases at the termination point. For users, the risk to network and infrastructure services at their locations will ultimately determine the feasibility of relying on terrestrial networks. Since all of the alternative architectures permit access to data via the internet, a user could procure terrestrial or satellite internet service as the primary or backup source of internet connectivity.

4.3.5 Decision analysis and resolution form

DAR forms are used to quantify the relative risk of implementing an alternative distribution architecture from a NOAA perspective. To quantify risk, an alternative is scored, based on multiple score factors, relative to the other alternatives. These score factors are grouped into evaluation criteria based on schedule risk, operational risk, security risk, cost risk, technical risk, scalability risk, and performance risk. The score factors are then averaged to obtain a base score for each evaluation criterion, ranging from one to three, with one being a high risk and three being a low risk. The higher the score, the more favorable the alternative.

Each evaluation criterion is proportionately weighted in accordance with its relative importance. Those weights are designated, through collaboration with the government, as percentages totaling 100%. The weights should be assigned with consideration to the scoring factors, which are intended to provide additional insight into the factors used to quantify the risk. To examine the impact of variations in the evaluation criteria weight factors, a sensitivity analysis was performed. In this analysis, the weight for a particular evaluation criterion was changed by +/- 5%. The other evaluation criteria weights were incrementally changed by an equal amount to maintain a total weight of 100%. A description of the DAR form evaluation criteria and the associated weights are shown in Table 4.3-7. Scoring factor descriptions are given in Table 4.3-8.

Uncertainty in the score factors was taken into consideration during the DAR form analysis. If a score factor had a low confidence level associated with its numeric value, a (+) or (−) was associated with that score, meaning that the evaluator considered increasing or decreasing the score. To help quantify that uncertainty, a corresponding +/− 0.3 was associated with the base score, creating a high/low range of values. The goal was to reduce the uncertainty in order to identify an unambiguous selection in which uncertainty ranges did not overlap.

Table 4.3-7. Evaluation criteria, description, and associated weights used when evaluating the GRB and DCS alternative architectures in Project 3.

Evaluation criteria	Description	Weight (percent)	Scoring (risk)
Technical risk	How much technical risk does the alternative introduce (e.g., a solution that is technically complex in nature due to the number of new capabilities or interfaces that must be provided, or that requires the insertion of new or unproven technologies into sites/systems that are not familiar with deploying or using them)?	20	1 = High 2 = Moderate 3 = Low
Schedule risk	How much schedule risk does the alternative introduce (e.g., risk that the hardware/software costs, level of effort, or level of commitment/participation from and impact to other sites/systems required to implement the alternative may have been underestimated or not well understood upfront, thereby increasing the amount of time required to complete the implementation)?	10	1 = High 2 = Moderate 3 = Low
Operational risk	How much operational risk does the alternative introduce (e.g., risk that implementing the alternative requires significant enough reuse of other existing operational systems/components that operational performance or availability of those existing operational systems/components could be impacted)?	10	1 = High 2 = Moderate 3 = Low
Security risk	How much security risk does the alternative introduce (e.g., risk created by the alternative not complying with certain NIST SP 800-53 security controls/requirements, or impacting other existing operational systems/components' ability to maintain compliance with their NIST SP 800-53 security controls/requirements)?	20	1 = High 2 = Moderate 3 = Low
Cost	How much would implementing the alternative cost? This includes hardware/software costs, labor costs to implement, and operations/sustainment costs.	20	1 = High 2 = Moderate 3 = Low
Scalability	How easily and efficiently can the alternative be scaled out to handle increases in data load or users, without requiring significant additional costs or a re-architecture/redesign?	10	1 = High 2 = Moderate 3 = Low
Performance	How much would performance or latency of the data flows be impacted by the alternative?	10	1 = High 2 = Moderate 3 = Low

Table 4.3-8. Factors used to numerically score the evaluation criteria for each alternative.

Evaluation critieria	Score factors	Description
Technical	Both DCS and GRB capable	The alternative is able to support ingest and distribution of both DCS and GRB data.
	Network interface complexity	What external system interfaces are required to provide data to and distribute data from the alternative?
	Source-supported protocols	Does the system support a variety of data formats or protocols to permit integration at the application layer?
	System complexity	Are there multiple components involved utilizing complex technologies that may be difficult to integrate?
Schedule	Justification/authorization	Is the implementation of an alternative a major change to existing operations or security posture?
	Procurement	Is there procurement of hardware and software components and are they long-lead items?
	Implementation/V&V	Will the system require extensive testing to demonstrate that new technologies do not pose a risk to NOAA or user operations?
Operations	Service level agreements/ ownership	Are system components owned/operated by organizations outside the purview of NOAA, diminishing the ability to remediate issues?
	Source availability	Does the availability of the data source to provide GRB or DCS data to the alternative system have the potential to inhibit operations?
	Redundancy (with geographic diversity)	Does the alternative provide data redundancy at geographically disparate locations such that natural disasters are unlikely to impact both simultaneously?
	Additional operational support	Will the alternative require changes to the way NOAA operationally supports the alternative or systems it interfaces with?
Security	Identification and authorization	Does the alternative have the ability to meet NOAA requirements for identification and authorization?
	Auditing and logging	Does the alternative have the ability to meet NOAA requirements for auditing and logging system events?
	Access management	Will the alternative provide the ability to set access level controls?
	Physical/environmental protection	Does the alternative create new physical and environmental protection requirements?
Cost	Hardware cost	Expected relative cost of hardware to implement alternative?
	Software cost	Expected relative cost of software to implement alternative?
	Labor: document, implement, and test	Expected skill-set and time required to implement alternative? Are there new skill-sets?
	Ops/sustainment cost	Will additional personnel, licensing, or hardware replacement be required?
Scalability	Scalability	Can the alternative be scaled to support expanding data volume or users based on existing architecture?
	Existing capacity	Does the existing system have capacity to handle distribution to direct broadcast users?
Performance	Latency	Does the system induce a higher latency compared with other alternatives?
	Availability	How does the system availability compare with other alternatives?
	Transmit limits	Will moving direct-broadcast users to the alternative exceed the system data volume limits?
	Historical performance/ relevance	Are there historical performance data available for the alternative that may help reduce risk due to uncertainty?

4.3.5.1 GRB DAR form evaluation

A summary of the GRB DAR form is shown in Table 4.3-9.

Table 4.3-9. DAR form scores for GRB alternative architectures.

		Alt. 1: Cloud			Alt. 2: ESPDS			Alt. 3: Remote GRB receiver		
Evaluation criteria	***Weight (percent)***	***Base***	***Low***	***High***	***Base***	***Low***	***High***	***Base***	***Low***	***High***
Technical	20	2.75	2.53	2.75	2.5	2.5	2.50	2	1.85	2
Schedule	10	2.33	2.33	2.33	2.67	2.57	2.77	1.67	1.67	1.87
Operational	10	2.5	2.43	2.50	2.75	2.60	2.75	2.75	2.75	2.83
Security	20	2.50	2. 50	2.50	3.0	3.0	3.0	3.0	2.93	3.0
Cost	20	2.25	2.1	2.33	2.75	2.6	2.83	1.5	1.35	1.65
Scalability	10	2.5	2.5	2.5	2.50	2.50	2.65	2.00	2.00	2.15
Performance	10	2.75	2.68	2.75	2.50	2.43	2.50	2.50	2.43	2.50
Total weighted score		2.51	2.42	2.52	2.69	2.63	2.73	2.19	2.11	2.26

The following factors were taken into consideration when scoring the DAR form criteria. These factors are a combination of facts, observations, and other data considered in assigning values to the rating criteria.

Technical risk

- The remote GRB receiver is not capable of handling DCS data, resulting in a low score for this factor.
- ESPDS is rated lower in network complexity because it requires NOAA network configuration change approvals for every user interface. Depending on how the cloud architecture is configured, it may require the same configuration change approvals. It is likely N-Wave upgrades will be required to support operational GRB distribution between CBU and NSOF.
- ESPDS subscription services support secure FTP file transfers.
- ESPDS/PDA subscription services are currently frozen due to the latency spikes that occur for push services. A design change to keep a consistent throughput without queueing and latency spikes, while including additional users, could be complex.
- The system complexity score was rated high for ESPDS because it is performing its intended function. A 2 was assigned for the cloud because it has not been implemented operationally. The remote GRB receiver was given the lowest score because it involves putting that system into a new configuration in which it may not have been intended to operate.

Schedule risk

- Remote GRB receiver scored lowest on authorization because the ground segment would be put into a test configuration to support operations.
- There may be some resistance in adding a significant number of new users to ESPDS, along with the associated volume of GRB data flows. Nonetheless, the implementation of a complex system upgrade carries increased schedule risk.

- Remote GRB receiver scored low on procurement due to additional network services required.
- Cloud alternative scored lowest on the verification and validation (V&V) testing because it is not currently used in a NESDIS operational system.

Operational risk

- ESPDS scored low on redundancy because GRB data would not be available in the event of a failover to CBU.
- The cloud alternative scored low regarding operational support requirements because NESDIS does not know how to operate a system in a cloud environment and there likely will be specialized skills that need to be developed, along with training for operators and administrators.

Security risk

- ESPDS and the remote GRB receiver scored best in the security category since these assets already operate with an ATO. A cloud alternative would need to gain ATO.

Cost

- The cost of the alternative architectures was not quantified in Project 3. In general, upgrading the network link between CBU and NSOF and operationalizing a test configuration are expected to be the most cost-prohibitive. Since ESPDS is not approaching its design capacity in data-pull cases, and if a sufficient number of users switch to pulling their data, the expected impact to current operational costs would be minimal. However, addressing the push services issue with a design modification to meet user requirements incurs a cost risk.

Scalability

- Because provisioning services within the cloud environment is so simple, it scored highest on scalability.
- The cloud and remote GRB receiver do not have existing capacity to support operations, while ESPDS does.

Performance

- No system should have any difficulties meeting a one-minute latency requirement.
- ESPDS does not meet the stated availability requirement from Project 1, but the cloud and GOES-R GS do.
- Effectively, the cloud would not have limitations regarding the transmission of GRB data, while ESPDS or the lack of a robust network link to support GRB distribution from CBU may.
- ESPDS has over two years of operational statistics to project expected future performance. The other two alternatives have not been used operationally by NESDIS.

4.3.5.2 DCS DAR form evaluation

A summary of the DCS DAR form is shown in Table 4.3-10.

Table 4.3-10. DAR form scores for DCS alternative architectures.

		Alt. 1: Cloud			Alt. 2: ESPDS			Alt. 3: Remote DCS receiver			DADDS		
Evaluation criteria	***Weight (percent)***	***Base***	***Low***	***High***	***Base***	***Low***	***High***	***Base***	***Low***	***High***	***Base***	***Low***	***High***
Technical	20	2.25	2.18	2.25	2.25	2.25	2.25	1.50	1.50	1.58	2.50	2.50	2.50
Schedule	10	2.33	2.13	2.33	2.33	2.33	2.33	1.33	1.33	1.33	3.00	3.00	3.00
Operational	10	2.50	2.43	2.58	2.50	2.35	2.50	2.25	2.10	2.33	2.75	2.75	2.83
Security	20	2.50	2.50	2.58	3.00	3.00	3.00	1.75	1.68	1.83	3.00	3.00	3.00
Cost	20	2.25	2.10	2.33	2.75	2.68	2.83	1.50	1.35	1.50	3.00	2.78	3.00
Scalability	10	3.00	3.00	3.00	2.50	2.35	2.65	2.50	2.35	2.50	3.00	2.70	3.00
Performance	10	2.50	2.43	2.65	2.75	2.60	2.75	2.00	2.00	2.15	3.00	2.85	3.00
Total weighted score		2.43	2.35	2.49	2.61	2.55	2.64	1.76	1.68	1.81	2.88	2.79	2.88

The factors taken into consideration when scoring the DCS DAR form criteria are similar to those used for GRB. These factors are a combination of facts, observations, and other data considered in assigning values to the rating criteria.

Technical risk

- The only alternatives that support both DCS and GRB data types are ESPDS and ESPDS/cloud architectures.
- Integrating a new antenna at a remote site put the remote receiver in last place, followed by ESPDS and the CSP. DADDS is ready to support users now.
- DADDS system and antenna are in use today, but it is unclear whether ESPDS or CSP protocols will meet current DCS user needs.
- Cloud is by far most complex in that it is new and can only distribute 8 KB files from ESPDS. ESPDS will require users to deal with receiving 8 KB files, remote antenna installation, networking, and software applications.

Schedule risk

- Remote antenna performed poorly in all categories due to cost, testing, and justification requirements.
- DADDS would have no schedule impacts.

Operational risk

- ESPDS requires OSPO approval to distribute data that is not currently distributed by PDA even though it is available to support HRIT/EMWIN.
- Operational support required for CSP and remote antenna site. Otherwise, no changes for ESPDS and DADDS.

Security risk

- ESPDS and DADDS scored well because these systems have ATOs.
- Cloud will need to be integrated into NOAA boundary.
- Remote receiver will require physical security at a remote site and applications installed for continuous monitoring, reporting, and logging system activity.

Cost

- DADDS has no associated additional cost.
- ESPDS has minor labor costs.
- CSP has moderate costs associated with new services and labor costs.
- Remote antenna has hardware, software, labor, and remote operational costs.

Scalability

- All systems scored well. There may be some some minor cost associated with scaling ESPDS or remote antenna.

Performance

- DADDS has performance history and can meet current needs, even with the addition of DCS users; reported latencies are on the order of seconds.
- ESPDS has high throughput capacity but has had latency problems associated with DCS data in particular.
- ESPDS latencies will carry over to CSP, and there is no historical NOAA performance data.
- Remote receiver has no historical precedent, and inter-site communications would need to be addressed to ensure latency requirements are met.

4.3.6 Areas for future study

The DAR process should be performed again after quantitative cost and performance metrics are determined for ESPDS and the cloud alternative, as it pertains to GRB distribution. This will require an in-depth investigation of current ESPDS system margin and the impacts of adding additional users and the associated data transfers.

There is a potential to move primary GRB L-band downlinks from Suitland, although Suitland would remain a backup site. This would require implementing ESPDS or ESPDS/cloud alternatives suggested in this study and replacing the existing GRB link between WCDAS, CBU, and NSOF with operational terrestrial network links. Currently, NOAA N-Wave network links exist to transfer data between these sites for testing purposes, and present a possible alternative. (This may not consider all factors at other GRB receive locations such as AWC or NHC.)

ESPDS consists of a primary operational system at NSOF in Suitland, Maryland, and a backup system at CBU in Fairmont, West Virginia. The backup system at CBU does not interface with the GOES-R ground segment because it was not necessary to support the primary functions at that site, the production of KPPs, and the distribution of data over GRB. However, if the GRB distribution capability will be supplanted by an ESPDS or ESPDS/cloud alternative, an interface between ESPDS and the GOES-R GS at CBU should be investigated to enable GRB data distribution during contingency operations.

4.4 Project 4. Cost of Alternative Architectures

4.4.1 Introduction

4.4.1.1 Project objectives

The scope of Project 4 addresses the SPRES program topic area Mitigation Options and Feasibilities. The objective of this project was to develop rough order of magnitude (ROM) costs and schedule estimates for the alternative distribution architectures that were developed during Project 3. These estimates were developed leveraging knowledge and experience gained in studying and defining alternative architectures in Project 3, using the Solers Capability Maturity Model Integration (CMMI) Maturity Level 3 certified cost estimation process, as well as the estimation team's experience designing NOAA data distribution systems. Cost estimates were segregated into (1) alternative implementation costs and (2) operations and maintenance (O&M) costs. This separation enabled a more direct comparison between alternatives that rely on NOAA-procured infrastructure, where a large portion of hardware and software costs are incurred during development, and pay-as-you-go cloud services, which distribute costs over the period of operations. Cost and schedule estimates were then used to reevaluate the decision analysis and resolution (DAR) form, an alternative distribution system trade study produced during Project 3. Using quantitative cost and schedule estimates produced during Project 4, along with performance metrics produced during Project 5, the DAR form was reevaluated to improve fidelity of scores generated during Project 3.

4.4.1.2 Project outcome

Project 4 resulted in ROM costs being generated for all the alternative architectures investigated during Project 3. The ROM costs included both implementation of the alternative and five years of operations cost. Implementation ROM cost estimates captured the labor, hardware, software, and, in the case of cloud alternatives, cloud service costs. The ROM estimate for the five-year period of operations included additional operational staff required, recurring license, hardware support contracts, cloud service costs, and hardware technical refresh costs.

This project also developed estimated timelines to implement each of the alternatives. These were based on high-level implementation tasks and the associated labor estimates.

Finally, the cost and implementation schedule estimates were used to reevaluate the trade study that was originally completed as part of Project 3. The qualitative cost, performance, and schedule scores were replaced with quantitative outcomes of Project 4, as well as by the performance data that was collected during Project 5. The results of the trade study reevaluation have reaffirmed the preferable alternatives based on the Project 3 study and have increased the margins when compared with other alternatives evaluated in Project 4. The DADDS and ESPDS systems ranked highest primarily because these are operational systems and have sufficient capacity, or can be scaled, to accommodate existing DCS or GRB direct broadcast users.

4.4.2 Approach to the costs of alternatives

This section describes the process used to develop ROM cost and schedule for implementing four DCS and three GRB alternative architectures. This includes the assumptions, the process used to develop labor level-of-effort (LOE) estimates, defining material and service costs, and the labor rates that are an integral part of the implementation and O&M cost estimates. Using this estimation framework, cost estimates are detailed in the remaining subsections.

4.4.2.1 Cost estimation process

Solers followed an existing project cost estimation process that has undergone review during its Capability Maturity Model Integration, Level-3 (CMMI, ML-3) certification process. Figure 4.4-1 graphically shows the process used to develop project cost estimates.

1. Establish an estimating team. This step was completed during the generation of the SPRES Project 4 proposal. The estimation team consisted of personnel having a major role in the development of the alternatives in SPRES Project 3. They were able to leverage experience with similar data distribution projects developed for NOAA and application of the ROM estimation process to those projects.
2. Identify scope and deliverables. The estimation team identified the scope for the implementation of each alternative architecture, the deliverables that would be required for each implementation, and the high-level timeline for each implementation. The scope and requirements for each implementation were finalized through collaboration with NOAA before proceeding to step 3.
3. Define technical solution, work breakdown structure (WBS), and components/tasks. At this point, each implementation is divided into a WBS that defines the technical solution and component/tasks at a more granular level. Each architecture implementation WBS is recorded in individual, formal estimation sheets that are used by each of our three estimators for cost estimation. At this point, ground rules and assumptions that form the basis for the estimate are defined. For example, the ground rules may specify specific components that will be part of the architecture, specific products that must be used as part of the solution, selections for development environment tools or processes, and schedule and/or cost constraints imposed by the customer or data users. Assumptions are unknown factors that may affect the estimate. Examples of assumptions are performance or interface requirements for a particular component for which no specifications have been provided, customer-furnished hardware or software that will be required as part of the solution, the types of engineering services that will be required to complete an open-ended project support and non-software task with limited customer specification, and the length of time engineering services will be provided when no duration for a project support or non-software task has been specified. The ground rules/assumptions, WBS, and component/task definitions are recorded in the estimation sheets and reviewed by the estimation team and the customer.

4. Size software and services summary and overview. Once the draft estimation sheets for each alternative architecture have been reviewed and approved with the customer, the process of sizing the efforts to implement each of the alternative architectures begins. At this point, the Solers Historical Project Database is used to select reference projects that are of similar size and complexity to the implementation of each of the alternative architectures. Solers has both software development and non-software reference projects. It uses three available options for sizing software components.
   a. *Estimate by analogy*: Utilize the SEER estimate-by-comparison tool to assess the size of the software being estimated in relation to known reference projects in the Solers historical database.
   b. *Estimate by expert judgment*: Utilize the Solers sizing and estimation worksheet for software to estimate the size by engineering judgment, informed by known reference projects in the Solers historical database. Solers utilizes the Delphi method for estimates by expert judgment, in which three independent assessors estimate each component of the WBS and then the three independent estimates for each WBS component are averaged for the final estimate.
   c. *Hybrid*: Complete the estimate by analogy and the estimate by expert judgment to improve accuracy and then reach a final size estimate based on both estimates.

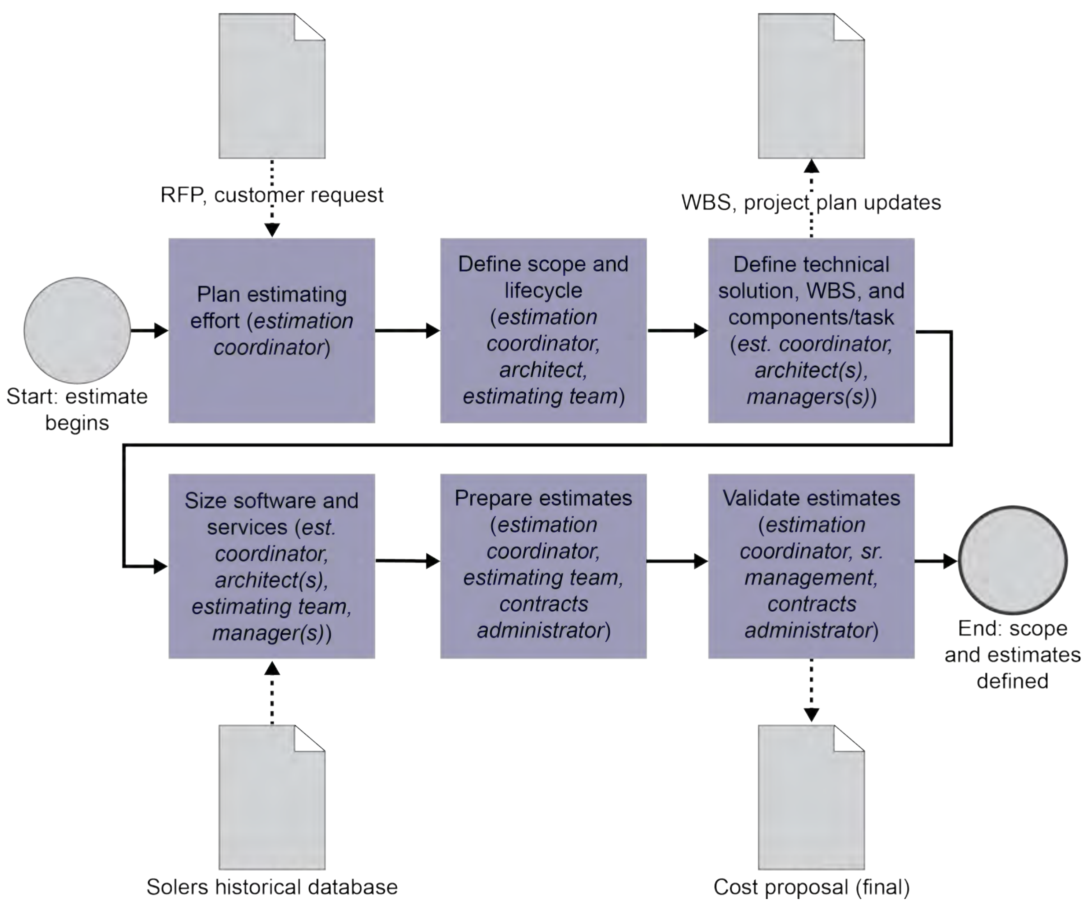


Figure 4.4-1. Project cost estimation process.

5. Prepare estimates summary and overview. During this step, estimates are produced using the methods described in the previous step for each of the WBS components and then summarized for an overall ROM cost and schedule estimate for each of the alternative architectures.
6. Validate estimates summary and overview. This is one of the final tasks in Project 4. Once the draft ROM estimations for schedule and cost for each of the alternative architectures are completed, they are reviewed and validated with the customer, and any comments or feedback received from the customer is fed back into the estimation sheets. Solers then folds the estimated ROM costs and schedule for each of the alternative architectures into the DAR spreadsheet developed and delivered as part of Project 3 in order to provide the customer more detailed actionable data in this report.

4.4.2.2 Overarching assumptions

It is assumed that any architecture implemented as an alternative means of distributing DCS or GRB data to existing direct broadcast users would become part of NOAA's critical infrastructure. This requires that the system be developed with sufficient availability, low latency, provisions for contingency operations, a maximum time to restore service, and an acceptable level of information assurance. In addition, the system would be tested with users to ensure that they are able to attain the expected performance. This drives the implementation timeline in terms of required verification and validation of system interfaces and performance criteria. In addition, it mandates that support staff are trained and capable of resolving operational issues that may arise due to system anomalies. It is suggested that system developers provide a support role in initial system operations if a cloud alternative is to be implemented. The primary purpose is to supplement an operational staff with subject-matter expert (SMEs) who will assist in developing methods of implementing a new paradigm in NESDIS data operations. It requires that additional staff be added to support expansion of existing systems or implementation of specialized technologies that do not fall within the existing domain of the current operational staff. These overarching assumptions are considered in the implementation and O&M labor estimates.

4.4.2.2.1 Labor rates

Full-time employment was considered to be 1,920 hours of direct labor per year. This estimate was based on an employee with 10 Federal holidays and two weeks of annual leave per year. The labor rates were fixed at a fully burdened rate of $130/hour for all labor categories relating to implementation of the alternative architectures. The average hourly labor rates from the Bureau of Labor and Statistics for the Washington, D.C., metropolitan area are shown in Table 4.4-1. Standard occupational classification (SOC) codes were cross-referenced with labor types allocated to SPRES tasks. The allocation of the labor types in terms of percentage of total project direct labor are used to weight the hourly labor rates to establish an average hourly rate for direct labor. Using a wrap rate of 2.0 to develop the fully burdened direct labor cost gives an average hourly rate of $126.10/hour. Therefore, the previous assumption of $130/hour was considered adequate for the purposes of this ROM cost.

O&M labor rates were reduced to $100/hour with the expectation that these positions would be filled by junior-level employees and that senior-level or SME labor categories would not be required. O&M labor rates were fixed over the five-year cost projection.

Table 4.4-1. Labor rates for SOC codes in Washington, D.C., metro area.

SPRES resource type	Mean wage/hr (2018)* (dollars)	Standard occupational classification*		Project time allocations (percent)	Weighted rate (dollars)
		Code	Description		
Project manager	83.40	11-3021	Computer and information system managers	18	15.01
System architect	79.72	11-9041	Architectural and engineering managers	7	5.58
System engineer	50.67	15-1121	Computer systems analysts	13	6.59
Software developer	58.86	15-1133	Software developers, system software	15	8.83
Integration and test engineer	62.24	15-1111	Software quality assurance analysts and testers	22	13.69
Security architect/ engineer	55.23	15-1122	Information security analysts	15	8.28
Configuration manager	50.67	15-1121	Computer systems analysts	6	3.04
Quality assurance	50.67	15-1121	Computer systems analysts	4	2.03
			Total	100	63.05
				Fully burdened (wrap rate = 2.0)	$126.11

Source: Bureau of Labor and Statistics website: https://www.bls.gov/oes/current/oes_nat.htm.

There were no labor costs associated with system technical refresh. This is because systems such as ESPDS or DADDS will undergo tech refresh regardless of whether system scaling is required. The LOE associated with tech refresh will not change as a result of system scaling; scaling will only increase the quantity of the requisite hardware and software required.

4.4.2.2.2 Material costs

Material costs included hardware, hardware support, software, license, and service costs. In order to make a more effective cost comparison between the cloud service provider pay-as-you-go cost model and alternatives requiring upfront costs to procure infrastructure, annual operational material costs were estimated over a period of five years. After a period of five years, NOAA infrastructure would be expected to undergo a technical refresh in which any hardware procurement that occurs during the initial implementation would need to be repurchased. The tech refresh cost was averaged annually over that five-year cost projection with no escalation in material cost.

Cloud services and associated costs were developed using data available from Amazon Web Services. It was assumed that the services implemented would need to be compliant with Federal Risk and Authorization Management Program (FedRAMP) high-baseline requirements. In addition, services will reside in the GovCloud (US-East) region.

4.4.2.2.3 ESPDS scaling cost estimates

ESPDS is a key component in all alternative GRB architectures and in three of the four DCS alternative architectures. To determine the additional system resources required to support projected loading under each alternative distribution scenario, an ESPDS scaling model was used. This model uses the additional daily data distribution volume and the number of products distributed to determine the system impacts. The model outputs additional system resources that are required, including;

- Compute resources
- Storage resources
- Virtual machines
- Network resources

Using the model outputs, the associated line items are identified in a recent ESPDS bill of materials (BOM) to associate a cost impact. Of note is that there are shared material cost impacts based on the model output in some cases. Firewall, compute, and storage impacts can result in fractions of a blade[15] being required. Especially for the network resources, the unit expense is too great to be fully borne by a single user who happens to cause the requisite procurement to scale network resources. In addition, there are blade chassis that are shared by storage blades and compute blades forming the cluster. A proportionate cost of these shared resources was factored into the material cost estimates.

Section 4.3.1.1.1 provides a summary analysis of the GRB users, including a listing of the data use, number of receivers, and associated products and daily data volumes (see Table 4.3-3).

ESPDS receives DCS data from the DADDS system packaged in 8 KB files. The data that ESPDS would be distributing to DRGS users, the DCS direct broadcast users at risk to RFI, is shown in Table 4.4-2. The number of products received from DADDS is based on ESPDS data transfer metrics collected by OSPO during system operations. Table 4.4-3 is a summary of the ESPDS model inputs used to calculate system impacts for each alternative for both GRB and DCS.

Table 4.4-2. Daily volume and number of products sent to DRGS users.

Summary of expected DCS product use				
Number of DRGS users	Number of DADDS products (per day)	Size of product (KB)	Number of files distributed by alternative (per day)	Volume of data distributed by alternative (GB per day)
26	21,000	8	546,000	4.166

[15]A blade is one of several server modules in a single chassis. It is widely used in data centers to save space and improve system management. Either self-standing or rack-mounted, the chassis provides the power supply, and each blade has its own CPU, RAM, and storage. See “Blade Server,” PCMag Encyclopedia, accessed May 18, 2020, https://www.pcmag.com/encyclopedia/term/blade-server.

Table 4.4-3. ESPDS model input summary.

ESPDS scaling model input summary					
Alternative		Files transferred (per day)*	Volume transferred (GB per day)*	Number of users (concurrent transfer)
GRB	ESPDS	1,237,097	7,947.9	40
	Cloud	84,558	393	1
DCS	ESPDS	546,000	4.2	26
	Cloud	21,000	0.2	26

*Based on direct broadcast user surveys conducted during SPRES Projects 1 and 2, as well as on Project 6 work.

Table 4.4-4. Cost of scaling ESPDS for alternative architectures.

ESPDS BOM input matrix				
	GRB ESPDS	GRB/cloud	DCS ESPDS	DCS/cloud
Network-attached storage (NAS) flows (Gb/s)	9.24	0.46	0.01	0
Egress (Gb/s)	9.24	0.46	0.01	0
Cisco UCS Blade Servers	2	1	1	0
VMs	2	0	0	0
Implementation cost	$196,665.00	$93,134.00	$34,133.69	$ —
Annual cost	$62,532.00	$31,392.00	$19,016.58	$ —

The ESPDS scaling model was run with the inputs shown in Table 4.4-4. The annual costs include licensing and support costs for hardware and software components. For the DCS/cloud alternative, there were no system impacts since ESPDS would be required to distribute a small amount of data. These costs are included in the alternative cost estimation sheets in Appendix I.

4.4.2.3 DCS alternative architecture ROM costs

NESDIS uses several methods to distribute DCS data to users. Users can access DCS webservers over terrestrial networks or receive data via satellite. Satellite distribution services utilizing the GOES L-band downlink include HRIT and DRGS. DRGS is considered the downlink at high risk to interference, so the sizing of the alternate distribution systems was predicated on the number of DRGS users. During the SPRES program, 26 sites were identified that rely on a DRGS downlink.

4.4.2.3.1 DCS/ESPDS alternative ROM cost

The DCS/ESPDS alternative will distribute DCS data to DRGS users over terrestrial networks. ESPDS is capable of sending data over the public internet or through Federal networks that interface with N-Wave. Users would need to obtain an account on ESPDS enabling them to log into a portal and subscribe to DCS products. Currently OSPO is not approving new user accounts on ESPDS because system capacity has been fully allocated to existing users. If the requisite system modifications are conducted to support the new users, it is assumed that these accounts could be approved. ESPDS currently receives and stores all DCS messages from DADDS. Therefore, it would be distributing data currently available on the system. Currently, there is no way of distinguishing DCS products based on sensor platform, so users would receive all DCS files that PDA receives from DADDS.

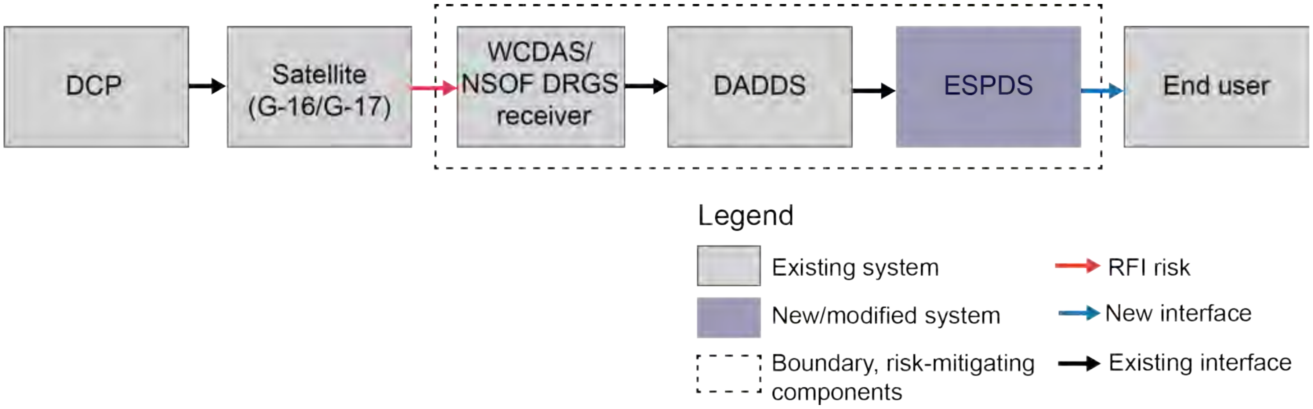


Figure 4.4-2. DCS/ESPDS alternative architecture data flow diagram.

As indicated in Figure 4.4-2, ESPDS would need to be modified to implement this alternative. Twenty-six DRGS users would need to get accounts on ESPDS and integrate their DCS data receive systems to ESPDS at NSOF and CBU. ESPDS has network connectivity through the public internet or other networks that peer with N-Wave. Integration at CBU is required to ensure that data will continue to be available during ESPDS contingency operations. The primary method of transferring data to users is via secure file transfer protocol (SFTP) or file transfer protocol secure (FTPS). The system can function as either the client or server; however, that configuration needs to be agreed upon through negotiations between OSPO and the user.

In addition to the interface changes at NSOF and CBU, ESPDS system modeling requires additional compute resources and storage nodes to support the additional 546,000 product transfers amounting to 4.17 GB of data every day.

4.4.2.3.2 DCS/cloud alternative ROM cost

The DCS/cloud alternative data flow is shown in Figure 4.4-3. The purpose of this system is to move the distribution burden from ESPDS to a cloud service provider. It will require ESPDS to interface with a cloud service provider, while the 26 DRGS users interface with the cloud to obtain DCS data. Again, the files will not be organized by DCP message, so it is expected that all DCS files written to the cloud by ESPDS will be sent to the end users. However, since data transfer volumes are low for DCS, the transfer costs are low. The data throughput changes for ESPDS and the cloud provider are summarized in Table 4.4-5.

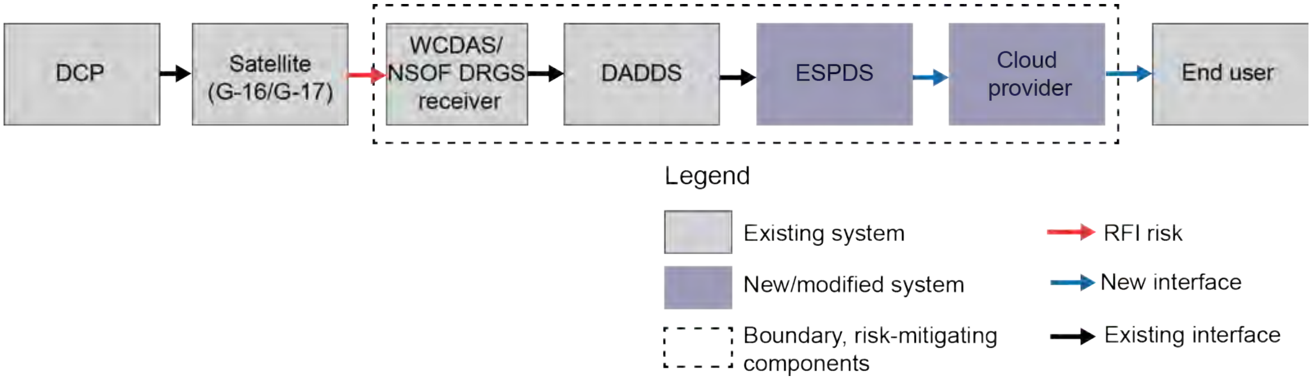


Figure 4.4-3. Data flow diagram for DCS/cloud alternative architecture.

Table 4.4-5. Data distribution requirements for DCS/cloud alternative.

Component	Distribution requirements
ESPDS	Number of additional products/day: 21,000
	Volume of additional data/day: 164 MB
Cloud	Number of additional products/day: 546,000
	Volume of additional data/day: 4.166 GB

Two different cloud provider implementations were considered, as shown in Figure 4.4-4. One case requires the users to pull products from the cloud storage, referred to as a user-initiated transfer (UIx) service. The second case, which uses a secure FTP (or similar) service that automatically pushes products to users upon arrival in cloud storage, is referred to as a NOAA-initiated transfer (NIx) service. In both cases it is expected that all DCP messages will be sent to the end user. The NIx service is a more complex implementation and relies on compute instances to run distribution

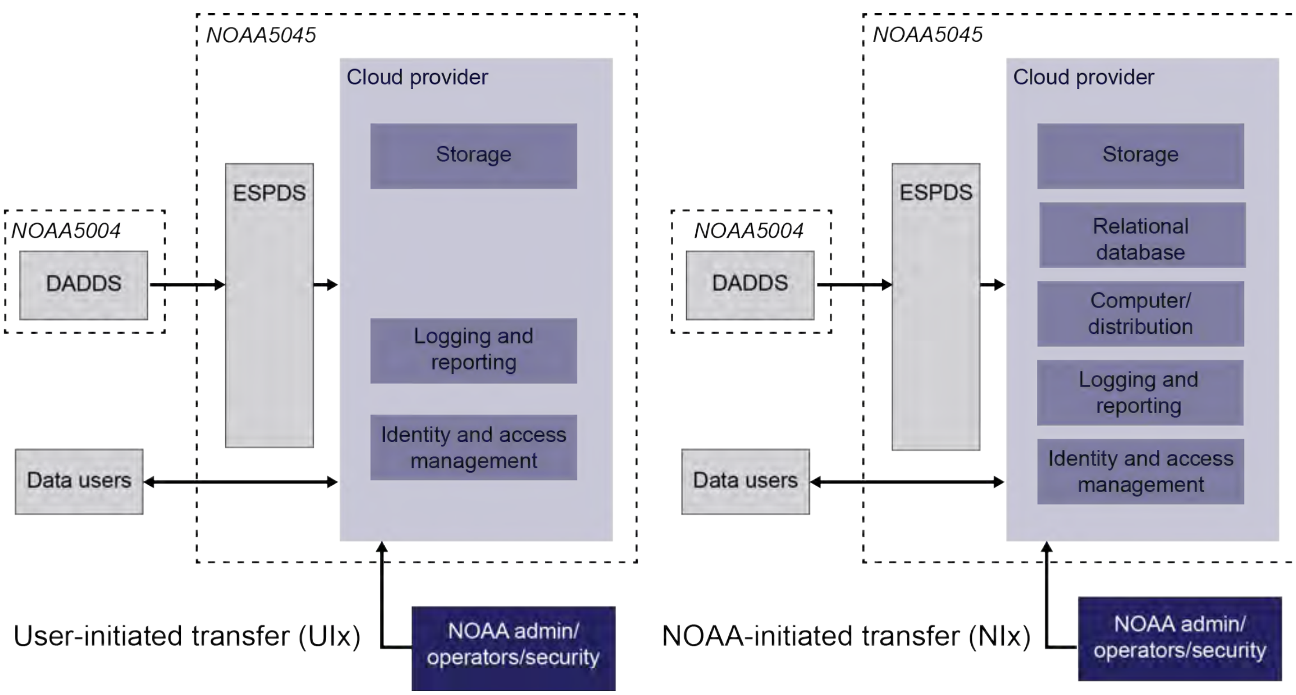


Figure 4.4-4. Two cloud service implementations: user-initiated transfers (UIx) and NOAA-initiated transfers (NIx).

servers. In addition, database services are required to manage automated file distribution services to all DRGS end users. The NOAA-initiated file transfer service is expected to reduce the latency between the time the file arrives in cloud storage and the time the data transfer begins. In the UIx service, S3 can send a notification to the user, who would be required to initiate the file transfer. The NOAA Big Data Project (BDP) has an architecture similar to UIx, and its estimates of file transfer latencies are on the order of five seconds. Both implementations require a level of identity and access management, as well as logging and reporting services, to meet NESDIS information assurance requirements. It was assumed that cloud services will require Federal Risk Assessment and Authorization Program (FedRAMP) high compliance and reside in Amazon Web Services GovCloud.

4.4.2.3.3 DCS/remote receiver alternative ROM cost

Figure 4.4-5 shows the functional flow diagram of a remote receiver integrated with the DADDS distribution system at NSOF and/or WCDAS that can distribute products using HRIT/EMWIN satellite broadcast, DADDS, or LRGS webservers. However, since the GOES-R program is planning to decommission the GRB receive equipment at NSOF, the option of moving the DRGS receivers from NSOF to CBU was investigated. Moving DCS equipment from NSOF to CBU had previously been considered by the DCS program office, but no cost estimates were available. DCS operators suggested that all DCS equipment, including the DADDS and LRGS distribution systems, be moved to CBU. In this case, the DADDS and LRGS webservers will be reintegrated with ESPDS, NWS, and other systems that have point-to-point connections. Since CBU is not staffed, cost provisions for a full-time system operator were made. The existing receiver equipment at NSOF is expected to be fully compatible with the IF composite signal that is available at CBU.

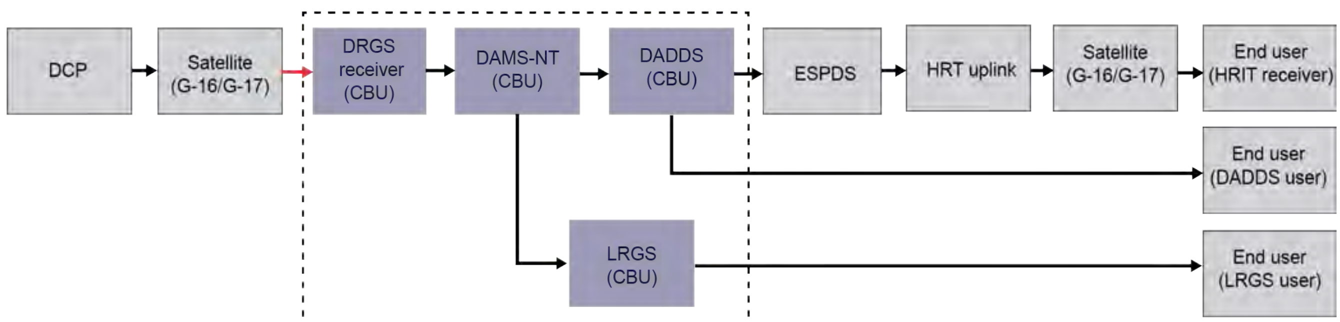


Figure 4.4-5. Remote receiver implementation proposes moving DCS equipment from NSOF to CBU.

Implementation of a DCS remote receiver assumes that movement of equipment can be planned in such a way that this backup DCS system at NSOF can be shut down, disassembled, moved, and integrated with equipment at CBU without significant impact to operations. But it is understood that this procedure would result in reduced data availability in the event of a failure of the WCDAS DCS system. A phased movement of equipment may be advantageous if redundancy currently exists at NSOF. It is expected that any DCS modifications required would be minimal and completed within two months.

4.4.2.3.4 DCS/DADDS alternative ROM cost

The DADDS alternative uses existing DCS distribution services at NSOF and CBU to disseminate data to users. These webservers are termed DADDS or LRGS and have the capacity to meet the distribution requirements of existing DRGS users in terms of volume. Some users have stated that DADDS is not capable of meeting their requirements because it relies on public internet, which is not reliable in their geographic locations. Figure 4.4-6 shows the data flow diagram for this alternative distribution system.

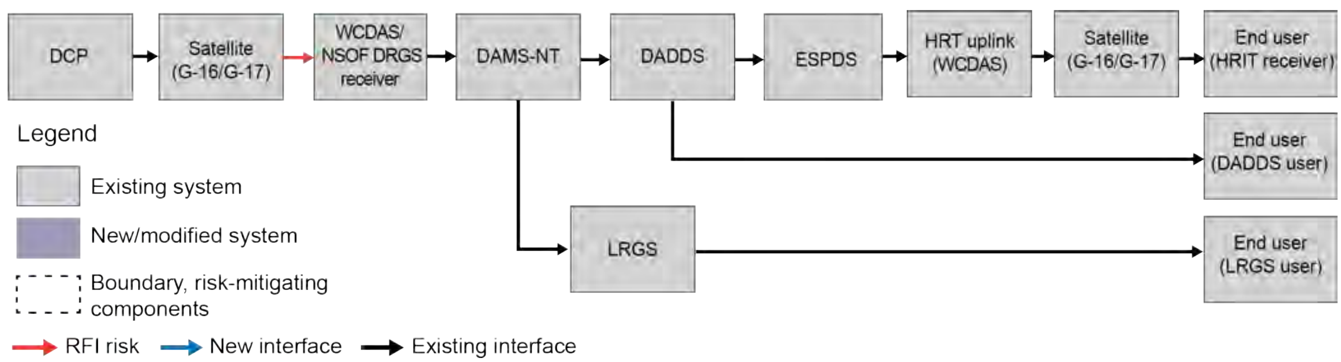


Figure 4.4-6. Existing DCS distribution services.

Although the current DADDS system is capable of meeting the existing DRGS user needs, the reliance on public internet, which could induce unforeseen performance bottlenecks, needs to be considered. Broadband service availability is tracked by the FCC, with information available on its website for physical addresses. However, additional research and testing may be required to ensure that the availability of service and performance meets user requirements.

4.4.2.4 GRB alternative architecture ROM costs

The relatively high data rates associated with GRB cause significant increases in the cost of implementing a terrestrial distribution alternative. The expected data transfer volumes are summarized in Table 4.3-2. These values were based on the GRB products used and average product size. The GRB is capable of providing a maximum data transfer rate of 31 Mbps. For users who obtain both GOES-East and GOES-West data, the maximum rate is 62 Mbps. An estimated 77% of the existing capacity is being utilized, so the GRB data volume does have capacity to grow beyond current data transfer rates, impacting the alternative architecture with no change in the number of end users or products they require. Changes in the GRB data transfer rates could increase in the future due to ABI operating mode or if additional data products associated with new sensors are integrated as proposed into future GOES-R series satellites.

4.4.2.4.1 GRB/ESPDS alternative ROM cost

The ESPDS alternative data flow is shown in Figure 4.4-7. It relies on the GRB downlink at NSOF and the GOES-R PPZ to forward Level 1b and GLM data to ESPDS for subsequent distribution to users. This data flow currently exists, and no changes are required to support this alternative. Twenty-six of the 41 GRB users that were identified during the SPRES project will need to interface with ESPDS to ingest the required GOES-R products. The physical interface can traverse the public internet or can utilize private networks if there is an interconnection with the N-Wave network. The remaining users have an existing interface with ESPDS and do not need to go through the system integration or account approval process. ESPDS does not have an interface to the GOES-R ground segment at CBU. Therefore, if there is a failure in either the GOES-R or ESPDS components at NSOF, this alternative would not be capable of sending data to end users.

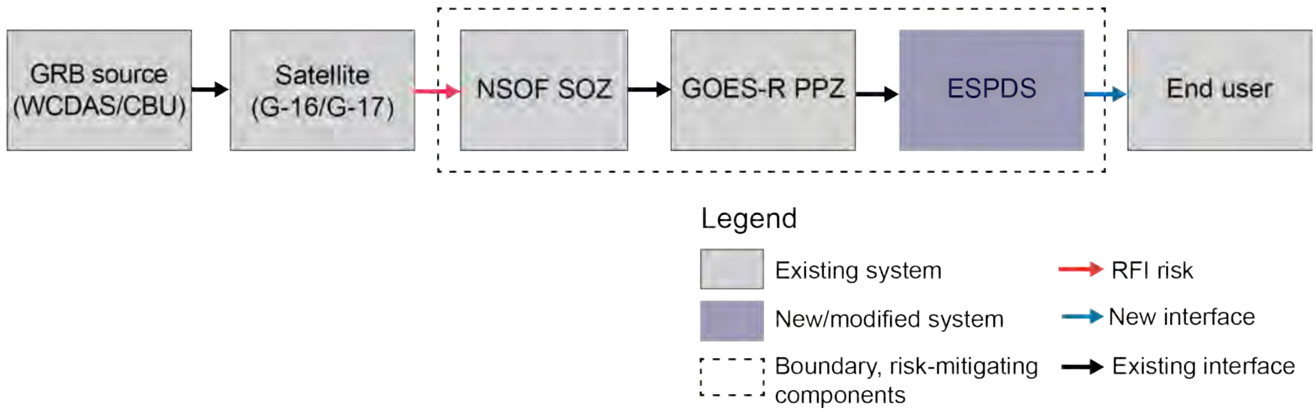


Figure 4.4-7. ESPDS alternative data flow diagram.

Table 4.4-6 shows the additional products and volume of data the 41 GRB users are expected to consume daily. These estimates are based on the products used at each site and the number of receivers for GOES-East, GOES-West, or both. This alternative will affect the ESPDS operational environment at NSOF since the data is not available from CBU and there is no need or ability to fully load-test the I&T environment.

Table 4.4-6. GRB/ESPDS alternative architecture distribution requirements.

GRB/ESPDS alternative	Number of additional products/day: 1,237,097
	Volume of additional data/day: 7.762 TB

4.4.2.4.2 GRB/cloud alternative ROM cost

The GRB/cloud alternative data flow is shown in Figure 4.4-8. The purpose of this system is to move the distribution burden from ESPDS to a cloud service provider. It will require ESPDS to interface with a cloud service provider, while the existing 41 GRB users interface with the cloud to obtain GOES-R Level 1b and GLM data. For the purposes of developing ROM costs, this data is expected to be transferred over the internet. However, users may be able to obtain a direct connection to Amazon Web Services, which can result in reduced data transfer costs, either from cloud storage or from using a NOAA distribution service running on EC2 instances. The data throughput changes for ESPDS and the cloud provider are summarized in Table 4.4-7.

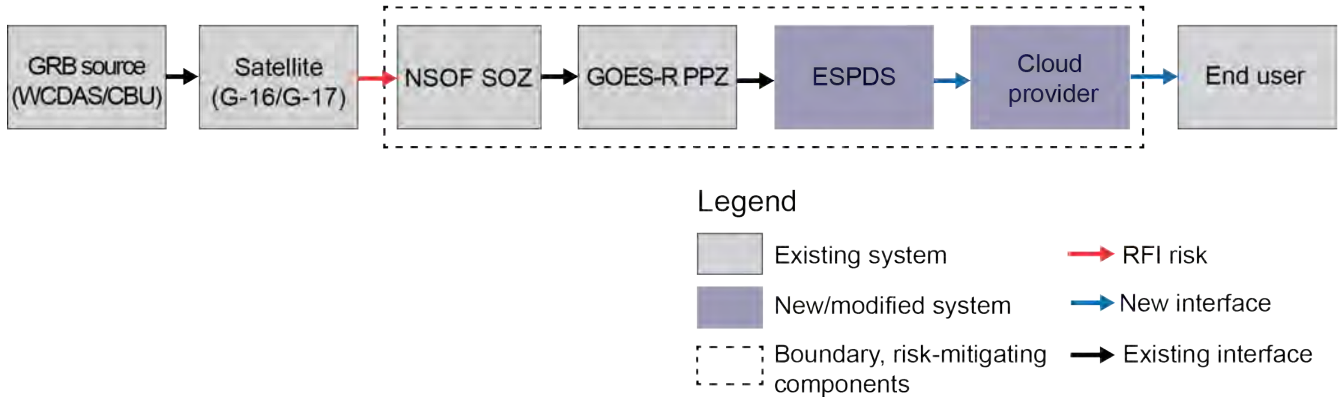


Figure 4.4-8. GRB/cloud alternative architecture data flow diagram.

Table 4.4-7. GRB/cloud alternative data throughput requirements.

ESPDS	Number of additional products/day: 84,558
	Volume of additional data/day: 393.2 GB
Cloud	Number of additional products/day: 1,237,097
	Volume of additional data/day: 7.762 TB

As with the DCS/cloud alternative, two different cloud provider implementations were considered, as shown in Figure 4.4-9. One case requires the users to pull products from the cloud storage, i.e., the user-initiated transfer (UIx) service. The second case uses a secure distribution service (such as S/FTP/S) protocol, which automatically pushes products to users upon arrival in cloud storage, i.e., the NOAA-initiated transfer (NIx) service. The NIx service is a more complex implementation and relies on compute instances to run distribution servers. In addition, database services are required to determine how the appropriate files are transferred to end users. The NOAA-initiated file transfer service is expected to reduce the latency between the time the file arrives in cloud storage and the time the data transfer begins. In the UIx service, S3 can send a notification to the user, who would be required to initiate the file transfer. The NOAA Big Data Project (BDP) has an architecture similar to UIx, and estimates of file transfer latencies are on the order of five seconds. Both implementations require a level of identity and access management, as well as logging and reporting services, that meet NESDIS information assurance requirements. It was assumed that cloud services will require Federal Risk Assessment and Authorization Program (FedRAMP) high compliance and reside in Amazon Web Services GovCloud.

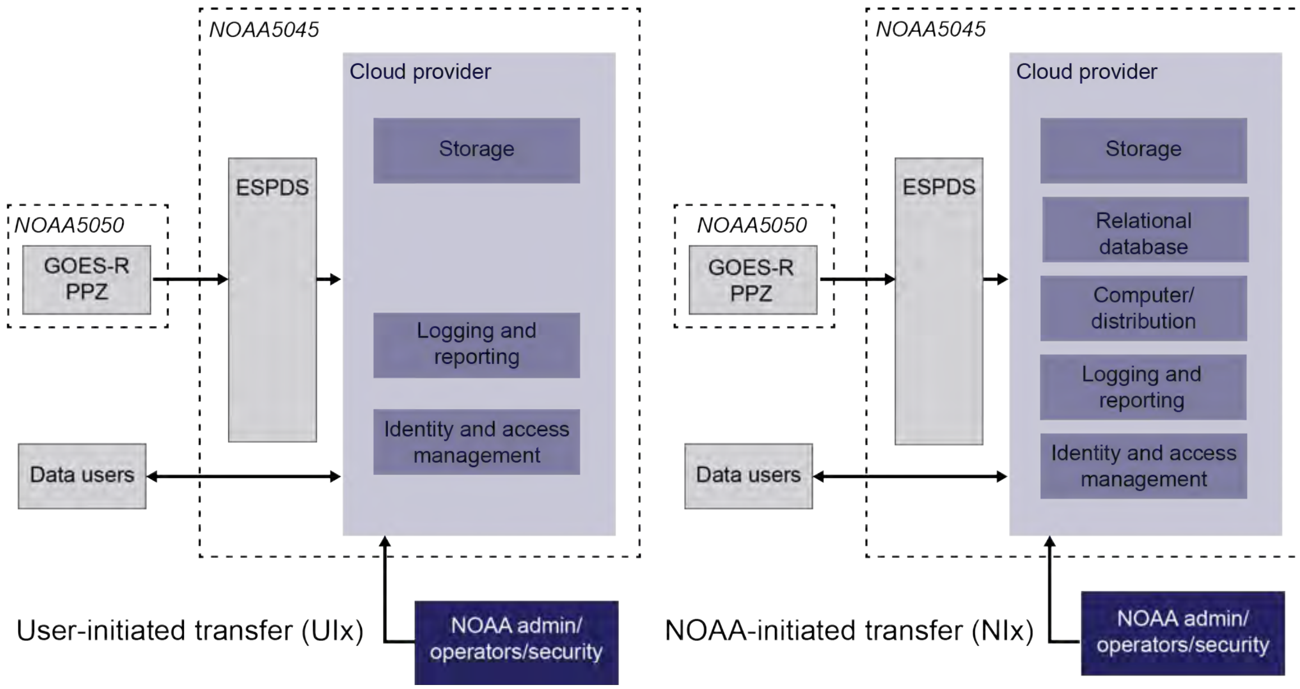


Figure 4.4-9. Two cloud service implementations: user-initiated transfers (UIx) and NOAA-initiated transfers (NIx).

4.4.2.4.3 GRB/remote receiver alternative ROM cost

Initial implementation of the remote receiver assumed installation in an area where RFI levels would not cause degradation of the GRB downlink. The GRB data would then be sent to a NOAA facility for subsequent distribution to GRB users. However, GRB data is produced from raw sensor data at the GOES-R downlink sites located at WCDAS and CBU. Currently, a terrestrial link exists to send GRB data from those sites to NSOF for controlled distribution of products over terrestrial networks so they can be validated prior to broadcast over GRB. The GOES-R program is planning to decommission the GRB downlinks at NSOF in favor of terrestrial distribution from WCDAS and CBU. This data flow concept is shown in Figure 4.4-10, where the SOZ no longer receives data via

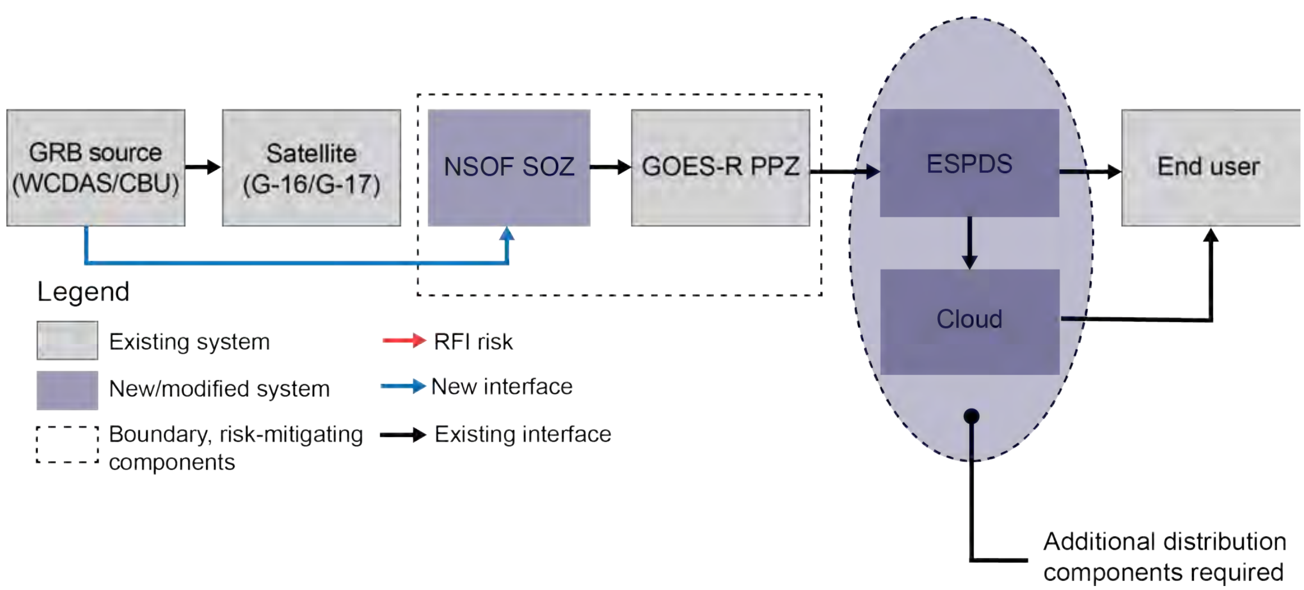


Figure 4.4-10. NSOF receiving GRB data over terrestrial link.

GRB but rather over a terrestrial link to WCDAS and CBU. Also illustrated in this figure, the end users will require that an alternative distribution component be implemented in order to mitigate the risk of RFI at all GRB downlink sites. Cost of these additional distribution systems is considered independent of this alternative.

4.4.3 Summary of ROM costs and schedules

This section contains a summary of Project 4 implementation cost, O&M cost, and schedule to implement, as well as a brief discussion of the findings. A more detailed explanation of the alternative architecture ROM costs and schedule to implement appears in Appendix I.

4.4.3.1 Cost summary

Table 4.4-8 and Table 4.4-9 contain cost summaries for the DCS and GRB alternative data distribution systems. The implementation costs considered labor, hardware, support contracts, software, licenses, and service costs required to begin operating the alternative architecture. The O&M cost includes labor, licensing, and system support contract costs, and, where applicable, technical refresh cost and additional temporary labor to assist in transitioning cloud-based services into operations. Depending on the implementation timeline, licensing and support costs may carry over into the first year of O&M, reducing the first year's material cost. Additional staffing requirements for the ESPDS, cloud, and DCS remote receiver alternatives had considerable impacts on O&M cost.

The DADDS alternative was the highest-ranking option in the DCS alternative trade study and has a major cost advantage over other alternatives due to a lack of any additional O&M cost to support distribution to DCS direct broadcast users. ESPDS was the highest-ranking option in the GRB alternative trade study that was capable of mitigating RFI at the end-user sites. The remote receiver alternative cost advantage is misleading because it mitigates only GRB RFI at NSOF in Suitland, Maryland. To mitigate RFI at the remaining GRB downlink sites, either the ESPDS or cloud distribution alternatives would need to be implemented. ESPDS O&M cost were dominated by the need to add operational staffing to support the GRB data users.

Table 4.4-8. DCS alternative cost summary.

DCS alternative distribution systems: cost summary							
Alternative	Implementation cost (dollars)	O&M cost (dollars)					Cost of ownership, first 5 years (dollars)
		Year 1	Year 2	Year 3	Year 4	Year 5	
ESPDS	117,334	107,581	121,843	121,843	121,843	121,843	712,287
Cloud (UIx)	604,667	448,707	199,107	199,107	199,107	199,107	1,849,802
Cloud (NIx)	754,431	895,444	645,844	396,244	396,244	396,244	3,484,451
Remote receiver	401,233	201,780	201,780	201,780	201,780	201,780	1,410,133
DADDS	91,520	—	—	—	—	—	91,520

Table 4.4-9. GRB alternative cost summary.

GRB alternative distribution systems: cost summary							
Alternative	Implementation cost (dollars)	O&M cost (dollars)					Cost of ownership, first 5 years (dollars)
		Year 1	Year 2	Year 3	Year 4	Year 5	
ESPDS	376,738	366,511	406,243	406,243	406,243	406,243	2,368,221
Cloud (UIx)	1,020,153	1,115,458	881,554	631,954	631,954	631,954	4,913,027
Cloud (NIx)	1,177,872	1,874,774	1,139,053	1,139,053	889,453	889,453	7,109,658
Remote Receiver	228,693	24,820	24,820	24,820	24,820	24,820	352,793

There are two cloud entries in the table that reflect two different approaches to cloud distribution. The user-initiated transfer (UIx) is a simpler implementation that relies on the user to pull data from cloud storage, similar to NOAA's Big Data Project. The NOAA-initiated transfer (NIx) is a more complex implementation that sends products to users upon arrival in cloud storage. The expected advantage of the NIx implementation is reduced latency. The cloud service costs were dominated by distribution over the internet, and UIx versus NIx implementations had a marginal impact on total cost of services. Rather, it was the labor associated with system complexity that resulted in high cost of ownership.

4.4.3.2 Schedule summary

The estimated time to implement the DCS and GRB alternative architectures is shown in Table 4.4-10. These estimates were used to update the scores of the schedule evaluation criteria used to evaluate the DAR forms in Appendix I.

Table 4.4-10. DCS and GRB alternative implementation timelines.

DCS alternative	Implementation (months)	GRB alternative	Implementation (months)
ESPDS	4	ESPDS	6
Cloud (UIx)	9	Cloud (UIx)	11
Cloud (NIx)	12	Cloud (NIx)	13
Remote receiver	6	Remote receiver	6
DADDS	4	—	—

4.4.4 Findings and recommendations

When considering the risk involved in implementing an alternative DCS distribution system, the DADDS/LRGS option outperformed the remaining alternatives. It is an existing distribution system with redundant webservers at both WCDAS and NSOF. In addition, USGS/EROS operates a DRGS downlink in Sioux Falls, South Dakota, and makes all DCS data available to users registered with NOAA via the LRGS system. The number of DADDS/LRGS data sources should make data highly available to users; however, additional investigation may be warranted to determine operational availability metrics that were not available during the SPRES program. In addition, DADDS and LRGS provide the simplest distribution systems as the data traverses a minimal number of components before distribution to the end user.

The ESPDS and cloud alternatives were the only two GRB distribution systems considered, as they are also capable of distributing data to end users. Of these two, ESPDS is considered a lower-risk alternative when compared to the cloud. It is an existing NESDIS data distribution system built to scale in order to support a growing user base. This reduces any development effort when compared with the cloud alternative, which will require the development team, working collectively with operational staff, to develop methods of fully integrating cloud services into operations. The O&M cost of the cloud alternative is also higher, due to additional operational staff and high data transfer cost. There is a potential to reduce data transfer costs if users can obtain direct connection to the cloud service providers rather than rely on internet transfers.

The remote receiver alternative mitigates RFI only at NSOF and improves data availability at that location for subsequent distribution to end users. The GOES-R program office is planning to decommission GRB at NSOF and terrestrially distribute data from WCDAS and CBU to NSOF. Effectively, this is an improvement to the remote receiver alternative in that it completely eliminates the risk to RFI at NSOF. GRB is generated at WCDAS and CBU and could be distributed terrestrially.

The more complex cloud–NIx implementation, where NOAA initiates data transfer upon file arrival in cloud storage, resulted in increased implementation and O&M costs. Native cloud services should be benchmarked to determine if the additional cost provides adequate performance benefit.

Recommendations

- Since the distribution of data via terrestrial networks is contingent on the reliability of the physical network layer, that information should be collected at the SPRES DRGS and GRB downlink sites. This includes availability and performance of internet services, direct connections to cloud service providers, and direct connection to NOAA distribution via the N-Wave network.
- The availability of direct connections to cloud service providers and the potential savings should be investigated. This has the potential to substantially reduce data transfer costs, but this service varies based on geographic location.
- Determine if full-time staff would be required to operate the DCS system at CBU. If required physical system interaction at NSOF is infrequent, having permanent staff at CBU may not be required.
- Integrate ESPDS and the GOES-R GS at CBU. This will make data available via ESPDS or the cloud alternative in the event a ground system failure occurs at NSOF.
- Investigate performance of cloud services. The more complex cloud–NIx implementation, where NOAA initiates data transfer upon file arrival in cloud storage, resulted in increased implementation and O&M costs. Native cloud services should be benchmarked to determine if the additional cost provides adequate performance benefit.

4.5 Project 5. Alternative Communication Techniques for Satellite Downlinks

4.5.1 Introduction

This project had the objectives of identifying the satellite communication (SATCOM) requirements of GOES next-generation satellites (GOES-NEXT) and determining the ability of current and future SATCOM technologies to meet those needs. Project 5 supports the SPRES program objective area Mitigation Options and Feasibilities. The study identified requirements and constraints for expected GOES-NEXT instrumentation and processed data distribution needs, alternative data distribution/rebroadcast architectures, user-driven performance requirements, and future RFI environments in which GOES may operate. The study then identified candidate satellite rebroadcast technologies and architectures leveraging existing, near-term, and advanced technologies with the potential to meet GOES-NEXT requirements. Additional instruments and/or upgrades to the existing instrument suite could potentially impact data rates, data product volumes, and bandwidth required to broadcast the existing and potentially new data products. Predicting the precise satellite system architecture is not possible at this time due to the ongoing NSOSA study and undefined instrumentation requirements for GOES-NEXT. However, based on available information:

- The sources of the L-band data would be similar to the instrumentation that is currently on GOES R-U series. For example, GRB would be generated from data collected from an improved ABI.
- L-band use will continue for the distribution of GRB, DCS, HRIT, and GOES telemetry, and will continue to use four downlinks with data and users similar to GOES-R.
- Modest increases in bandwidth are expected for GRB and HRIT, while DCS and telemetry bandwidths will remain constant.

The study leveraged data from other SPRES projects. The principal dependencies were on Project 3, which defined the alternative architectures, and Project 7, which produced expected RFI environments. The Project 5 effort used supplemental data from other projects as needed (e.g., equipment data from Projects 2 and 6).

The study conducted a broad survey of potential technologies for the GOES-NEXT distribution system. The focus was to create a comprehensive list of interference mitigation technologies. Twenty-five different technologies or improvements to the current GOES technologies were investigated (Table 4.5-1), several of which have potential for moderate to high RFI reductions. Some of these technologies reduce the desired NOAA signal margin (for example, cancellation/nulling and polarization diversity), but the several dB in margin loss might be offset by large (>20 dB) reduction in interference. These approaches should be evaluated against a broader set of operating conditions to determine if they negatively reduce link availability in some scenarios, but they are likely to provide an overall improvement in reception in an interference-limited environment.

Table 4.5-1. System design technologies.

Technology	Comment (value, risk, cost, etc.)
1. Move signal frequencies within band	Effective for small bandwidth signals; benefit depends on political factors
2. Limiter/blanker	Low RFI value (no advantage over AWGN interference)
3. Wavelets	Low RFI value (no advantage over AWGN interference)
4. Fountain codes	Moderate RFI value, too much additional latency
5. Long interleaver	Moderate RFI value, too much additional latency
6. Code division multiple access (CDMA)/ frequency hopping	Moderate RFI value, minimum processing gain achievable
7. Layered division multiplexing (LDM)	Moderate RFI value, high technical risk (immature)
8. Orthogonal frequency division multiplexing (OFDM)	Low RFI value
9. Multi-user multiple-input and multiple-output (MU-MIMO)	Low RFI value, high cost, high technical risk (immature)
10. Single-user MIMO (SU-MIMO)/satellite diversity	Low RFI value, high cost, high technical risk (immature)
11. Adaptive code modulation (ACM)	Not applicable to broadcast channel
12. Machine learning demodulation	Low RFI value (gain likely only a few dB when SNR low), high technical risk (immature)
13. Intelligent software-defined radio (SDR)	Support new waveform improvements
14. Cancellation/nulling	High RFI value, but high technical risk (immature) and cost
15. Adaptive polarization	Low RFI value because many signals already use both polarizations
16. Choke-ring antennas	Moderate RFI value, but high technical risk (immature)
17. Shielding	High RFI value, but high operational risk and cost.
18. Increase the receive dish size	Low RFI value, high operational risk and cost
19. Earth station diversity	Moderate RFI value, requires double the RF equipment and interconnect
20. Orthogonal signal spectrum overlay (OSSO)	Low RFI value, high technical risk (immature)
21. Satellite diversity	Low RFI value, very expensive
22. Improved modulation and coding selection	Moderate RFI value, not much additional bandwidth or link margin available
23. Polarization diversity	Low RFI value because many signals already use both polarizations
24. Improved preselection filtering	High RFI value, high risk (immature), and cost
25. Improved preselector amplifier	High RFI value, depends on current NOAA receiver design

4.5.2 GOES-NEXT communications requirements

GOES-NEXT communication requirements are driven by a complex set of factors, including projected scientific instrumentation data generation, ground segment design, user performance needs, future processed data products, and an uncertain RFI environment at receiving ground stations. New and improved instruments and/or upgrades to the existing instrument suite would impact data rates, data product volumes, and bandwidth required to broadcast the existing and potentially new data products. User applications enabled by new capabilities would also shape the required data generation and rebroadcast throughput requirements.

In consultation with the NOAA Technology, Planning, and Integration for Observation (TPIO) group to determine the state of definition for GOES-NEXT (GEO-XO), this project sought to determine potential impacts to the current satellite downlink requirements. GEO-XO definition is focused on space-based observation innovations through the NOAA Satellite Observing System Architecture (NSOSA) Study. NSOSA is investigating multiple orbits that would potentially require satellites in geostationary, Tundra, and LaGrange orbits. NOAA is also considering alternative sources for data products that include outsourcing selected products to commercial entities that can provide satellite data and data products from international satellite assets. There is also a possibility of new instruments, particularly those that provide higher-resolution infrared (IR) sounding data across a larger portion of the IR spectrum.

The NSOSA Study's observational objectives encompass a broad set of measurement needs but are not described in sufficient detail as to indicate an expected growth in GOES-related data distribution demands. The NOAA Space Platform Requirements Working Group (SPRWG) of the NSOSA study did not study the communication chain from satellites to ground to users, but deferred those analyses to a future architecture study.[16] The NESDIS System Architecture and Requirements Division (SARD) confirmed that payload definitions are subject to satellite constellation architecture decisions. NOAA is at the beginning of the concept definition phase, and is far from defining the instruments or the changes to existing GOES-R series instrumentation that would have an effect on the current L-band broadcasts.

NOAA’s Stage 1 frequency allocation filing for GOES-NEXT describes the spectrum requirements.[17] As shown in Table 4.5-2, the frequency plan continues with three rebroadcast downlinks in 1675–1695 MHz, as follows:

1. Data Collection Platform Report (DCPR) center frequency changes, but the bandwidth remains the same as in GOES-R. The frequency change to 1675.25 MHz would cause DCPR to be completely co-channel with the proposed LTE deployment in 1675–1680 MHz.
2. GRB center frequency and bandwidth both change. The bandwidth is projected to increase to 16 MHz, which is approximately a 60% increase over GOES-R. The combination of bandwidth increase and change in center frequency would cause the lower end of the GRB downlink to be at 1676 MHz, causing significant (4 MHz) overlap with the proposed LTE deployment in 1675–1680 MHz.
3. HRIT maintains the same center frequency but increases bandwidth to 1.5 MHz. The bandwidth increase represents approximately 25% growth in link capacity.

These changes relative to GOES-R formed the basis for estimating GOES-NEXT throughput demand since no other information was available.

[16]U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, “NOAA Space Platform Requirements Working Group (SPRWG) Final (Cycle 2b) Report” (Washington, DC, March 25, 2018), https://www.nesdis.noaa.gov/sites/default/files/SPRWG_Final_Report_20180325_Posted.pdf.

[17]U.S. Department of Commerce, National Telecommunications and Information Administration, “Quantitative Assessment of Spectrum Usage” (Washington, DC, November 2016), https://www.ntia.gov/report/2016/quantitative-assessments-spectrum-usage.

Table 4.5-2. GOES-NEXT frequency use plan and comparison with GOES-R frequency use.

Service	Lower frequency	Upper frequency	Center frequency	Bandwidth
DCPR	1675.05 MHz	1675.45 MHz	Change from 1679.9 to 1675.25 MHz	No change
GRB	1676 MHz	1692 MHz	Change from 1686.6 to 1684 MHz	Increase from 9.79/10.9 to 16 MHz
Telemetry	1692.996 MHz	1693.004 MHz	1693 MHz (no change)	No change
HRIT	1693.5 MHz	1694.85 MHz	1694.1 MHz (no change)	Increase from 1.21 to 1.5 MHz

Based on these findings, the following assumptions were made regarding rebroadcast of GOES data for the GOES-NEXT/GOES-XO:

1. Regardless of the space observing architecture, GOES-NEXT data will be rebroadcast with downlinks located in the 1675–1695 MHz band.
2. GOES-NEXT will maintain DCPR, GRB, and HRIT as separate downlink services in the 1675–1695 MHz band per the Stage 1 frequency allocation filing.
3. Throughput from GOES-R to GOES-NEXT will be proportional to the projected growth in downlink spectrum bandwidth. As a result, 60% growth in GRB traffic and 25% growth in HRIT over GOES-R is projected, while DCP throughput is projected to remain the same as in GOES-R.
4. To allow for maximum flexibility in GOES-NEXT frequency planning, the study was conducted such that the three downlinks can exist anywhere within the band. Therefore, performance was assessed in terms of co-channel interference from LTE as well as out-of-band interference.

4.5.2.1 Ground segment latency

The ground segment latency associated with the alternative architectures developed during Project 3 was determined given knowledge of the component latencies within the GRB and DCS processing chain. The component latencies were determined from a combination of operational data obtained from the ESPDS operational system and pilot projects conducted to demonstrate cloud service provider implementations. These include the NOAA Big Data Project (BDP), which makes GOES-R Level 1b and GLM instrument products accessible to users via Amazon Web Services, and the NOAA Data Exploitation (NDE) in the Cloud pilot at the NDE Proving Ground (NPG), which demonstrated the capability to ingest data for the purpose of generating and distributing higher-level NDE products.

Figure 4.5-1 shows the end-to-end alternative architectures developed to distribute GRB data during Project 3. The additional components associated with alternative architectures are enclosed with a dashed line. Those components in the yellow box add latency to the GRB product distribution. For the GRB alternative distribution systems, the time to downlink data and distribute from the NSOF satellite operations zone (SOZ) is expected to have similar latencies as the GRB receivers that end users have implemented today. Therefore, these system components are expected to add no latency to the product delivery. The added latency, then, is associated with GOES-R product processing zone (PPZ), ESPDS, and cloud provider components that are being used to distribute data terrestrially to end users.

The ESPDS system measures the average time to distribute all products to its end users each day. ESPDS users are globally dispersed and rely on a mixture of public and private networks to transfer data. The ESPDS data transfer times averaged approximately 4.1 seconds over the period of one month in September 2019. The latency associated with the GOES-R PPZ was also measured during ESPDS testing to be less than one second. NOAA conducted the NDE in the Cloud pilot project to investigate the possibility of conducting product generation using Amazon Web Services. During that pilot project, the time it takes to transfer data from BDP, Simple Storage Service (S3) to the NPG ingest service was measured to be less than one second. Discussions with North Carolina Institute for Climate Studies (NCICS), the managers of that Amazon Web Services S3 bucket, indicate that users typically pull data within five seconds of it arriving in the S3 bucket. Therefore, the cloud provider is expected to add no more than five seconds of latency. These component latencies are also shown in Figure 4.5-1.

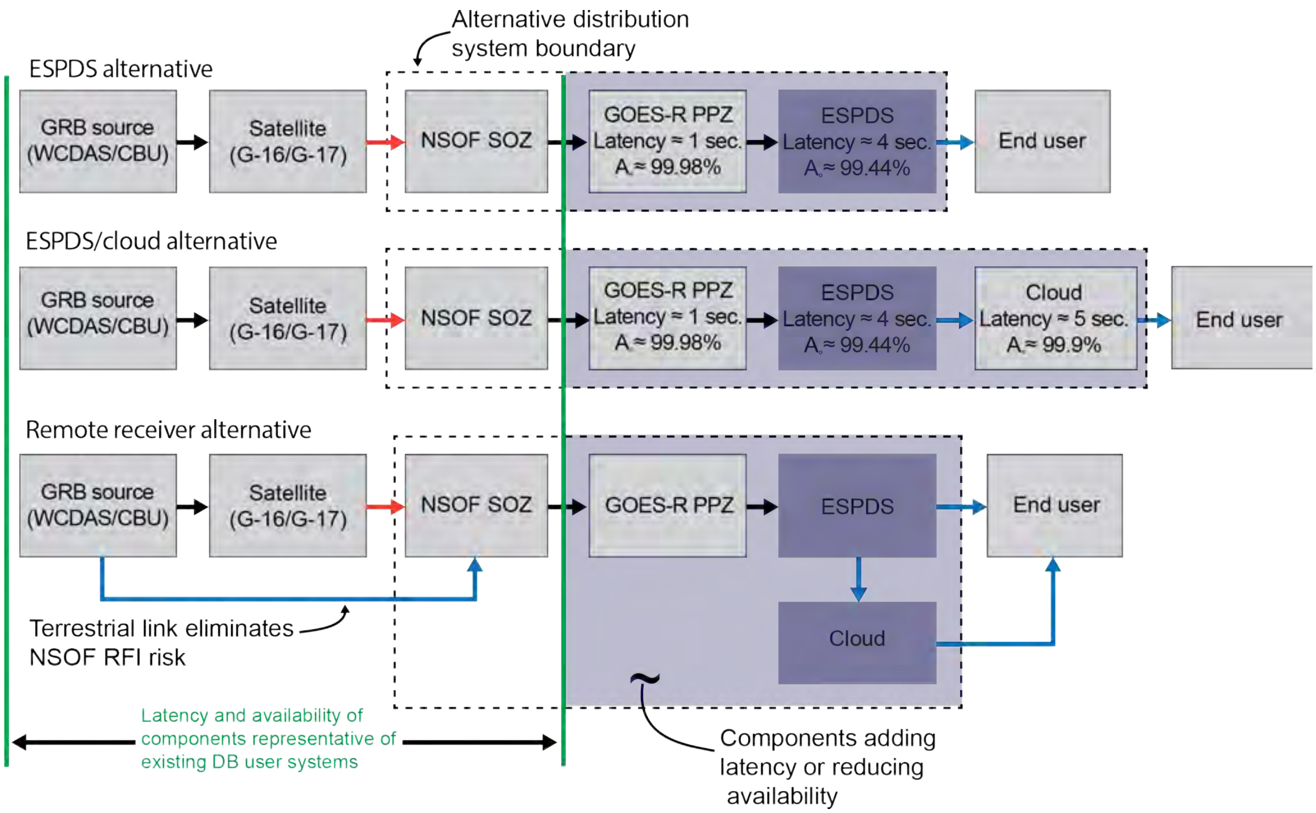


Figure 4.5-1. Alternative GRB data distribution components, associated latency, and availability.

Figure 4.5-2 shows the end-to-end alternative architectures developed to distribute DCS data during Project 3. The additional components associated with alternative architectures are enclosed with a dashed line. Those components in the yellow box add latency to the DCS product distribution. These alternatives consider the DADDS distribution system. Latencies associated with this system were obtained from published test results conducted by the DCS program office. On average, DADDS distributes products to users in less than five seconds.

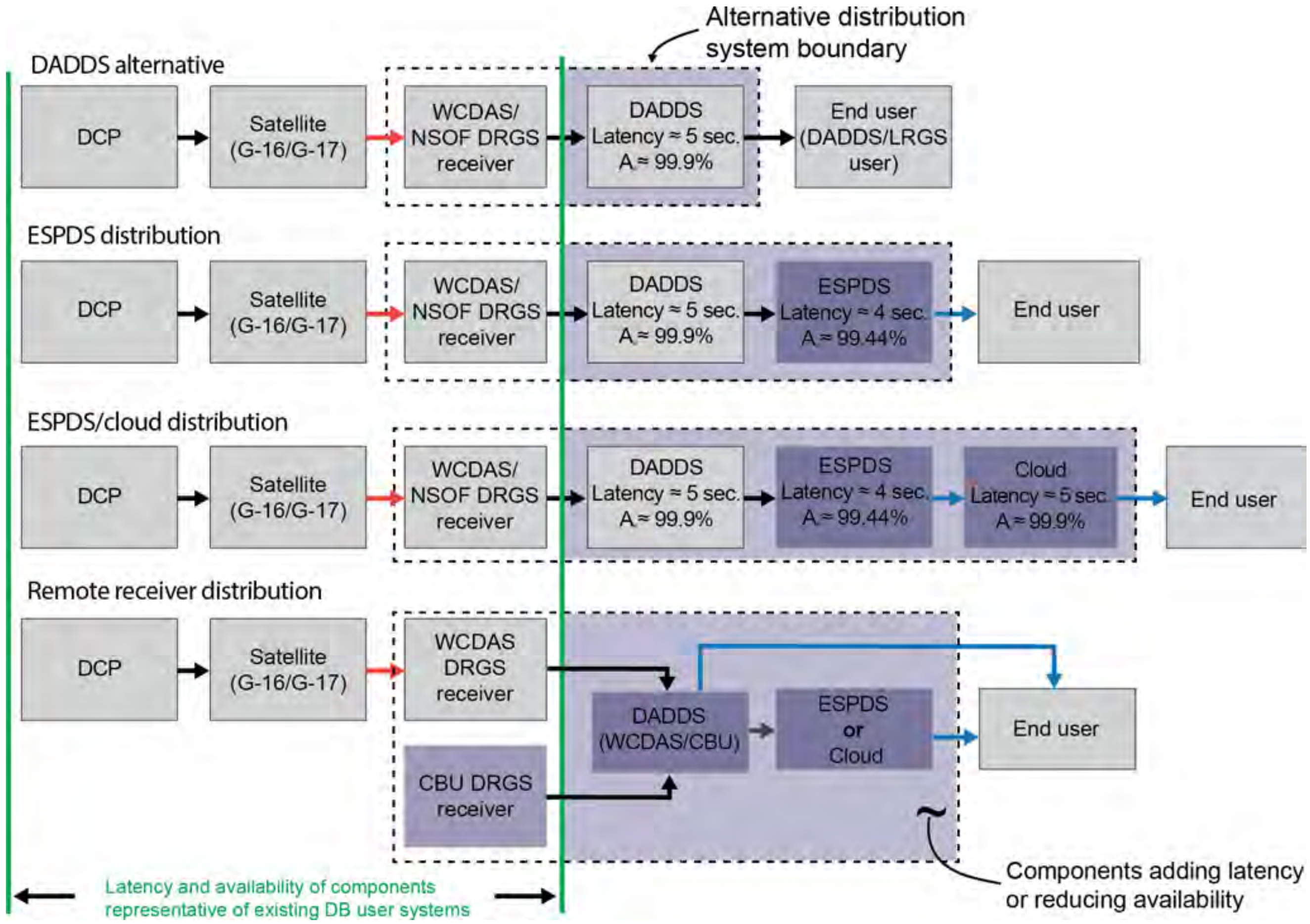


Figure 4.5-2. Alternative DCS data distribution components, associated latency, and availability.

With this information, the total latency added (t_a) to products delivered to end users, through the alternatives shown in Figure 4.5-1 and Figure 4.5-2, is determined by summing the component latencies. Table 4.5-3 presents the expected added latency associated with the alternative architectures. The GRB and DCS remote receiver alternatives do not add latency to the distribution of products to end users, but are additional data sources that improve the availability of data at the NSOF SOZ. The GRB remote receiver alternative would need to be paired with additional distribution components (i.e., ESPDS or ESPDS/cloud), which would add latency. But this implementation is independent of the decision to implement a remote receiver that mitigates the GRB RFI risk at NSOF only. The DCS remote receiver option mitigates the DRGS RFI risk of simultaneous interference at NSOF and WCDAS.

Table 4.5-3. GRB alternative architecture added latency.

Rebroadcast	Alternative	Added latency (t_a)
GRB	ESPDS	5 seconds
	ESPDS/cloud	10 seconds
	Remote receiver	N/A
DCS	DADDS	5 seconds
	ESPDS	9 seconds
	ESPDS/cloud	14 seconds
	Remote receiver	N/A

Table 4.5-4. DCP reporting periods.

Reporting period	DCPs reporting (percent)
Random	3.63
5 minutes	0.07
6 minutes	3.32
10 minutes	0.01
12 minutes	0.02
15 minutes	1.03
30 minutes	0.17
1 hour	90.98
3 hours	0.65
4 hours	0.03
12 hours	0.10

All DCS and GRB alternative architectures can support distribution of data to end users in less than 15 seconds. Table 4.5-4 shows the percentage of 13,327 DCPs, identified during SPRES Project 1, that transmit data at the specified reporting period. This shows that a large majority, 91%, report hourly, which suggests that an additional 15 seconds of latency should not significantly degrade data value. However, there are a small number of DCPs that report at relatively high frequencies. In addition, approximately 4% are random-reporting DCPs that send data when preset triggers are exceeded. In cases where data must be received with low latency, the number of feasible alternatives may be reduced.

It should be noted that data may be traversing public and private networks en route to the end users. These networks may add additional latencies to products before they reach their destinations. To verify sufficient network performance to meet a given user's latency needs, network testing services may be employed in order to verify that network performance is acceptable before an alternative distribution method is chosen.

All DCS and GRB alternative architectures are composed of system components that could be scaled to support additional data growth that may accompany next-generation geostationary satellites. ESPDS has approximately 30% utilization of its initial design capacity and can be scaled to support nine times its existing utilization in terms of daily distribution volume. The cloud was built to facilitate scaling of services, which is one of the main advantages of implementing this alternative. DCS data rates are expected to expand at a relatively slow rate due to the fact that data growth is driven by DCP deployment. Consistent system performance monitoring can provide adequate notice to enable timely scaling of that distribution system.

4.5.2.2 Ground segment availability

The method of determining the availability of alternative distribution architectures was similar to that used to determine latency. The availability of system components was obtained from a combination of operational experience, system requirements documentation, and published service level agreements. The system component availabilities used to calculate A_o (alternative availability) are based on a 30-day operational period. The availability of the PPZ is 99.98% and is based on the GOES-R program ground segment functional and performance specification. The availability of the cloud service provider is based on the advertised Amazon Web Service S3 instance availability, below which Amazon Web Service offers to begin reducing service cost. The availability of DADDS is estimated based on operator experience, and A_o data is not collected.

Operational data outages are recorded for ESPDS, and system availability is calculated based on the previous 30 days. Because that system continuously undergoes changes, there is variance associated with operational availability. However, over the period from August 2018 through

October 2019, the system operated with at least a 99.44% availability (planned and unplanned). As shown in Figure 4.5-3, a trend toward increased system availability can be seen, which suggests that it should continue to improve as system deficiencies are remediated.

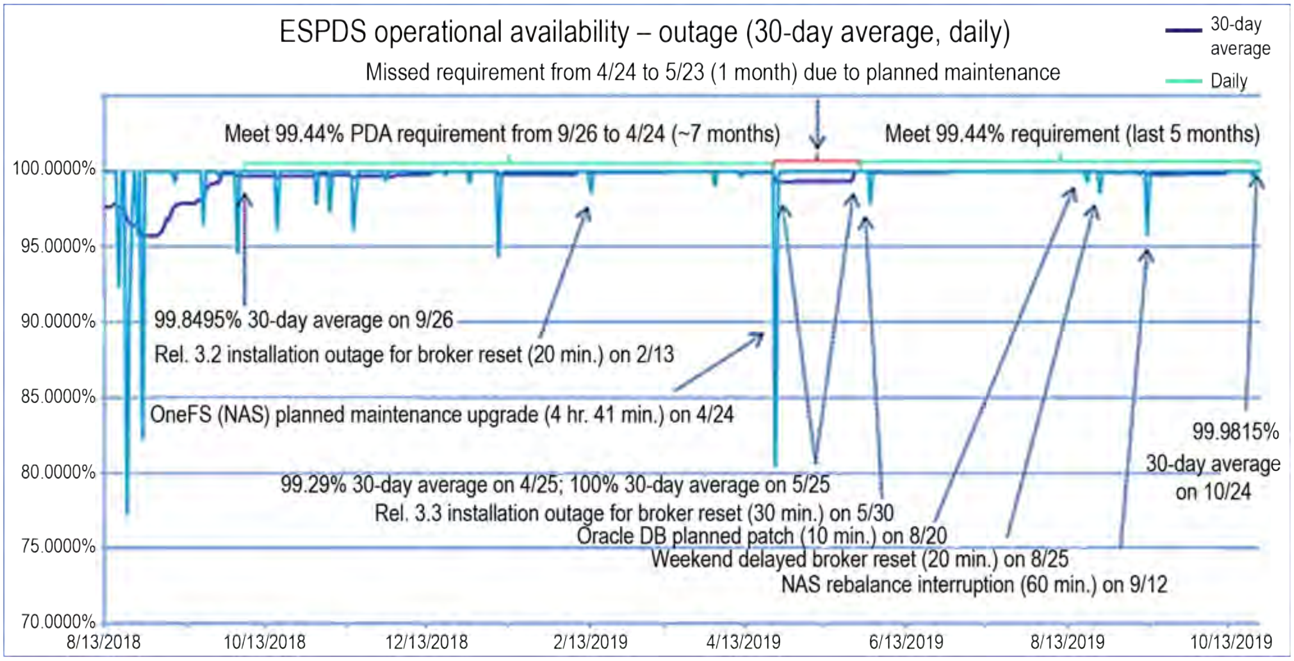


Figure 4.5-3. Thirty-day ESPDS operational availability.

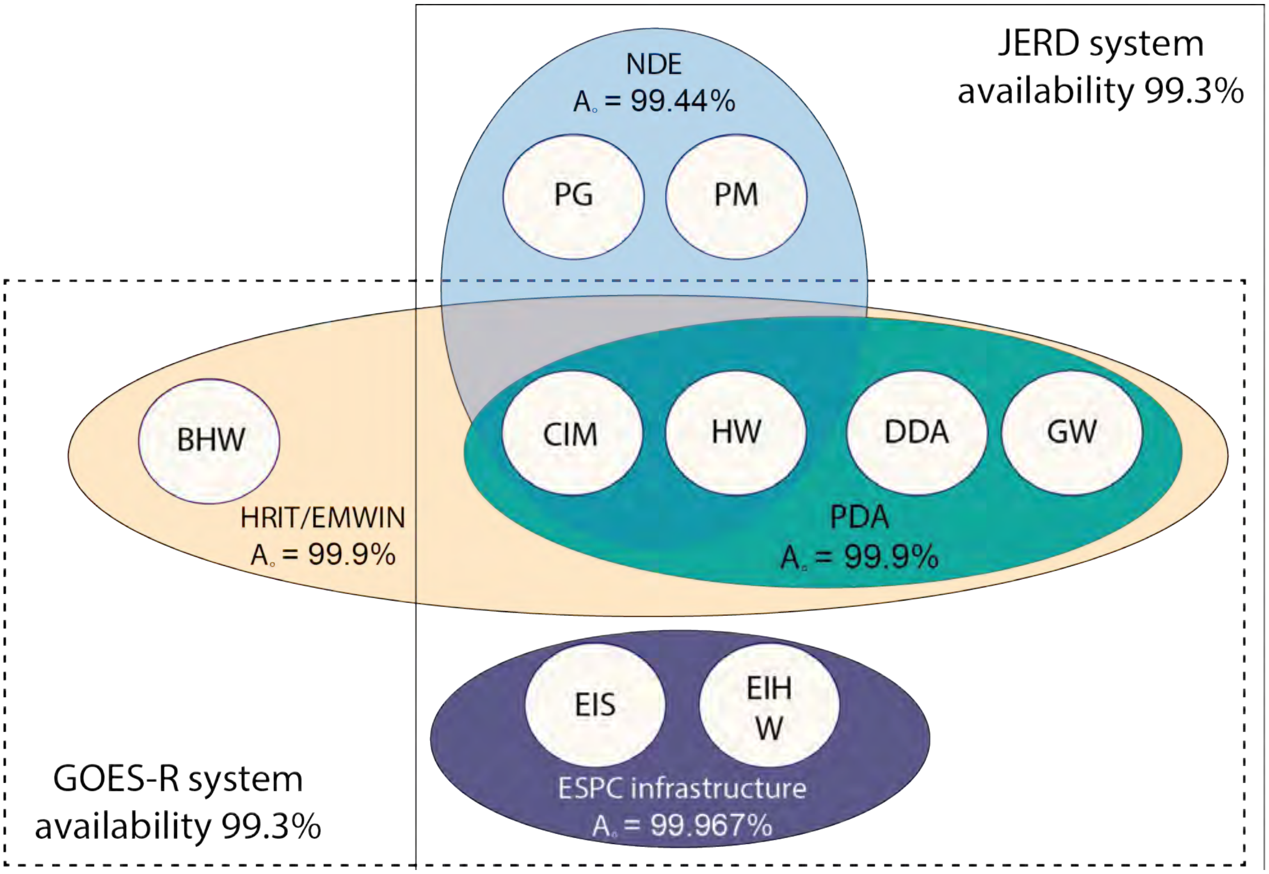


Figure 4.5-4. ESPDS system operational availability (A_o) Venn diagram.

When examining ESPDS system availability, it should be considered that the system serves several functions, some of which would not be utilized in the alternative distribution architectures. This is illustrated in Figure 4.5-4, where Product Distribution and Access (PDA) and Environmental Satellite Processing Center (ESPC) infrastructure components would be used to distribute data, but HRIT/EMWIN broadcast hardware and NDE product generation (PG) and product management (PM) components would not need to factor into the alternative architecture system availability. Therefore, the availability of the ESPDS component shown is a conservative value of 99.44%.

Alternative availability is based on the product of the availability of each component within the alternative data processing chain. The availability of GRB and DCS alternative distribution systems are shown in Table 4.5-5. The remote receiver in each case serves to increase data availability to the alternative distribution system that NOAA selects to implement. Therefore, it will not affect data availability to the end user. Note that alternative availability can be improved by placing components in parallel. For instance, placing ESPDS at CBU and NSOF in parallel could increase the availability of that system from 99.44% to 99.997%.

Table 4.5-5. GRB alternative distribution system availability.

Rebroadcast	Alternative	System availability (percent)
GRB	ESPDS	99.42
	Cloud	99.3
	Remote receiver	NA
DCS	DADDS	99.9
	ESPDS	99.42
	Cloud	99.3
	Remote receiver	NA

4.5.3 Interference tolerance/mitigation needs

The amount of RFI to be mitigated is the predicted RFI in excess of an established protection criterion. The analysis here assumes that an exclusion zone will be established such that RFI remains below the interference threshold at some desired confidence level. The mitigation needs are then quantified by the amount of RFI that exceeds the threshold at higher confidence levels.

Consider Figure 4.5-5, which shows RFI as a function of exclusion zone distance for Wallops DCS reception. Suppose that protections are established such that RFI does not exceed the threshold 95% of the time. This corresponds to a protection distance of approximately 300 km. The remaining RFI potential for DCS is up to 52 dB RFI 4% of the time and 52–65 dB 1% of the time. These RFI risk levels provide a gauge for evaluating the effectiveness of proposed mitigation technologies.

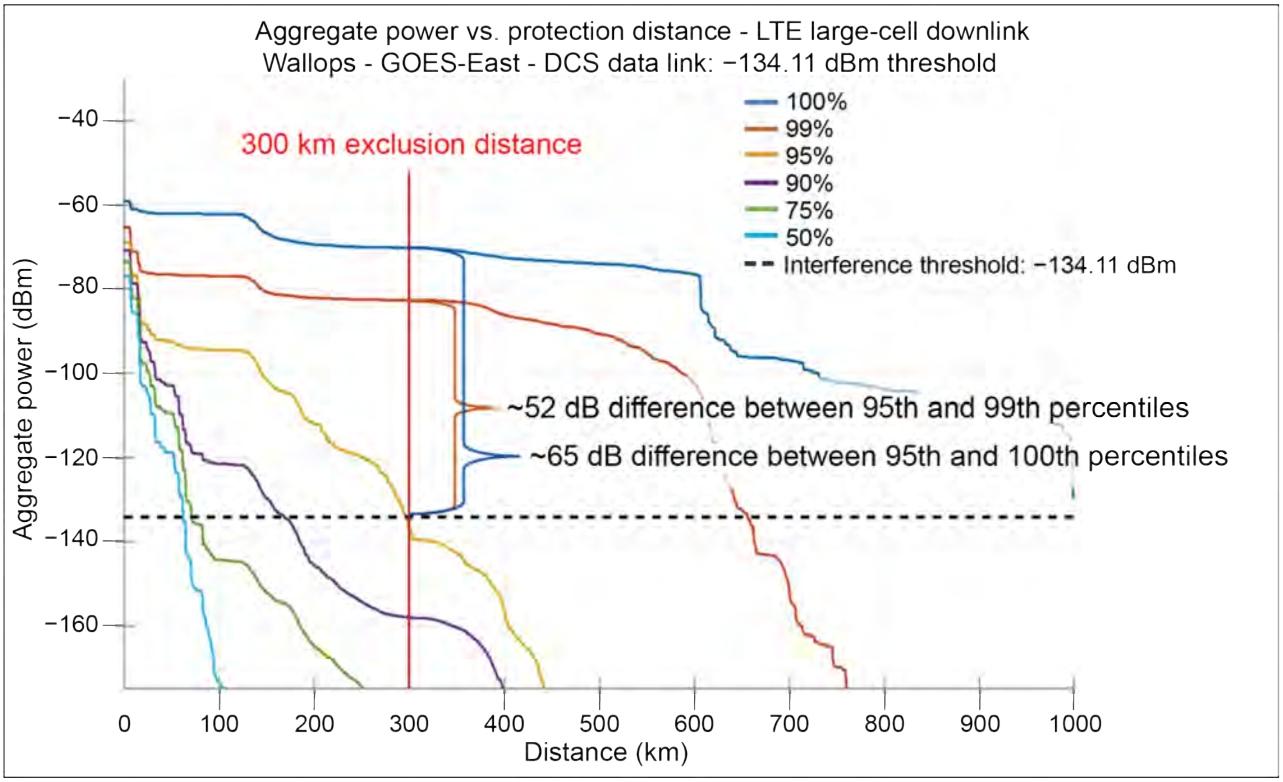


Figure 4.5-5. The amount of RFI reduction required to mitigate interference can be found as the difference between the threshold and RFI for a given confidence level.

This approach was applied to each site using Project 7 RFI projections assuming that sharing rules establish protections at the 95th percentile without any additional technology requirements applied to GOES. Table 4.5-6 lists the RFI threshold exceedance levels for each of the GOES Federal ground stations being studied in Project 7, with RFI from LTE downlinks deployed in the 1675–1680 MHz band. Data shows that RFI reductions depend on the location and scenario. GOES-NEXT technologies would need reductions ranging from 3 dB to in excess of 65 dB to ensure GOES data reception.

Table 4.5-6. RFI levels in excess of the 95% threshold for each GOES Federal ground station.

Location	Ground station	RFI difference (dB) (100%–95%)	RFI difference (dB) (99%–95%)
Wallops Island, VA	DCS East	65.25	52.81
Wallops Island, VA	DCS West	61.30	45.67
Vicksburg, MS	DCS East	56.09	33.99
Wallops Island, VA	GRB East	45.71	33.54
Wallops Island, VA	GRB West	48.67	31.93
Suitland, MD	DCS East	73.14	26.87
Suitland, MD	DCS West	60.51	24.81
Cape Canaveral, FL	GRB East	38.08	24.05
Columbus Lake, MS	DCS East	38.68	20.94
Rock Island, IL	DCS East	54.98	17.55
Rock Island, IL	DCS West	49.59	15.57
Norfolk, VA	GRB East	39.91	15.32

Table 4.5-6. cont.

Table 4.5-6. RFI levels in excess of the 95% threshold for each GOES Federal ground station.

Location	Ground station	RFI difference (dB) (100%–95%)	RFI difference (dB) (99%–95%)
St. Louis, MO	DCS East	41.93	15.20
Cincinnati, OH	DCS East	55.95	14.70
Sioux Falls, SD	DCS East	61.76	14.42
Houston, TX	GRB West	30.26	13.55
Miami, FL	GRB East	29.55	13.49
Kansas City, MO	GRB West	31.99	12.92
Monterey, CA	GRB West	21.10	12.87
Sacramento, CA	DCS West	34.76	12.77
Sioux Falls, SD	DCS West	48.75	12.72
Houston, TX	GRB East	28.72	12.19
Miami, FL	GRB West	27.76	11.78
Stennis, MS	GRB East	26.79	11.37
Suitland, MD	GRB East	39.72	9.93
Suitland, MD	GRB West	26.61	9.02
Fairmont, WV	DCS East	34.40	8.94
Hickam AFB, HI	GRB West	23.99	8.35
Monterey, CA	GRB East	25.31	8.24
Fairmont, WV	DCS West	33.14	8.08
Kansas City, MO	GRB East	22.43	8.01
Fairmont, WV	GRB East	18.77	7.80
Boise BOR, ID	DCS West	17.07	7.64
Boulder, CO	GRB East	17.36	7.64
Fairbanks, AK	GVAR	14.04	7.54
Ford Island, HI	GRB West	13.84	7.52
Norman, OK	GRB West	20.20	6.97
Norman, OK	GRB East	20.22	6.91
College Park, MD	GRB West	17.77	6.60
Anchorage, AK	GRB West	14.05	6.08
College Park, MD	GRB East	15.54	5.98
Boise NIFC, ID	DCS West	9.93	4.63
Omaha, NE	GRB West	22.04	4.31
Boulder, CO	GRB West	10.28	4.19
Omaha, NE	GRB East	18.54	4.03
Fairmont, WV	GRB West	11.65	3.64
Elmendorf AFB, AK	GRB West	7.51	3.26
Huntsville, AL	GRB East	9.60	3.15
Huntsville, AL	GRB West	12.23	3.12
Omaha, NE	DCS West	**	**

Omaha, NE (USACE) was not covered in the analysis.

4.5.4 Relevant user operational requirements

The study considered users' operational requirements and ground system infrastructure impacts in evaluating RFI mitigation technologies presented in the trade study. Factors affecting ground station implementation, concept of operations, and acquisition and operational budgets were considered. Also taken into consideration were size, weight, cooling, and prime power (antenna and receive chain) of the equipment that would either replace or modify existing ground equipment infrastructure that includes antenna size, number of antennas, and receive chain

Antenna field size: The largest impact to the ground station operations and infrastructure are solutions that require the additional space and facility support for larger antennas, shielding, and additional antennas for data downlink diversity. Impacts can also be realized in the concept of operations when accommodating concepts that require additional antennas.

Prime power: Operational impacts will also exist at many of the Federal sites for those techniques that require significant increases in prime power for receive chain equipment or additional receive chain equipment (e.g., preamplifiers and replacement of existing LNAs with cryogenically cooled LNAs). The observations made during SPRES Project 6 and the team's knowledge of existing sites indicate that only the largest sites (e.g., Fairbanks, Fairmont, and Wallops Island) may be able to provide the resources to accommodate these modifications. The Air Force MARK IV-B systems may be able to accommodate these changes with major modifications of the existing receiver chain. The most limited sites would be the DCS, commercial GRB, and HRIT sites due to limited space and power, as well as cost considerations.

Mobility: All ground stations are fixed locations with fixed receivers, so technologies requiring receiver mobility are not practical.[18]

Past upgrades: Past experience suggests that the least impact to ground system operations results from techniques that incorporate RFI protection through system improvements that do not increase the system's footprint (e.g., error correction coding, improved filtering, and modulation techniques). Polarization techniques can be and have been used as well; however, they will most likely impact the antenna feeds. Every generation of GOES satellites has changed some or all of these.

DCS is a legacy system spanning the generations of GOES satellites. Legacy terrestrial in-situ platforms have changed little over the years, with the satellite upconverting the UHF transmissions to L-band. Changing modulation techniques would not be feasible, from an operational or cost point of view, since it would require replacement or upgrade of the thousands of platforms in service. Solutions that use signal processing and/or filtering and processing in the receive chain would be operationally feasible by limiting the impact to modifying or upgrading the receiver equipment chain.

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[18]U.S. Navy does deploy AN/SMQ-11 HRIT terminals on ships, but they are not part of this technology study. The focus here is on the land-based ground stations.

Cost impacts: Cost impacts of new technologies are divided into two categories:

1. Nonrecurring engineering costs: These are costs associated with technology research and development activities needed to mature and evaluate their performance.
2. Acquisition costs: These are costs associated with implementation. Costs allocated to satellite features are approximately 10 times more expensive (based on system cost data) than ground system infrastructure changes. Ground system costs vary and are generally ranked from high to low in the following order: antenna systems including LNAs; replacement of receiver systems and/or the addition of receiver components; modification of filters; and upgrade of existing software-driven components such as demodulation and decoding that utilize programmable digital signal processing.

Additional facility cost impacts will also generally follow the order of acquisition costs. Receiver components that require large increases in prime power will increase the cost significantly more than those that do not. Equipment size can require additional facility floor space and cooling, which can be a major cost driver. Existing ground stations that upgraded to GRB have already gone through considerable changes due to the replacement of GVAR antenna systems and receive chains with GRB. Commercial users of GRB also required total replacement of a $50,000 system with one that costs $250,000; however, the new system receives 15 times the data volume and higher-resolution data.

GOES-Next RFI reduction solutions that limit the implementation to ground changes would offer the lowest acquisition and operational cost and the greatest flexibility to be modified through the satellite system lifecycle.

4.5.5 Satellite architecture

The GOES-R geostationary satellites are located at 75.2° and 137.2° west longitude. The large angular separation between the satellites could potentially provide some diversity gain to earth stations if the same data is broadcast from both satellites. The L-band spectrum is used to broadcast from the GOES-R spacecraft to earth stations. Thus, the interference is from LTE base stations to NOAA earth stations.

Low earth orbit (LEO) satellite architectures are not appropriate for these data broadcasts. Each satellite would have to see the full coverage of DCPs and be able to relay the data to all earth station sites with low latency. This could be achieved only through extensive LEO crosslinks. LEO architectures may provide some satellite diversity but would also require earth stations to have tracking antennas. This overly complex architecture would have little advantage over a GEO network.

4.5.6 Current and emerging SATCOM technologies

This section identifies and evaluates options to meet the rebroadcast downlink performance requirements for GOES-NEXT. This is challenging because technical solutions for GOES-NEXT downlink performance rely on a complex interaction of technology performance and system constraints. Updates to current technologies could significantly affect space and ground segments.

4.5.6.1 General considerations

The following are some general RFI mitigation considerations:

- Filtering: If overload is an issue, RF filtering may be required. Filtering, at the receiver, may also be needed to control intermodulation products. Additional filtering at the LTE base station to reduce out-of-band emissions (OOBE) further than the specification has not been shown to be required.
- Spatial separation: The default RFI approach is to increase the separation between NOAA and LTE operations to increase the RF isolation from the LTE transmitter to the NOAA receiver.
- Spectrum assignments: The current NOAA bandwidth requirement is 11.6 MHz. The future NOAA bandwidth requirement is 17.9 MHz. One approach would be for NOAA and LTE to divide the band. This is not feasible, unless the future NOAA bandwidth requirement can be reduced using more spectrally efficient modulation. This, of course, will have performance implications. With no change in the modulation, the LTE allocation will overlap at least 2.9 MHz of the NOAA spectrum.
- Design alternatives: The following general design alternatives were considered:
    - Accept reduced availability for lower-priority data packages. Operate the lowest-priority data packages closer to or in the interference, while the highest-priority packages have maximum separation from the interference.
    - Use the full bandwidth for all four NOAA signals and use a variety of spreading techniques (code-division multiple access [CDMA], layered division multiplex [LDM], interleaving, etc.) to operate in the interference.
    - Employ a variety of diversity techniques (earth station, satellite, polarization, multiple-input and multiple-output [MIMO], etc.) to reduce the interference.
    - Reduce the interference power input to the receiver through a variety of techniques, including cancellation, nulling, and shielding.

Table 4.5-7 summarizes the 25 technologies evaluated in the above general considerations.

Table 4.5-7. Technologies considered for GOES-NEXT study.

Method	Description
1. Move signal frequencies within band	Optimize the frequency plan by moving the DCP, GRB, HRIT/EMWIN, and telemetry signal center frequencies to minimize RFI risks from LTE. The expanded bandwidth of GOES-NEXT rebroadcast downlinks does not accommodate all signals without in-band sharing with proposed LTE systems.
2. Limiter/blanker	A limiter limits RF power above a specified threshold, whereas a blanker (often implemented as a notch filter) attenuates narrowband signals. Limiters and blankers are not effective against the expected Gaussian-noise-like nature of the RFI.
3. Wavelets	Wavelets enable signals to be decomposed into desired and undesired components but are not effective against the expected Gaussian-noise-like nature of the RFI.
4. Fountain codes	Fountain codes are a form of forward error correction (FEC) coding that allows data to be recovered from a subset of the total data. Fountain codes are not effective where interference is Gaussian-noise-like and latency is constrained.
5. Long interleaving	Interleaving spreads a burst of interference over a large number of symbols, allowing FEC to correct the affected symbols. Interleaving is not effective where interference is Gaussian-noise-like and latency is constrained.
6. CDMA/frequency hopping/spread spectrum	These techniques apply pseudo-random codes to spread the signal in the frequency domain to achieve a much wider bandwidth (hence spread spectrum) signal and increase the signal's resistance to interference sources. Spreading is not effective against broadband Gaussian interference, and GOES downlink spectrum is not wide enough to accommodate spreading of all the rebroadcast links without significant overlap.
7. Layered division multiplexing (LDM)	LDM, also known as cloud transmission (cloud Txn), involves the superposition of multiple signals, with different transmit power levels, forming a multilayer signal. LDM would reduce the overall link margin (reducing link availability) and may not be effective as an interference management technique.
8. Orthogonal frequency division multiplexing (OFDM)	OFDM is a method of digital signal modulation in which a single data stream is divided into a large number of orthogonal, digitally modulated narrowband channels. It is not an effective mitigation technique against broadband interference that is superimposed on the desired signal.
9. Single-user MIMO	SU-MIMO is a multi-transmitter and -receiver technology for wireless communication that allocates the bandwidth of a wireless access point to a single device. SU-MIMO can be used to remove broadband interference but requires multiple antennas.
10. Spatial multi-user MIMO	Spatial MU-MIMO could use multiple ground stations that are separated by kilometers and receive signals independently, but it requires significant collaboration among them to recover signal information.
11. Adaptive code modulation (ACM)	ACM matches modulation and coding schemes to the conditions of the radio link. ACM for broadcast such as GOES would reduce performance to all users based on the most disadvantaged user.
12. Machine learning (ML) modulation/demodulation	ML applications for communication systems is a growing field, but the technology has not been shown to be effective or mature for use in interference mitigation.
13. Software-defined radio (SDR)	SDR radios allow software updates to earth stations to support new waveforms, as well as processing that can improve performance and mitigate interference as these approaches are developed. While not a stand-alone approach, using an SDR for receivers is an enabling technology.
14. Interference cancellation/ nulling	Interference cancellation system would use several monitoring antennas that surround the NOAA satellite downlink dish antenna to encode the interference signal and subtract it from the desired GOES signal that is received on the GOES downlink antenna. The approach is applicable to co-channel interference but not to adjacent-channel or out-of-band interference. Nulling uses beamforming to apply antenna gain nulls in the direction of the interference. The effectiveness of nulling depends on the directionality of the interference.
15. Adaptive polarization	Polarization can be adapted to minimize the impact of interfering signals by maximizing orthogonality of the desired and unwanted signal. This method would have limited effectiveness due to the significant polarization variations expected in the LTE signal environment produced by LTE antenna sidelobes and emissions from multiple base stations.

Table 4.5-7. cont.

Table 4.5-7. Technologies considered for GOES-NEXT study.

Method	Description
16. Choke-ring antenna feed	First designed by NASA's Jet Propulsion Laboratory, choke-ring antennas are used as a feed on an earth station dish antenna to reject the off-angle signals. Choke-ring antennas tend to have non-optimal gain patterns toward the dish antenna; as a result, they may reduce the link margin by a few dB. Choke-ring antennas are used to mitigate multipath fading, and their potential for mitigating wideband interference would need to be analyzed.
17. Antenna shielding	Shielding refers to installing artificial barriers or shrouds on or around the earth station dish to shield the antenna from radiation outside the main beam. Effective shielding requires that the shield be taller than the feed height, which may be prohibitively high for GOES locations with large antennas and/or limited space (e.g., on rooftops).
18. Increase dish size	Increasing the size of an earth station antenna increases the peak gain and the resulting SNR of the desired signal, which in turn increases the margin of the link. However, sidelobes, where much of the LTE energy would be directed, are not reduced.
19. Earth station diversity	Earth station diversity uses multiple antennas that are spread sufficiently far apart so that the interference becomes uncorrelated. Antennas located hundreds of kilometers apart are required given the large size of the expected exclusion zones (for downlink sharing).
20. Orthogonal signal spectrum overlay (OSSO)	OSSO is a digital modulation technique in which the information is spread over many time intervals. OSSO is a new technology, and no studies on its effectiveness in mitigating wideband interference could be found.
21. Satellite diversity	Utilizing multiple satellites for one ground station can improve link quality and resilience to interference. In the current GOES system, only limited data is replicated on both GOES-East and GOES-West. Therefore, satellite diversity would be limited to only a small percentage of the data, or additional satellites would be required. Finally, satellite diversity requires that the earth station is able to see both satellites. A beamforming antenna solution could facilitate this.
22. Improved modulation and coding	Improved modulation and coding selection means selecting a more appropriate modulation and coding for the signals to improve performance. For example, the DCP channel is narrowband (400 kHz), and there may be an opportunity to increase bandwidth and coding gain to improve link margin. A narrower, more spectrally efficient waveform might be selected for GRB so that it can avoid interference.
23. Polarization diversity	Polarization diversity techniques require two receivers operating on orthogonal polarizations. GOES could transmit circular polarization, while the ground stations receive both vertical and horizontal polarizations. In the simplest approach, the receiver could switch between these two signals based on the best signal quality, assuming that interference is much less on one linear polarization compared to the other polarization.
24. Improved preselection filtering	Superconducting filters pose high potential for providing the protection from RFI. The filters are capable of reducing out-of-band interference without degrading the sensitivity, amplitude, phase, or group delay stability, or adding dispersion within the bandpass.
25. Improved preselector amplifier	The current Harris GRB receivers use a downconverter with very high (55–60 dB) preamplifier gain. This large amount of gain can create large signal levels and adjacent-channel intermodulation of the LTE RFI signal, which would significantly decrease the frequency-dependent rejection (FDR) when attempting to receive a NOAA satellite downlink signal. Using a lower gain can improve FDR of adjacent and out-of-band signals.

4.5.6.2 GOES-NEXT rebroadcast design trade study

The trade study of the candidate technologies and architectures assesses their expected performance, costs, and risks. A number of technology evaluation metrics and scoring factors were used. The evaluation criteria are described in Table 4.5-8, while Table 4.5-9 shows the ranking criteria for each evaluation criterion. The latency is based on the allowable user delays. Table 4.5-10 shows the weighting used with each ranking criterion. These values were based on reasonable estimates and are not from an official source.

Table 4.5-8. Evaluation criteria description.

Evaluation criteria	Description
Latency	• How much latency performance is enabled by the alternative?
Performance potential	• How much RFI mitigation performance is enabled by the alternative?
Technology combination	• How likely is the technology to be able to significantly add RFI mitigation performance when combined with other technologies?
Complexity	• Combination of cost, technical risk, and schedule risk: –Cost: All costs to implement the alternative. Costs are considered as a percentage increase compared to the existing implementation. –Technical risk: Technical risk is measured by the maturity of the underlying technologies and expected level of effort required to reach a sufficient level of maturity for implementation. –Schedule risk: Schedule risk is measured by the level of effort required to implement the alternative. Schedule risk considers whether the technology has been implemented before and whether changes to infrastructure (e.g., data networks) are needed to support the proposed solution.
Operational risk	• How much operational risk does the alternative introduce? Operational risks include aspects of system operation that would be different from existing GOES operations.
Scalability	• How easily and efficiently can the alternative be scaled out to handle increases in data load or users, without requiring significant additional costs or a re-architecture/redesign?

Table 4.5-9. Ranking criteria.

Evaluation criteria	Score = 0	Score = 1	Score = 2	Score = 3	Score = 4
Latency	—	>5 sec	>1 sec	<1 sec	—
Performance potential	>0 dB	>2 dB	>5 dB	>10 dB	>15 dB
Technology combination	—	3 or more technology conflicts	2 or 3 technology conflicts	0 or 1 technology conflicts	—
Complexity	Impractical	High	Medium	Low	—
Operational risk	—	High	Medium	Low	—
Scalability	—	Satellite changes	Uplink ground station changes	User ground station changes	—

Table 4.5-10. Ranking criteria weighting.

Evaluation criteria	Weighting (percent)
Latency	20
Performance potential	30
Technology combination	10
Complexity	20
Operational risk	10
Scalability	10
Total	100

Technology scalability is a measure of the difficulty of implementing the technology to the NOAA data distribution system incrementally. For example, if the technology requires the modification of the satellite, then this technology is not easily inserted incrementally because of the long satellite design timelines and the inability to make changes to the technology once the satellite is launched.

Table 4.5-11 shows the location of each technology within the NOAA data distribution system (in the uplink ground stations, in the satellite, or in the user ground station). An “X” means that inserting the technology impacts the design of the specific system segment. An “N” means that more assets are required. In the far right column, “Scalability score,” the score is 3 when the technology impacts the user ground station, 2 if it impacts the uplink ground station, and 1 if it impacts the satellite. This analysis assumes that a bent-pipe satellite architecture is used; in bent-pipe architecture, the satellite design would not have to change if the NOAA signal frequencies were to be moved.

Tables 4.5-12 through 4.5-16 present a summary of the scores and ranks for the GRB, DCP, HRIT, and telemetry signals. The numbers (1=low, 2 or 3=high) represent the scores. The highest-ranking technologies for GOES-NEXT are identified: shielding (#17), cancellation/nulling (#14), moving frequencies within a band (#1), improved preselection filtering (#24), and improved preselector amplifier (#25). There are significant differences in the RFI mitigation technology rankings for each signal type due to signal bandwidth, antenna size, signal polarization, and other factors.

Table 4.5-11. Technology location (uplink, satellite, or ground station) is used to determine the technology scalability.

	Uplink ground station		Satellite		User ground station					
Technology list	Uplink data processing	Modem	Power amplifier	Antenna	Antenna	Pre-selection filter	Pre-amplifier	Modem	Downlink data processing	Scalability score
1. Move signal frequencies within band	—	—	—	—	—	X	—	X	—	3.0
2. Limiter/blanker	—	—	—	—	—	—	—	X	—	3.0
3. Wavelets	—	—	—	—	—	—	—	X	—	3.0
4. Fountain codes	—	X	—	—	—	—	—	X	—	2.0
5. Long Interleaver	—	X	—	—	—	—	—	X	—	2.0
6. CDMA/frequency hopping	—	X	—	—	—	—	—	—	—	2.0
7. LDM	X	X	—	—	—	—	—	—	X	2.0
8. OFDM	—	X	—	—	—	—	—	—	—	2.0
9. MU-MIMO	X	X	—	X	X	N	N	X	X	1.0
10. SU-MIMO	X	X	—	X	X	N	N	X	X	1.0
11. ACM	—	X	—	—	—	—	—	X	—	2.0
12. Machine learning demodulation	—	—	—	—	—	—	—	X	—	3.0
13. Intelligent SDR	—	—	—	—	—	—	—	X	—	3.0
14. Cancellation/nulling	—	—	—	—	X	N	N	X	X	3.0
15. Adaptive polarization	—	—	—	X	X	—	—	X	—	1.0
16. Choke-ring feed	—	—	—	—	X	—	—	—	—	3.0
17. Shielding	—	—	—	—	X	—	—	—	—	3.0
18. Increase the receive dish size	—	—	—	—	X	—	—	—	—	3.0
19. Earth station diversity	—	—	—	—	N	N	N	N	X	3.0
20. OSSO	X	X	—	—	—	—	—	X	X	2.0
21. Satellite diversity	X	N	N	N	X	—	—	—	X	1.0
22. Improved modulation and coding selection	—	X	—	—	—	—	—	X	—	2.0
23. Polarization diversity	—	—	—	X	X	—	—	X	X	1.0
24. Improved preselection filtering	—	—	—	—	—	X	—	—	—	3.0
25. Improved preselector amplifier	—	—	—	—	—	—	X	—	—	3.0

Note: Scalability score is 3 if the technology impacts the user ground station, 2 if it impacts the uplink ground station, and 1 if it impacts the satellite. Shading is used to highlight ranking.

Table 4.5-12. GRB signal technology trade study summary.

Evaluation criterion	Performance			Risks		Scalability		Average score	Margin	Rank
	Latency	Interference mitigation	Technology combination	Complexity	Operational risk					
Weight	20%	30%	10%	20%	10%	10%		100%	(percent)	
1. Move signal frequencies within band	3	1	1	3	3	3		2.2	31	7
2. Limiter/blanker	3	0	3	2	3	3		1.9	41	14
3. Wavelets	2	0	3	2	3	3		1.7	47	17
4. Fountain codes	1	2	3	3	3	2		2.2	31	7
5. Long interleaver	1	2	3	3	3	2		2.2	31	7
6. CDMA/frequency hopping	3	0	2	2	3	2		1.7	47	17
7. LDM	2	0	3	2	3	2		1.6	50	23
8. OFDM	3	0	2	2	3	2		1.7	47	17
9. MU-MIMO	2	3	3	1	2	1		2.1	34	11
10. SU-MIMO	2	3	3	1	2	1		2.1	34	11
11. ACM	2	1	3	1	2	2		1.6	50	24
12. Machine learning demodulation	2	1	3	2	3	3		2.0	38	13
13. Intelligent SDR	2	2	3	2	3	3		2.3	28	6
14. Cancellation/ nulling	3	4	3	3	2	3		3.2	0	1
15. Adaptive polarization	3	0	3	2	2	1		1.6	50	21
16. Choke-ring antennas	3	2	3	2	2	3		2.4	25	5
17. Shielding	3	4	3	2	1	3		2.9	9	3
18. Increase the receive dish size	3	1	3	1	1	3		1.8	44	15
19. Earth station diversity	3	1	3	1	1	3		1.8	44	15
20. OSSO	3	0	2	2	3	2		1.7	47	17
21. Satellite diversity	2	0	3	1	2	1		1.2	63	25
22. Improved modulation and coding selection	3	1	3	2	3	2		2.1	34	10
23. Polarization diversity	3	0	3	2	2	1		1.6	50	21
24. Improved preselection filtering	3	3	3	2	2	3		2.7	16	4
25. Improved preselector amplifier	3	3	3	3	3	3		3.0	6	2

Note: The numbers (1=low, 2 or 3=high) represent the scores. Shading is used to highlight ranking.

Table 4.5-13. DCP signal technology trade study summary.

Evaluation criterion	Performance			Risks		Scalability	Average score	Margin	Rank
	Latency	Interference mitigation	Technology combination	Complexity	Operational risk				
Weight	20%	30%	10%	20%	10%	10%	100%	(percent)	
1. Move signal frequencies within band	3	4	1	3	3	3	3.1	3	2
2. Limiter/blanker	3	0	3	2	3	3	1.9	41	20
3. Wavelets	2	0	3	2	3	3	1.7	47	21
4. Fountain codes	1	2	3	3	3	2	2.2	31	12
5. Long interleaver	1	2	3	3	3	2	2.2	31	12
6. CDMA/frequency hopping	3	2	2	2	3	2	2.3	28	7
7. LDM	2	2	3	2	3	2	2.2	31	12
8. OFDM	3	0	2	2	3	2	1.7	47	21
9. MU-MIMO	2	3	3	1	2	1	2.1	34	16
10. SU-MIMO	2	3	3	1	2	1	2.1	34	16
11. ACM	2	1	3	1	2	2	1.6	50	23
12. Machine learning demodulation	2	1	3	2	3	3	2.0	38	18
13. Intelligent SDR	2	2	3	2	3	3	2.3	28	9
14. Cancellation/ nulling	3	4	3	3	2	3	3.2	0	1
15. Adaptive polarization	3	2	3	2	2	1	2.2	31	10
16. Choke-ring antennas	3	2	3	2	2	3	2.4	25	6
17. Shielding	3	4	3	2	1	3	2.9	9	4
18. Increase the receive dish size	3	1	3	2	1	3	2.0	38	18
19. Earth station diversity	3	0	3	1	1	3	1.5	53	24
20. OSSO	3	2	2	2	3	2	2.3	28	7
21. Satellite diversity	2	0	3	1	2	1	1.2	63	25
22. Improved modulation and coding selection	3	1	3	2	3	2	2.1	34	15
23. Polarization diversity	3	2	3	2	2	1	2.2	31	10
24. Improved preselection filtering	3	3	3	2	2	3	2.7	16	5
25. Improved preselector amplifier	3	3	3	3	3	3	2.7	16	5

Note: The numbers (1=low, 2 or 3=high) represent the scores. Shading is used to highlight ranking.

Table 4.5-14. HRIT/EMWIN signal technology trade study summary.

Evaluation criterion	Performance			Risks		Scalability	Average score	Margin	Rank
	Latency	Interference mitigation	Technology combination	Complexity	Operational risk				
Weight	20%	30%	10%	20%	10%	10%	100%	(Percent)	
1. Move signal frequencies within band	3	4	1	3	3	3	3.1	3	2
2. Limiter/blanker	3	0	3	2	3	3	1.9	41	21
3. Wavelets	2	0	3	2	3	3	1.7	47	23
4. Fountain codes	1	2	3	3	3	2	2.2	31	11
5. Long interleaver	1	2	3	3	3	2	2.2	31	11
6. CDMA/frequency hopping	3	1	2	2	3	2	2.0	38	18
7. LDM	2	2	3	2	3	2	2.2	31	11
8. OFDM	3	0	2	2	3	2	1.7	47	23
9. MU-MIMO	2	3	3	1	2	1	2.1	34	16
10. SU-MIMO	2	3	3	1	2	1	2.1	34	16
11. ACM	2	1	3	1	2	2	1.6	50	25
12. Machine learning demodulation	2	1	3	2	3	3	2.0	38	18
13. Intelligent SDR	2	2	3	2	3	3	2.3	28	8
14. Cancellation/nulling	3	4	3	3	2	3	3.2	0	1
15. Adaptive polarization	3	2	3	2	2	1	2.2	31	9
16. Choke-ring antennas	3	2	3	2	2	3	2.4	25	6
17. Shielding	3	4	3	2	2	3	3.0	6	3
18. Increase the receive dish size	3	2	3	2	1	3	2.3	28	7
19. Earth station diversity	3	1	3	2	2	3	2.1	34	14
20. OSSO	3	1	2	2	3	2	2.0	38	18
21. Satellite diversity	2	2	3	1	2	1	1.8	44	22
22. Improved modulation and coding selection	3	1	3	2	3	2	2.1	34	14
23. Polarization diversity	3	2	3	2	2	1	2.2	31	9
24. Improved preselection filtering	3	3	3	2	2	3	2.7	16	5
25. Improved preselector amplifier	3	3	3	3	3	3	3.0	6	3

Note: The numbers (1=low, 2 or 3=high) represent the scores. Shading is used to highlight ranking.

Table 4.5-15. Telemetry signal technology trade study summary.

Evaluation criterion	Performance			Risks		Scalability	Average score	Margin	Rank
	Latency	Interference mitigation	Technology combination	Complexity	Operational risk				
Weight	20%	30%	10%	20%	10%	10%	100%	(Percent)	
1. Move signal frequencies within band	3	4	1	3	3	3	3.1	3	2
2. Limiter/blanker	3	0	3	2	3	3	1.9	41	18
3. Wavelets	2	0	3	2	3	3	1.7	47	20
4. Fountain codes	1	2	3	3	3	2	2.2	31	10
5. Long interleaver	1	2	3	3	3	2	2.2	31	10
6. CDMA/frequency hopping	3	0	2	2	3	2	1.7	47	20
7. LDM	2	2	3	2	3	2	2.2	31	10
8. OFDM	3	0	2	2	3	2	1.7	47	20
9. MU-MIMO	2	3	3	1	2	1	2.1	34	14
10. SU-MIMO	2	3	3	1	2	1	2.1	34	14
11. ACM	2	1	3	1	2	2	1.6	50	24
12. Machine learning demodulation	2	1	3	2	3	3	2.0	38	16
13. Intelligent SDR	2	2	3	2	3	3	2.3	28	7
14. Cancellation/ nulling	3	4	3	3	2	3	3.2	0	1
15. Adaptive polarization	3	2	3	2	2	1	2.2	31	8
16. Choke-ring antennas	3	2	3	2	2	3	2.4	25	6
17. Shielding	3	4	3	2	1	3	2.9	9	4
18. Increase the receive dish size	3	1	3	2	1	3	2.0	38	16
19. Earth station diversity	3	1	3	1	1	3	1.8	44	19
20. OSSO	3	0	2	2	3	2	1.7	47	20
21. Satellite diversity	2	1	3	1	2	1	1.5	53	25
22. Improved modulation and coding selection	3	1	3	2	3	2	2.1	34	13
23. Polarization diversity	3	2	3	2	2	1	2.2	31	8
24. Improved preselection filtering	3	3	3	2	2	3	2.7	16	5
25. Improved preselector amplifier	3	3	3	3	3	3	3.0	6	3

Note: The numbers (1=low, 2 or 3=high) represent the scores. Shading is used to highlight ranking.

Table 4.5-16. Trade study summary results.

Technology	Scores				Ranks			
	DCP	GRB	HRIT	Telemetry	DCP	GRB	HRIT	Telemetry
1. Move signal frequencies within band	3.1	2.2	3.1	3.1	2	7	2	2
2. Limiter/blanker	1.9	1.9	1.9	1.9	20	14	21	18
3. Wavelets	1.7	1.7	1.7	1.7	21	17	23	20
4. Fountain codes	2.2	2.2	2.2	2.2	12	7	11	10
5. Long interleaver	2.2	2.2	2.2	2.2	12	7	11	10
6. CDMA/frequency hopping	2.3	1.7	2	1.7	7	17	18	20
7. LDM	2.2	1.6	2.2	2.2	12	23	11	10
8. OFDM	1.7	1.7	1.7	1.7	21	17	23	20
9. MU-MIMO	2.1	2.1	2.1	2.1	16	11	16	14
10. SU-MIMO	2.1	2.1	2.1	2.1	16	11	16	14
11. ACM	1.6	1.6	1.6	1.6	23	24	25	24
12. Machine learning demodulation	2	2	2	2	18	13	18	16
13. Intelligent SDR	2.3	2.3	2.3	2.3	9	6	8	7
14. Cancellation/nulling	3.2	3.2	3.2	3.2	1	1	1	1
15. Adaptive polarization	2.2	1.6	2.2	2.2	10	21	9	8
16. Choke-ring antennas	2.4	2.4	2.4	2.4	6	5	6	6
17. Shielding	2.9	2.9	3	2.9	4	3	3	4
18. Increase the receive dish size	2	1.8	2.3	2	18	15	7	16
19. Earth station diversity	1.5	1.8	2.1	1.8	24	15	14	19
20. OSSO	2.3	1.7	2	1.7	7	17	18	20
21. Satellite diversity	1.2	1.2	1.8	1.5	25	25	22	25
22. Improved modulation and coding selection	2.1	2.1	2.1	2.1	15	10	14	13
23. Polarization diversity	2.2	1.6	2.2	2.2	10	21	9	8
24. Improved preselection filtering	2.7	2.7	2.7	2.7	5	4	5	5
25. Improved preselector amplifier	3	3	3	3	3	2	3	3

Note: The numbers (1=low, 2 or 3=high) represent the scores. Shading is used to highlight ranking.

Table 4.5–16 shows a summary of the ranks for the GRB, DCP, HRIT, and telemetry signals. The number (1=low, 2 or 3=high) represents the score. Several potential technologies for GOES-NEXT are identified: shielding (#17), cancellation/nulling (#14), moving frequencies within a band (#1), improved preselection filtering (#24), and improved preselector amplifier (#25). There are significant differences in the RFI mitigation technology rankings for each signal type due to signal bandwidth, antenna size, signal polarization, and other factors.

4.5.6.3 Potential combined technology RFI performance

A combination of RFI mitigation technologies can provide high RFI mitigation levels. Some of the technologies investigated in this study can be combined, and the total RFI performance will be approximately the sum of the individual RFI improvements. Some technologies conflict (and cannot simultaneously be used), or the total RFI performance is less than the sum of the

Table 4.5-17. Technology conflicts (blue) and combination scores.

Technology list	1. Move signal frequencies within band	2. Limiter/blanker	3. Wavelets	4. Fountain codes	5. Long interleaver	6. CDMA/Frequency hopping	7. LDM	8. OFDM	9. MU-MIMO	10. SU-MIMO	11. ACM	12. Machine learning demodulation	13. Intelligent SDR	14. Cancellation/nulling	15. Adaptive polarization	16. Choke-ring feed	17. Shielding	18. Increase the receive dish size	19. Earth station diversity	20. OSSO	21. Satellite diversity	22. Improved modulation and coding selection	23. Polarization diversity	24. Improved preselection filtering	25. Improved preselection amplifier	Combination scores
1. Move signal frequencies within band						X	X	X												X						1.0
2. Limiter/blanker																										3.0
3. Wavelets																										3.0
4. Fountain codes					X																					3.0
5. Long interleaver				X																						3.0
6. CDMA/frequency hopping	X																			X						2.0
7. LDM	X																									3.0
8. OFDM	X																			X						2.0
9. MU-MIMO										X																3.0
10. SU-MIMO									X													X				3.0
11. ACM																						X				3.0
12. Machine learning demodulation																										3.0
13. Intelligent SDR																										3.0
14. Cancellation/nulling																										3.0
15. Adaptive polarization																							X			3.0
16. Choke-ring feed																										3.0
17. Shielding																										3.0
18. Increase the receive dish size																										3.0
19. Earth station diversity																										3.0
20. OSSO	X					X		X																		2.0
21. Satellite diversity																										3.0
22. Improved modulation and coding selection											X															3.0
23. Polarization diversity															X											3.0
24. Improved preselection filtering																										3.0
25. Improved preselector amplifier																										3.0

Note: A dark blue box (X) shows a conflict. The right column provides a summary combination score, which is 3 for zero or one conflict, 2 for two to five conflicts, and 1 for more than five conflicts. Shading is used to highlight ranking.

individual RFI improvements. For example, moving the signals within the band is incompatible with using CDMA or frequency hopping spreading. Table 4.5-17 provides a summary of the technology conflicts. A red marking shows a conflict. The right column provides a summary "combination score." The combination score is 3 for zero or one conflict, 2 for two to five conflicts, and 1 for more than five conflicts.

When combined, the recommended technologies would significantly reduce the RFI risks. The best interference mitigation technologies are summarized in Table 4.5-18. These include: cancellation/nulling (#14), choke-ring antennas (#16), shielding (#17), improved preselection filtering (#24), and improved preselector amplifier (#25). The amount of RF improvement is provided for both co-channel interference and adjacent-channel interference. Cancellation/nulling will work in adjacent-channel situations where the RFI limitation is due to LTE transmit mask energy (and not to NOAA preamplifier intermodulation energy). To be conservative, this case is neglected. Unfortunately, improved preselection filtering (#24) and improved preselector amplifier (#25) do not help with co-channel interference. Combining multiple interference mitigation technologies will significantly reduce the interference to NOAA ground stations, with up to 40 dB improvement. The 40 dB value has some risk in that it may not be possible to combine all of these technologies in certain scenarios (i.e., when a specific site will not support a large shield or the current NOAA preamplifier[19] at a site is already well designed). However, a 20 dB RFI reduction at all sites appears to be achievable with low risk.

Table 4.5-18. RFI mitigation performance of best technologies.

Technology	Co-channel interference	Adjacent-channel interference
14. Cancellation/nulling	20 dB	—
16. Choke-ring antennas	10 dB	10 dB
17. Shielding	10 dB	10 dB
24. Improved preselection filtering	—	10 dB
25. Improved preselector amplifier	—	10 dB
Total	40 dB	40 dB

It is worth noting that some technologies offer significant non-RFI mitigation benefits and should be considered by NOAA. These are listed in Table 4.5-19. For example, GRB could reduce the occupied bandwidth by 2.56 MHz using a DVB-S2X (an extension of DVB-S2) with a 5% roll-off instead of DVB-S2X with a 25% roll-off.

[19]This study only investigated the new GRB receiver preamplifier, and found that its design could be significantly improved.

Table 4.5-19. Recommended system design technologies.

Technology	Benefit
1. Move signal frequencies within band	• Select which ground-station users are impacted by interference • Select which signals are impacted by co-channel or adjacent-channel interference
13. Intelligent software-defined radio (SDR)	• Maximize flexibility for future upgrades
22. Improved modulation and coding selection	• Improve capacity

The potential technologies were evaluated using multiple metrics. The metrics included latency (delay in data transmission), performance potential (interference mitigation against additive white Gaussian noise), technology combination (the ability to combine technologies to provide high performance), complexity (cost, technical risk, and schedule risk), operational risk, and scalability (satellite modifications versus ground station modifications).

The analysis identified several potentially effective technologies, which are ranked for each of the downlinks in Table 4.5-20:

- Cancellation/nulling (#14): Extra antennas and receivers are added; the interference is subtracted from the desired satellite signal. The extra antennas can be added near the ground station feed to create a highly directive antenna feed, or the extra antennas can be added surrounding the dish antenna. This approach is technically complex and high risk.
- Choke-ring antennas (#16): The dish antenna feed is modified so that signals arriving from the horizon are reduced.
- Shielding (#17): An RF barrier, such as a wall or fence, is built surrounding the ground station antenna to attenuate RFI signals arriving from the horizon. This approach would be expensive to implement and potentially not operationally feasible on rooftop locations.
- Improved preselection filtering (#24): Cryogenic preselection filters are used to reject adjacent-channel signals. This approach is technically complex and high risk.
- Improved preselector amplifier (#25): The ground station's preamplifier is replaced with a high-intercept point amplifier and/or the gain is reduced. This reduces the amount of intermodulation energy generated with strong adjacent-channel signals. This approach provides value only if the existing ground station has a poorly designed preamplifier.
- Move frequencies within a band (#1): This approach optimizes the frequency plan by moving the DCP, GRB, HRIT/EMWIN, and telemetry signal center frequencies. The optimization must consider each signal separately in terms of its margin, bandwidth, availability targets, and waveform.

Combining multiple interference mitigation technologies could significantly reduce the interference to NOAA ground stations, with up to 40 dB improvement. The 40 dB value is probably an upper limit, and may not be applicable to all systems due to the variation in equipment and installation limitations. Therefore, it may not be possible to combine all of these technologies in certain scenarios (for example, a specific site may not support a large shield, or the current NOAA preamplifier at a site may already be well designed). However, a 20 dB RFI reduction at all sites appears to be achievable with low risk.

Table 4.5-20. GOES rebroadcast downlink trade study results.

Technology	Ranks			
1. Move signal frequencies within band	2	7	2	2
2. Limiter/blanker	20	14	21	18
3. Wavelets	21	17	23	20
4. Fountain codes	12	7	11	10
5. Long interleaver	12	7	11	10
6. CDMA/frequency hopping	7	17	18	20
7. LDM	12	23	11	10
8. OFDM	21	17	23	20
9. MU-MIMO	16	11	16	14
10. SU-MIMO	16	11	16	14
11. ACM	23	24	25	24
12. Machine learning demodulation	18	13	18	16
13. Intelligent SDR	9	6	8	7
14. Cancellation/nulling	1	1	1	1
15. Adaptive polarization	10	21	9	8
16. Choke-ring antennas	6	5	6	6
17. Shielding	4	3	3	4
18. Increase the receive dish size	18	15	7	16
19. Earth station diversity	24	15	14	19
20. OSSO	7	17	18	20
21. Satellite diversity	25	25	22	25
22. Improved modulation and coding selection	15	10	14	13
23. Polarization diversity	10	21	9	8
24. Improved preselection filtering	5	4	5	5
25. Improved preselector amplifier	3	2	3	3

Note: Shading is used to highlight the ranking.

4.6 Project 6. Detailed Survey of Receiving Equipment

Project 6 is a detailed survey of GOES earth station receiving equipment that includes:

- On-site assessments of Federal GOES ground stations and receiver sites for verification of characteristics for protection criteria.
- Documentation of the GOES data distribution architecture, its commercial applications, and the potential impact on the national infrastructure.
- Conducting GOES ground station surveys to determine system and configuration requirements.
- Conducting a littoral RFI analysis for the U.S. Navy Environmental Satellite Receiver/Processor (ESRP)–Afloat (AN/SMQ-11) as a simulation-based analysis. The analysis should determine if large geographic separation and frequency offsets would be required to minimize interference between a deployment of commercial high-power large-cell networks in the 1675–1689 MHz band and incumbent Federal shipborne and ground-based radar systems that operate or are planned to operate in and adjacent to the 1675–1680 MHz band.

The scope of Project 6 spanned two of the SPRES program topic areas: GOES Data Use and RFI Modalities and Risks. In the course of the data collection, an extensive database of site hardware, performance parameters, and other related site data was built up and delivered to NOAA. A graphic summary of performance tests is covered in this section, and the specific results of the site tests are tabulated in Appendix F. Using the database and results from other projects, Project 6 concluded with a closer look at the risks of RFI on the GOES data flows and on each site.

4.6.1 On-site assessment of GOES receiver sites and earth station surveys

The SSC team visited 32 different GOES earth station sites during the period of the project. The sites were chosen by NOAA using criteria set forth initially in the contract request for proposal (RFP). The sites were a combination of civilian agency and Department of Defense (DoD) sites. The measurements conducted at each site were determined by uniqueness of configuration. That is, sites with a hardware configuration identical to one already tested did not undergo another system performance or antenna pattern test.

The following measurement and data collection activities were conducted at each site:

- Collect background spectrum data to evaluate existing and potential RFI both within the Met-Sat band and in the adjacent frequencies. The spectrum data shows a snapshot of the spectrum over a period of approximately 24 hours, which can be used as a baseline for future investigations of RFI or to evaluate changes in spectrum usage.
- Take propagation measurements to evaluate factors such as clutter loss and reflection interference.
- Measure system performance as it relates to interference by executing system RF link margin measurements and system frequency-dependent rejection (FDR) measurements.

- Take antenna pattern measurements to verify the antenna pattern against theoretical antenna gain patterns for use in future RFI analysis.
- Collect geographic location data for use in future RFI analysis.
- Evaluate the site for a variety of conditions that would allow the installation of an RFI monitoring system (RFIMS), including available equipment, tower space, site access, and construction limitations.

4.6.1.1 Background spectrum data collection

With the advent of potential spectrum sharing and spectrum auctions located in-spectrum and adjacent to the Met-Sat band, it is important to have a baseline of spectrum use in the area of the surveyed GOES downlink facilities. This baseline will allow future evaluation of interference and can be used as a gauge for spectrum encroachment. The measurements represent approximately 24 hours of data collection at each site and show spectrum usage with high resolution.

The background spectrum measurements were conducted at each GOES site surveyed covering the frequency band from 1620–1710 MHz. This frequency range includes not only the Met-Sat band but also auctioned spectrum above and below the Met-Sat band, as well as mobile-satellite-allocated spectrum. The data collected was plotted to display the maximum hold power in dBm over frequency, time that the specific signal was received over frequency (waterfall plot), and the percentage of time that particular frequency signal was received. The resultant plots are for each polarization of the antennas, horizontal or vertical at four different azimuths. The waterfall plots and the percent of time plots show only signals that were collected above a threshold of −100 dBm.

Many sites had a very quiet RF environment. Those sites were usually rural in nature. The sites with the highest noise floors and largest number of signals were urban or suburban, as expected. The signal collection was done over a relatively short period of time, usually not more than 24 hours, so this collection activity represents a small snapshot in time. However, it does give a good representation of the RF spectrum activity in the area.

Figures 4.6-1 through 4.6-3 show spectrum plots from Fairmont, West Virginia; Columbus, Mississippi; and Seattle, Washington. All showed varying levels of RF signals.

The collection data can be used as a baseline for future investigations of potential interference or to track changes in the RF environment. Additionally, the impact of nearby signals such as Ligado and AWS signals above 1700 MHz on the overall noise floor, even with filtering, can be evaluated. This could be useful for future system design analysis and potential improvement.

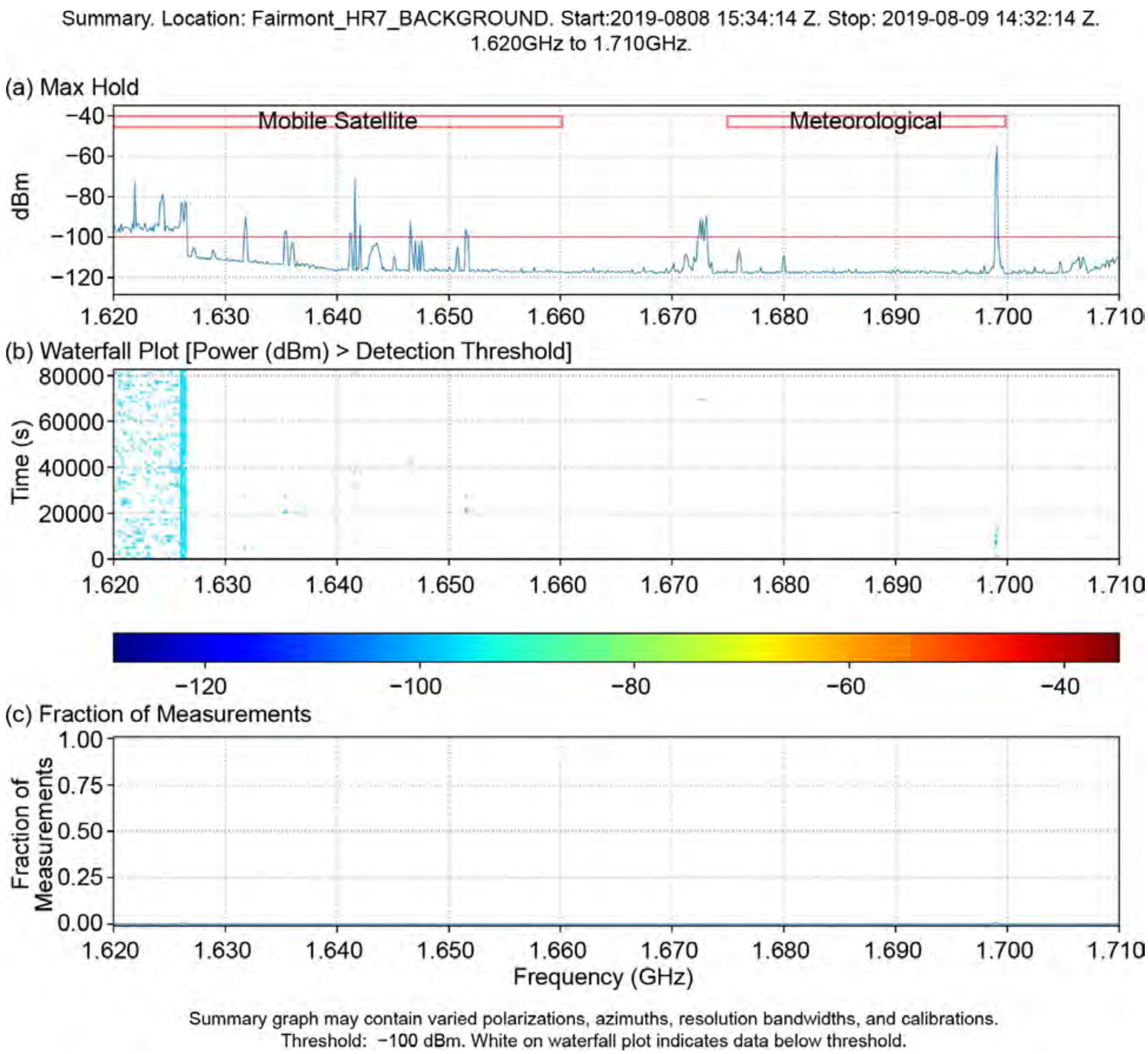

Figure 4.6-1. Spectrum plots showing very quiet RF environment (Fairmont, West Virginia), with a possible Ligado test signal near 1675 MHz and the propagation measurement test signal at 1699 MHz.

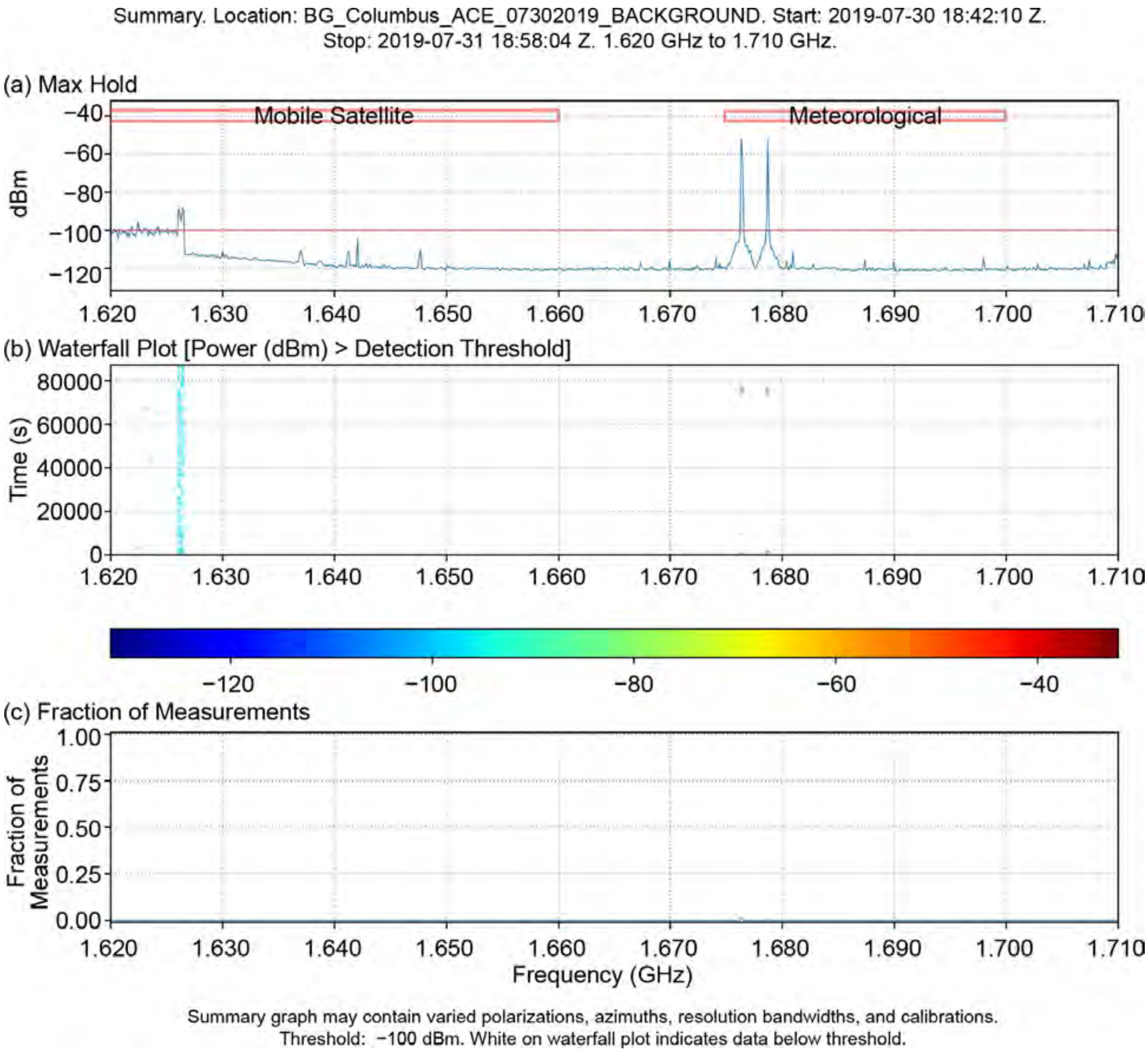

Figure 4.6-2. Extremely quiet spectrum collection (Columbus, Mississippi). The two strong signals between 1675 and 1680 MHz are the propagation measurement test signals.

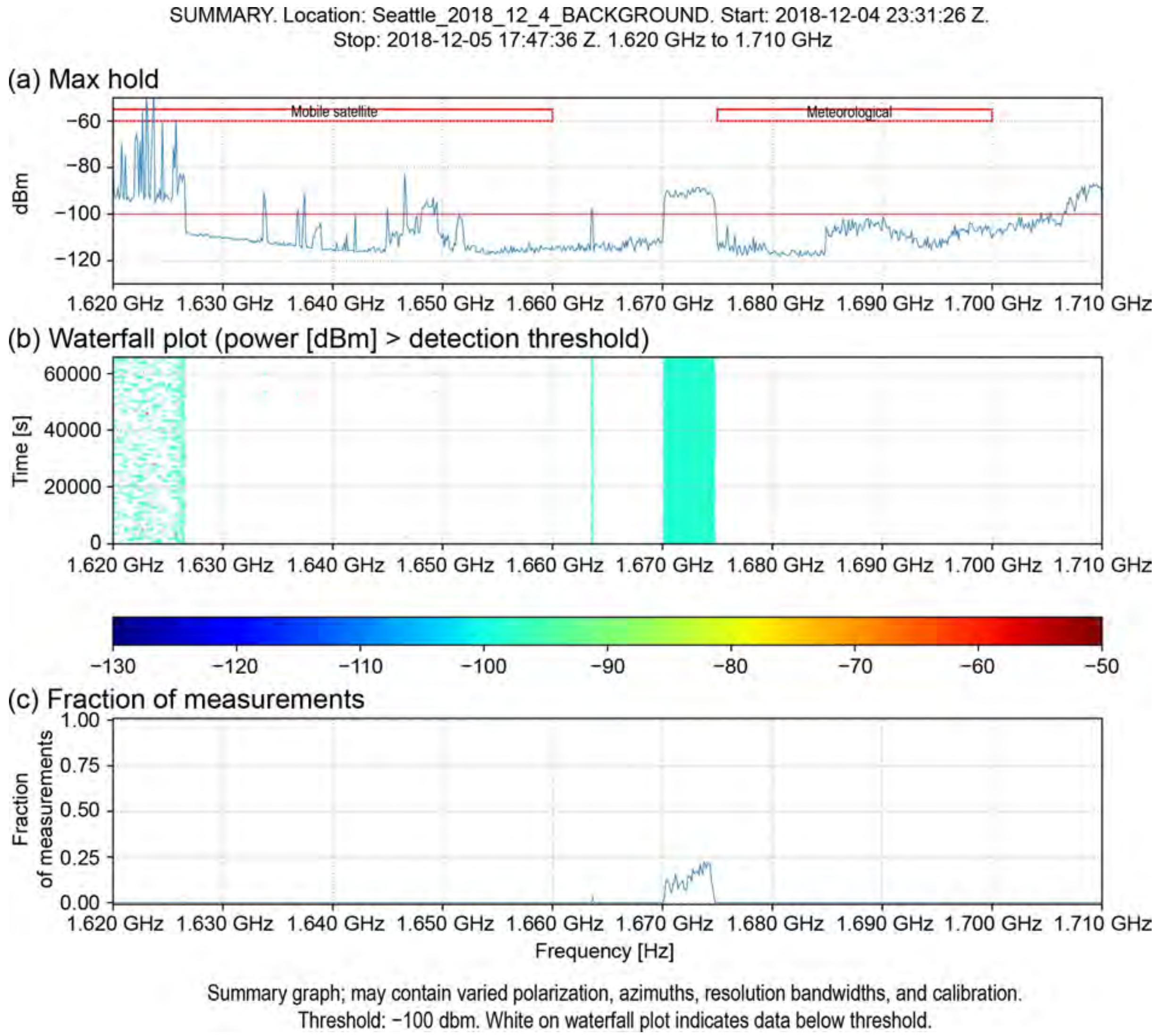

Figure 4.6-3. Spectrum plot (Seattle, Washington) clearly showing Ligado signal at 1670–1675 MHz.

4.6.1.2 Propagation measurements and clutter-loss analysis

The test objective was to measure local clutter enhancement as it relates to RF propagation loss. This reflection-scattering enhancement factor is used to enable accurate propagation modeling for exclusion zone predictions. Propagation loss measurements are critical to being able to predict the interference at NOAA sites at high risk of reflection-scattering interference.

A continuous wave (CW) RF signal was transmitted from two vehicles that drove around the GOES downlink site in a route determined by a 150 dB propagation loss contour centered at the downlink antenna. The vehicles drove two different routes to reduce the amount of time to collect and record data. The vehicles' transmitters operated on two different frequencies. Figure 4.6-4 shows the 150 dB contour around the NSOF site in Suitland, Maryland.

The receive antenna was mounted to the height of the feed of the GOES downlink antenna feed if possible. In most cases, the antenna height was measured between 3.5 m and 4.5 m.

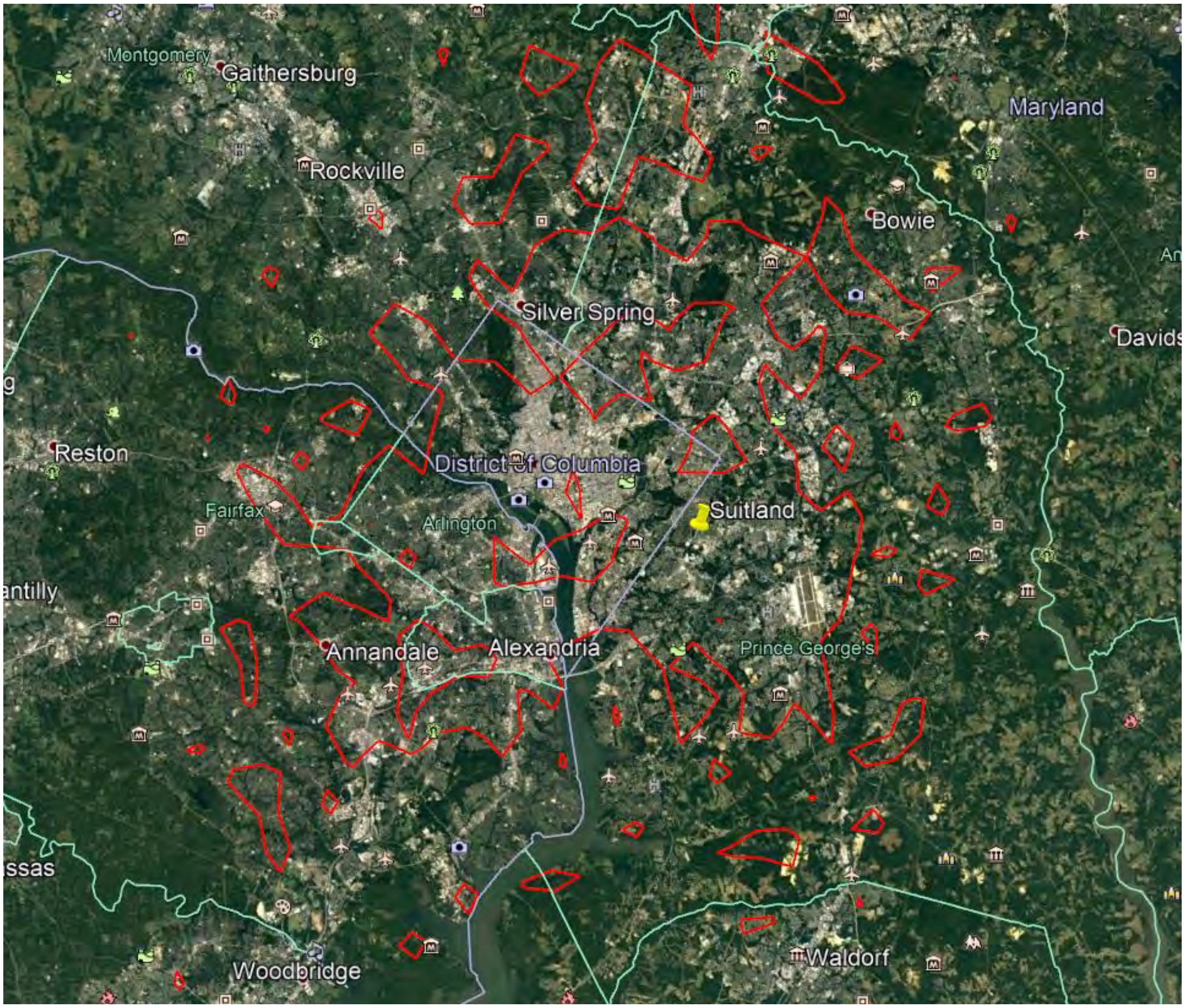

Figure 4.6-4. A 150 dB contour plot around NSOF in Suitland, Maryland.

The position of the propagation measurement transmitter was recorded as latitude and longitude values using a GPS logger or RideWithGPS application on a smartphone. A low-noise amplifier (LNA) received and amplified the signal collected, and the signal level was measured using a Tektronix RSA306B spectrum analyzer. A Reactel cavity filter, model 4C7-1685-66S11, before the LNA was also used to minimize the impact of external interference, i.e., from cell towers. The spectrum analyzer was connected to a laptop, which saved the collected data using custom SSC software. The received signal power and GPS locations were then parsed to associate the received power values with transmitter positions. Only transmitter positions where the signal power was measured above the background noise are considered when calculating path loss and clutter loss. If the signal was below the background noise, then its power could not be measured. To determine clutter loss, a MATLAB software program used both Shuttle Radar Topography Mission (SRTM) terrain data and Terrain Integrated Rough Earth Model (TIREM).

The SRTM terrain data was used to create 90% confidence terrain profiles to input into the propagation model. The terrain profiles are vectors of the elevation between the receiver and transmitter positions. For analyses in Hawaii and the contiguous United States, the terrain profile resolution was approximately 30 m, while in Alaska the terrain resolution was approximately 90 m.

SSC custom MATLAB software fetched the terrain data from SRTM by reading a matrix of elevations from a GeoTIFF file that correspond to a one-degree by one-degree square of terrain. The MATLAB software then created the terrain profile by identifying the elevation values in the matrix that lie on the path between the transmitter and receiver. The MATLAB software then ran TIREM, using the terrain profile and link parameters to calculate the median path loss.

Heat map plots of the drive routes were generated and overlaid on Google Earth maps to show the clutter loss associated with the transmitter location. Distribution plots were also generated that displayed the percentage of locations that measured a particular level of loss.

Figure 4.6-5 shows the clutter-loss trace (heat map) around the NSOF site in Suitland, Maryland. The white star in the lower right indicates the location of the receiver in Suitland.

Figure 4.6-6 is the clutter-loss distribution plot for the NSOF site in Suitland, Maryland.

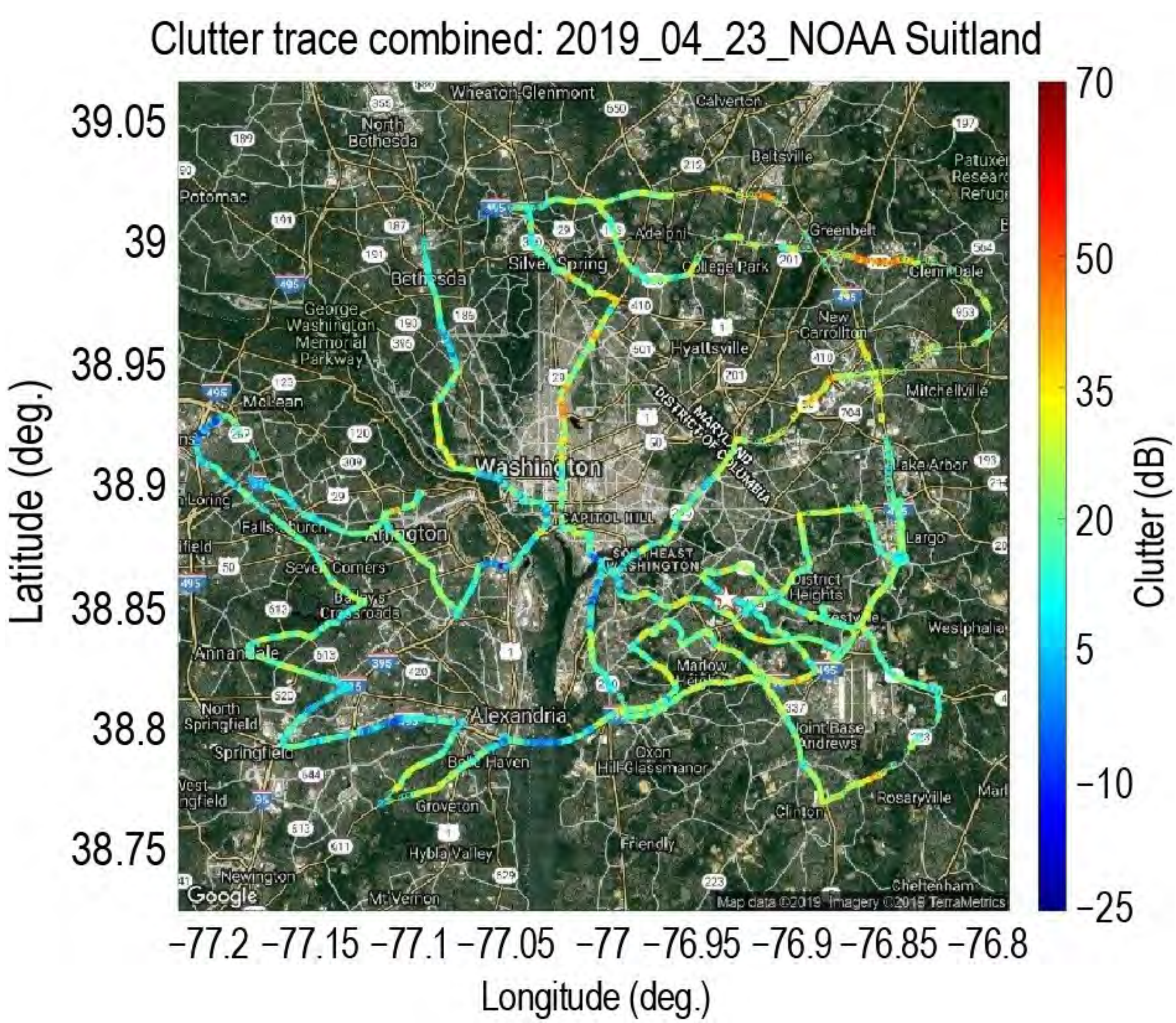

Figure 4.6-5. Clutter trace at the NSOF site in Suitland, Maryland.

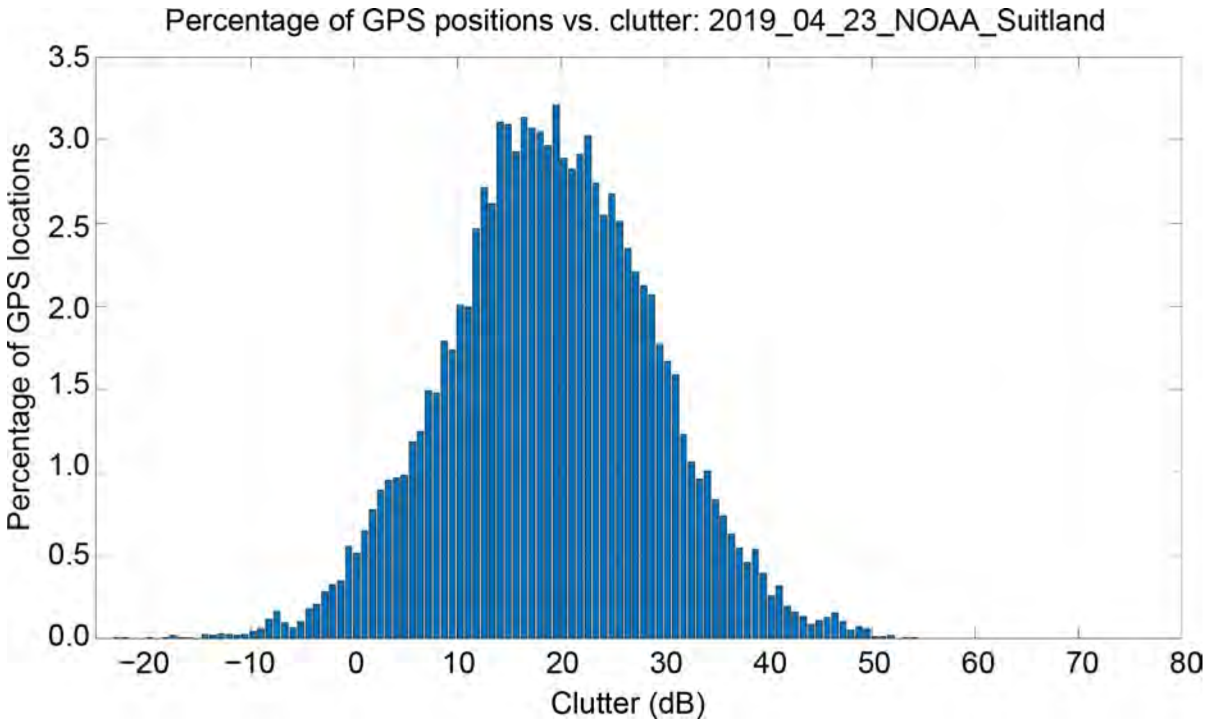

Figure 4.6-6. Clutter-loss distribution at the NSOF site in Suitland, Maryland.

The analysis of clutter enhancement to propagation loss reveals that the effects of clutter on RF propagation need to be taken into consideration when evaluating potential interference to GOES downlink systems. The findings from clutter-loss measurements can be leveraged to exclusion zone analysis of GOES downlinks in Project 7.

4.6.1.3 RF margin and frequency-dependent rejection

For each site that was designated for RF margin and frequency-dependent rejection (FDR) tests, a minimum of two runs were conducted to check for consistency. For GRB user sites, typically, margin and FDR tests were done using the right- and left-hand circular polarization (RHCP and LHCP) receive paths. It should be noted that the only GRB hardware not tested was the Navy FMQ-26 due to the fact that it has not yet been deployed at any ground sites. However, background and clutter tests were still conducted in Monterey and Norfolk at the sites where the FMQ-26 is designated to be placed.

At DCS sites, two tests were done on the same linear receive path. At two HRIT sites, margin tests were completed, but frequency separation (13 MHz) made it impossible to interfere with the HRIT signal from 1675–1680 MHz. Of the 400 kHz wide DCS signal centered at 1679.9 MHz, 300 kHz was overlapped by the 1675–1680 MHz interfering test signal. As a result, a low FDR value was recorded. The frequency separation of the lower edge of the GRB signal at 1681.15 MHz and the upper edge of the interfering signal was 1.15 MHz.

The frequency separation of the lower edge of the HRIT signal at 1693.5 MHz and the upper edge of the interfering signal was 13.5 MHz. For HRIT, the only margin tests performed were for a Tennessee Valley Authority (TVA) site in Knoxville, Tennessee, and a U.S. Marine Corps system at the Naval Information Warfare Systems Command (NAVWAR) facility in San Diego, California. It became clear that test signals in the 1675–1680 MHz band could not be set at a high enough level to cause any detectable interference in the HRIT due to the frequency separation.

A GOES receiver's susceptibility to interference depends on several factors such as antenna gain, preamplifier noise, proper antenna feed alignment to the satellite, external noise, and receiver performance. SSC made measurements to determine the impact of interfering signals on the ability of the GOES receiver to operate while receiving interference. Two measurements were made: a signal margin measurement and an FDR measurement. The receiver's margin is the amount that the system noise level (or the interference level) could increase and still allow signal reception. The margin value includes antenna gain, preamplifier noise, and receiver performance. FDR is the amount that the interference power is reduced because of the frequency difference between the GOES signal and the interference signal. FDR results depend on additional factors such as the receiver selectivity, transmitter emission mask, and the frequency difference between the receiver and transmitter frequencies. These factors can vary by antenna type, receiver type/make/model, and the overall system configuration.

The FDR test is similar to the margin test except that the FDR test signal frequency is 1675–1680 MHz, while the frequency used for the margin test is the same frequency as the GOES signal under test. The margin test used a representative transmitted emission mask with a 5 MHz bandwidth at a frequency co-channel to the NOAA signal under test. The FDR test used the 5 MHz test signal centered at 1677.5 MHz, which is the center of the 1675–1680 MHz band.

The methods of measuring the margin and the FDR were closely aligned, using the same test equipment and equipment setup, and the data was recorded in the same spreadsheet for calculations and analysis. As a result, the two tests were completed during the same test period.

The test approach had an engineer situated near the GOES downlink antenna under test, transmitting the LTE-like interfering signal at the feed of the antenna, and another engineer near the GOES receivers, collecting intermediate frequency (IF) signal measurements. The interfering signal was transmitted off-angle and at close range from a tripod-mounted directional antenna. For the margin test, the interferer was co-channel to the NOAA signal under test, at the same center frequency. For FDR, the interfering signal was transmitted at 1677.5 MHz. The test was coordinated between the two test engineers according to the test plan, and collected data and test parameters were recorded in a spreadsheet for analysis. Figure 4.6-7 shows the equipment setup for the margin and FDR measurements. At sites other than NSOF, the interferer was in front of the dish and pointed directly at the antenna feed. At NSOF, the interferer was behind the antenna because of its location on the edge of a roof. The interfering antenna was mounted on a tripod and was not moved during each test. If the tripod/antenna was moved or bumped, the test was restarted. For most tests, the interfering antenna was 5–10 m away.

During margin and FDR testing, the interfering signal was increased until significant interference was reached. Significant interference at GRB user sites was defined as the point where the number of uncorrected frames was greater than zero on the Quorum GRB-200 receiver. For DCS

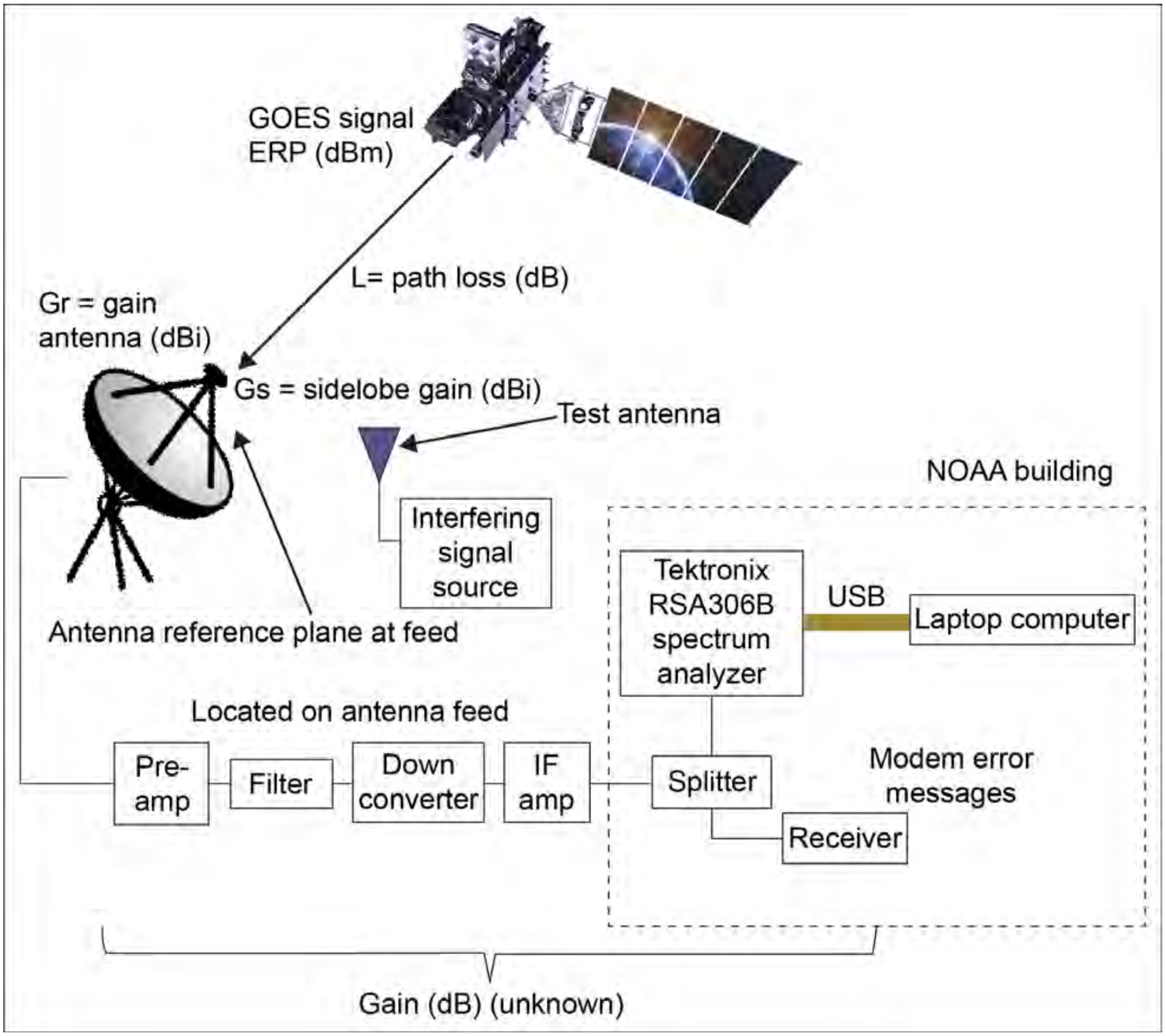

Figure 4.6-7. Block diagram of margin and FDR equipment setup.

sites, significant interference coincided with loss of pilot and was therefore set as a criterion for the test. Trends have shown that the pilot is more tolerant than a data channel. Unlike any of the data channels, it was also the one field that could consistently be measured at all sites.

The measured margin and FDR values were spread over several dB even for a given antenna size. This may have been due to the overall system performance, weather conditions, or slight variations in measurement procedures. It is of value to note that measurements made at a site that were just minutes apart with the same equipment and equipment setup show variances of several dB. Some of the variance that was greater between sites, such as Wallops Island, Virginia, and Suitland, Maryland, may have been due to the differences in antenna system design as well as the available positioning of the interfering source.

Figure 4.6-8 is a scatter plot of the margin measurements by site. Figure 4.6-9 is a scatter plot of FDR measurements by site.

Some of the differences in results could be related to system optimization. That is, some systems may have had issues with some portion of the RF and IF systems such as the feed performance, the accuracy of the antenna pointing, or receiver issues, resulting in less than fully optimized systems. Any deficiencies in the system optimization could result in poor margin or FDR values. The margin and FDR values observed in those cases indicate the need to optimize setup in order to maximize resilience to interference.

The field measurements also revealed the impact of weather on the margin and FDR measurements. This was most noticeable at WCDAS when an afternoon thunderstorm approached in the boresight of the dish under test. The test was delayed to the next day in order to avoid the impact of the storm. System margin needs to be considered when additional interfering signals are added to the operating environment.

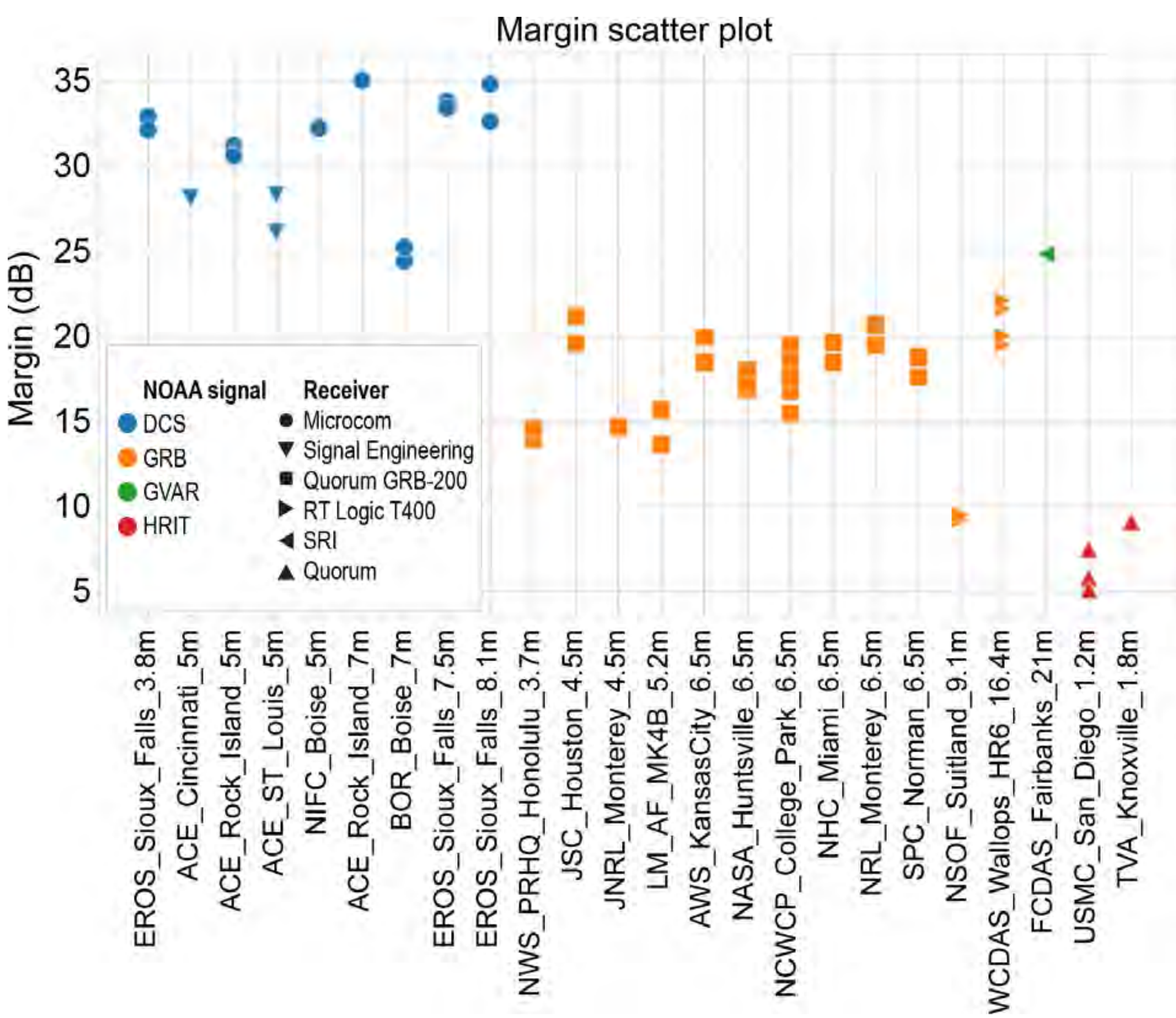

Figure 4.6-8. Margin scatter plot by site.

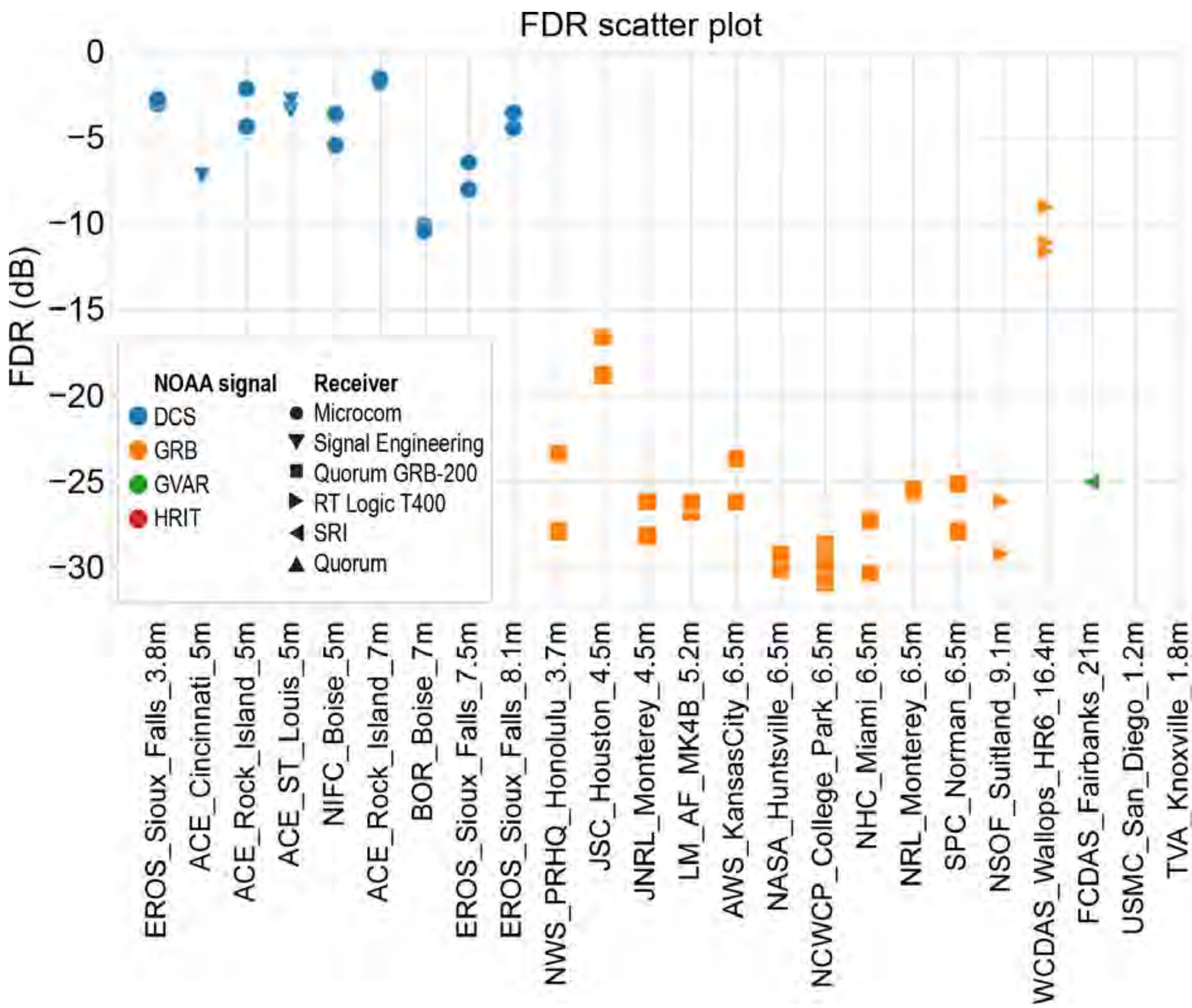

Figure 4.6-9. FDR scatter plot by site.

DCS systems will have the greatest impact from signals in the 1675–1680 MHz range due to the frequency overlap of DCS signals in the band. For HRIT, the tests indicated that an LTE emitter at 1675–1680 MHz would have no impact. For all cases, due to variations in conditions at each site, one should not expect to see the same kind of consistency in results as in an anechoic chamber or other highly controlled environment.

4.6.1.4 Antenna pattern measurement

The antenna gain pattern for the satellite downlink antenna has an impact on the ability to reject unwanted signals. The antenna pattern in Figure 4.6-10 is the NOAA-provided GOES 9.1 m, −10 dB gain pattern used for analysis and design purposes. The intent of this measurement is to determine the validity of the gain pattern.

The objective of the antenna gain measurement was to validate the predicted NOAA GOES receiver antenna gain values at low elevation angles. In all cases, the antenna position was not changed to measure the gain. This resulted in a measurement that is true to the elevation at which the antenna is utilized.

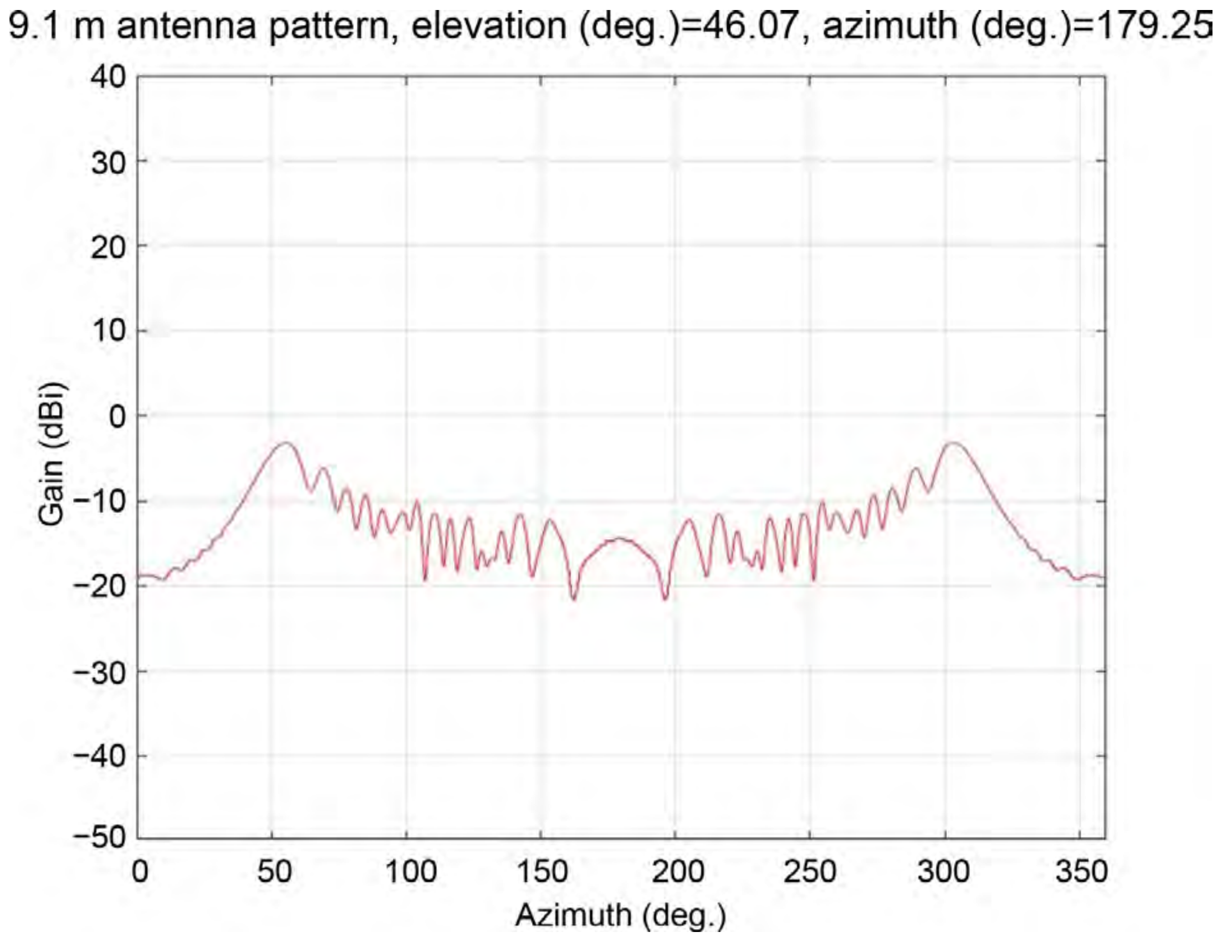

Figure 4.6-10. A 9.1 m antenna at 46.07° elevation average gain plot.

The provided antenna gain pattern was modified to match the elevation of the antennas at each site where the measurements were made. There was an assumption from the beginning of the project that it would not be necessary to measure the gains at all sites. The assumption is based on the concept that antennas of similar type and size have the same gain patterns.

This test used transmissions from a known antenna and power measurements made at the GOES receiver intermediate frequency (IF) input through an RF splitter. The test approach is shown in Figure 4.6-11, where the known antenna is walked around the GOES earth station antenna. The test engineer wore a backpack with a laptop computer and a CW signal source powered by the computer's universal serial bus 3 (USB 3) port. The engineer also had a sub-meter-accurate GPS receiver to log the test location for post-test measurement plotting. The test engineer walked around the dish in a flower-shaped pattern (Figure 4.6-11) to the extent that the surrounding terrain would allow. This walking pattern allowed for a large number of collected data points for use in the analysis and plots.

The measurement data was collected with a computer-controlled spectrum analyzer connected to the IF port of the dish under test. The computer ran SSC-authored custom software that collected the power received and the time. This data was combined with the GPS data collected to generate the plots of antenna gain versus heading, position versus power received, position

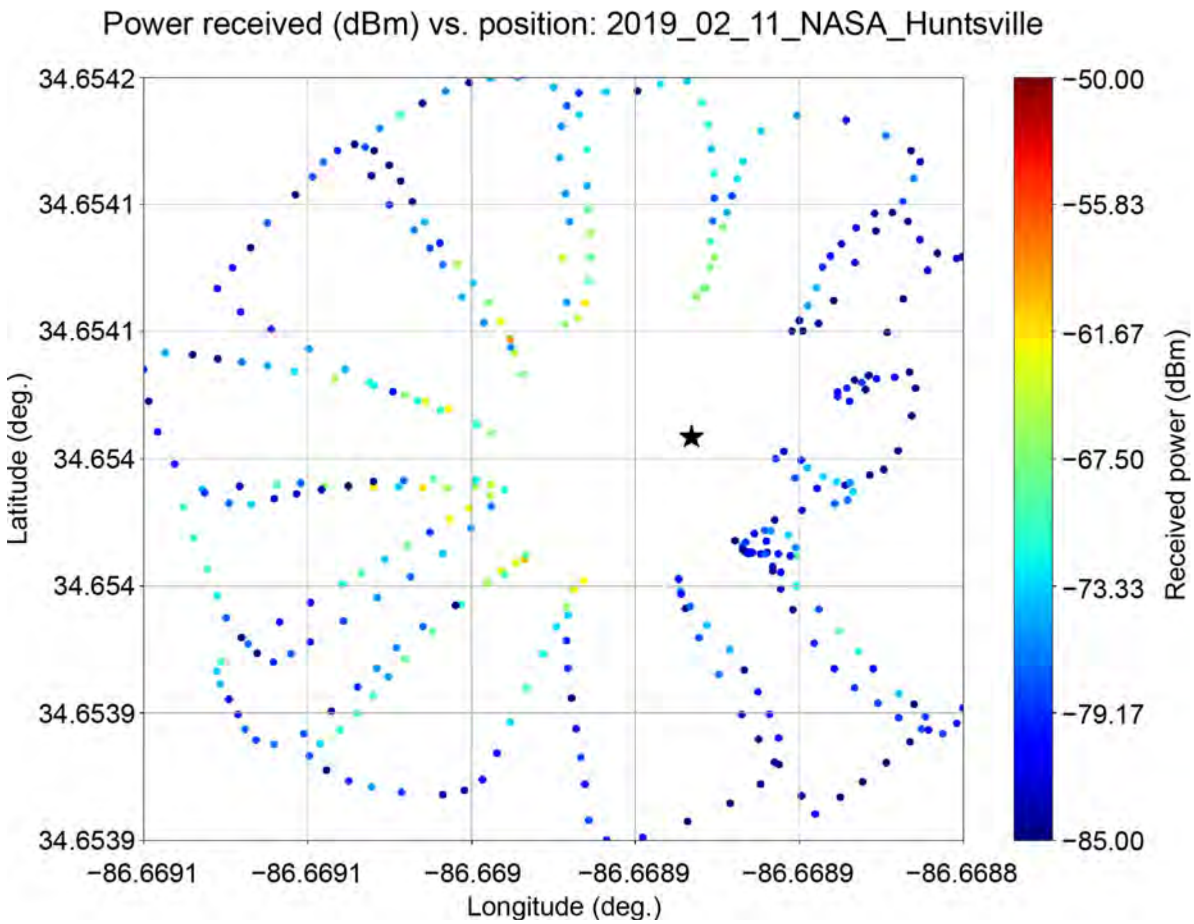

Figure 4.6-11. Antenna gain measurement collection pattern shown at NASA in Huntsville, Alabama.

versus time, and a power histogram. The antenna gain versus heading was then plotted (Figure 4.6-12) with the antenna gain plot corrected for elevation overlaid on the plot.

The antenna gain plots generally matched the predicted antenna gain overlay pattern. The discrepancies are likely attributable to one or more factors:

- Signal reflections from nearby objects. These could include cars parked near the dish, buildings or other dishes nearby, or walls and fences near the antennas under test.
- The inability of the test engineer to hold the transmitting antenna perfectly stable and level while walking around the dish.
- The inability of the test engineer to walk a symmetrical path around the dish.
- The inability to have the receiving antenna at the same height as the GOES antenna's feed assembly.
- The gain pattern used for reference was for a 9.1 m dish and may or may not be applicable to other dish sizes.

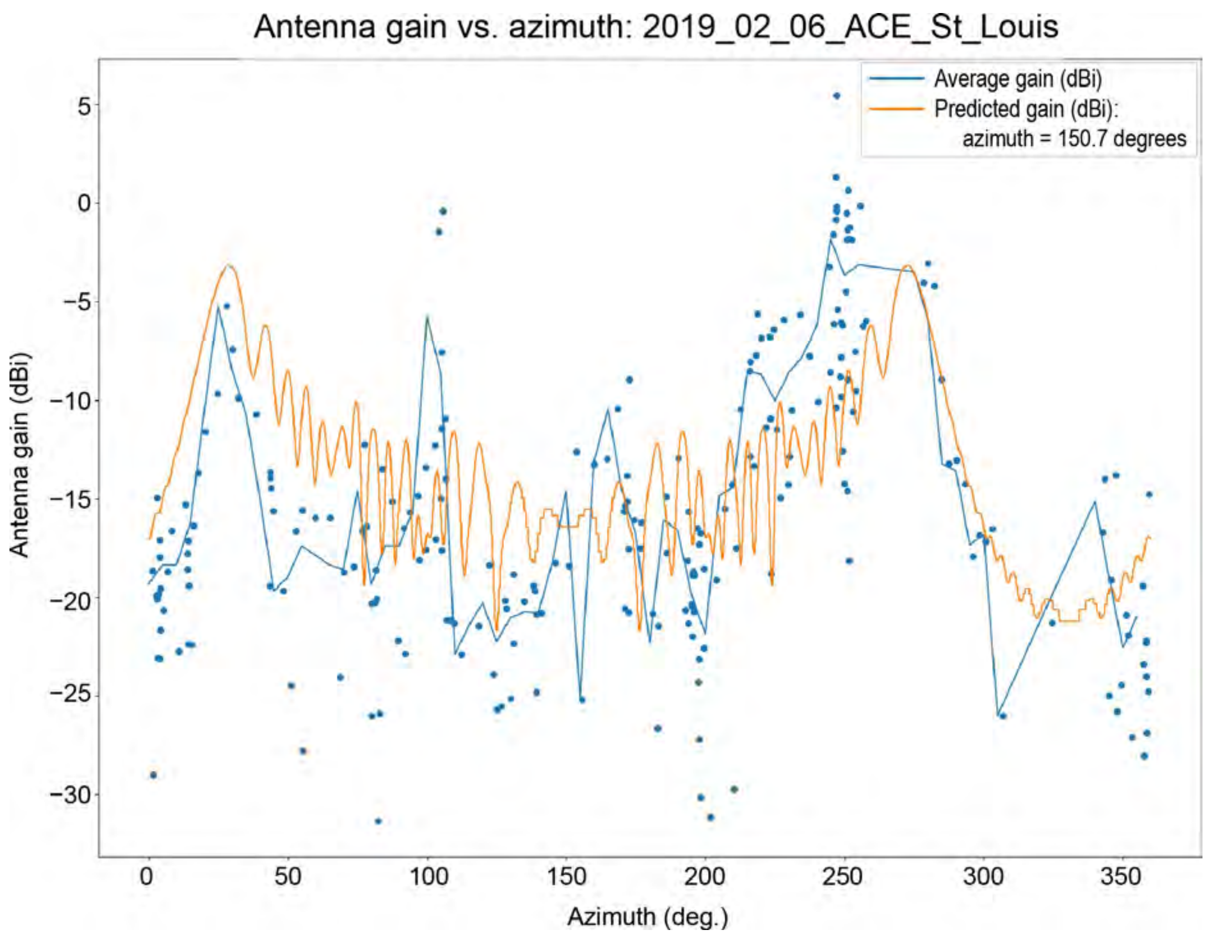

Figure 4.6-12. Antenna gain versus azimuth for the U.S. Army Corps of Engineers (USACE) site in St. Louis, Missouri.

4.6.1.5 Radio frequency interference monitoring system

For reliable spectrum sharing, some method to monitor the spectrum regularly near the potentially affected GOES receiver system is likely to be required. The spectrum-monitoring system would ideally be able to not only identify the potentially interfering signal, but also determine its angle of arrival.

NOAA is developing an RFIMS which will be used to detect and classify interference to polar-orbiting NOAA satellite receivers in the 1695–1710 MHz band, which has spectral coverage down to 1675 MHz. Deployment plans for this system are uncertain, and it is not known if there is any overlap with Federal GOES-R receive sites. If so, it may be able to provide some monitoring of this band at such sites, albeit above the desired sensitivity. If deployed, the system would be installed only at non-DoD sites, so only those sites were included in the survey.

Each GOES receiver location is unique in terms of how and where an RFIMS would be installed. The concerns, issues, and questions related to system installation, its operation range, type of equipment needed, availability of a secure space for equipment installation, electrical power requirements, and possible local zoning concerns. NOAA supplied a list of questions and requirements for the SSC team to address with representatives at each site, with the results delivered to NOAA in spreadsheet format. The results will aid NOAA, and in some cases other site users, in determining the needs and feasibility of installing the RFIMS at each site.

4.6.2 Littoral study

A separate analysis was performed to assess the impact of frequency division duplex (FDD) LTE services to Navy ship-based GOES receiver systems (AN/SMQ-11) operating off U.S. coastlines. If it was determined that there is an RFI risk to the Navy receivers, this littoral analysis would consider possible RFI risk mitigation approaches, such as LTE antenna downtilt.

This study considered regions along the East, Gulf, and West coasts of the U.S. In addition, analysis that factored in critical maritime ship channels for Navy operations was conducted. Commercial deployments (large cell and small cell) and simulation models were leveraged from the Project 11 study where the RFI imposed on Federal ground stations due to the use of the 1675–1680 MHz band for LTE derivatives was analyzed. A “baseline” FDD deployment was considered for commercial operation within the band using cell tower databases and a set of consistent parameters to describe all antennas of interest within 200 km of each potential ship location.

The AN/SMQ-11 is the U.S. Navy ship-based meteorological receiver, which is deployed with a planar-array antenna subsystem and mounted 50–150 feet above the waterline for various ship classes. Planar arrays provide highly symmetrical antenna patterns with a narrow main beam. They can be directed toward any point in space; as a result, the pointing angle of the antenna was calculated according to the locations of the receivers. All meteorological receivers in the study along the East and Gulf coasts were assumed to be pointing to GOES-East, and all receivers along the West Coast were assumed to be pointing to GOES-West. The AN/SMQ-11 receives the GOES-R HRIT signal.

The analysis identified no impact and no appreciable RFI risk for AN/SMQ-11 users due to the out-of-band-emissions generated from LTE deployments in the 1675–1680 MHz band. As a result, no exclusion zones are required for U.S. Navy AN/SMQ-11 users due to the LTE deployments covered. This study identified that the proposed out-of-band emission limits by the FCC for the 1675–1680 MHz band are sufficient in protecting HRIT end users.

4.6.3 GOES data distribution architecture

The objective of this task was to evaluate the GOES data distribution architecture impacts resulting from RFI occurring at direct broadcast downlink sites. To accomplish this goal, the direct broadcast services susceptible to RFI were identified. The GOES data distribution network was then mapped to identify direct broadcast receipt sites and downstream distribution network nodes, representing data users, and their interrelationships. Together, this information permitted analysis of the overall distribution network impacts due to RFI occurring at any given node.

The data distribution architecture consists of data generation sites that produce environmental data. In the case of DCS data, each Data Collection Platform (DCP), of which there are over 40,000, constitutes a data generation site. For the GRB data distribution network, there are two data generation sites, the primary at WCDAS and a backup at CBU. The environmental data produced is uplinked to the GOES-R satellite, where it undergoes a frequency translation to L-band, and is broadcast to tier 1 users. Tier 1 users operate GRB and/or DRGS receivers. Tier 1 users can function as the end users of the environmental data, or they can distribute that data to tier 2 users in the distribution network. The process of data dissemination to lower-tier users can extend through many layers, illustrated in Figure 4.6-13. However, NOAA-operated distribution services are limited to the first 4 tiers in the distribution network. In addition, the distribution of data to sub-tier layers may occur over RF broadcast or terrestrial distribution. The impetus behind this network mapping strategy was to determine the extent of impacts due to data loss at a particular distribution node. Figure 4.6-13 shows how a failure of a node (user) within a higher-level tier can cascade to lower-level tiers. One-to-one, many-to-one, and many-to-many node relationships exist within the distribution network. Also worth noting is that users may exist in multiple tiers if they support receipt of more than one distribution service. The service used to obtain direct broadcast data determines the tier for that particular network node. The distribution tier concept identifies the number of upstream dependencies on other distribution system components without having to understand the distribution service architectures. This SPRES project investigates the potential RFI impacts to tier 1 users and the cascading effects on lower tiers in the distribution network.

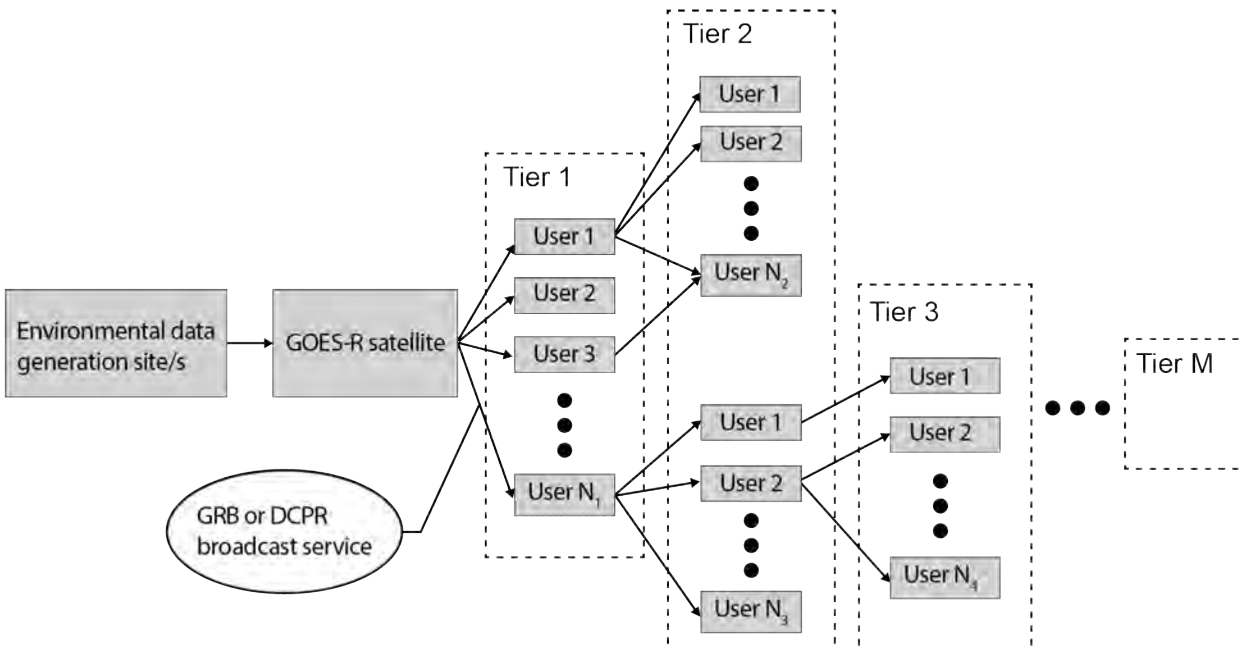

Figure 4.6-13. GOES-R multitier data distribution network.

4.6.3.1 Tier 1 distribution services

The GRB data generation and uplink sites are shown in Figure 4.6-14. The primary generation and uplink site for GRB data is at WCDAS. The backup site is located at CBU. Although GRB data is produced at both sites simultaneously, only the site designated as primary uplinks GRB to the GOES-R satellites. The satellite performs a frequency translation and rebroadcasts the GRB data in L-band. This diagram constitutes the end-to-end data flow for tier 1 data users. SPRES Project 1 identified 41 GRB receiver sites, 20 of which are considered critical or important.

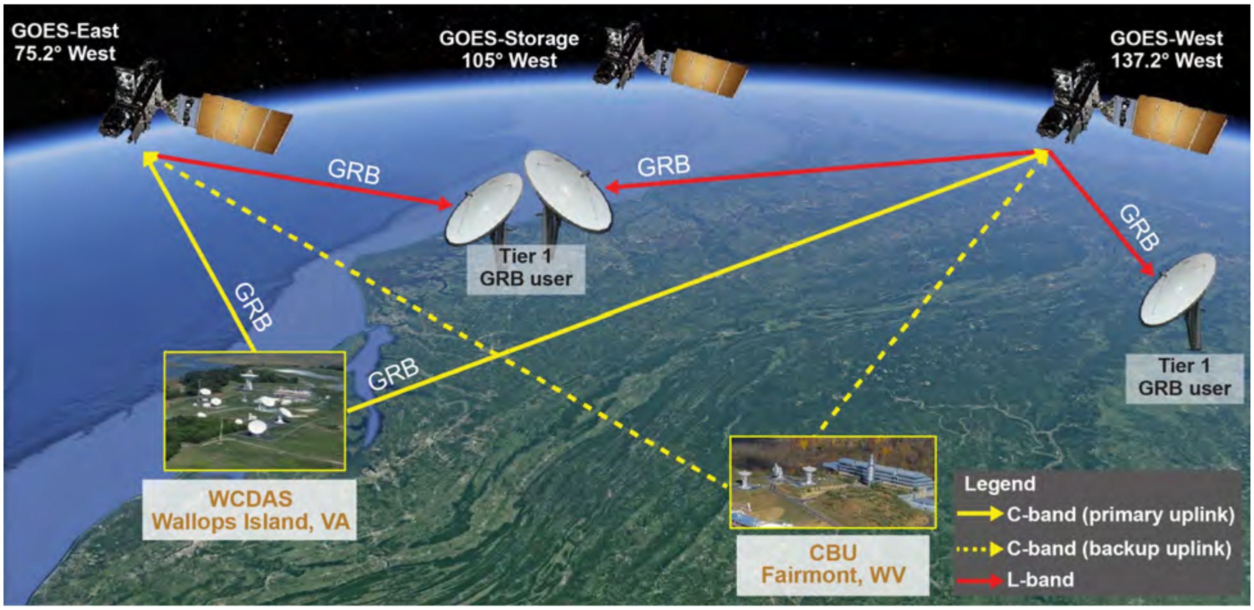

Figure 4.6-14. End-to-end data flow from primary and backup GRB generation and uplink sites to tier 1 GRB users.

NESDIS estimates that there are more than 40,000 DCPs used in North and South America, of which approximately 75% relay data through the GOES-R DCPR transponders. Those platforms uplink data at frequencies, and within time windows, allocated by NESDIS to prevent interference. The uplink occurs in ultra-high frequency (UHF) at 401.9 MHz. The satellite translates the frequency to the 1679.7–1680.1 MHz band and broadcasts the data over its footprint. The DCPR footprint is shown in Figure 3.1-2. Users that wish to receive the sensor data directly from the satellite relay must demodulate the specific frequency and identify the data of interest using unique enumerators, such as DCP identification numbers. The receivers used to obtain DCPR data from the satellite broadcast are called DRGS. They are directional antennas that point to the satellite through which the user's DCP is relaying data. The end-to-end data flow from sensor to tier 1 DRGS users is shown in Figure 4.6-15. SPRES Project 1 identified 26 DRGS users, 14 of which are considered critical or important.

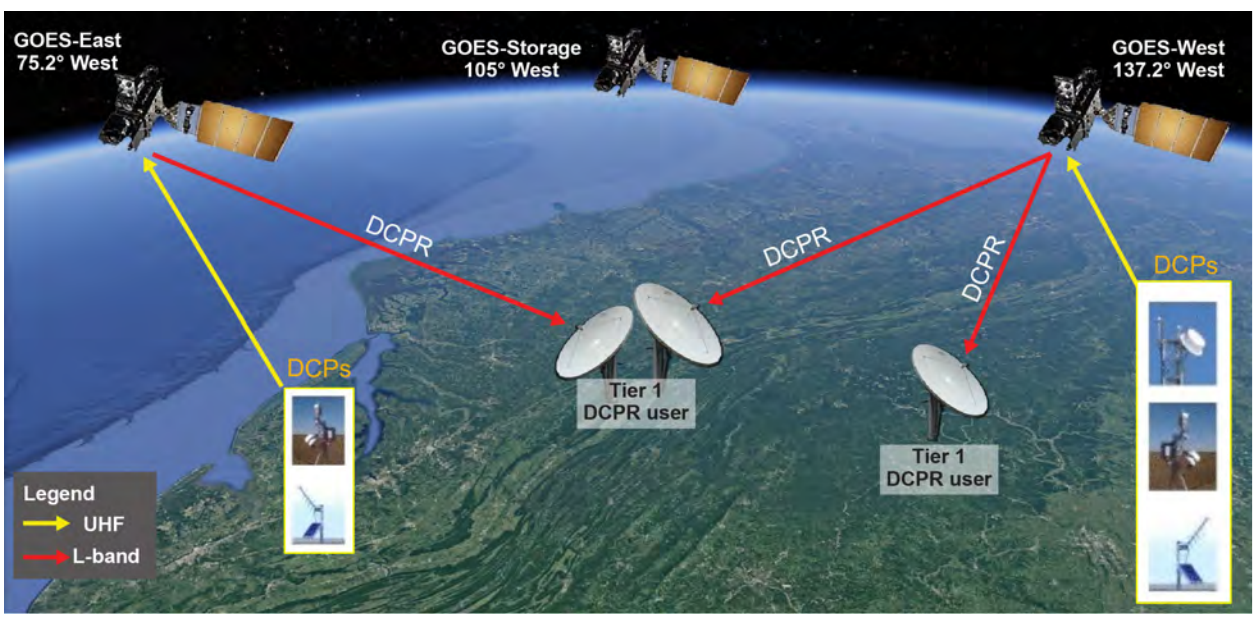

Figure 4.6-15. DCPR data flow from DCPs to tier 1 DCPR service users.

DCP sensors operate in two distinct modes, random and self-timed. Random sensors report on a predesignated channel based on environmental triggers. To increase the likelihood of successful transmission, the data is repeated three times. Self-timed DCP sensor radio transmission equipment is configured to report at a specified time and periodicity that constitute a reporting window allocated by NOAA. There is no redundancy built into the system for data reporting. If the sensor does not report during the allocated window, it waits until the next reporting window to transmit updated data. The previous value is simply lost. Sensors can be configured to transmit both the current and previous period readings to increase reliability of data transmission, albeit with extended latency.

4.6.3.2 Tier-to-tier distribution services

Several nodes within the GOES distribution network distribute data to lower-level tiers. For any user relying on higher-tier distribution services, it is important to understand the end-to-end data flows as well as where the risks to L-band interference may result in data loss to that user.

4.6.3.2.1 ESPDS/PDA distribution service

NOAA uses the Product Distribution and Access (PDA) system and the NWS Integrated Dissemination Program (IDP) system to distribute GRB data to near-real-time data users over terrestrial networks. PDA relies on a GRB downlink at NSOF. The ground segment has a dedicated network interface with PDA and distributes GRB data, along with higher-level processed products, to users. Figure 4.6-16 shows the flow of data from the tier 1 GRB receiver at NSOF to PDA users. PDA distributes data to hundreds of users worldwide through public and privately operated networks.

4.6.3.2.2 NWS Integrated Dissemination Program Distribution Service

While PDA distributes data both internal and external to NOAA, the Integrated Dissemination Program Distribution Service (IDP) is part of the NWS terrestrial distribution network and provides GRB downlink redundancies at two NWS National Centers for Environmental Prediction (NCEP) sites. The GRB receivers utilize a Local Data Management (LDM) system from Unidata that is able to ingest products from either of the GRB receivers. The receivers are located at geographically diverse sites, NOAA Center for Weather and Climate Prediction (NCWCP) in College Park, Maryland, and Space Weather Prediction Center (SWPC) in Boulder, Colorado. Although no empirical evidence was provided, NCEP indicated this receive system is very robust and operates with high product availability. Figure 4.6-17 shows the end-to-end data flow to NWS NCEP centers.

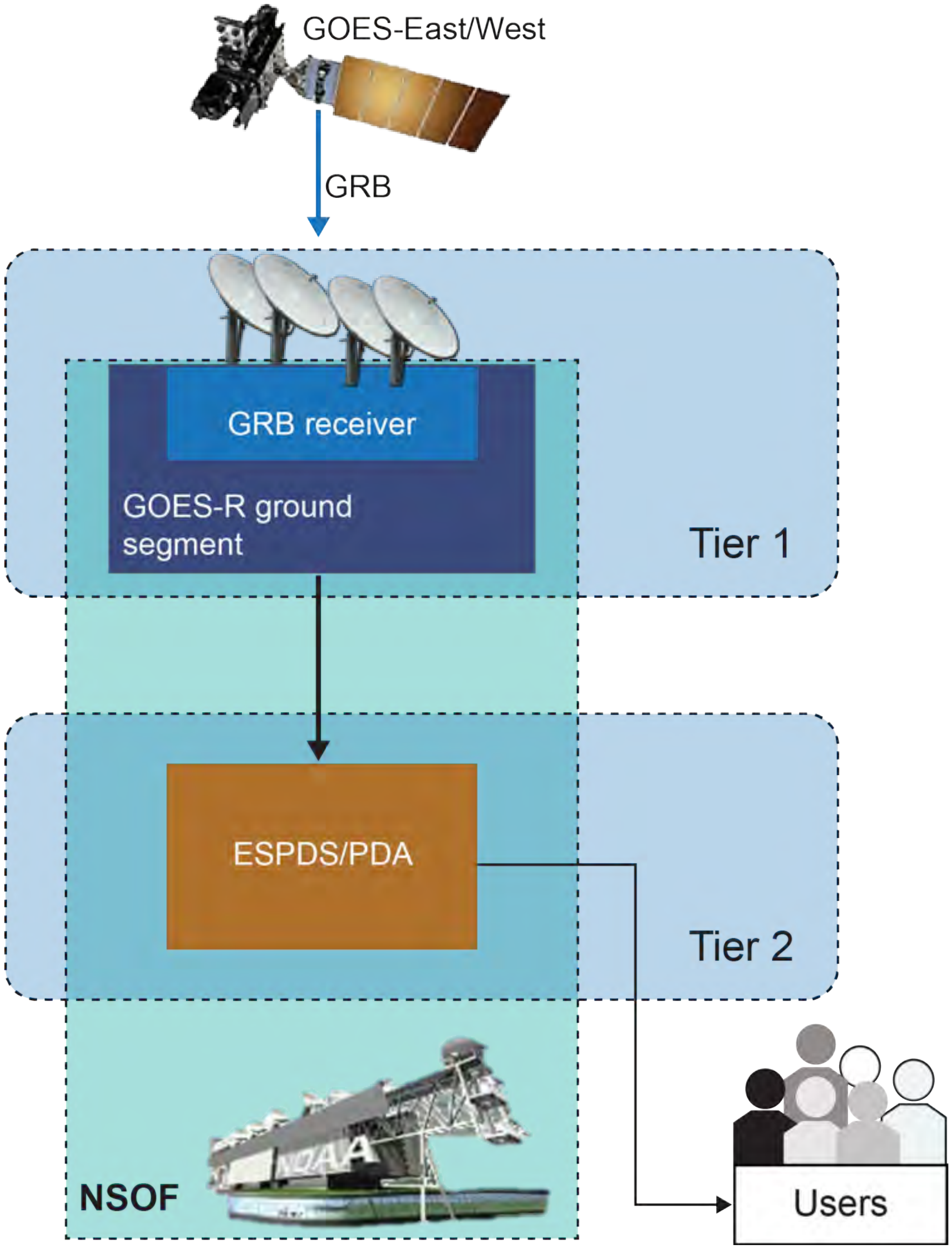

Figure 4.6-16. End-to-end ESPDS data flow.

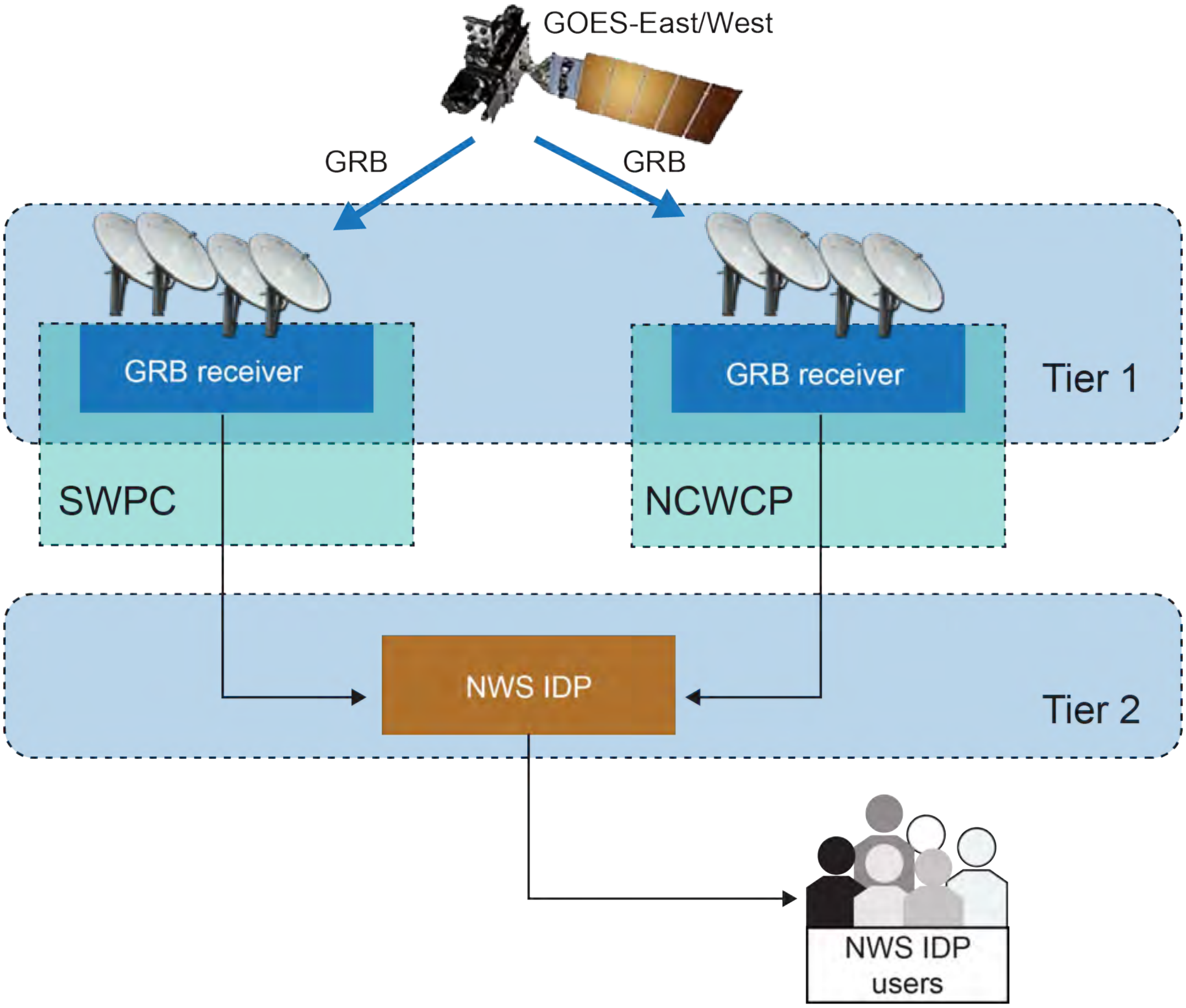

Figure 4.6-17. IDP end-to-end product flow.

4.6.3.2.3 DCS Administrative and Data Distribution Systems

The DCS Administrative and Data Distribution System (DADDS) is physically located at WCDAS and NSOF. DADDS has redundant distribution servers operating at both sites that meet the direct broadcast user availability requirements identified in SPRES Project 1. DADDS receives data from the DRGS receivers at WCDAS and NSOF and serves that data over the public internet to users. In addition to DCP data, the DADDS system also distributes administrative information to registered users. DADDS is a tier 2 distribution network node as it receives data from collocated DRGS receivers. The DADDS system high-level architecture is shown in Figure 4.6-18.

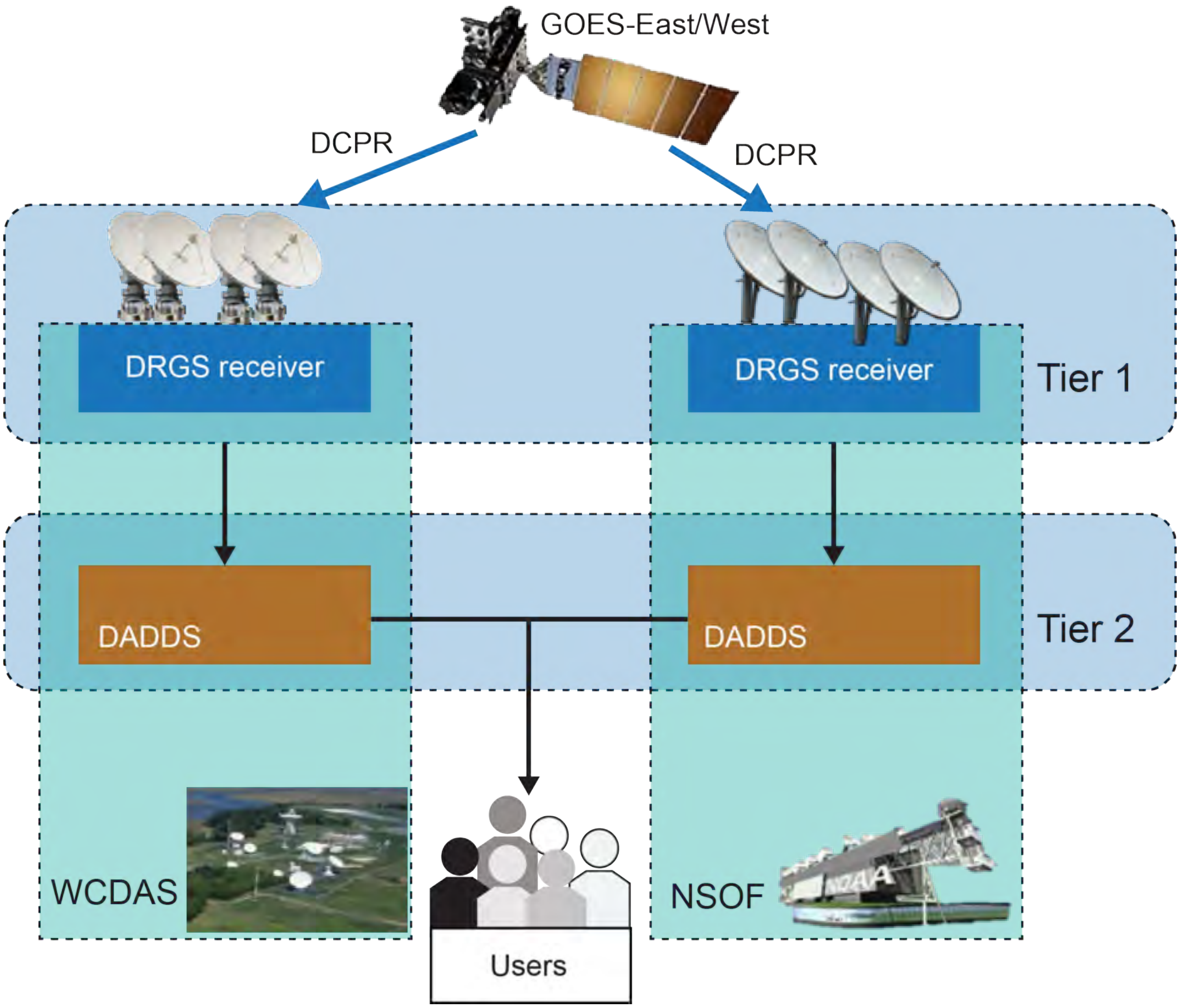

Figure 4.6-18. DADDS end-to-end product flow.

4.6.3.2.4 Local Readout Ground Station distribution service

The Local Readout Ground Station (LRGS) is another DCS terrestrial distribution service, with publicly accessible data servers operated by both NOAA and USGS. NOAA operates two redundant LRGS webservers at NSOF and WCDAS, serving data over the public internet to end users. In addition, USGS operates an LRGS system at its Earth Resource Observation and Science (EROS) center in Sioux Falls, South Dakota. Users must be sponsored by NOAA in order to obtain an account and access any of the three LRGS distribution systems. The LRGS distribution architecture is shown in Figure 4.6-19.

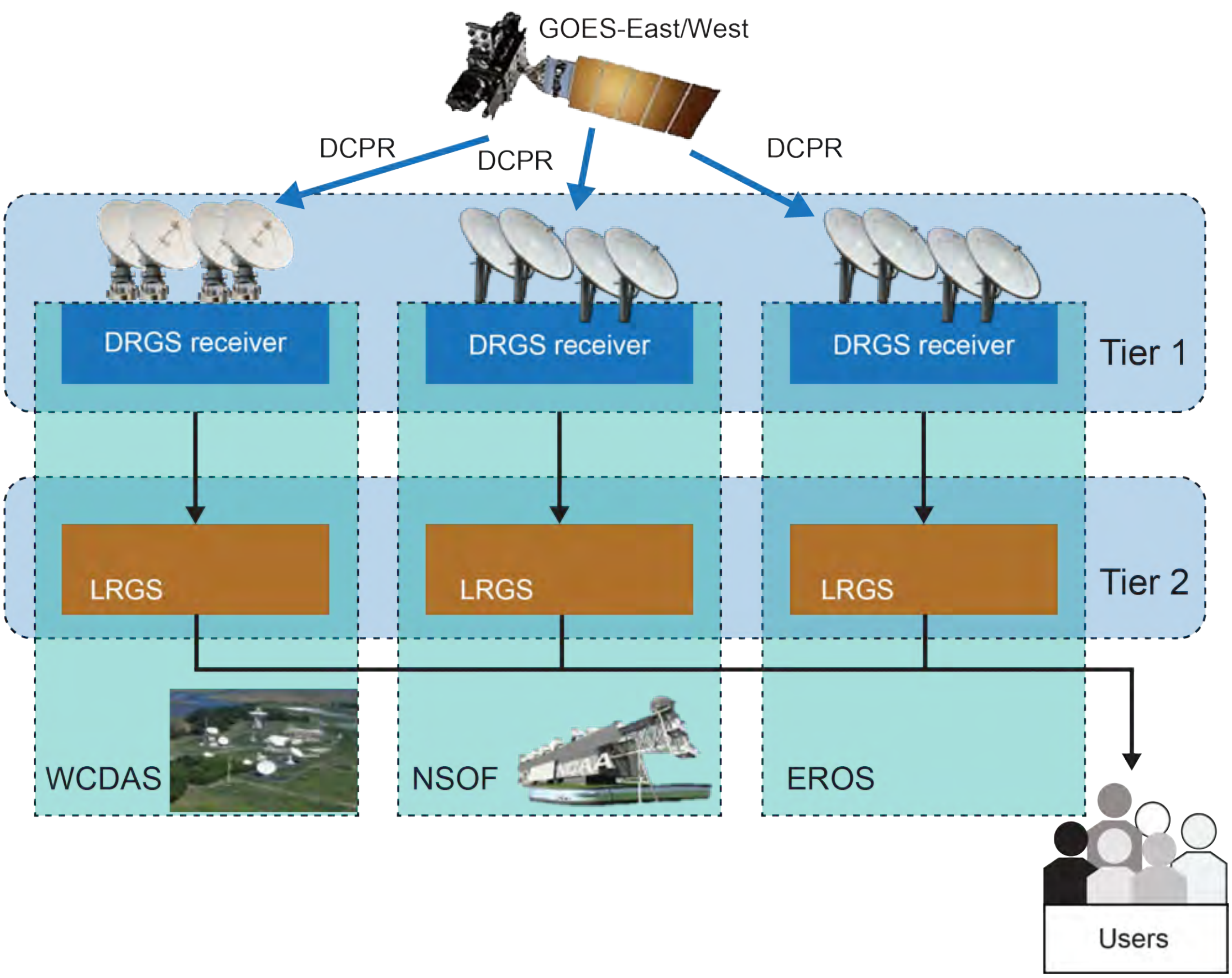

Figure 4.6-19. LRGS end-to-end data flow.

In addition to obtaining data from DRGS systems at each location, LRGS software is able to ingest data from multiple services, both satellite and terrestrial. Multiple LRGS systems within an organization can be networked in a ring topology, effectively providing a dispersed system of satellite receivers providing data to multiple LRGS systems, each located at the client's facility. This is illustrated in Figure 4.6-20. Several existing users operate LRGS with multiple inputs, and users have reported losing DRGS service without realizing that a distribution service was no longer functional. This anecdotal evidence illustrates the LRGS ability to transition seamlessly to alternative data sources without impacting user operations.

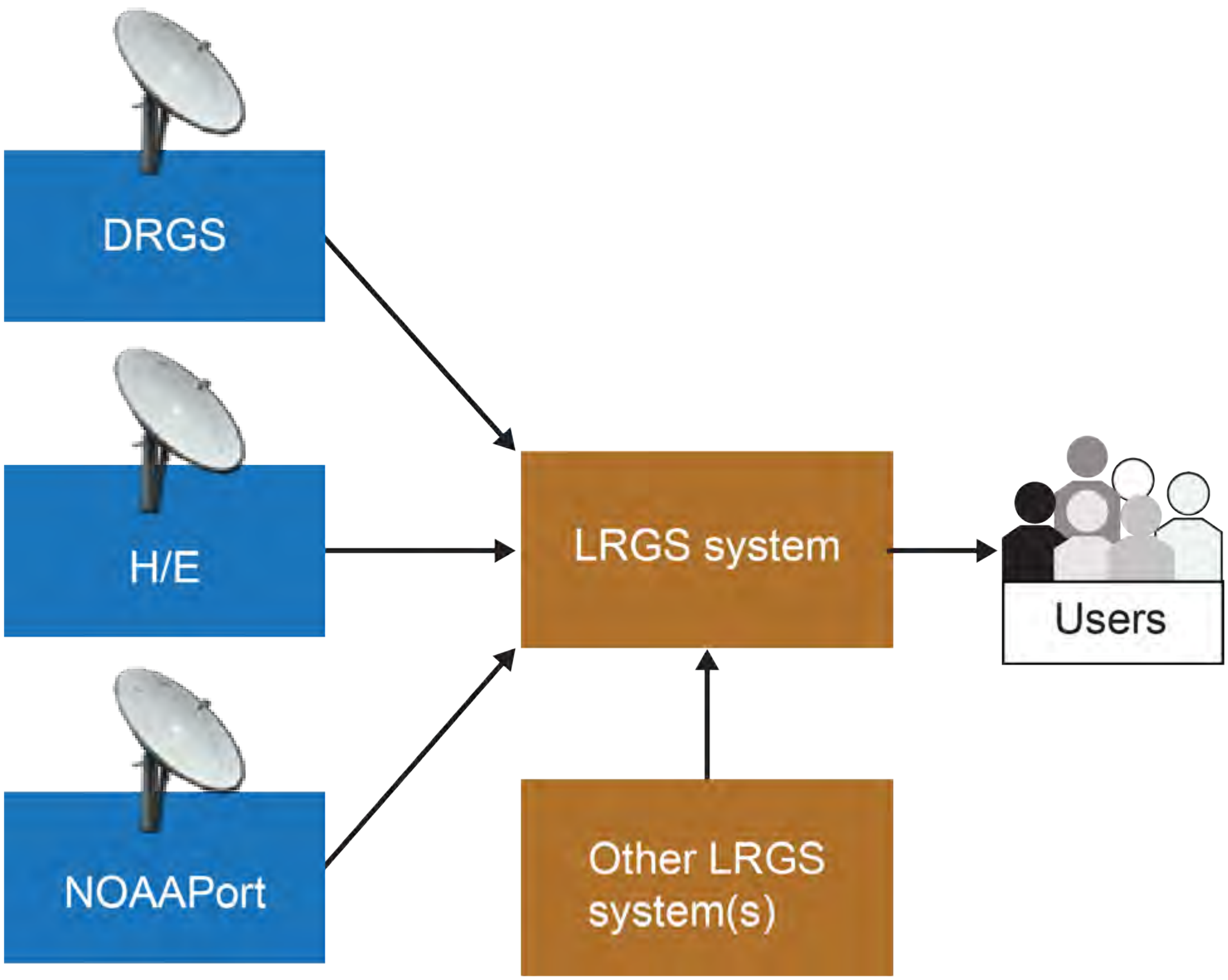

Figure 4.6-20. LRGS data ingest capabilities.

4.6.3.2.5 NOAAPort/Satellite Broadcast Network distribution service

The NWS satellite distribution service, known as NOAAPort/Satellite Broadcast Network (SBN), was put in place to support NWS forecasting operations. Approximately 150 NWS Weather Forecast Offices (WFOs) and River Forecast Centers (RFCs) operate NOAAPort receivers to support daily operations. This broadcast contains a variety of environmental data to support forecasting operations, and one of its channels carries DCS data that has been processed by the NWS Hydrometeorological Automated Data System (HADS). The NWS HADS receives DCP data from a terrestrial connection to the DADDS webservers located at NSOF and WCDAS. That data is processed by HADS and uplinked to the NOAAPort satellite from Holmdel, New Jersey. The Galaxy-28 satellite is currently being used for NOAAPort broadcast. There is a backup ground station located in Fairmont, West Virginia. Users that have a NOAAPort receiver are able to obtain DCP data from the NWS processing system that resides in tier 3, as shown in Figure 4.6-21. The NOAAPort receivers operate at 4040 MHz (in commercial C-band) and are not susceptible to RFI being studied in the SPRES program.

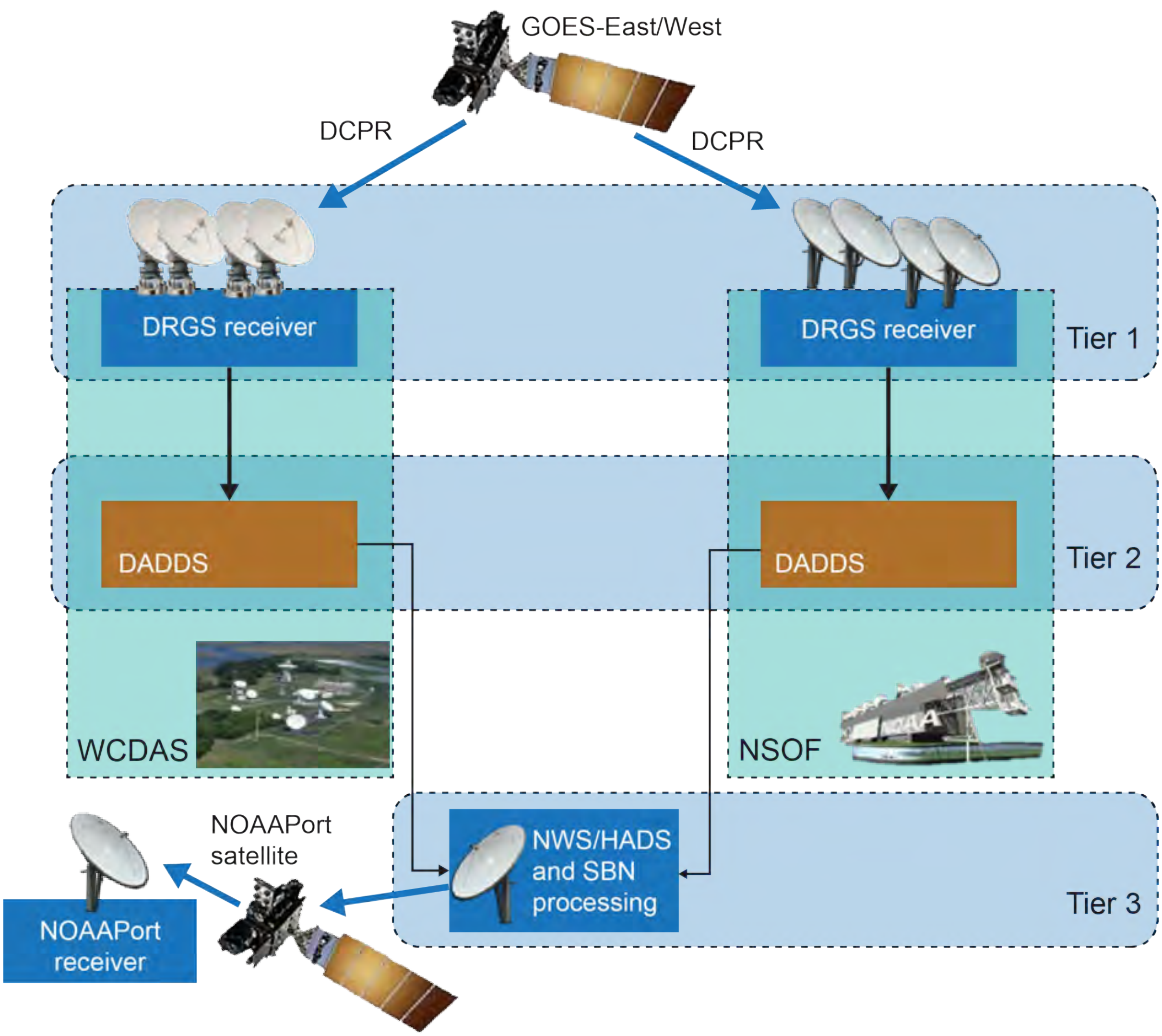

Figure 4.6-21. NOAAPort end-to-end data flow.

NOAAPort/SBN GOES-R data is sourced from the sectorized, tiled imagery that originates from a command and data acquisition station (CDAS). This format of data is not carried over GRB and is in a modified configuration from the Level 1b data that is broadcast via GRB. Not all users' needs can be met with the sectorized, tiled imagery.

Since NOAAPort/SBN is distributed to users by commercial satellite, no study was undertaken regarding the potential impact of spectrum sharing in 3.7–4.2 GHz, as that is out of scope to this SPRES effort.

4.6.3.2.6 High Rate Information Transfer/Emergency Manager Weather Information Network

Users who require DCP data via satellite distribution, but who do not want to acquire a relatively expensive DRGS system, can use an HRIT receiver. In the GOES-R series satellite, the HRIT broadcast is combined with EMWIN data provided by the NWS. In legacy GOES spacecraft, these broadcasts were sent over two independent frequencies. However, in the GOES-R series satellites, the broadcasts are combined into a single digital stream called HRIT/EMWIN at 1694.1 MHz using a bandwidth of 1.205 MHz. Data in this broadcast is contained in virtual channels and prioritized by groups. In the event that two-way communications between DCP and operator is required, HRIT/EMWIN receivers would not be capable of supporting data collection platform interrogation (DCPI). But this service does allow the HRIT/EMWIN user to acquire all DCP data with lower-cost receiver equipment and demodulation of a single broadcast. As a result it is simpler than installing a DRGS, although it incurs a slight data latency penalty.

Since the HRIT/EMWIN downlink center frequency is at 1694.1 MHz, it is less susceptible to interference from 1675–1680 MHz mobile network operations.[20] However, DCS data for the HRIT/EMWIN broadcast is ultimately obtained from a DRGS downlink at WCDAS or NSOF. Therefore, the source of the DCS data used in this broadcast is highly susceptible to RFI. In addition, the receiver at NSOF has a relatively low margin, which implies that this redundant receiver may not provide the expected improvement in data availability. Figure 4.6-22 shows the end-to-end data flow for the HRIT/EMWIN broadcast. DCPR data is received at NSOF and WCDAS and ingested into DADDS. The DCS messages are distributed from DADDS to the ESPDS. ESPDS writes DCS messages into a file until it reaches 8 kB in size. It then inserts that file into the HRIT/EMWIN broadcast. The broadcast is sent terrestrially to the operational GOES command and data acquisition station, nominally WCDAS, where it is uplinked to the GOES-R satellite. The GOES-R satellite uplink equipment at WCDAS is considered to be in tier 4. Any user with an HRIT/EMWIN receiver in the satellite footprint can receive the broadcast. There is a backup ESPDS and GOES-R uplink site located at CBU. All DADDS systems located at WCDAS and NSOF interface with ESPDS systems located in NSOF and CBU, so all system components have full redundancy.

[20] HRIT/EMWIN is the closest GOES-R service to the AWS-3 uplinks in 1695–1710 MHz and the additional LTE services above 1710 MHz. Determination of the effects of RFI from these services, if any, is out of scope of this SPRES study. However, it may be a factor in the reliability of HRIT/EMWIN, for which due diligence outside of this study might be valuable.

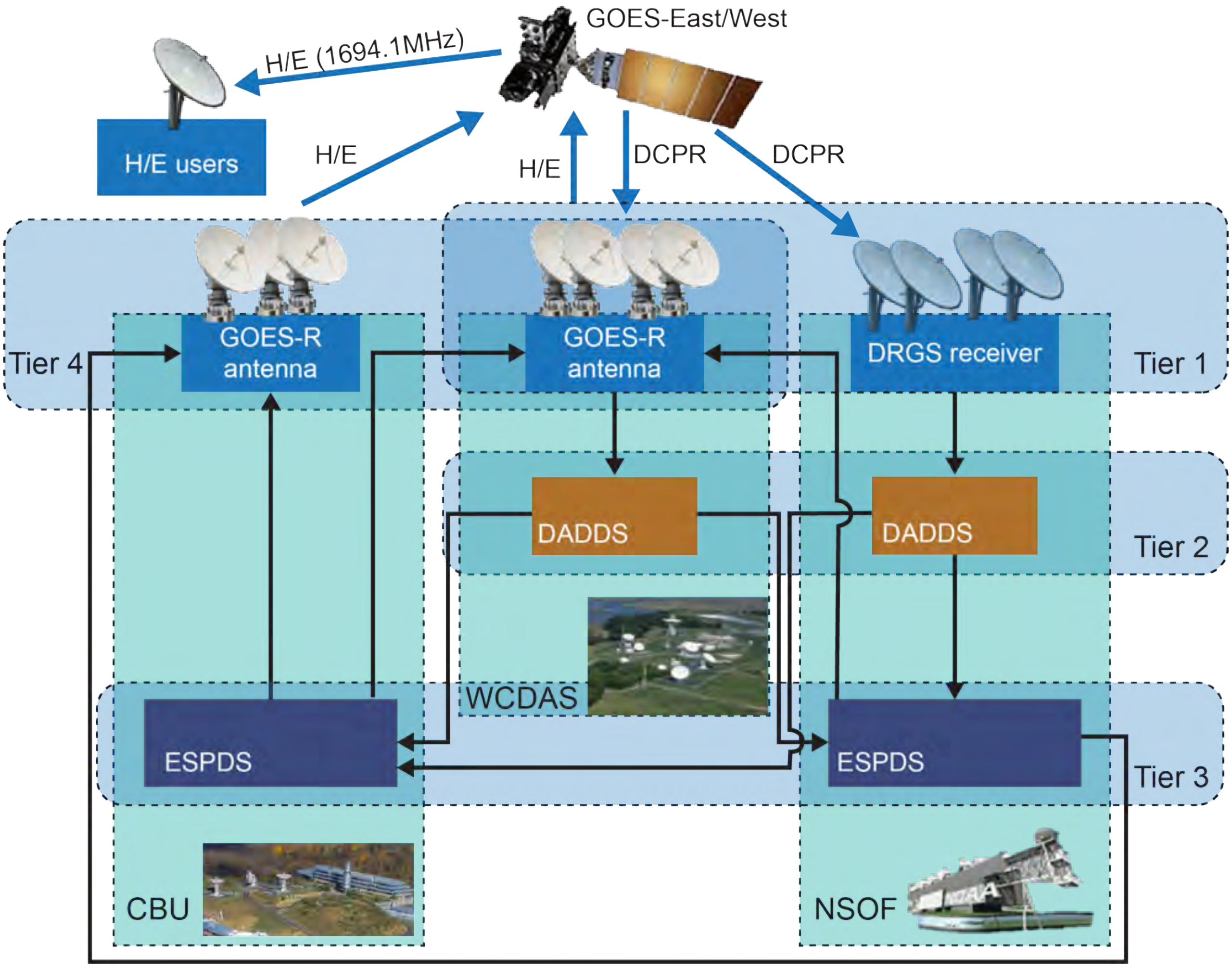

Figure 4.6-22. HRIT/EMWIN end-to-end data flow.

4.6.3.3 Overall distribution network

The overall GRB and DCS distribution networks shown in Figure 4.6-23 and Figure 4.6-24 clearly illustrate how an interference event occurring in a tier 1 distribution node can impact the overall distribution network. If such interference occurs, it is safe to assume that all users operating a GRB receiver would be at a moderate risk for RFI resulting in data loss. There are two distribution services that could potentially be impacted. The NWS IDP network has two receivers located over 1,500 miles apart, providing data to a centralized data manager. Project 6 did not investigate the likelihood of different interference sources occurring at both sites. However, if adequate protection is implemented, RFI-caused data loss experienced by both sites simultaneously is unlikely. Therefore, the likely impact to NWS/IDP users is low. On the other hand, PDA relies on a single GRB receiver at NSOF in Suitland, Maryland. If interference is experienced at this site resulting in GRB data loss, PDA will not be able to distribute L1b and GLM products that are normally distributed over GRB, and it will also miss higher-level products that are generated by the GOES-R ground segment at NSOF. PDA distributes this data to hundreds of users worldwide.

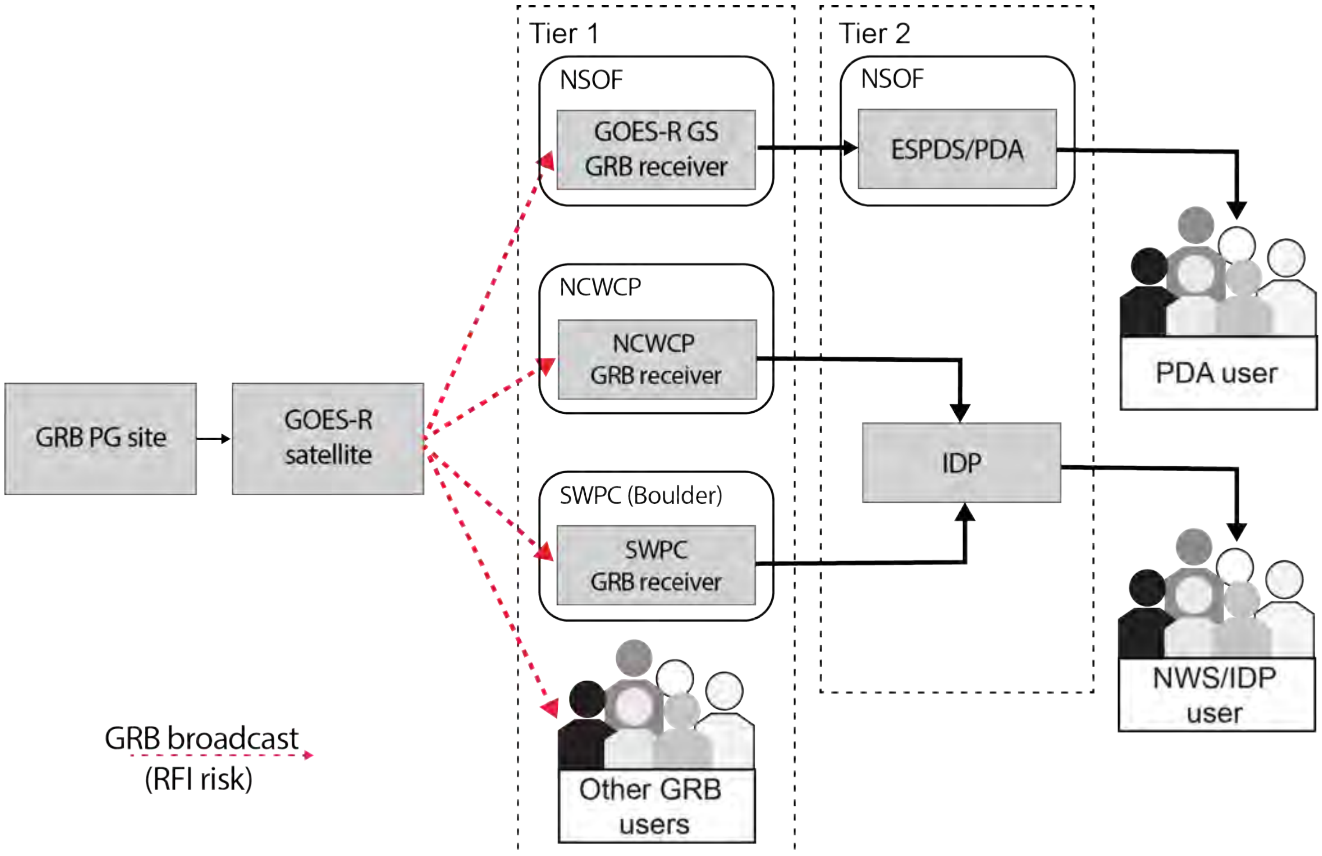

Figure 4.6-23. NOAA GRB data distribution services.

Figure 4.6-23 shows the GRB distribution services operated by NOAA. It is worth noting that although there are several services available, all of them ultimately depend on a DRGS downlink.

In addition, the DRGS broadcast is most susceptible to RFI because of its proximity to the 1675–1680 MHz band. Therefore, all users that operate DRGS receivers are at a higher risk for RFI, with the potential for data loss. The LRGS service relies on three DRGS downlinks located at WCDAS, NSOF, and USGS/EROS. Although NSOF and WCDAS may be closely coupled in terms of simultaneous RFI events, the third downlink, located in Sioux Falls, South Dakota, has significant geographic separation and is unlikely to experience a simultaneous RFI event. The other three distribution services, NOAAPort, HRIT/EMWIN, and DADDS, ultimately rely on DRGS downlinks at WCDAS and NSOF. Analysis conducted in SPRES Project 11 shows that the exclusion zones for WCDAS and NSOF are likely to have significant overlap. This indicates that an anomalous propagation (AP) event occurring at one site has a significant chance of affecting the other. If this sort of AP event were to occur, there could be significant consequences for the DCS data users. As indicated in Figure 4.6-24, DADDS, NOAAPort, and HRIT/EMWIN users all would lose DCS data.

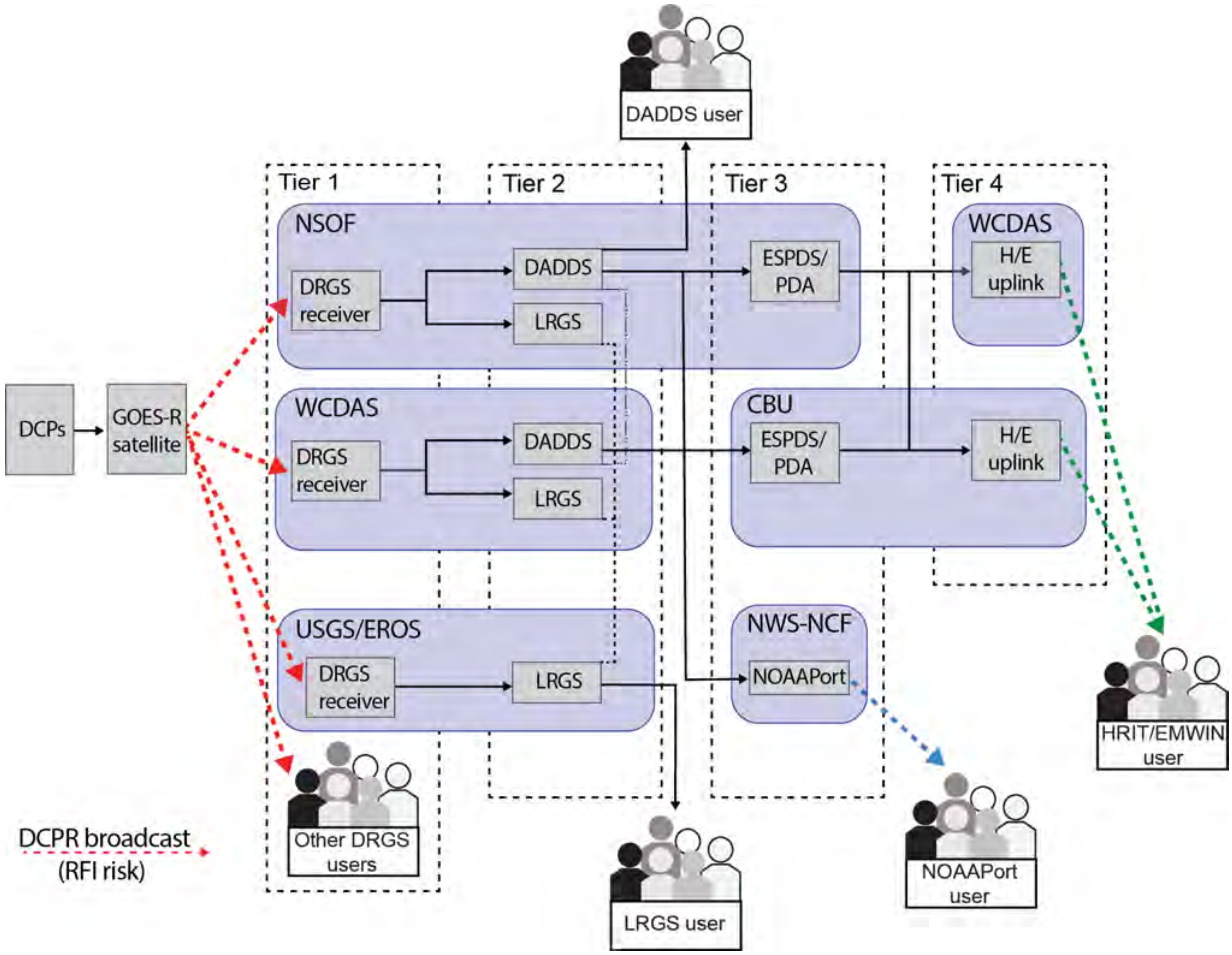

Figure 4.6-24. NOAA DCS data distribution services.

4.6.4 Overall risk assessment by site

A comprehensive RFI risk assessment was performed for each site using the following:

- The detailed survey data collected at each site
- A more thorough data distribution architecture analysis
- User impacts gathered from Project 1
- Other preliminary data from Projects 2, 8, and 9

The impacts of data loss at an individual node will have direct impacts to the user at that site and can have cascading impacts to users downstream if the node performs a distribution service. The direct impacts were determined using data from Project 1, where the user specified impacts to data loss based on survey questions. In addition, the critical and important sites were researched to determine which sectors of the economy they service based on North American Industry Classification System (NAICS) codes. Using NAICS codes and data from the Bureau of Economic Analysis, a correlation could be made between data loss at a node and the segment of the U.S. economy that could be impacted. Downstream nodes that may be impacted due to a loss of data at a distribution node were determined using network analysis so the total impact of the RFI event could be determined.

Another factor considered in Project 6 was the probability of data loss at a given node due to an RFI event. The probability would be affected by the service used to obtain data, redundant distribution services, susceptibility of a site to anomalous propagation, and user latency requirements. Knowing the probability of RFI resulting in data loss, and the associated user impacts of data loss, allows the total risk of an RFI occurrence to be determined.

In summary, Project 6 produced a user risk assessment to understand how RFI occurring at a network node could impact the overall distribution network. In order to develop a risk assessment, the overall likelihood of data loss and impacts to data loss were quantified in Sections 1.4 and 1.5 of the report. The results (Table 4.6-1) are the product of those two quantities. The overall risk can vary from 1–9, with 9 corresponding to the highest risk level. For those sites that had two different likelihood scores because they utilize both GRB and DCS service, the higher likelihood was used in the risk calculation.

Table 4.6-1. Overall RFI risk assessment for DCS and GRB critical and important sites.

State	City	Group 2 (department/ agency)	Affiliation	Overall impact to data loss (I)	Overall likelihood (L)	Overall risk (IxL)
MD	Suitland	DOC	NOAA/NESDIS, NSOF	3	2.75	8.25
VA	Wallops Island	DOC	NOAA/NESDIS, Satellite Command and Acquisition Stations	3	2.75	8.25
WA	Seattle	DOC	NOAA, NOS/NWS Western Region Office	3	2.5	7.5
VA	Norfolk	DoD	USN, NMOC Fleet Weather Center	3	2.5	7.5
WV	Fairmont	DOC	NOAA/NESDIS, CBU	2.75	2.5	6.88
FL	Miami	DOC	NWS, NHC	2.75	2.5	6.88

Table 4.6-1. cont.

Table 4.6-1. Overall RFI risk assessment for DCS and GRB critical and important sites.

State	City	Group 2 (department/ agency)	Affiliation	Overall impact to data loss (I)	Overall likelihood (L)	Overall risk (IxL)
FL	Cape Canaveral Space Force Station	DoD	USAF, 45th Weather Squadron	2.5	2.75	6.88
OK	Norman	DOC	NOAA/NWS, Storm Prediction Center	3	2.25	6.75
HI	Joint Base Pearl Harbor-Hickam	DoD	USAF, 17th Operational Weather Squadron	3	2.25	6.75
AK	Anchorage	DoD	USAF, Elmendorf-Richardson	3	2.25	6.75
SD	Sioux Falls	DOI	USGS, EROS/EDDN	2.75	2.33	6.41
MD	College Park	DOC	NOAA/NWS, NCWCP	3	2.08	6.24
IL	Rock Island	DoD	USACE, Mississippi Valley Division	3	2.08	6.24
VA	Chesapeake	DOC	NOAA, National Ocean Service	2.35	2.5	5.88
NE	Offutt AFB	DoD	USAF, Offutt	3	1.94	5.82
CO	Boulder	DOC	NOAA/NWS, SWPC	2.75	2.08	5.72
MO	St. Louis	DoD	USACE, Mississippi Valley Division	2.75	2.08	5.72
HI	Honolulu	DOC	NOAA/NWS, Pacific Region HQ Inouye Regional Center	2.5	2.25	5.63
AK	Fairbanks	DOC	NOAA/NESDIS, FCDAS	2.75	1.94	5.34
MO	Kansas City	DOC	NOAA/NWS, AWC	2.75	1.94	5.34
MD	Silver Spring	DOC	NOAA, NWS	2.75	1.94	5.34
ID	Boise	DOI	BOR	2.75	1.83	5.03
MS	Columbus Lake	DoD	USACE, Columbus Lake District	2.5	1.94	4.85
CA	Sacramento	DoD	USACE, South Pacific Division	2.5	1.83	4.58
AK	Anchorage	DOC	NOAA/NWS, Alaska Region Office	2.25	2	4.5
HI	Honolulu	DOC	NOAA/NWS, PTWC	2.5	1.75	4.38
OH	Cincinnati	DoD	USACE, Great Lakes and Ohio River Division	2.1	2.08	4.37
ID	Boise	DOI	BLM, NIFC	2.75	1.58	4.35
CA	Monterey	DoD	USN, FNMOC	3	1.44	4.32
MS	Vicksburg	DoD	USACE, Mississippi Valley Division	2.35	1.83	4.30
AL	Huntsville	NASA	Marshall Space Flight Center	2.1	1.94	4.07
TX	Houston	NASA	Spaceflight Meteorology Group	1.6	2.5	4
TN	Knoxville	TVA	River Forecast Center	2.1	1.83	3.84
CA	Monterey	DoD	USN, NRL	1.85	2	3.7
NE	Omaha	DoD	USACE	**	**	**

**Omaha, NE (USACE) was not covered in the analysis.

4.7 Project 7. Protection Studies

4.7.1 Introduction

Project 7 supports two SPRES program objective areas: RFI Modalities and Risks, and Mitigation Options and Feasibilities. This project evaluated the impact of a commercial deployment in the 1675–1680 MHz band on GOES ground station receivers. LTE frequency division duplexing (FDD) services are analyzed to determine the impacts of LTE downlinks and uplinks on GOES services. In particular, the study addresses large-cell downlink, uplink, and small-cell downlink configurations. The study provides protection and coordination recommendations of the band due to LTE deployments under anomalous and standard atmospheric propagation conditions. These techniques quantify the RFI risk to NOAA Met-Sat users under potential commercial deployments, which will affect the ability to maintain high reliability along GOES services in the 1675–1680 MHz band, and data links adjacent to this band.

4.7.2 Anomalous propagation background

Anomalous propagation reduces the propagation loss of over-the-horizon radio paths, which could have significant impact to spectrum sharing. Tropospheric ducting is a form of anomalous radio wave propagation that primarily occurs in flat, coastal regions, such as areas where the NOAA Wallops Command and Data Acquisition Station (WCDAS) site is located. Multiple anomalous RFI events have been experienced at WCDAS that were not attributed to nearby emitters under standard atmospheric conditions. Higher frequency (e.g., very high frequency [VHF] and ultra-high frequency [UHF]) signals experience the most dramatic increase of signal strengths from these anomalous refractivity profiles. Thus, emissions in 1675–1680 MHz are susceptible to ducting over long distances. It is possible that the propagation loss across the link can be less than free-space path loss under certain anomalous propagation conditions. Of specific interest to this project are the higher interference levels to the satellite ground station caused by the LTE signals from distant (100–500 km) commercial systems. (See Appendix J, section J.2, for additional information.)

An example of the relationship between temperature, humidity, and modified refractivity is presented in Figure 4.7-1, taken from NOAA sounding measurements at Marine Corps Air Station Miramar in February 2015. This figure illustrates the atmospheric variations in temperature and humidity, and the corresponding refractivity profile. In this particular case, an elevated duct exists, and radio frequency signals traveling horizontally will tend to turn toward regions with higher refractivity, which is measured in M-units (modified refractivity). In radio propagation, it is convenient to use M-units, which contain the effect of the earth's curvature. The temperature inversion that begins at 550 m has the effect of pulling energy back down into the elevated duct. Small-scale vertical variations in temperature and humidity, driven by the evaporation process, can also form near the sea surface and complement the larger atmospheric refractivity structure's effects that trap energy at higher frequencies (>3 GHz).

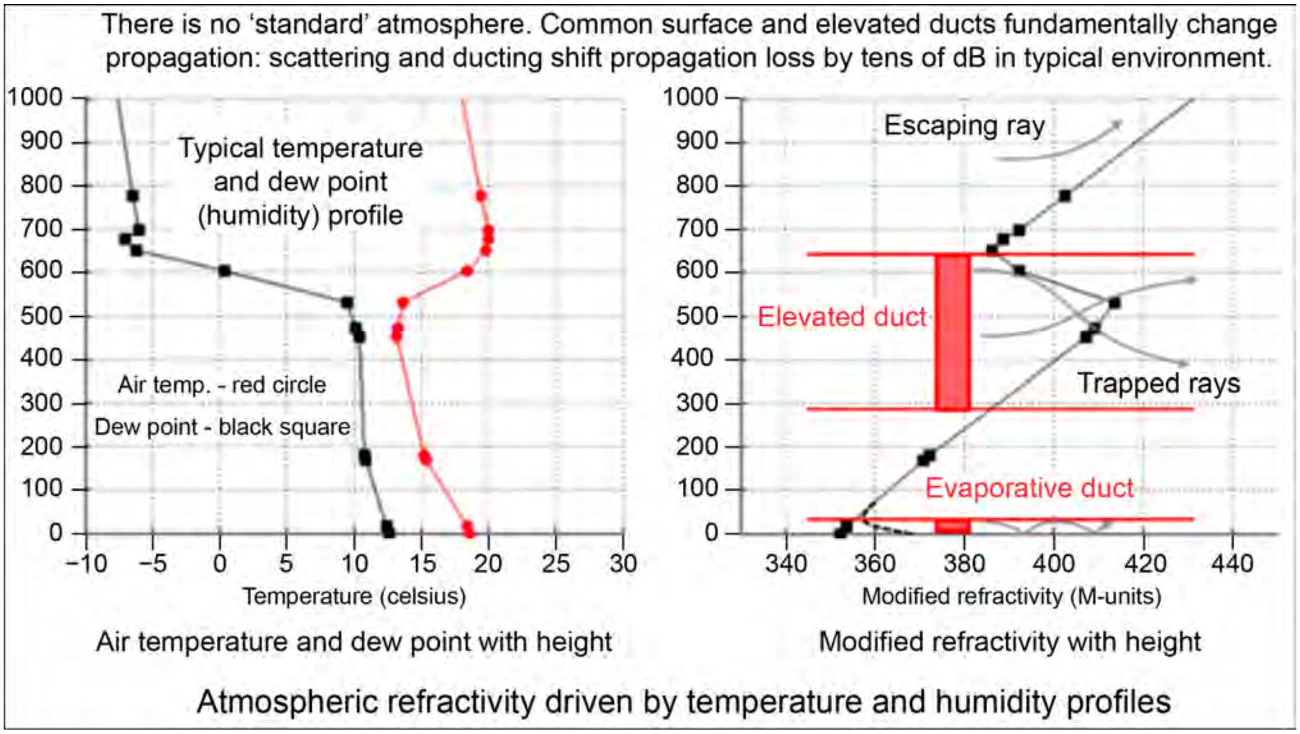

Figure 4.7-1. Temperature (left), humidity (left), and modified refractivity (right) example.

Several types of tropospheric weather events can generate significant anomalous propagation, allowing RF signals to propagate at greater amplitudes and distances, thus increasing the potential for impacting sensitive receivers even from large distances. Forms of anomalous propagation include tropospheric ducting, which primarily occurs in flat, coastal regions, such as areas where the WCDAS site is located (Wallops Island, Virginia). NOAA reported periods of radiofrequency transmissions in the 1670–1675 MHz band at WCDAS, some of which were traced to transmission towers located more than 100 km away by decoding the transmitter ID embedded in the signal. It is recognized that these transmitters may not have been operating in a manner typical of mobile wireless base stations or mobile units; nonetheless, these events are attributed to anomalous propagation. A statistical analysis of the events provides some empirical evidence of the anomalous propagation conditions that would affect 1675–1680 MHz band sharing.

Measurements taken from August 31, 2015 through April 1, 2018 indicated 708 distinct instances at which power levels of −120 dBm or greater were detected from towers located at least 100 miles from WCDAS, each event lasting in the aggregate for 28.4 minutes and sometimes much longer.[21] At −120 dBm, it is reasonable to expect that RFI would cause harmful degradation to satellite downlink reception and reducing system availability. Specific testing may narrow the range to a more exact level of disruption. Figure 4.7-2 provides a histogram of the power levels ranging

[21] The total duration of RFI across the entire period: 20,050 minutes (334.2 hours).
The statistics of the individual RFI events recorded by the monitoring equipment:

- Average duration: 28.4 minutes
- Maximum duration: 614.55 minutes

Many of the individual events occur minutes apart. It is common to see time-varying propagation due to atmospheric conditions. If assuming weather-based anomalous propagation as the cause, events that occur within minutes of each other can be combined into 118 weather-based events having the following statistics:

- Average duration: 85 minutes
- Maximum duration: 1360 minutes

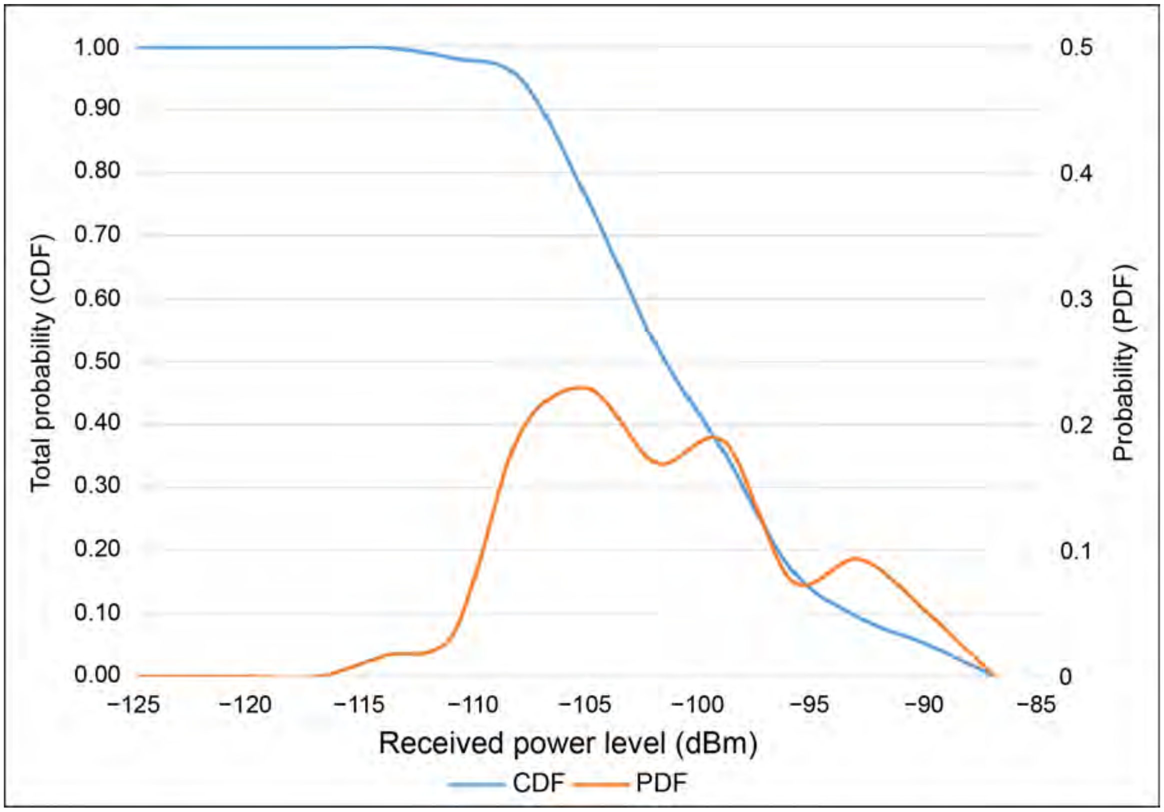

Figure 4.7-2. Cumulative and event probability distributions of interference power measurements at WCDAS.

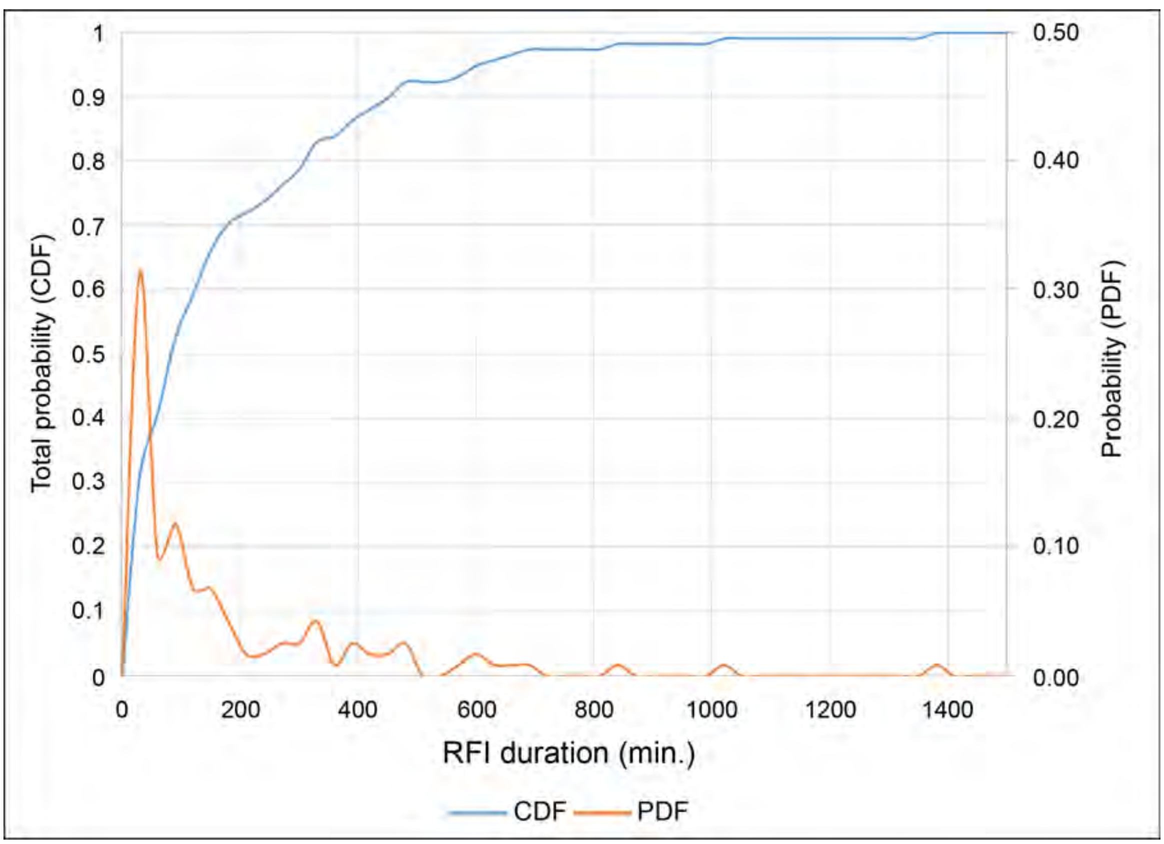

Figure 4.7-3. Cumulative and event probability distributions of interference event duration measurements at WCDAS.

from −120 dBm to −93 dBm. Given that −120 dBm was the minimum measurable signal level, data shows that anomalous propagation produced large interference power swings of at least 27 dB. The 50th percentile power level of the interference events is −107 dBm, and the 95th percentile power level of the interference events is −95 dBm, which indicates that anomalous propagation events produced path loss variations of at least 13 dB in 50% of the events, up to 25 dB in 95% of the events, and more than 25 dB in 5% of the events.

Figure 4.7-3 illustrates the histogram of event durations. Events lasted as long as 1,360 minutes, which is over 22 hours. The 50th percentile duration is 85 minutes, and the 95th percentile is 597 minutes (~10 hours).

These data provide empirical evidence proposing commercial AWS carrier applications in the 1675–1680 MHz band may impact user data receive locations due to anomalous propagation. This evidence is independent of the separation distance modeling described elsewhere in this report, which was done using radiosonde measurements and a standard mobile laydown used in a number of other spectrum planning exercises. The results of the modeling exercise stand on their own.

4.7.3 Methodology

This section describes the analysis methodology, including radio frequency propagation models and system parameters. The study established frequency division duplex (FDD) downlink and uplink operations in the 1675–1680 MHz band. Several alternate commercial deployments were analyzed to determine relative changes in RFI risks to GOES services under standard atmospheric and anomalous propagation conditions. Tropospheric ducting effects on RF signal propagation is a dominant anomalous propagation phenomena. Ducting occurs when temperature and humidity profiles in the atmosphere have strong gradients, which cause RF signals to refract at duct boundaries and become trapped rather than dissipate. This results in the reduction of propagation loss of over-the-horizon radio paths, which has significant impacts to the sharing of the 1675–1680 MHz band. Ducting characterizations were derived for each GOES ground station using historical radiosonde data. Refractivity index profiles were provided as input to the Anomalous Propagation Model (APM) produced by the Naval Warfare System Center in San Diego, California, which accounts for both ducting and terrain impacts to predict signal attenuation. Furthermore, extensive Monte Carlo simulations were conducted to effectively model the many uncertainties associated with location-dependent clutter and LTE parameters. Lastly, receiver selectivity specifications were extensively studied and modeled per Federal site location to represent the impacts of in-band and adjacent-band RFI.

4.7.3.1 Propagation modeling (This section should be read in association with Appendix J)

The modeling of radio wave propagation was conducted through the APM. The APM was developed by the Atmospheric Propagation Branch of Space and Naval Warfare System Center in San Diego, California, and is a part of the Advanced Refractive Effects Prediction System.[22] Both ducting and terrain effects are accounted for by the APM. Implemented is a hybrid ray-optic and parabolic equation (PE) that uses the complementary strengths of both methods to construct an efficient and accurate composite model. The APM was run in “automatic mode.” In this mode, when given the system and environmental inputs, the APM will automatically select appropriate PE parameters across three different hybrid states: full hybrid, partial hybrid, and airborne hybrid. For the Project 7 study, the model likely operated under the full hybrid and partial hybrid modes.

The APM takes the following inputs: terrain data (to represent the elevation profiles), refractivity data (to represent the refractive environment), receiver feed height, and signal frequency. A transmit antenna height is not required as an input as the APM returns a matrix of propagation loss values (height versus range).

As a validation step, standard atmospheric instances were compared to the Irregular Terrain Model (ITM). The ITM, also known as the Longley-Rice model, predicts the path loss of a radio signal between 20 MHz and 20 GHz, link distances ranging from 1–2000 km, and antenna heights ranging from 0.5–3000 m. The ITM, which was developed by the National Telecommunications and Information Administration (NTIA), has two prediction modes: a model for predictions over a region, also known as area mode, and a model for point-to-point link predictions. This study considered the ITM point-to-point link predictions as it takes into account detailed terrain paths to determine the propagation loss. The variation of the signal is computed by considering atmospheric changes, terrain profiles, and free space. Fluctuations of the signal arise from situational (confidence), time (reliability), and location variabilities.

4.7.3.1.1 Modeling of terrain

Shuttle Radar Topography Mission (SRTM) terrain data was used to generate terrain profiles that serve as an input into the APM and ITM. As a result of the extensive computation time of the APM, the terrain profiles were generated radially outwards from each ground station every 0.1° ranging out to 1000 km rather than generating a terrain profile to each LTE transmitter. Conducting an analysis of ducting requires a large analysis radius (>1000 km); as a result, tens of thousands of LTE transmitters could potentially be analyzed. However, when applying the ITM, terrain profiles directly from the ground station to the LTE transmitters were used as an input. This is due to the shorter analysis radius required for standard atmospheric conditions. For analysis in Hawaii and the continental United States, the terrain profile resolution was approximately 30 m, while in Alaska the terrain resolution was approximately 90 m.

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[22]Wayne L. Patterson, “Advanced Refractive Effects Prediction System (AREPS) Version 1.0 User’s Manual” (San Diego: Space and Naval Warfare Systems Center, 1998), http://www.dtic.mil/dtic/tr/fulltext/u2/a348559.pdf.

4.7.3.1.1.1 Clutter model

In addition to the propagation loss obtained from the APM and the ITM, this study included an additional loss to account for buildings, trees, and other obstacles (clutter). Clutter is site-specific and drives the size of protection distances of the Federal ground stations. There are no standard clutter models that are widely accepted because of the wide range of antenna heights, RF frequencies, types of land use, and types of terrain (hilly, flat, etc.). Thus, SSC performed drive tests surrounding the surveyed locations (see Table 4.7-4) in order to identify the impact of clutter around each Federal site.

Site-specific clutter-loss data collected by SSC in SPRES Project 6 was leveraged from the quantization of RFI at NOAA earth stations. Clutter loss values are sorted into 10° bins (to effectively represent a large sample of data in a relative direction) around the NOAA ground station. Per bin, Gaussian distributions are produced and fed into Monte Carlo simulations. These distributions are applied based on the heading of the LTE transmitter relative to the ground station. This process will allow for large obstacles, such as nearby buildings shadowing the ground station, to be captured.

The Project 6 clutter-loss data was adjusted to account for differences between the measurement systems and the LTE and GOES system configurations. Testing was completed between two antennas relatively low to the ground (low-to-low link), whereas this study considered LTE transmitters that are mounted 25–55 m high. Thus, to overcome the differences in the propagation tests and the simulation use cases, only the measured clutter losses were used if the LTE transmitter was beyond the radio horizon of the receiver. Any LTE transmitter beyond the receiver's radio horizon closely resembles a low-to-low link, especially under anomalous propagation conditions. If this condition was not met, the clutter surrounding the receiver was considered only where half of the clutter loss was taken. The process of separately treating the clutter in the proximity of the transmitter/receiver terminals was derived from the ITU-R P.2108-8 recommendation, where clutter corrections are made for each terminal (transmit and receive) independently. Figure 4.7-4 represents the clutter distributions generated for the 10° bin in a bearing of 100°–110° from WCDAS relative to true north. The left plot displays the distribution applied to an LTE transmitter

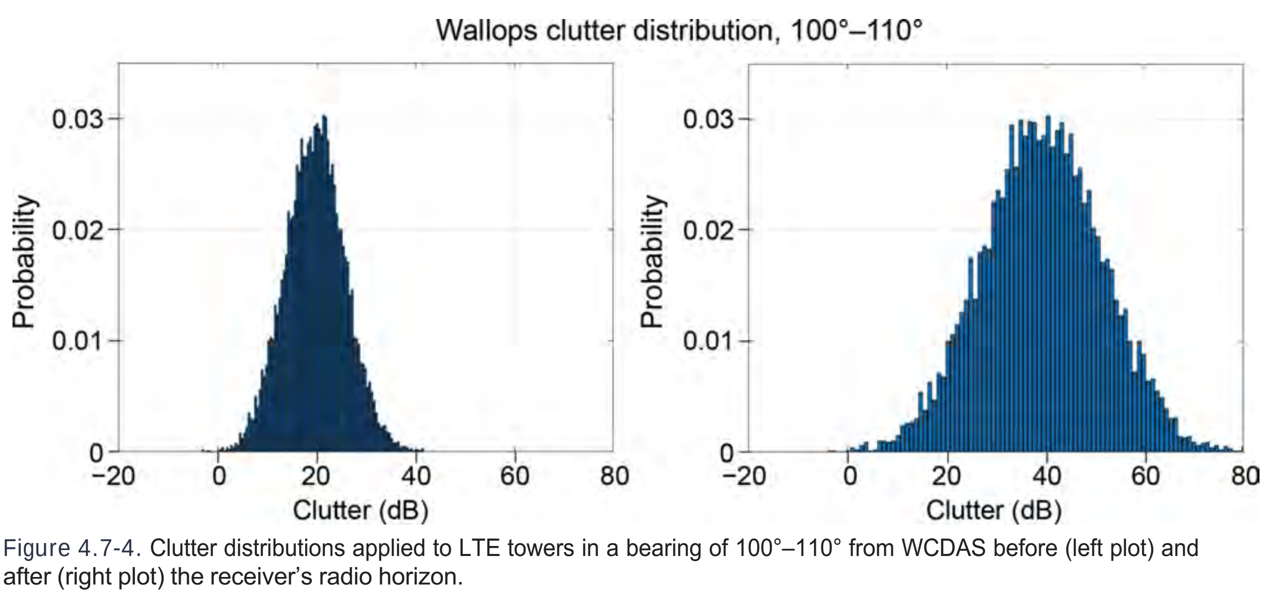


Figure 4.7-4. Clutter distributions applied to LTE towers in a bearing of 100°–110° from WCDAS before (left plot) and after (right plot) the receiver's radio horizon.

located within the receiver's radio horizon, whereas the right plot is the distribution for an LTE transmitter beyond the receiver's radio horizon.

4.7.3.1.1.2 Radiosonde data

To determine the index of refraction versus height for each site, radiosonde data collected nationally was applied. The NWS has taken upper-air observations with radiosondes since the 1930s. A radiosonde is an instrument typically carried by balloons into the atmosphere to transmit measurements of pressure, temperature, relative humidity, and more. The sensors of the radiosonde are linked to a transmitter that sends the sensor measurements to a ground-tracking antenna. Figure 4.7-5 displays the map of radiosonde locations worldwide. The radiosonde locations are spaced hundreds of kilometers apart, and measurements are collected twice a day at each location.

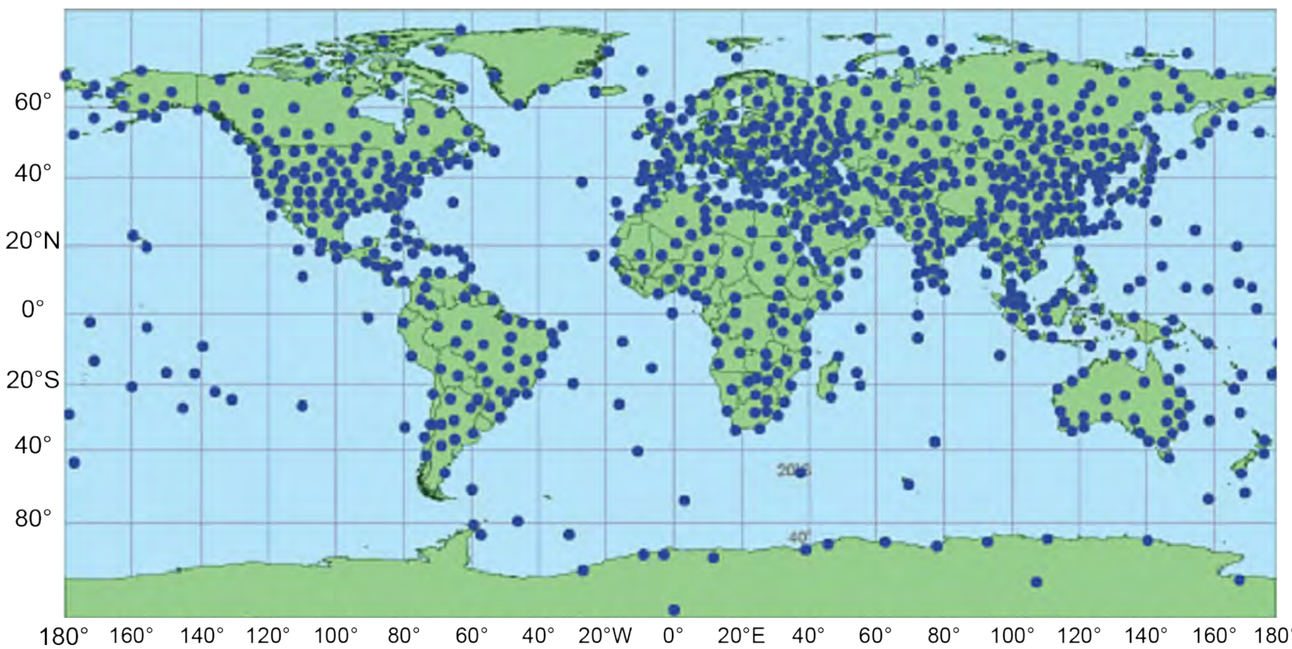


Figure 4.7-5. Map of radiosonde locations worldwide.
Source: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, "Radiosondes," accessed May 19, 2020, https://www.weather.gov/jetstream/radiosondes.

4.7.3.1.1.3 Propagation model validation

Validations of the propagation models were completed under standard atmospheric conditions. Comparisons between the APM, ITM, and TIREM were made. The validation process involved computing the propagation loss from the ground stations located at Boulder, Colorado; Fairmont, West Virginia; Miami, Florida; Norman, Oklahoma; and Wallops Island, Virginia, to a subset of tower locations reported by the AWS. These locations cover various terrain intensities that are critical within a propagation analysis. The three models are developed using diverse algorithms; however, shared parameters between the three models were kept consistent. These parameters include: operating frequency, terrain profile, and transmit and receive antenna heights.

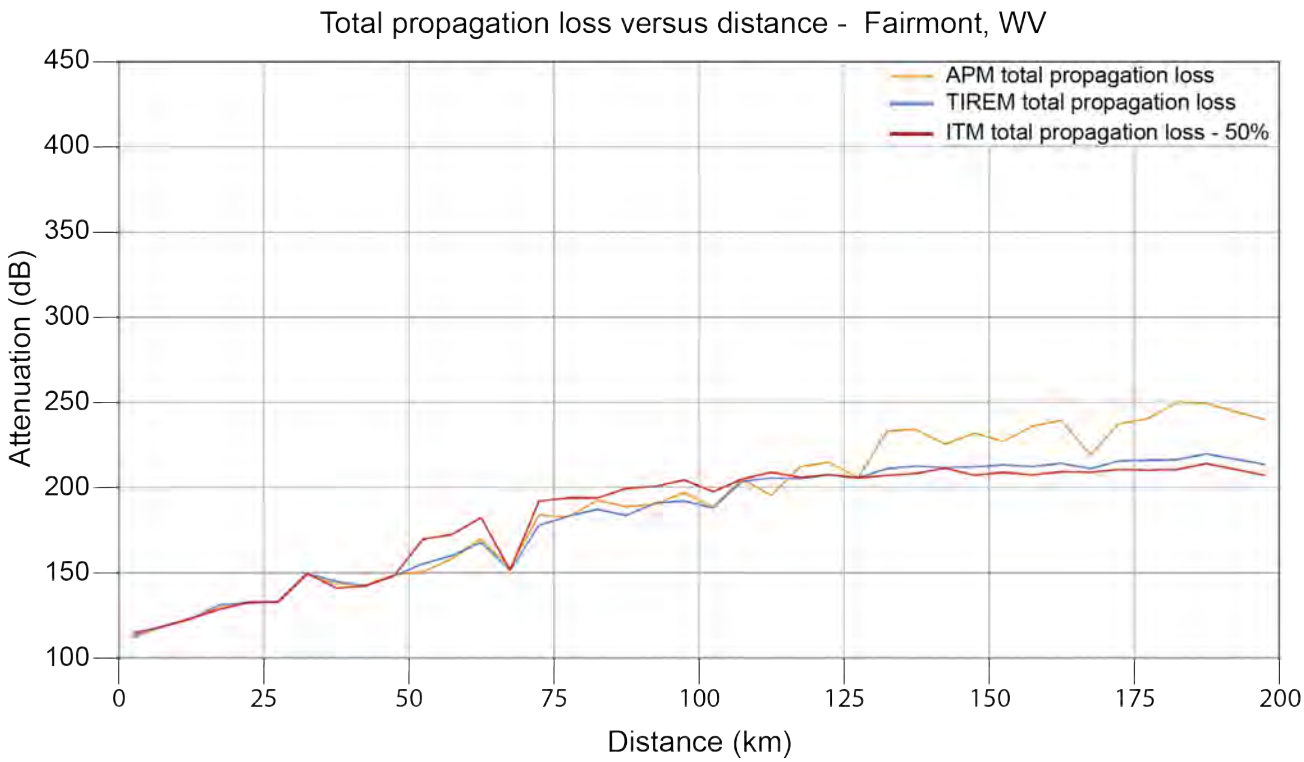


Figure 4.7-6. Comparisons of propagation loss versus distance at Fairmont, West Virginia, between the APM (orange), TIREM (blue), and ITM (red).

Outputs from the propagation models are reported at different confidence levels, driving the difficulties in comparing propagation models. It was assumed that outputs from the APM and TIREM are reported at the mean; thus, outputs from the ITM were matched to remain consistent. To perform comparisons, propagation loss versus distance statistics were created. Figure 4.7-6 represents the average propagation loss experienced from the ground station to each tower as a function of distance at Fairmont, West Virginia. Lines in orange, blue, and red are outputs from the APM, TIREM, and ITM, respectively. Fairmont is a region that consists of mostly intensive terrain where the ground station is located primarily in a valley. A divergence between the models occur at approximately 120 km, where APM deviates from the ITM and TIREM. A correlation within the first 100 km is critical for a region of mountainous terrain, because the exclusion zones will not exceed this radius. Project 7 addresses RFI at an aggregate level; thus, distances where the models deviate present a minimal impact to the analysis. Validations were conducted at several locations with different terrain effects, with each producing similar correlation among models.

4.7.3.2 Interference analysis approach (This section should be read in association with Appendix J)

Interference analysis is divided into three stages: determination of ducting occurrence at each Federal site, propagation modeling, and RFI analysis.

Ducting occurrence was identified through propagation loss characterizations associated with the Federal ground stations. Three years of radiosonde data (2016–2019) were analyzed to develop a statistical characterization of propagation loss associated with historical ducting data. Analyzing three years of individual refractivity profiles through the APM for locations in all directions around the site is computationally expensive. The statistical characterizations were therefore developed by sampling propagation loss predictions from APM at a subset of locations at distances of 50 km, 100 km, 200 km, and 500 km from each ground station. Histograms and probability distributions of the propagation loss statistics returned from the APM were then created. Each refractivity profile analyzed was associated with one of six probability percentile ranges: 0%–1% (the worst ducting case, which occurs 1% of the time), 1%–5%, 5%–10%, 10%–25%, 25%–50%, and 50%–100% (standard atmospheric conditions). Four refractivity profiles from each probability range were identified for further use in the detailed modeling used to assess interference and protection criteria.

Figure 4.7-7 illustrates the ducting effects between various probability bins. These are refractivity profiles based on measured instances of temperature, humidity, and pressure in proximity to WCDAS. The left profile has a significant surface duct (presence of an inversion of refractivity as a function of altitude) at approximately 100 m in altitude. The application of this profile leads to significant radio frequency propagation effects and could occur approximately 1% of the time. The rightmost profile presents a monotonic refractivity versus altitude and no duct. This profile represents standard atmospheric conditions, and the RF propagation effects are described by standard propagation models (e.g., ITM and TIREM). Lastly, the two middle profiles are cases with moderate ducting.

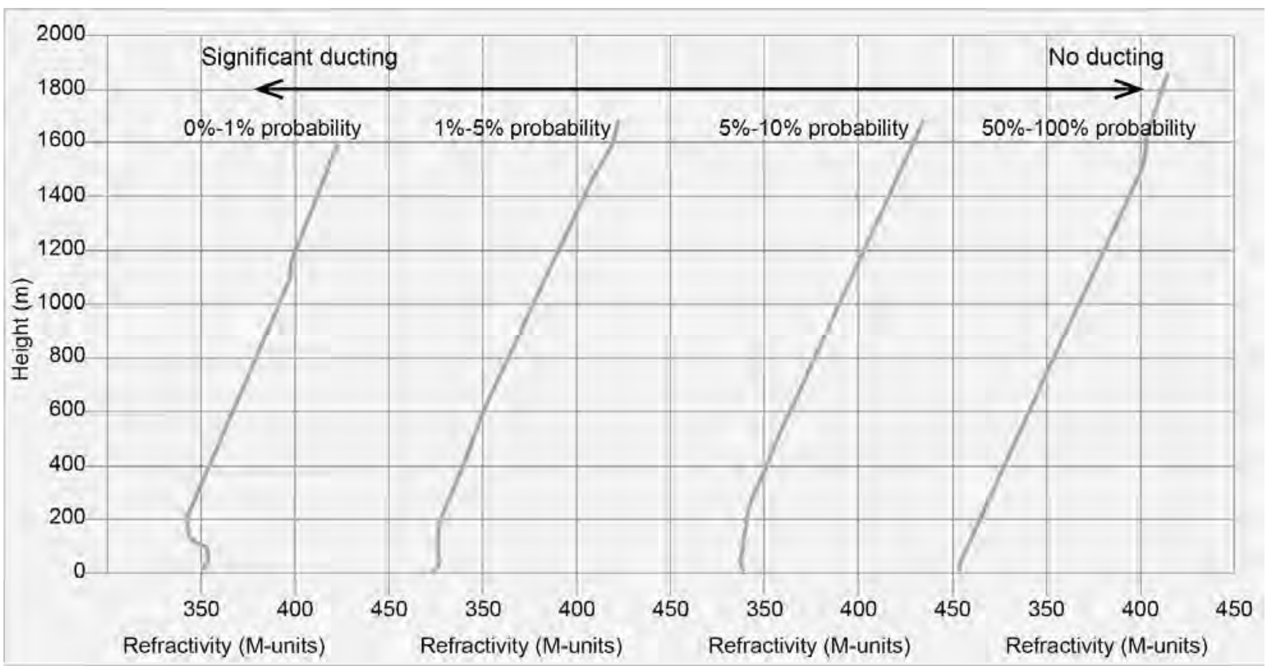


Figure 4.7-7. Example refractivity profiles from the Wallops Island radiosonde.

Figure 4.7-8 represents the output of the APM in a standard atmospheric environment, as represented by the rightmost refractivity profile in Figure 4.7-7, assuming flat terrain. The absence of a surface duct allows for high propagation loss near the surface.

To illustrate the impact of the leftmost refractivity profile above, Figure 4.7-9 shows a heat map of propagation loss versus range and altitude, assuming a significant ducting condition and flat terrain. At an altitude of approximately 100 m, there is a surface duct that allows for guided energy near the surface. This instance would result in significant RFI impacts due to the absence of terrain obstructions to the surface duct. Terrain significantly impacts propa-

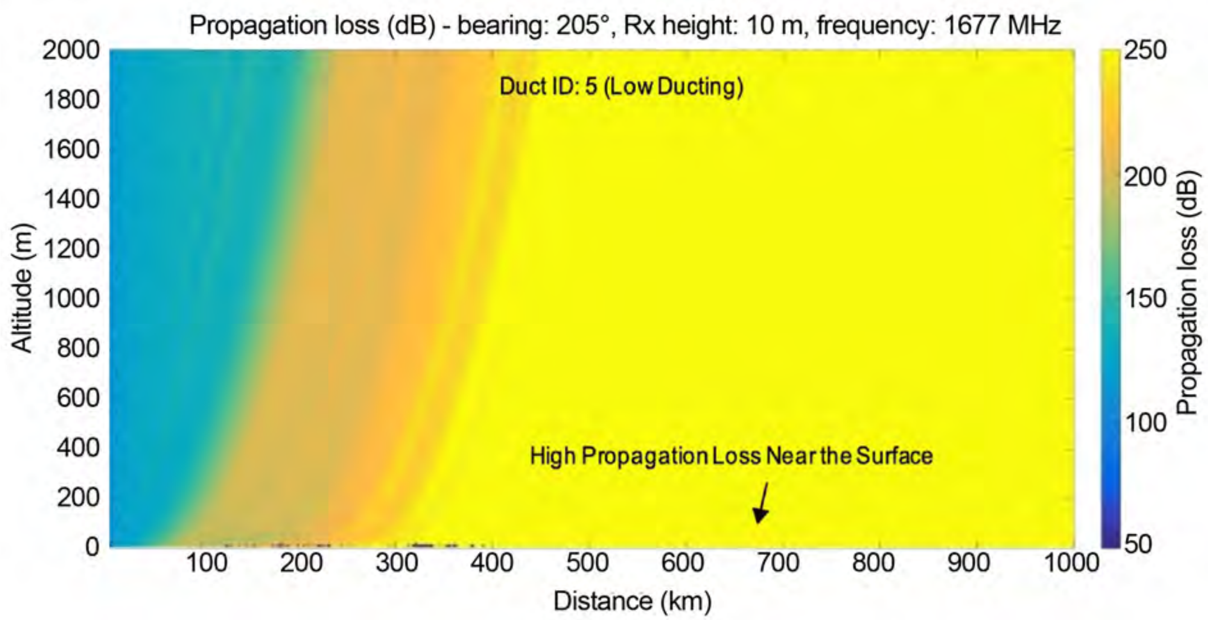


Figure 4.7-8. Propagation loss heat map for a flat terrain profile under standard atmospheric conditions.

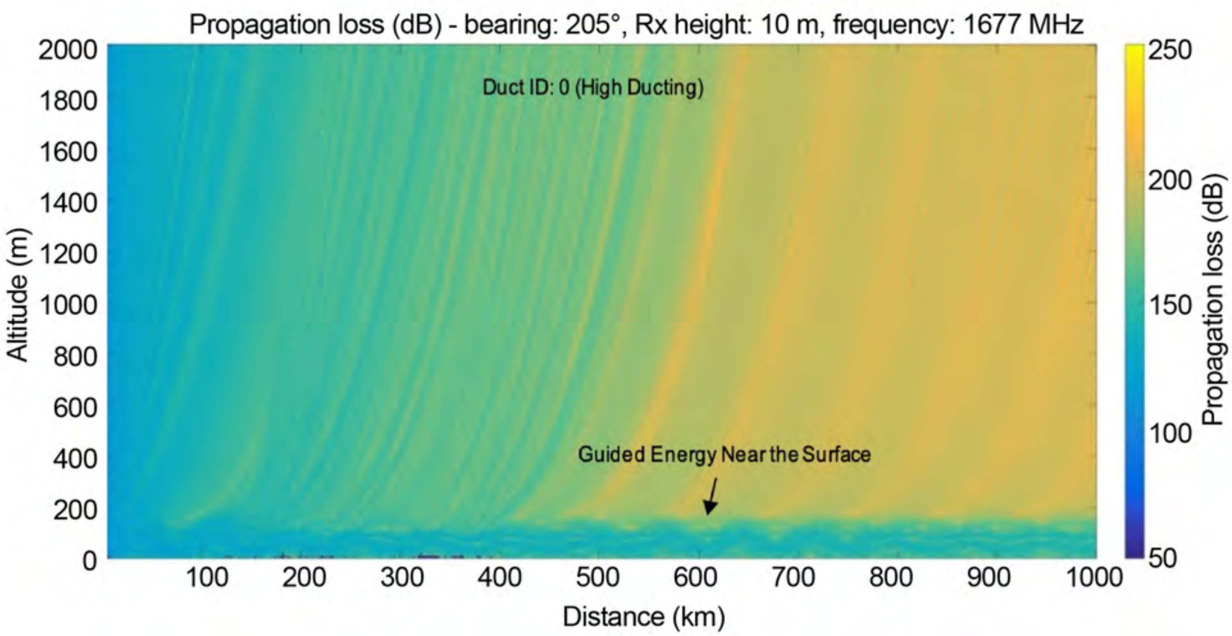


Figure 4.7-9. Propagation loss heat map for a flat terrain profile with significant ducting.

gation, even with high ducting conditions. Figure 4.7-10 is a heat map of the propagation loss versus range and altitude as outputted by the APM with terrain blockage included (indicated by the dark blue regions). A surface duct is present at an altitude of approximately 100 km that is eventually impacted by terrain blockage at a distance of 220 km. As a result, Federal sites located within significant terrain will experience a smaller impact of RFI due to surface ducts.

A major interference factor is the spatial size of ducting conditions. The propagation loss changes slowly with distance in ducting conditions; therefore, a large number of transmitters can cause interference to the Federal ground stations. The extent of the duct is difficult to estimate because of the sparse number of radiosonde locations in the United States and the limited ability of remote sensors to directly measure the index of refractions in three dimensions.

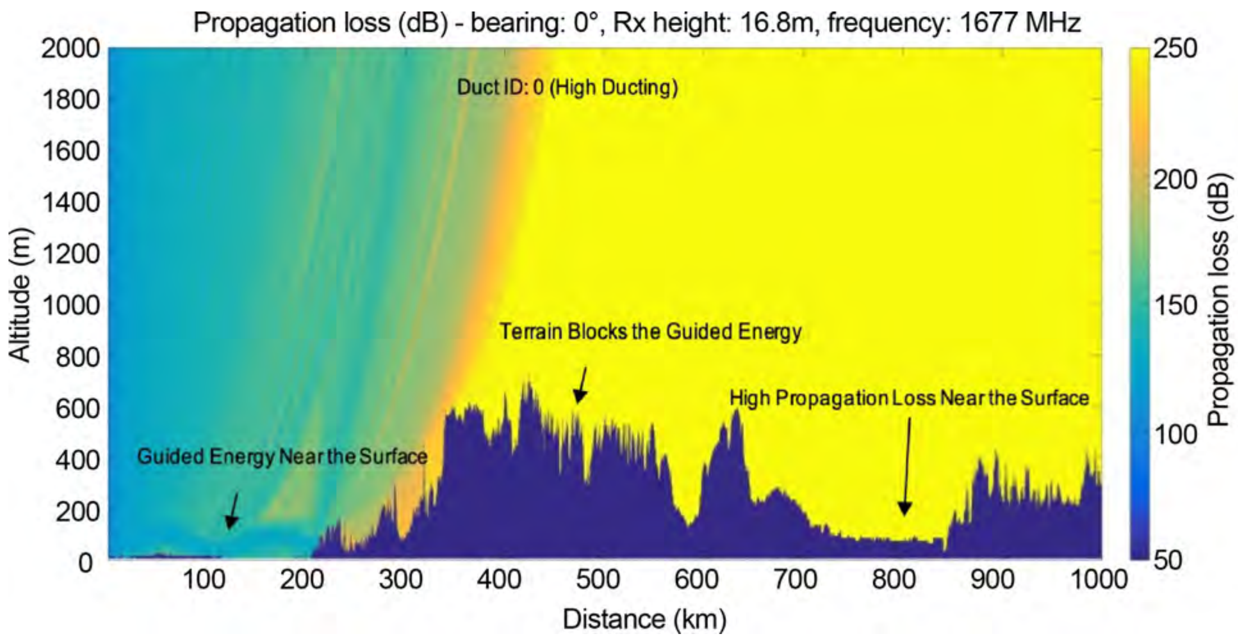


Figure 4.7-10. Propagation loss heat map with significant terrain and ducting.

Duct size was determined by creating a statistical model of duct size using a correlation analysis of radiosonde data at different radiosonde locations. The process involved selecting a radiosonde location and identifying the presence of a duct. Readings from radiosondes at other locations were analyzed for the same time period to determine if those locations also experienced a duct. The statistics regarding the correlation of ducting conditions between pairs of radiosonde sites were identified to produce an assessment of duct size probability as a function of distance.

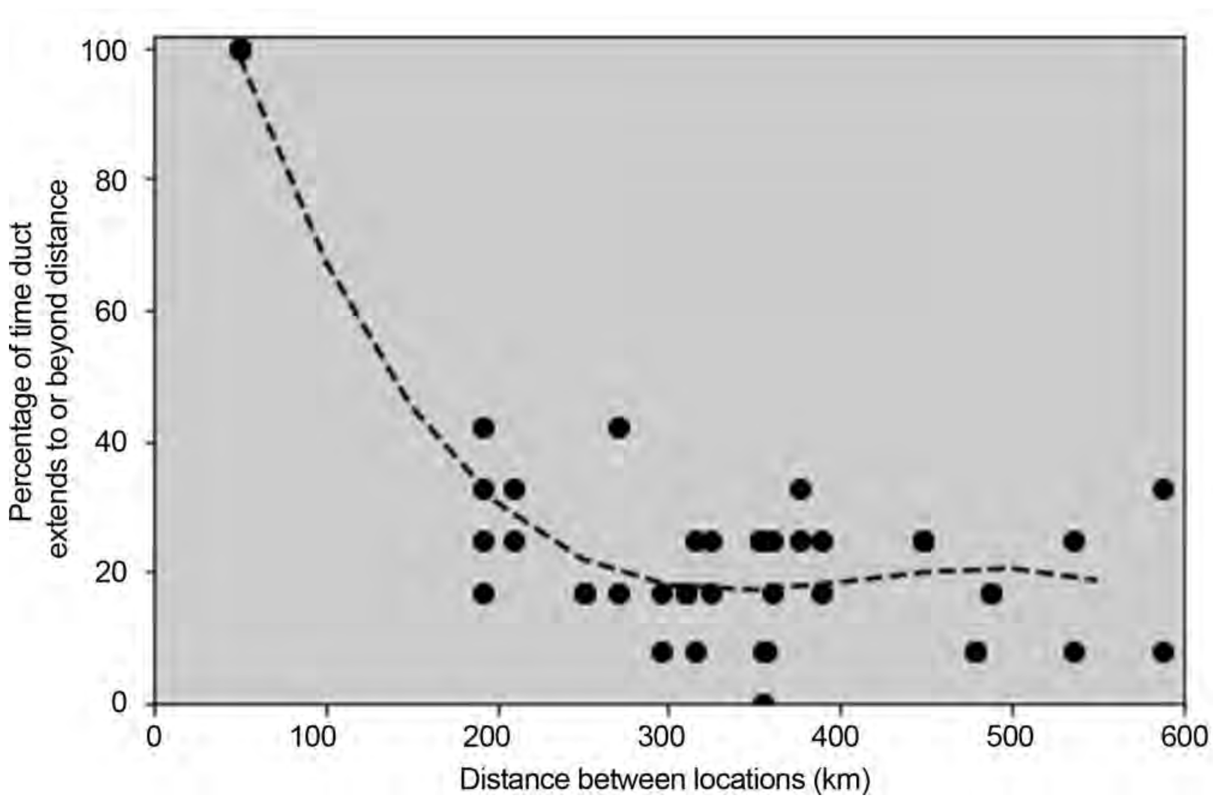


Figure 4.7-11. Duct size exceedance probability estimation based on pair-wise correlations of radiosonde readings of all continental U.S. radiosonde locations.

The correlation analysis assessed all radiosonde locations in the continental United States to create the probability distribution.

Figure 4.7-11 displays the fraction of time that a duct is at least as large as the distance on the horizontal axis. The significant distance between adjacent radiosonde locations limits the minimum duct size that can be determined. There were no radiosonde separations of less than 180 km; thus all observations were at 180 km and greater. To ensure that a minimum duct size is maintained, a duct size of 50 km was assumed at 100% total probability (i.e., all ducts are at least 50 km in size).

Propagation analysis was primarily conducted using APM, with some analysis performed using ITM as validation. Figure 4.7-12 outlines the propagation analysis using APM and ITM, which varies due to computation requirements of APM. With APM, the analysis calculated propagation losses for every 0.1° bearing from the ground station. This method captures significant terrain features and allows for an efficient computation process. When applying the ITM, terrain profiles were generated directly from the ground station to each LTE transmitter.

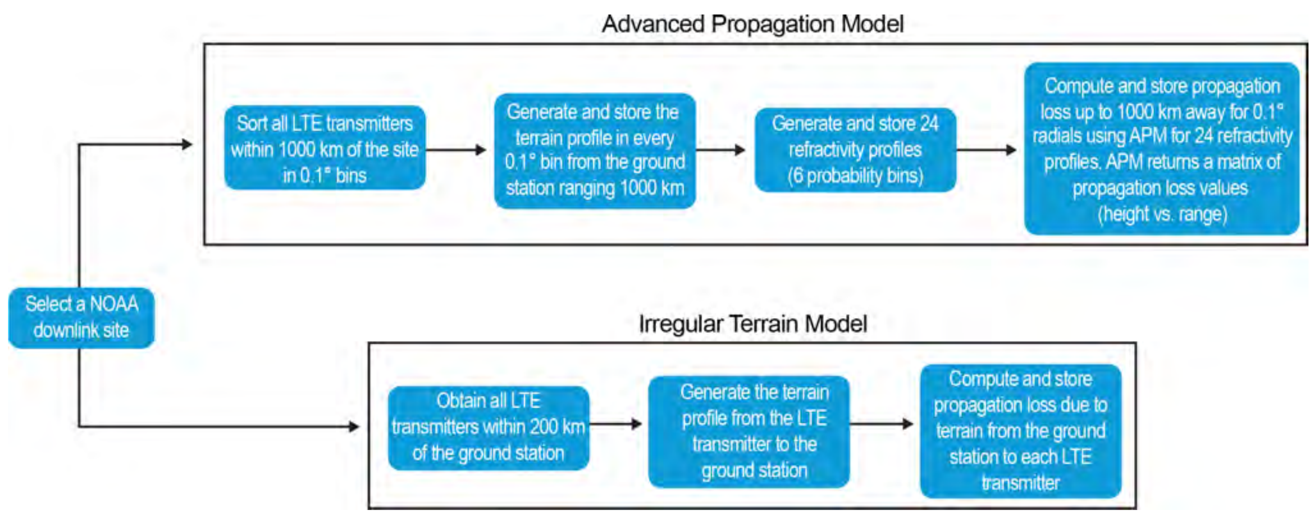


Figure 4.7-12. Propagation modeling approach.

Table 4.7-1 lists the critical propagation parameters used as inputs to the APM. Table 4.7-2 lists the critical propagation parameters used as inputs to the ITM.

The propagation loss values produced by the propagation models were used to conduct the final interference analysis stage. This analysis used a Monte Carlo simulation that enabled a statistical treatment of the various randomized parameters (e.g., duct probability, duct size, clutter, and LTE antenna pointing angles). The analysis primarily focused on results produced by the APM to address anomalous propagation conditions.

The amount of aggregate RFI to a satellite ground station receiver from a distribution of LTE transmitters is dominated by the signal from the closest LTE transmitter. It is assumed that the spectrum-sharing approach between the ground station and the LTE network will require that no LTE

Table 4.7-1. APM input parameters.

Parameter	Value	Discussion
Terrain resolution	30 m	Profiles generated every 0.1° around the Federal site
Refractivity profile	M-units vs. height	24 refractivity profiles (4 profiles in each of the 6 percentiles)
Frequency	1677.5 MHz	Center frequency of 1675–1680 MHz
APM	Automatic mode	—
Output height resolution	5 m	To account for antenna mount heights of 25 m, 35 m, 45 m, 55 m
Output distance resolution	30 m	Based on terrain resolution
Receiver antenna height	3.5–45 m	From Project 6 site characterizations

Table 4.7-2. ITM input parameters.

Parameter	Value	Discussion
Terrain resolution	30 m	Profiles generated directly from the ground station to the LTE transmitter
Frequency	1677.5 MHz	Center frequency of 1675–1680 MHz
ITM mode	Point-to-point	Accepts detailed terrain path
Receiver antenna height	3.5–45 m	From Project 6 site characterizations
Transmit antenna height	25–55 m	eNB antenna mount heights of 25 m, 35 m, 45 m, and 55 m in dense urban, urban, suburban, and rural regions

towers be allowed within a certain “protection” zone. These exclusion zones can either be based on distance (e.g., a circular exclusion zone), or be of an irregular shape that minimizes the area and population covered. The following sections describe the process of creating exclusion zones.

A circular exclusion zone excludes LTE transmitters for a given distance from the ground station. This provides a simple protection criterion that can be expressed in terms of protection distance. This method can produce inefficient sharing criteria because expanding the zone to mitigate interference primarily coming from one direction produces increases in exclusion zone size in all directions.

Irregularly shaped exclusion zones can reduce the size of an exclusion zone by incrementally excluding the most offending LTE transmitters until RFI falls below the threshold. Once all offending transmitters are identified, a polygon is created that encompasses them. Irregular exclusion zones reduce the area impacted compared to circular exclusion zones. This approach is somewhat sensitive to changes in LTE deployments, as different tower locations can produce changes to the exclusion zone.

An alternate method for producing irregular exclusion zones is a mix of the circular and polygon methods. The process identifies the nearest LTE transmitter within the determined protection distance. An envelope is then created around the selected LTE transmitters.

All three exclusion zones can be analyzed in terms of the area and population they encompass. Of these two metrics, population is probably the most important factor, since commercial carriers use population served when they place value on spectrum and markets. Further, each method allows analysis to assess different percentiles produced by the Monte Carlo analysis model.

4.7.4 Findings/results of analysis

To determine the degradation of the GOES receiver performance, aggregate RFI versus protection distance plots were analyzed along with geographic projections of exclusion zones. The aggregate RFI versus protection distance plots consist of six curves representing the 100th, 99th, 95th, 90th, 75th, and 50th percentiles of the Monte Carlo simulation. The 100th percentile represents the worst ducting condition that could occur, the 99th percentile indicates the top 1% of ducting conditions, and the 95th percentile represents the ducting conditions that occur 5% of the time. The intersection points of the curves with the protection limit represent the minimum protection distance required.

Note that these statistics incorporate uncertainties from all the study parameters. Parameters modeled as random variables include duct sizes, duct strengths, and clutter loss for the analysis of each GOES downlink station. LTE downlink and uplink analyses include the randomization of LTE eNB sector pointing, and the randomization of UE transmit power and location as described in Section 4.7.3.1.

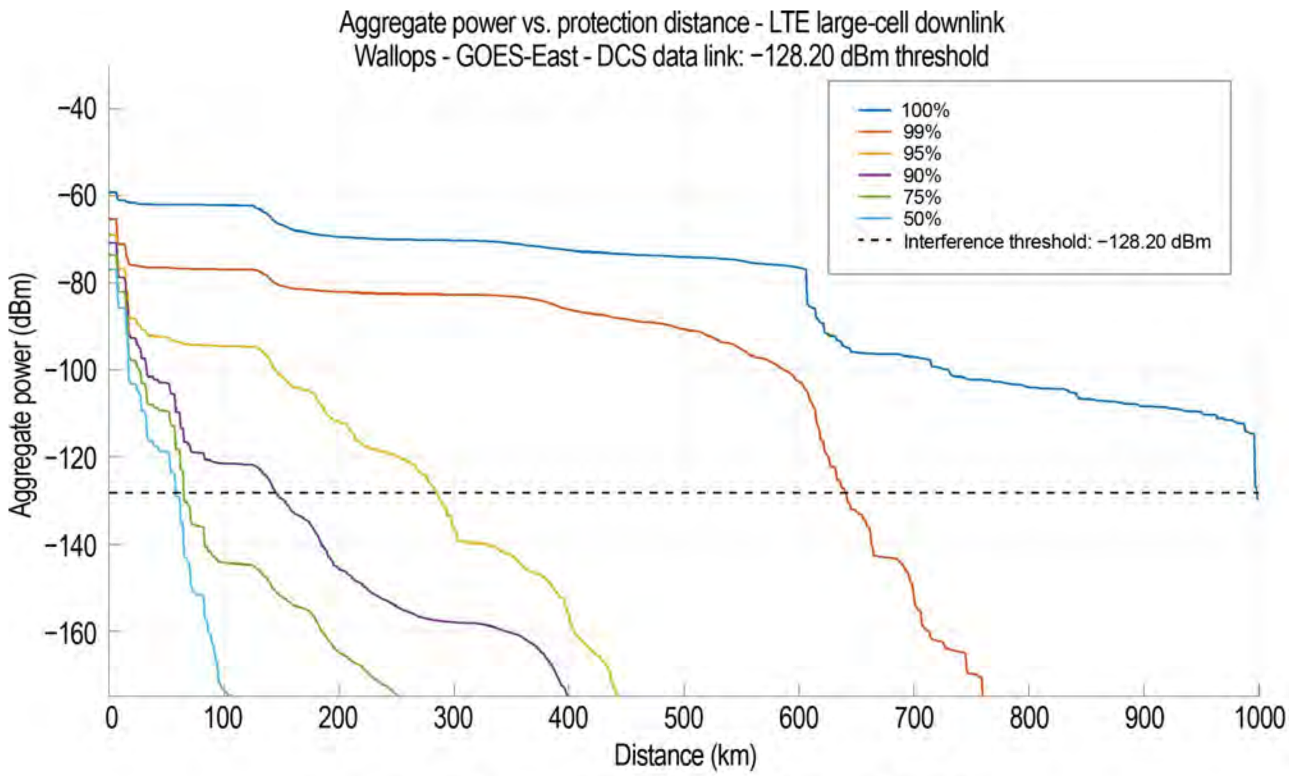
Protection criteria were developed for each ground station. Several Federal sites have multiple receivers, which may be receivers for different data services (e.g., GRB and DCS) or receivers for the same data service but received from different GOES satellites (e.g., GOES-East and GOES-West). For the latter case, protection criteria developed for each receiver were ultimately combined into composite exclusion zones to serve as final recommendations. Sites accessing multiple services via direct rebroadcast would use the exclusion zone providing the greatest protection criteria.

The results discussion presented here focuses on WCDAS. This provides an explanation of the analysis process and impacts analysis. The results for the other sites are summarized.

4.7.4.1 LTE large-cell downlink

Analysis of RFI risks to GOES operations due to spectrum sharing with LTE in the 1675–1680 MHz band shows the need for large exclusion zones. Exclusion zones for WCDAS are the most significant due to a combination of anomalous propagation impacts, relatively flat terrain, and dense LTE deployments at moderate to long distances from the ground station. RFI originating from the dense LTE deployments in Washington, D.C.; Richmond and Norfolk, Virginia; and Baltimore, Maryland, are captured under strong ducting conditions that will drive the size of the exclusion zones. The regions surrounding this site are primarily flat in terrain; thus, the surface ducts likely will not be obstructed by terrain.

Figure 4.7-13 displays the required protection distances at various percentiles to protect the DCS data link at WCDAS when pointing to GOES-East (top plot) and GOES-West (bottom plot). Results are provided at the 100th, 99th, 95th, 90th, 75th, and 50th percentiles. A protection distance of approximately 300 km (95th percentile) is required under ducting conditions that occur 5% of the time. The protection distance for the 50th percentile would be approximately 33 km. The large difference in RFI power as a function of exclusion distance among the percentiles indicates the impact of anomalous propagation on RFI. Steps in the curves seen at small distances



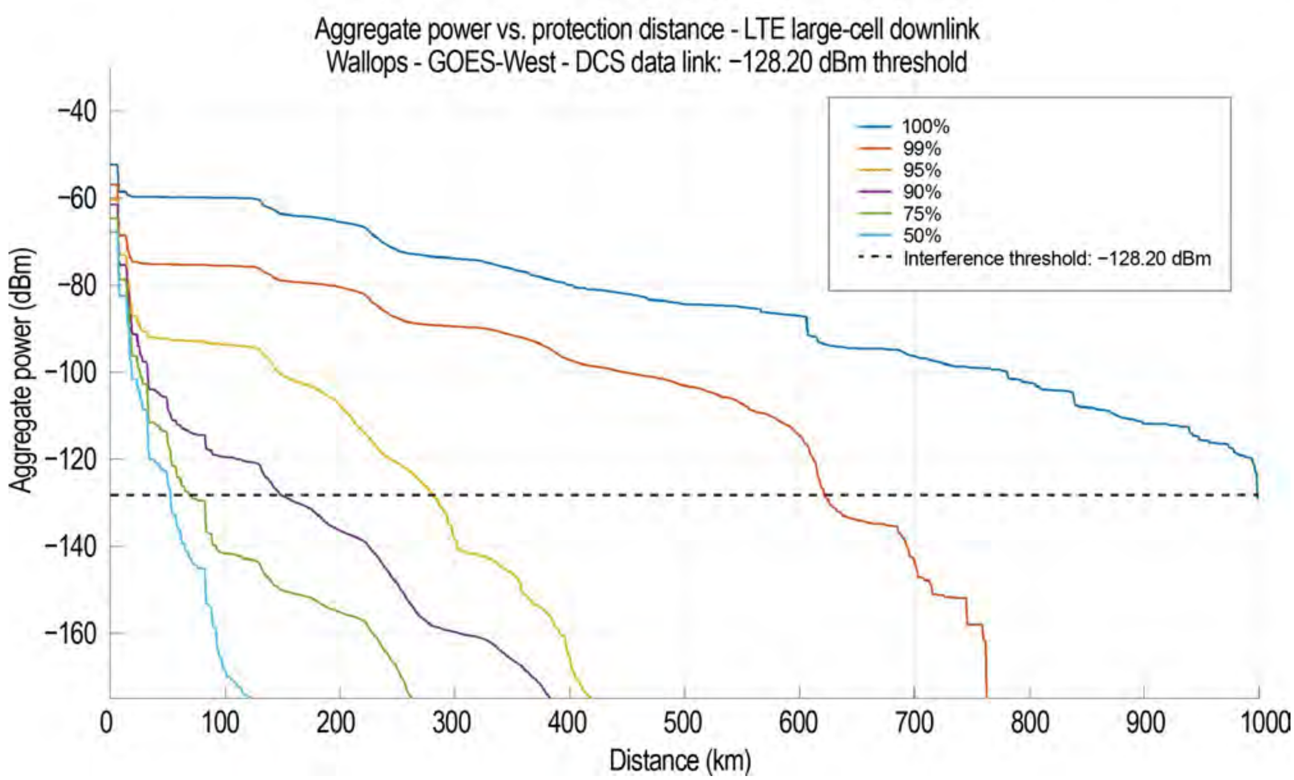


Figure 4.7-13. Aggregate power versus protection distance for DCS data link at WCDAS: GOES-East (top plot) and GOES-West (bottom plot).

represent towers being excluded that have high contributions to RFI due to their close proximity to the ground stations. Increases in slope are caused by the exclusion of dense LTE deployments associated with cities (e.g., Washington, Richmond, and Norfolk). Large exclusion zones are needed due to in-band operations of the DCS and a large density of LTE transmitters seen by the receiver due to anomalous propagation.

To determine the composite circular exclusion zone, the largest protection distances between the two instances are taken. For example, when pointing to GOES-East, the required protection distance is 299 km at the 95th percentile, whereas the protection distance necessary when pointing to GOES-West is 295 km. Therefore, due to anomalous propagation, any protection distance less than 299 km will harm the DCS data link. This process can be applied to the other observed confidence levels, where a static protection distance of 63 km is required (50th percentile), and coordination zones are present between distances of 63 km and 84 km (75th percentile from the GOES-West case).

Figure 4.7-14 represents the interference-to-noise ratio (INR) heat maps at the 95th percentile of both instances when the ground stations are pointing to GOES-East (left plot) and GOES-West (right plot). Each colored dot represents the aggregate INR originating from a tower. The impact of RFI at an aggregate level is evident in this figure, where many offenders contributing below a −15 dB INR are encapsulated by the irregular polygon (dark blue scatters).

In both cases, the zones stretch to the north more than to the west and south due to terrain and LTE deployment densities. The terrain to the west and northwest disrupts the ducting effect and mitigates signal propagation, while the flat terrain up the coast allows interference signals from dense LTE deployments to propagate with less attenuation. The coastal areas to the south are similarly flat, but the LTE densities are much lower.

The impact of the relative azimuth of the dish is also observed. When pointing to GOES-West, the azimuth of the dish is approximately 250°; thus, the RFI due to LTE transmitters in Richmond, Virginia, will be greater than the instance when the dish is pointing to GOES-East. The process explained in Section 4.7.5.3 was applied to create the final exclusion zone recommendations to protect the DCS at WCDAS.

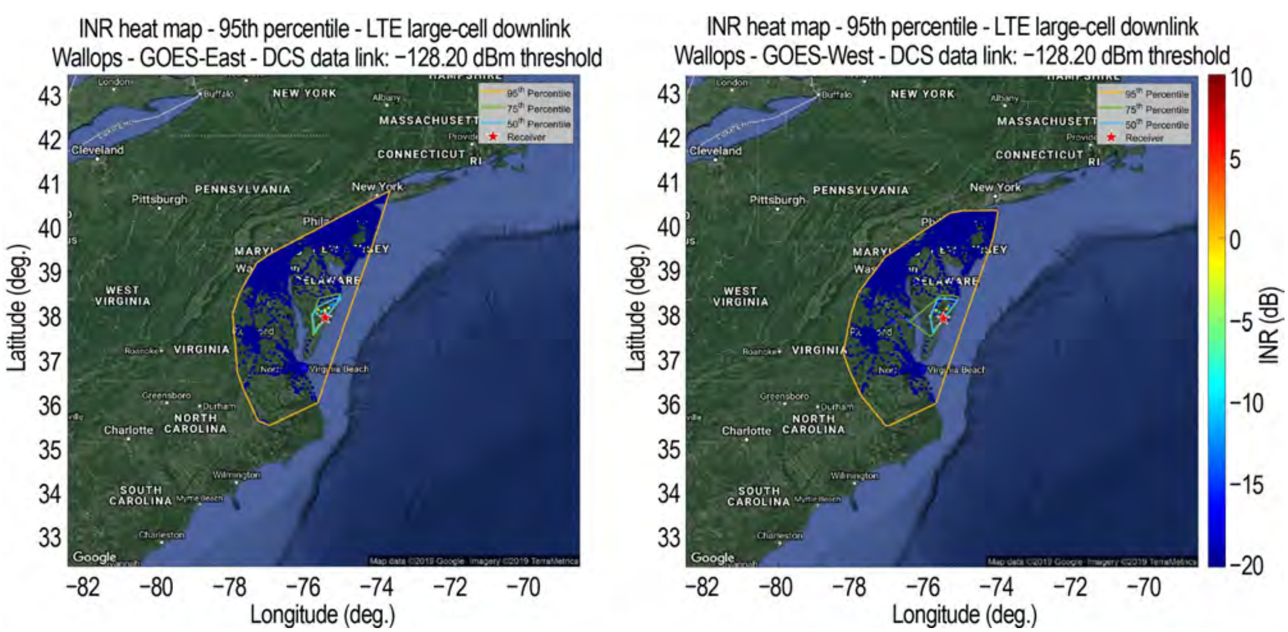


Figure 4.7-14. INR heat maps at the 95th percentile for DCS data link at ground stations pointing to GOES-East (left plot) and GOES-West (right plot), Wallops Island, Virginia.

Figure 4.7-15 displays the composite irregular exclusion zones at the 95th, 75th, and 50th percentiles. Compared to the GRB exclusion zones, the DCS exclusion zones are much larger due to the overlap of occupied frequencies by the DCS and LTE operations. The lower bound of the DCS band is at 1679.7. Assuming a 0.25 MHz guard band (3GPP specification for a 5 MHz signal) for the LTE signal between 1679.75 MHz and 1680 MHz, there is a .05 MHz overlap between received DCS and LTE signals.

To develop the composite alternate exclusion zones, consider a combination of the exclusion zones generated for the GOES-East and GOES-West receivers, as shown in Figure 4.7-16. The composite zones ensure the full protection of all receivers due to the close proximity of the GOES receivers. The alternate exclusion zones continue to be more circular because of the process described in Section 4.7.5. Figure 4.7-17 illustrates the composite alternate exclusion zones to protect the DCS data link at WCDAS. (See Appendix J, section J.1.1, for updated threshold information.)

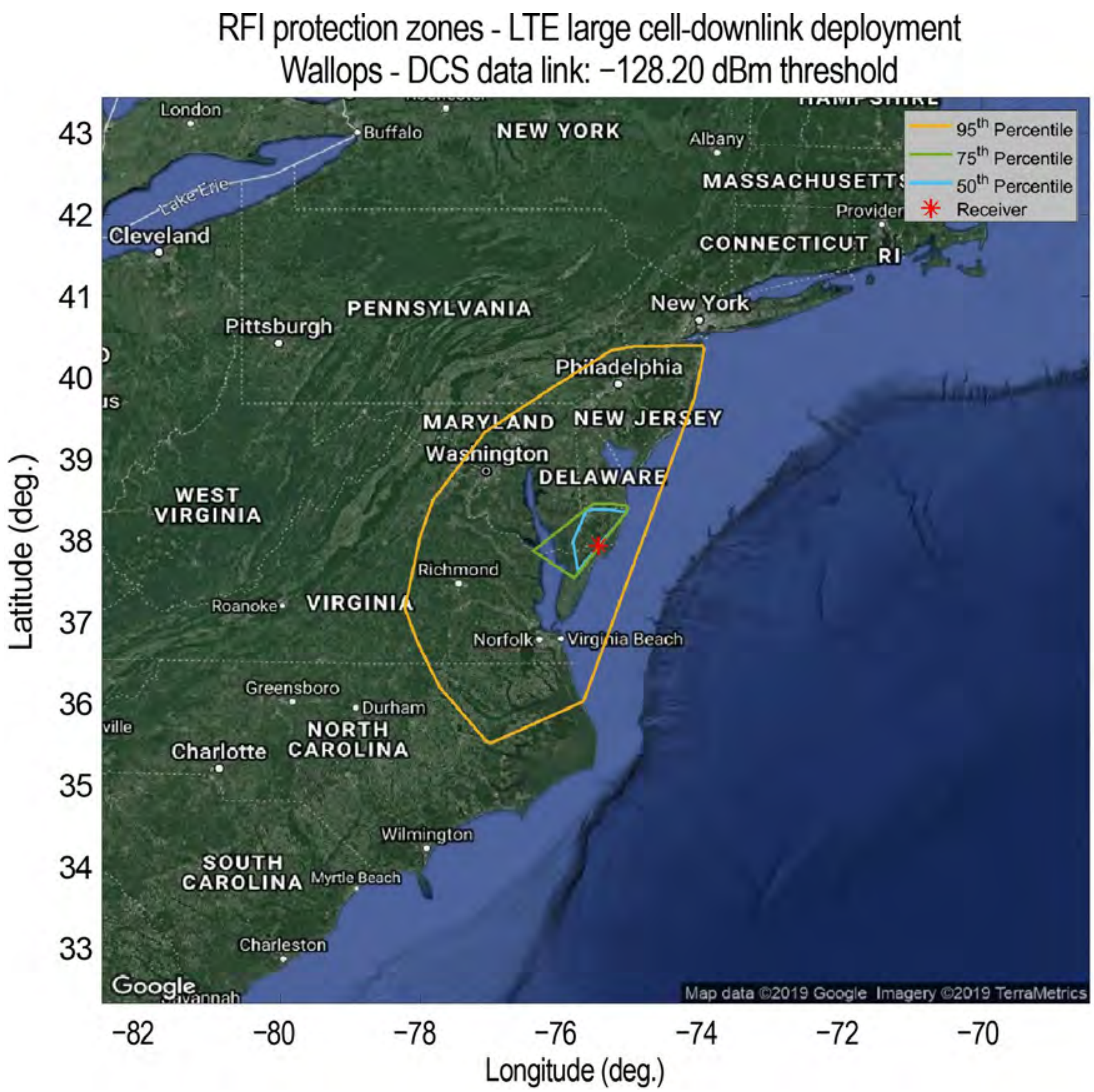


Figure 4.7-15. Composite irregular DCS exclusion zones, Wallops Island, Virginia.

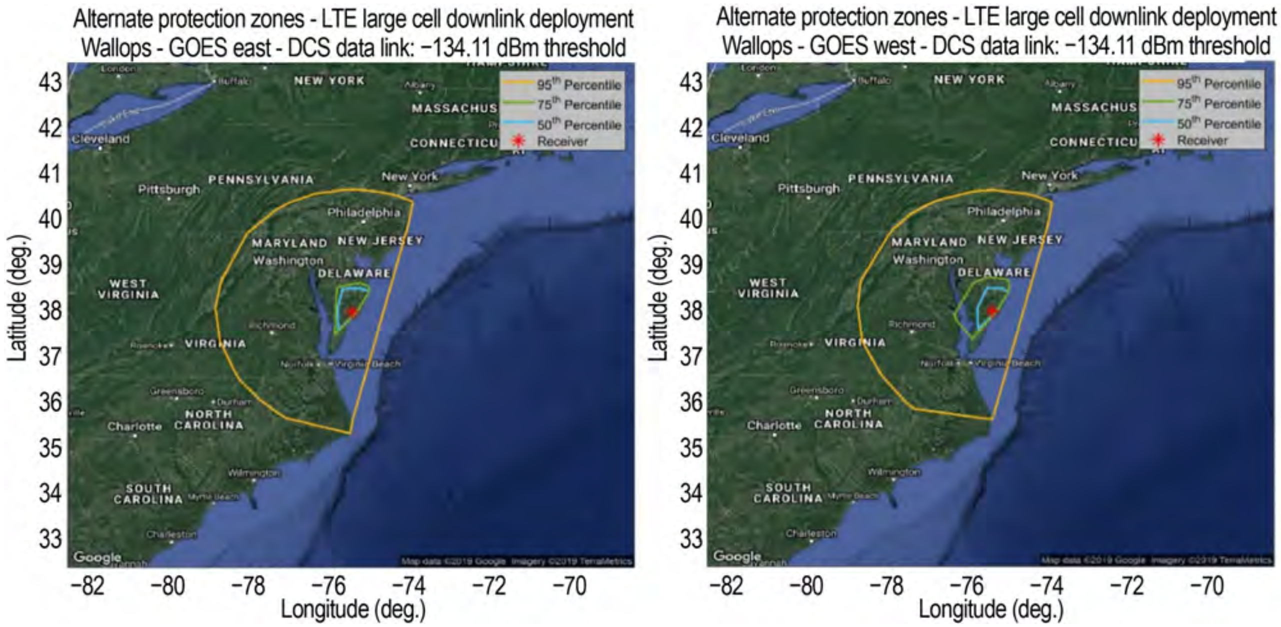


Figure 4.7-16. Alternate exclusion zones for GOES-East (left plot) and GOES-West (right plot), DCS data link, LTE large-cell downlink, Wallops Island, Virginia. (Note: These map contours do not reflect the revised -128.2 dBm interference threshold from Appendix J).

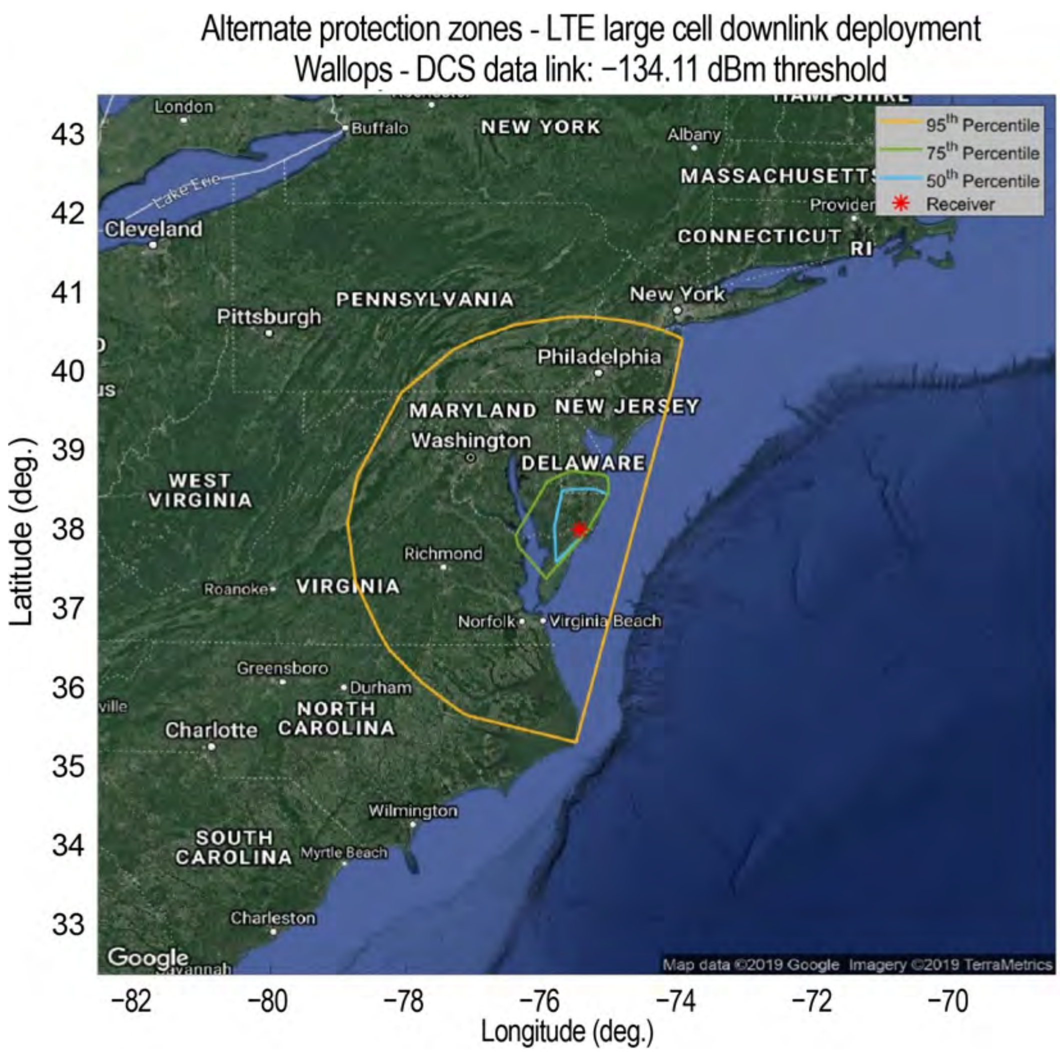


Figure 4.7-17. Composite alternate DCS exclusion zones, Wallops Island, Virginia. (Note: This map contour does not reflect the revised -128.2 dBm interference threshold from Appendix J).

WCDAS receives GRB from GOES-East and GOES-West. Composite exclusion zones were generated using the same approach applied to the DCS analysis. Figure 4.7-18 displays the composite exclusion zones for the 95th, 75th, and 50th percentiles. A final circular exclusion zone was found to require a protection radius of 203 km.

Table 4.7-3 lists the approximate area and population impacted of the composite exclusion zones for the DCS and GRB data links at WCDAS. The 2010 U.S. census and the built-in MATLAB function, “areaint,” from the Mapping Toolbox was applied to determine the population and area impacted. The results at Wallops Island, Virginia, represent one of the few cases where a circular exclusion zone is more efficient than an irregular exclusion zone in terms of the population impacted. This is largely due to the irregular polygon extending out to the densely populated New York City region to mitigate the area impacted.

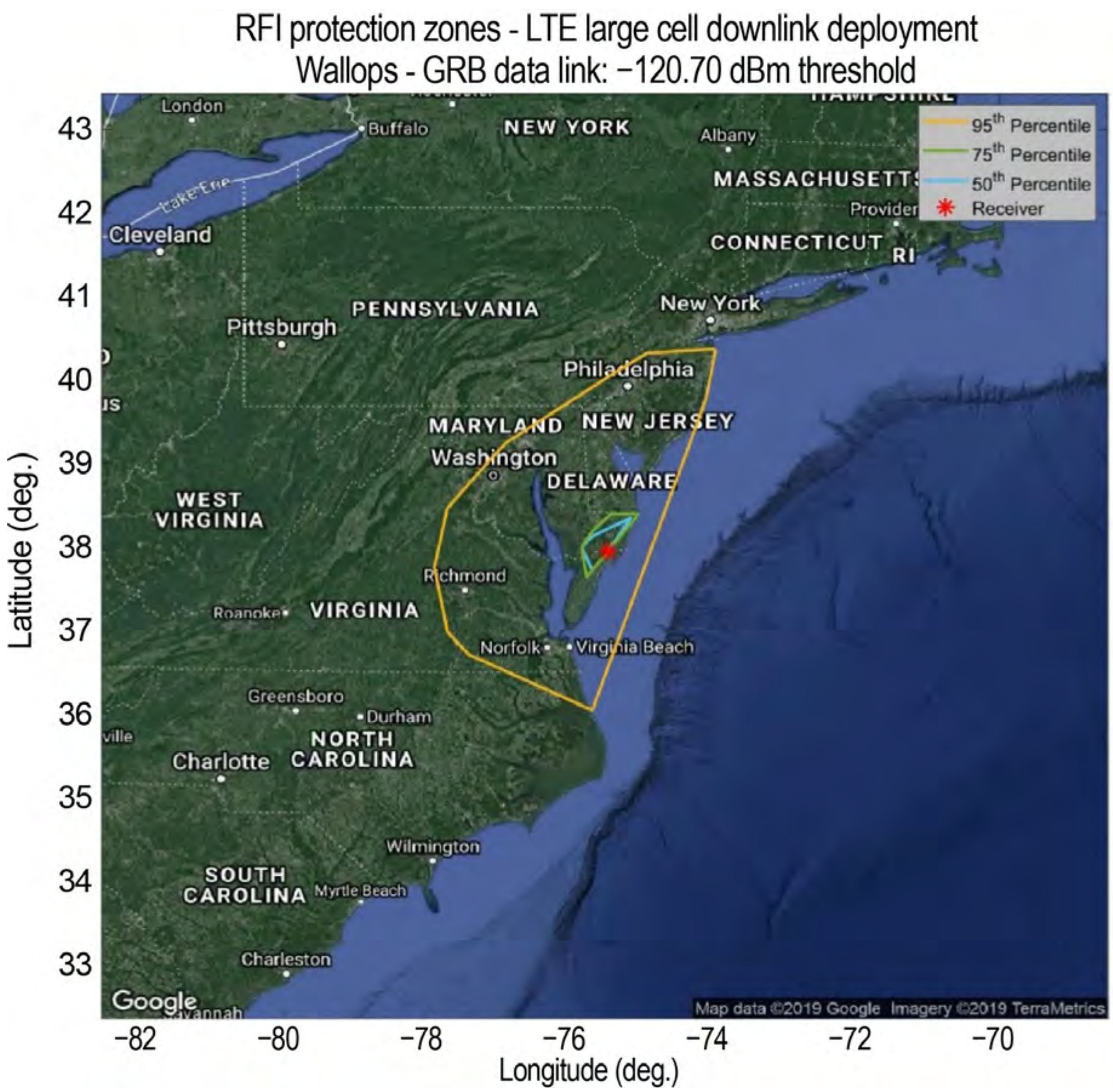


Figure 4.7-18. Composite irregular GRB exclusion zones, Wallops Island, Virginia.
(Note: This map contour does not reflect the revised -113.8 dBm interference threshold from Appendix J).

Table 4.7-3. Population and area impacted: LTE large-cell downlink, Wallops Island, Virginia.

Data link	Exclusion zone type	Percentile (%)	Population impacted	Radius (km)	Area impacted (km^2)
DCS	Circular	95	24,000,000	286	258,000
		75	340,000	70	15,000
		50	210,000	59	11,000
	Irregular	95	30,000,000	—	130,000
		75	280,000	—	7,600
		50	150,000	—	2,800
GRB	Circular	95	15,000,000	203	130,000
		75	190,000	40	5,000
		50	48,000	29	2,600
	Irregular	95	18,000,000	—	92,000
		75	50,000	—	2,000
		50	37,000	—	1,000

4.7.4.2 LTE large-cell uplink

The study also evaluated the protection criteria required for protecting GOES Federal sites due to LTE large-cell uplink deployments in the 1675–1680 MHz band. Spectrum sharing within the 1675–1680 MHz band is more applicable with uplink operations, because uplinks involve lower-power emitters, and users are within the clutter at low emissions. Compared to the large-cell downlink deployment, an uplink deployment will significantly reduce the exclusion zone sizes for many of the locations, even under anomalous propagation conditions. The risk of RFI due to uplink deployments occurs primarily under line-of-sight conditions (e.g., low clutter, less impactful terrain, and anomalous propagation events in high population centers).

Table 4.7-4 lists the protection distances required to protect the Federal sites from RFI due to an uplink deployment using the CSMAC tower deployment. These protection distances were derived from the results obtained from aggregate power versus protection distance statistics. In some cases, towers were not located close enough to the ground station to generate significant RFI. A minimum 1 km protection distance was assumed for these sites.

Table 4.7-4. Protection distances due to LTE large-cell uplink deployment.

Federal site	Data link	Confidence level (%)	Protection distance (km)	Population impacted
Anchorage, AK Elmendorf Air Force Base	GRB	95	1	<100
		75	1	<100
		50	1	<100
Anchorage, AK National Weather Service	GRB	95	1	<100
		75	1	<100
		50	1	<100

Table 4.7-4. cont.

Table 4.7-4. Protection distances due to LTE large-cell uplink deployment.

Federal site	Data link	Confidence level (%)	Protection distance (km)	Population impacted
Boise, ID Bureau of Reclamation	DCS	95	8	200,000
		75	7	190,000
		50	4	170,000
Boise, ID National Interagency Fire Center	DCS	95	32	470,000
		75	14	150,000
		50	11	100,000
Boulder, CO Space Weather Prediction Center	GRB	95	1	<100
		75	1	<100
		50	1	<100
Brevard County, FL Cape Canaveral Space Force Station*	GRB	95	1	<100
		75	1	<100
		50	1	<100
Cincinnati, OH U.S. Army Corps of Engineers	DCS	95	15	900,000
		75	10	400,000
		50	6	250,000
College Park, MD Center for Weather and Climate Prediction	GRB	95	1	<100
		75	1	<100
		50	1	<100
Columbus Lake, MS U.S. Army Corps of Engineers	DCS	95	7	20,000
		75	7	20,000
		50	1	<100
Fairbanks, AK Command and Data Acquisition Center	GVAR	95	0	0
		75	0	0
		50	0	0
Fairmont, WV NOAA Environmental Security Computing Center	DCS	95	25	130,000
		75	25	130,000
		50	10	30,000
Fairmont, WV NOAA Environmental Security Computing Center	GRB	95	6	17,000
		75	6	17,000
		50	1	<100
Hancock County, MS John C. Stennis Space Center*	GRB	95	1	<100
		75	1	<100
		50	1	<100
Honolulu, HI Joint Base Pearl Harbor-Hickam	GRB	95	1	<100
		75	1	<100
		50	1	<100
Honolulu, HI National Weather Service	GRB	95	1	<100
		75	1	<100
		50	1	<100

Table 4.7-4. cont.

Table 4.7-4. Protection distances due to LTE large-cell uplink deployment.

Federal site	Data link	Confidence level (%)	Protection distance (km)	Population impacted
Houston, TX Johnson Space Center	GRB	95	1	<100
		75	1	<100
		50	1	<100
Huntsville, AL NASA Short-term Prediction Research and Transition Center	GRB	95	1	<100
		75	1	<100
		50	1	<100
Kansas City, MO Aviation Weather Center	GRB	95	1	<100
		75	1	<100
		50	1	<100
Miami, FL National Hurricane Center	GRB	95	1	<100
		75	1	<100
		50	1	<100
Monterey, CA Naval Research Laboratory*	GRB	95	1	<100
		75	1	<100
		50	1	<100
Norfolk, VA Fleet Weather Center*	GRB	95	4	33,000
		75	1	<100
		50	1	<100
Norman, OK Storm Prediction Center	GRB	95	1	<100
		75	1	<100
		50	1	<100
Omaha, NE Air Force Weather Agency	GRB	95	1	<100
		75	1	<100
		50	1	<100
Rock Island, IL U.S. Army Corps of Engineers	DCS	95	20	310,000
		75	20	310,000
		50	20	310,000
Sacramento, CA U.S. Army Corps of Engineers	DCS	95	54	2,100,000
		75	11	400,000
		50	7	250,000
Sioux Falls, SD Earth Resources Observation and Science Center	DCS	95	15	75,000
		75	15	75,000
		50	1	<100
St. Louis, MO U.S. Army Corps of Engineers	DCS	95	19	900,000
		75	19	900,000
		50	12	550,000

Table 4.7-4. cont.

Table 4.7-4. Protection distances due to LTE large-cell uplink deployment.

Federal site	Data link	Confidence level (%)	Protection distance (km)	Population impacted
Suitland, MD NOAA Satellite Operations Facility	DCS	95	39	4,000,000
		75	33	3,300,000
		50	31	3,000,000
Suitland, MD NOAA Satellite Operations Facility	GRB	95	3	10,000
		75	1	<100
		50	1	<100
Vicksburg, MS U.S. Army Corps of Engineers	DCS	95	11	36,000
		75	4	18,000
		50	4	18,000
Wallops Island, VA Wallops Command and Data Acquisition Station	DCS	95	8	15,000
		75	1	<100
		50	1	<100
Wallops Island, VA Wallops Command and Data Acquisition Station	GRB	95	1	<100
		75	1	<100
		50	1	<100
Omaha, NE U.S. Army Corps of Engineers	DCS	**	**	**
		**	**	**
		**	**	**

*GRB site planned for 2020.
Note: Analysis was not run for GRB at the JTWC (Honolulu), but due to its close proximity to the other GRB sites, it is expected to have similar results. For similar reasons, given the presence of the NRL GRB receivers in Monterey, analysis for FNMOC was not run separately.
**Omaha, NE, U.S. Army Corps of Engineers site was not covered in the analysis.

In Table 4.7-4, the sites with minimal clutter surrounding the receiver and line-of-sight conditions to populated regions increase the size of exclusion zones required for an uplink deployment. For example, the receive sites located at Suitland, Maryland, and Cincinnati, Ohio, have feed heights of approximately 24 m and 44 m above ground level. These locations are in regions with a large number of LTE users with a higher potential of producing a line-of-sight link between themselves and the GOES receiver. Receive sites such as the U.S. Army Corps of Engineers in Sacramento, California, have an increased probability of line-of-sight conditions due to terrain. In addition to the large population density of Sacramento, suburban regions northeast of the city cause an increase in the protection distance due to instances where the LTE user is less likely to be obstructed by terrain, as seen in Figure 4.7-19. The figure displays the elevation profile versus distance from the receive site in Sacramento to suburban regions around Diamond Springs, California. The terrain profile indicates the general, increasing trend of terrain (3–600 m) in a bearing 60°–80° from the receive site. The minimum protection distance at the U.S. Army Corps of Engineers for an uplink deployment is 61 km at the 95th percentile (top 5% of ducting events) due to the line-of-sight links from the receive site to users in higher-elevated areas. A similar conclusion can be applied to other sites, such as the National Interagency Fire Center (NIFC) in Boise, Idaho.

Figure 4.7-19. Relative terrain from the receive site in Sacramento, California, to suburban regions northeast of the site.

4.7.4.2.1 Differences in protection distances: Large-cell downlink versus large-cell uplink

Exclusion zones to protect the GOES services are smaller for LTE uplink configurations. Table 4.7-5 represents the differences in protection distances for locations receiving DCS data. A large magnitude in difference of protection distances is evident. A mitigation of up to 291 km is possible, primarily due to the large differences in emission levels and antenna heights.

Table 4.7-5. Differences in protection distances between LTE large-cell downlink and uplink configurations.

Federal site	Data link	Large-cell downlink protection distance (km)	Large-cell uplink protection distance (km)	Difference in protection distance (km)
Boise, ID Bureau of Reclamation	DCS	59	8	51
Boise, ID National Interagency Fire Center	DCS	123	32	91
Cincinnati, OH U.S. Army Corps of Engineers	DCS	68	15	53
Columbus Lake, MS U.S. Army Corps of Engineers	DCS	55	7	48
Fairmont, WV NOAA Environmental Security Computing Center	DCS	103	25	78
Omaha, NE U.S. Army Corps of Engineers	DCS	**	**	**
Rock Island, IL U.S. Army Corps of Engineers	DCS	81	20	61

Table 4.7-261.

Table 4.7-5. Differences in protection distances between LTE large-cell downlink and uplink configurations.

Federal site	Data link	Large-cell downlink protection distance (km)	Large-cell uplink protection distance (km)	Difference in protection distance (km)
Sacramento, CA U.S. Army Corps of Engineers	DCS	133	54	79
Sioux Falls, SD Earth Resources Observation and Science Center	DCS	85	15	60
St. Louis, MO U.S. Army Corps of Engineers	DCS	81	19	62
Suitland, MD NOAA Satellite Operations Facility	DCS	171	39	132
Vicksburg, MS U.S. Army Corps of Engineers	DCS	154	11	143
Wallops Island, VA Wallops Command and Data Acquisition Station	DCS	286	8	278
**Omaha, NE U.S. Army Corps of Engineers site was not included in the analysisi.				

4.7.4.3 LTE small-cell downlink

SPRES Project 11 identified the substitution of large cells for small cells as a potential mitigation approach to reduce protection requirements. Results indicated that under standard atmospheric conditions, dense urban, urban, and suburban regions mitigated the protection distances of sites located in urban areas by approximately 5–10 km. Project 7 analyzed small-cell deployments under standard atmospheric and anomalous propagation conditions. Under anomalous propagation conditions, a few sites required greater exclusion zones as a result of high-density population centers at long distances from the site (e.g., from Wallops Island to New York City). Table 4.7-6 lists the protection distances at the 95th percentile for small-cell and large-cell deployments. This mitigation was effective for most of the sites, but had a negative or negligible effect for a handful of the sites (locations where the protection distances did not change, or instances where a larger exclusion zone is required).

Table 4.7-6. Minimum protection distances (95th percentile): Small-cell versus large-cell deployment. (Note: Small-cell protection distances in this table may need to be updated to reflect the corrected interference thresholds in Appendix J)

Federal site	Data link	Small-cell protection distance (km)	Large-cell protection distance (km)
Anchorage, AK Elmendorf Air Force Base	GRB	20	19
Anchorage, AK National Weather Service	GRB	18	18
Boise, ID Bureau of Reclamation	DCS	58	59
Boise, ID National Interagency Fire Center	DCS	81	123
Boulder, CO Space Weather Prediction Center	GRB	58	71

Table 4.7-6. cont.

Table 4.7-6. Minimum protection distances (95th percentile): Small-cell versus large-cell deployment.

Federal site	Data link	Small-cell protection distance (km)	Large-cell protection distance (km)
Brevard County, FL Cape Canaveral Space Force Station*	GRB	60	71
Cincinnati, OH U.S. Army Corps of Engineers	DCS	67	68
College Park, MD Center for Weather and Climate Prediction	GRB	19	20
Columbus Lake, MS U.S. Army Corps of Engineers	DCS	55	55
Fairbanks, AK Command and Data Acquisition Center	GVAR	0	0
Fairmont, WV NOAA Environmental Security Computing Center	DCS	103	103
Fairmont, WV NOAA Environmental Security Computing Center	GRB	69	69
Hancock County, MS John C. Stennis Space Center*	GRB	13	55
Honolulu, HI Joint Base Pearl Harbor-Hickam Air Force Base	GRB	19	18
Honolulu, HI National Weather Service	GRB	21	21
Houston, TX Johnson Space Center	GRB	55	66
Huntsville, AL NASA Short-term Prediction Research and Transition Center	GRB	24	24
Kansas City, MO Aviation Weather Center	GRB	41	44
Miami, FL National Hurricane Center	GRB	46	39
Monterey, CA Naval Research Laboratory	GRB	50	57
Norfolk, VA Fleet Weather Center*	GRB	35	104
Norman, OK Storm Prediction Center	GRB	33	31
Omaha, NE Air Force Weather Agency	GRB	28	28
Omaha, NE U.S. Army Corps of Engineers	DCS	**	**
Rock Island, IL U.S. Army Corps of Engineers	DCS	57	81
Sacramento, CA U.S. Army Corps of Engineers	DCS	140	133

Table 4.7-6. cont.

Table 4.7-6. Minimum protection distances (95th percentile): Small-cell versus large-cell deployment.

Federal site	Data link	Small-cell protection distance (km)	Large-cell protection distance (km)
Sioux Falls, SD Earth Resources Observation and Science Center	DCS	81	85
St. Louis, MO U.S. Army Corps of Engineers	DCS	71	81
St. Louis, MO U.S. Army Corps of Engineers	DCS	71	89
Suitland, MD NOAA Satellite Operations Facility	DCS	158	171
Suitland, MD NOAA Satellite Operations Facility	GRB	58	63
Vicksburg, MS U.S. Army Corps of Engineers	DCS	142	154
Wallops Island, VA Wallops Command and Data Acquisition Station	DCS	439	286
Wallops Island, VA Wallops Command and Data Acquisition Station	GRB	261	203
*GRB sites planned for 2020. **Omaha, NE, U.S. Army Corps of Engineers site was not included in the analysis.			

Figure 4.7-20 represents the exclusion zones for a large-cell downlink deployment (left figure) and a small-cell substitution (bottom figure) to protect the DCS data link at WCDAS. The top figure represents the large-cell deployment previously analyzed. The exclusion zones under anomalous

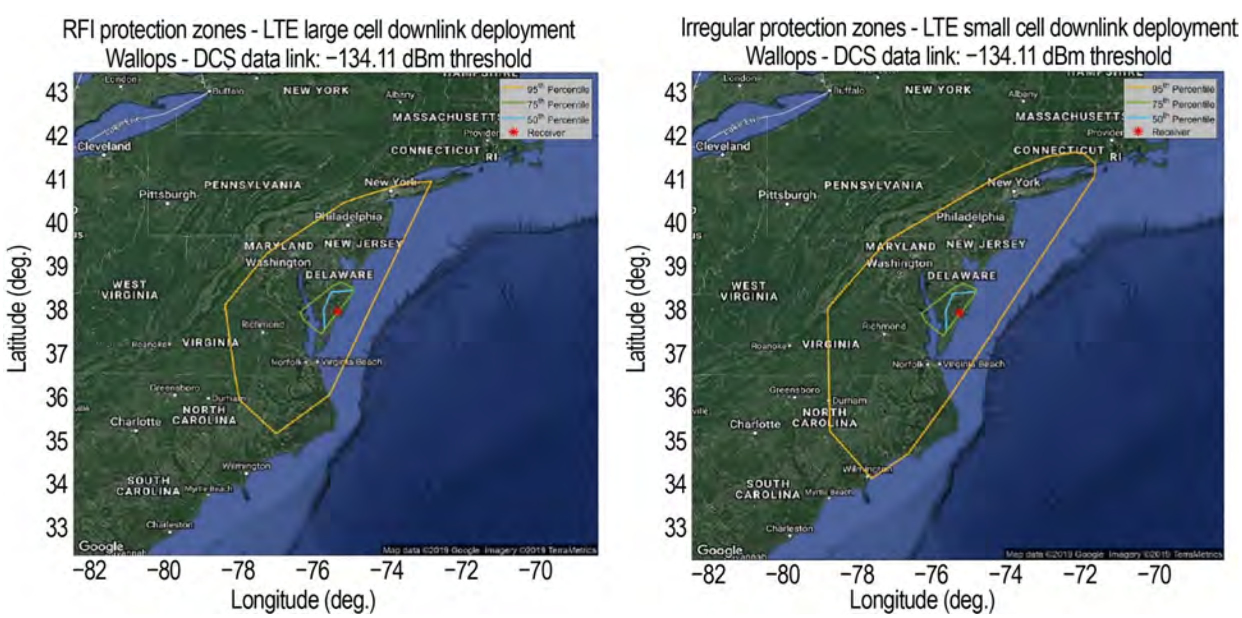


Figure 4.7-20. Composite irregular DCS exclusion zones for large-cell and small-cell downlink deployments, Wallops Island, Virginia. (Note: These map contours do not reflect the revised interference thresholds of -128.2 dBm from Appendix J).

propagation conditions expanded to exclude greater areas and more LTE users. No change was observed for standard atmospheric conditions because of the rural classification of the region. Despite the lower emissions, the density of small cells assumed in the study greatly outweighs the number of large cells, which has ultimately resulted in a greater exclusion zone needed to protect the DCS data link at WCDAS because of severe ducting events. (See Appendix J, section J.1.1, for updated threshold information.)'

Analysis of the GRB data link in Miami, Florida, has shown similar results to the findings in Project 11. Since the region is heavily populated (urban classification), a substitution for small cells resulted in less RFI experienced at the GOES receiver. Figure 4.7-21 displays the aggregate power versus protection

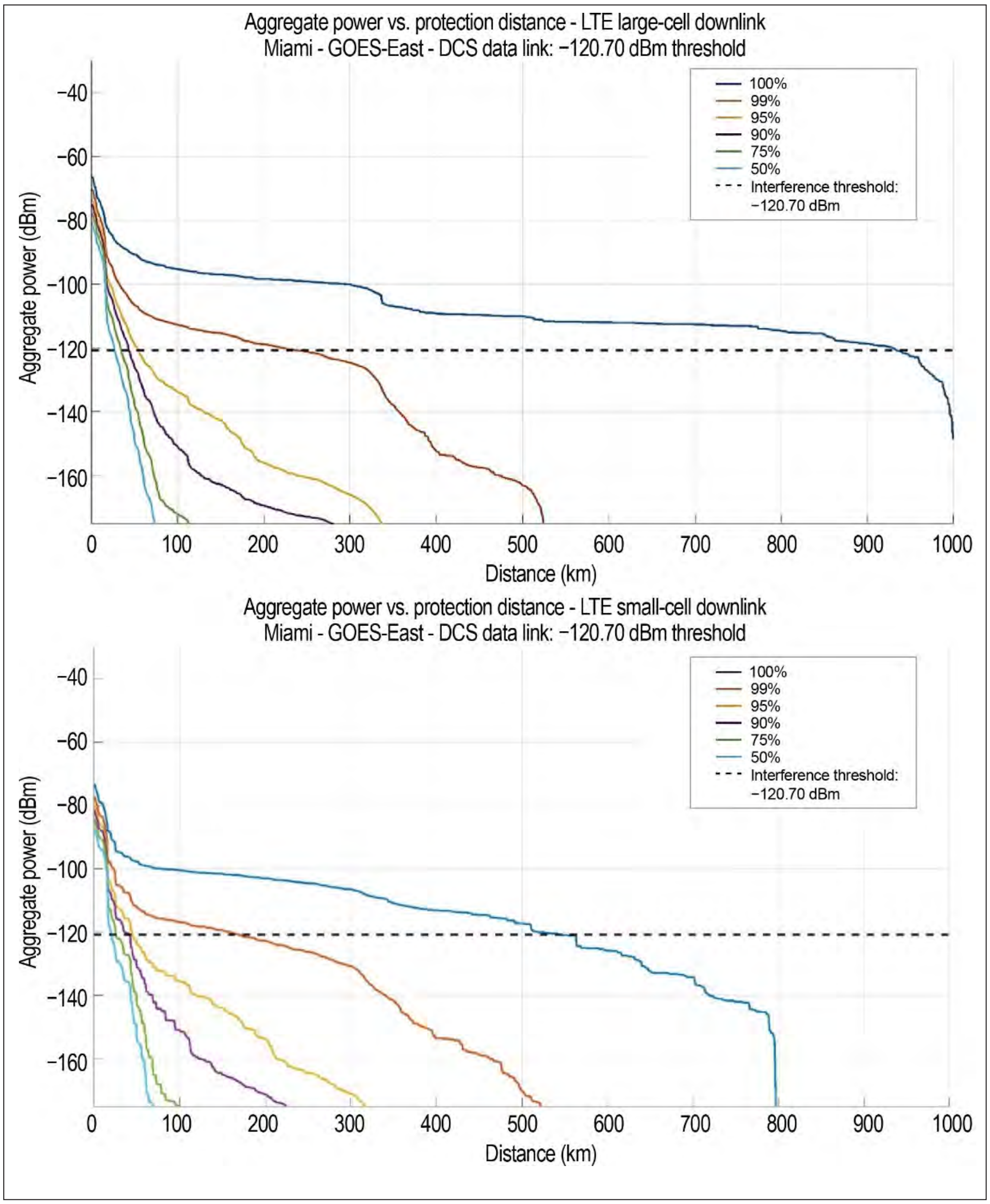


Figure 4.7-21. Aggregate power versus protection distance for large-cell deployment (top plot) and small-cell deployment (bottom plot), Miami, Florida. (Note: These graphs do not reflect the separation distances for the recalculated interference thresholds in Appendix J).

distance plots for the large-cell deployment (top plot) and the small-cell deployment (bottom plot). (See Appendix J, section J.1.1, for updated threshold information.)

The effectiveness of the small-cell deployment in Miami, Florida, is observed through the comparisons of protection distances at each reported percentile from the Monte Carlo simulations. Despite the moderately high impact of ducting on RFI (as observed in the large-cell case), Miami is farther away from other densely populated regions compared to Wallops Island. Thus, there will be a smaller number of potential small cells seen by the GOES receiver. Washington, D.C., Philadelphia, and New York City are examples of dense population centers within 500 km of WCDAS that have a major impact on the RFI experienced there. However, there are no similar locations that provide a similar impact within 500 km of Miami. Overall, this approach is impactful for most of the sites. Static exclusion zones are required, in addition to coordination zones in the event of anomalous propagation conditions. Because of the difficulties of implementing such zones, the findings of this deployment yield the conclusion that to ensure efficient spectrum sharing in the 1675–1680 MHz band, the band must be deployed as an LTE uplink band.

4.7.4.4 Impact of ducting on RFI risks

This section describes the impact of ducting on RFI risks at GOES ground station sites. The metric used was the difference in RFI between the 100th and 95th percentiles, and the 99th and 95th percentiles, where the 95th percentile was equal to the aggregate RFI threshold (see Figure 4.7-22). These metrics represent the additional RFI attributed to greater ducting conditions. The greater these two metrics are, the greater the impact ducting had on the amount of RFI at the GOES ground stations. (See Appendix J, section J.1.1, for updated threshold information.)

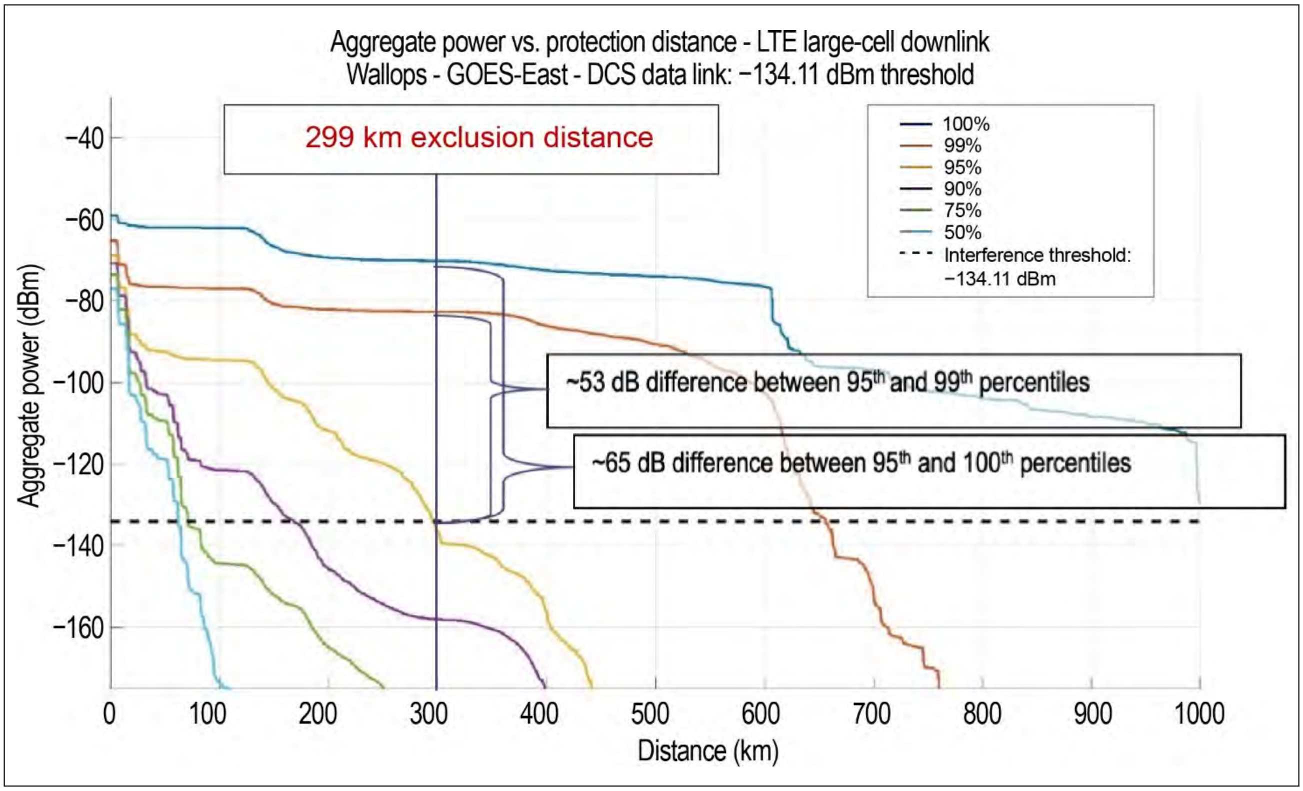


Figure 4.7-22. GOES-East DCS ducting impact metrics, Wallops Island, Virginia. (Note: These graphs do not reflect the separation distances for the recalculated interference thresholds in Appendix J).

Figure 4.7-22 indicates that if a 299 km circular exclusion zone is established to protect the GOES-East DCS data link, up to 53 dB of additional RFI can be expected 4% of the time, and 53–65 dB aggregate RFI 1% of the time, for the DCS link. Table 4.7-7 tabulates the rankings of each site by the greatest difference in RFI between confidence levels. Each site is ranked for the difference in RFI between the 100th and 95th percentiles and the 99th and 95th percentiles, and the ducting impact is classified relative to all sites analyzed in the study. This will assist in identifying sites with severe ducts that occur either 5% of the time or 1% of the time. The two scores are averaged to determine the impact of ducting relative to other GOES ground stations.

Table 4.7-7. Ranking of sites by the impact of ducting on RFI due to an LTE large-cell downlink deployment.

Site	ΔRFI (99%–95%)	ΔRFI (100%–95%)	Average score	Ducting impact on RFI
Wallops Island, VA	1	2	1.5	High
Suitland, MD	3	1	2	High
Vicksburg, MS	2	4	3	High
Rock Island, IL	6	6	6	Moderately high
Sioux Falls, SD	10	3	6.5	Moderately high
Cincinnati, OH	9	5	7	Moderately high
Columbus Lake, MS	5	9	7	Moderately high
Cape Canaveral, FL	4	10	7	Moderately high
St. Louis, MO	8	7	7.5	Moderately high
Norfolk, VA	7	8	7.5	Moderately high
Houston, TX	11	14	12.5	Moderate
Kansas City, MO	13	13	13	Moderate
Sacramento, CA	16	11	13.5	Moderate
Miami, FL	12	15	13.5	Moderate
Fairmont, WV	17	12	14.5	Moderate
Monterey, CA	14	16	15	Moderate
Stennis Space Center, MS	16	16	16	Moderate
Honolulu, HI (Hickam)	18	18	18	Moderately low
Norman, OK	23	20	21.5	Moderately low
Fairbanks, AK	21	23	22	Moderately low
Omaha, NE	26	19	22.5	Moderately low
College Park, MD	24	21	22.5	Moderately low
Honolulu, HI (NOAA)	22	24	23	Moderately low
Boulder, CO	20	26	23	Moderately low
Boise, ID (BOR)	19	27	23	Moderately low
Anchorage, AK (NOAA)	25	22	23.5	Low
Huntsville, AL	29	25	27	Low
Boise, ID (NIFC)	27	28	27.5	Low
Anchorage, AK (Elmendorf)	29	29	29	Low

4.7.4.5 Large-cell downlink: Antenna downtilt mitigation

SPRES Project 11 identified that applying a mechanical downtilt in a large-cell downlink deployment effectively mitigates the exclusion zones required. This process included the application of 2°, 3°, 4°, 5°, and 6° downtilts. Project 7 controlled the footprint of the large cells based on the classification of the tower. In the Monte Carlo simulations, the downtilt was randomized based on the classification of the tower. The effectiveness of applying an additional downtilt to offending antennas proved to still be an effective mitigation in Project 7, even under anomalous propagation conditions. Figure 4.7-23 displays the aggregate power versus protection distance assuming a 6° downtilt for all LTE downlink antennas within the analysis radius around WCDAS for the DCS data link, assuming the antenna is pointing to GOES-East. Compared to the deployment analyzed in Section 4.7.4.1, assuming a 6° downtilt for all antennas reduced the protection distance needed to protect the DCS data link at WCDAS by approximately 110 km under ducting conditions that occur 5% of the time. (See Appendix J, section J.1.1, for updated threshold information.)

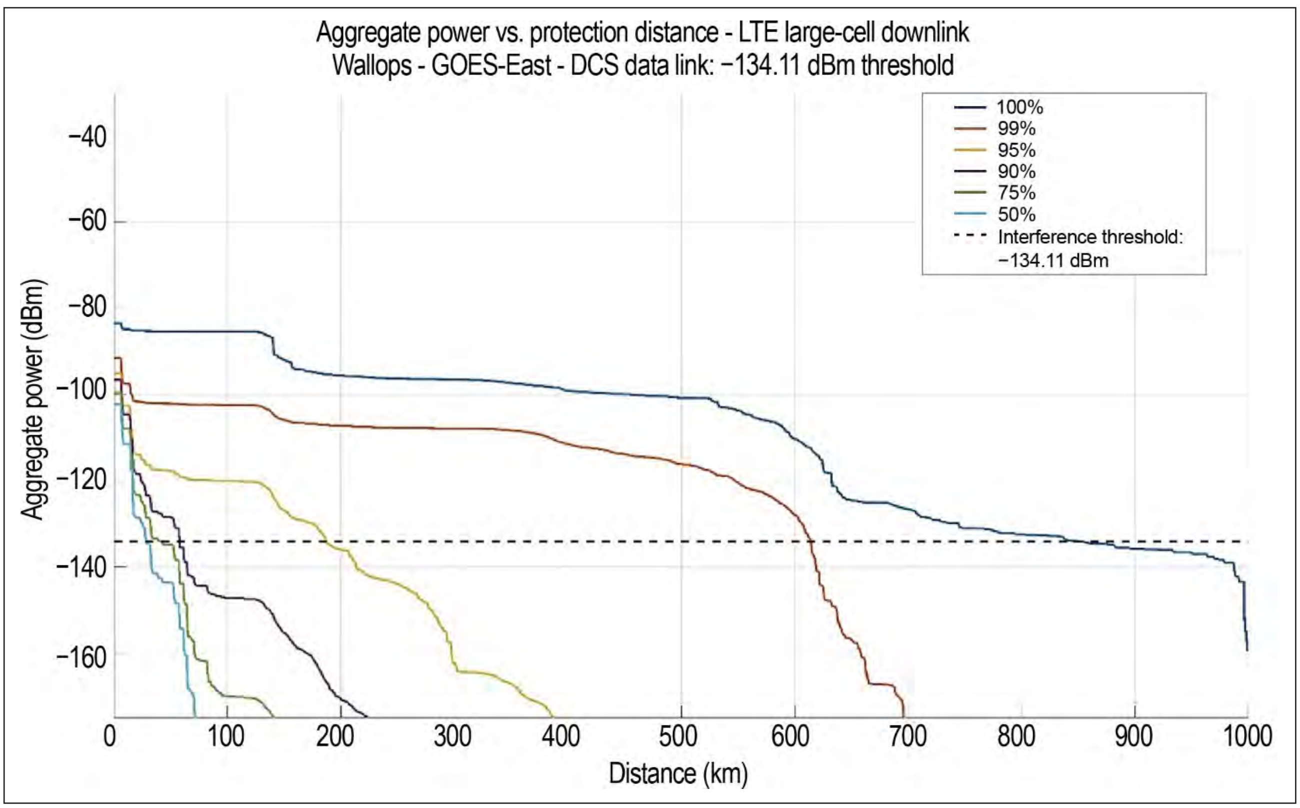


Figure 4.7-23. Aggregate power versus protection distance, 6° downtilt, DCS data link, Wallops Island, Virginia (GOES-East). (Note: These graphs do not reflect the separation distances for the recalculated interference thresholds in Appendix J).

Figure 4.7-24 presents the protection distances required to protect the GRB data link in Miami, Florida, assuming that all antennas are deployed with a 6° downtilt. The mitigation is effective again, compared to the results in Section 4.7.4.1. The protection distance is reduced by approximately 30 km for the top 5% of anomalous propagation events. (See Appendix J, section J.1.1, for updated threshold information.)

Despite the effectiveness of this mitigation, the applicability is not ideal. LTE carriers are likely to be unwilling to alter the coverage of their large cells. Many users, especially in urban regions, would have to be offloaded to other channels, making this mitigation an unrealistic approach. Additionally, the coordination time with the LTE operators to apply a downtilt of offending transmitters during anomalous propagation conditions could surpass the total length of the ducting event.

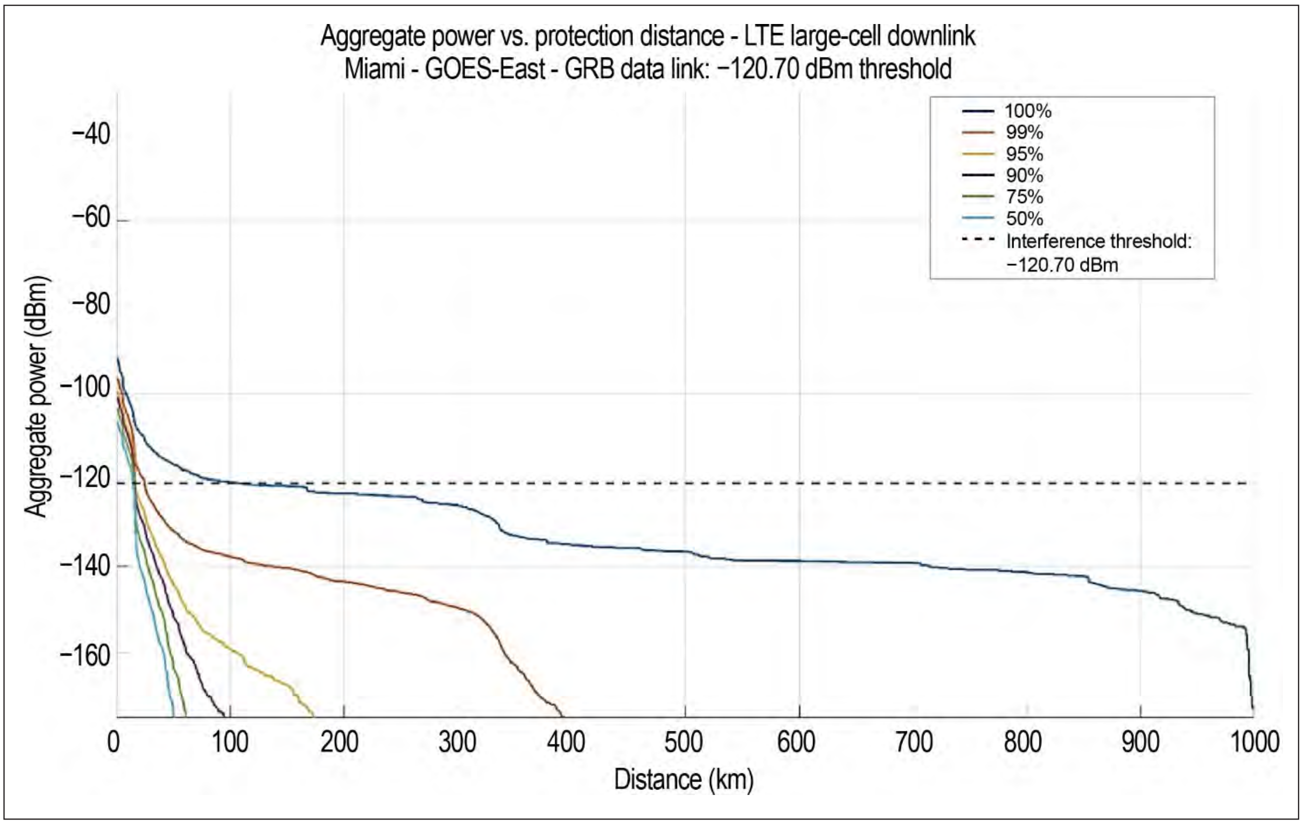


Figure 4.7-24. Aggregate power versus protection distance, 6° downtilt, GRB data link, Miami, Florida (GOES-East). (Note: These graphs do not reflect the separation distances for the recalculated interference thresholds in Appendix J).

4.7.4.6 Risk of RFI for the HRIT data link

HRIT sites are not at risk of RFI from LTE deployments in the 1675–1680 MHz band. A center frequency separation of 16.6 MHz is sufficient in protecting the HRIT data link. The out-of-band emission limits of a 5 MHz LTE signal and the HRIT receiver selectivity allow for non-interfering operations. Figure 4.7-25 represents this scenario. Interference would occur at the intersection points between the LTE and HRIT signals. However, very low power levels are being considered, such that the LTE signal cannot be seen by the HRIT receiver. The out-of-band emission limit is supported by the standard −13 dBm/MHz limit, in addition to the HRIT receiver specifications obtained from the NOAA satellite information system.[23] The filtering of the receiver is modeled through root-raised-cosine filtering with a roll of factor of 0.2.

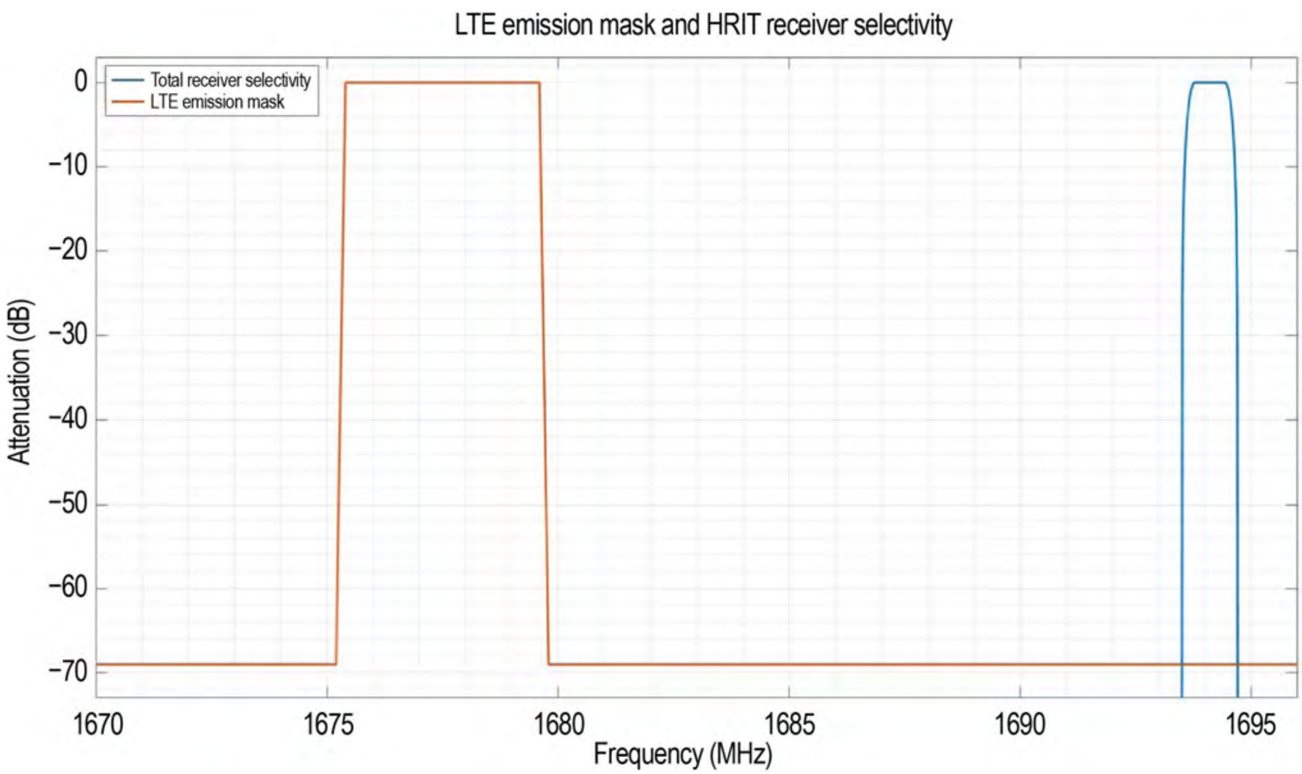


Figure 4.7-25. LTE emission mask (−13 dBm/MHz out-of-band emission limits) and HRIT receiver selectivity (root-raised-cosine factor, α = 0.3).

[23]U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, "HRIT Reception," accessed May 19, 2020, https://www.noaasis.noaa.gov/GOES/HRIT/reception.html.

The SPRES Project 6 findings support the conclusion that HRIT is not at risk of RFI. SPRES Project 6 FDR tests were unable to interfere with the HRIT data link using an LTE-like signal in the 1675–1680 MHz band. Additionally, the SPRES Project 6 Littoral Study also found that there is no risk of RFI through the ability of the HRIT receiver to reject spurious emissions and the strict out-of-band emission limits of the LTE signal. The littoral study looked at the risk of RFI to SMQ-11 systems mounted on different classes of Navy ships. This system is capable of rejecting up to 50 dB of spurious emissions. Analysis in Project 7 focused primarily on the risk of RFI to DCS and GRB data links.

4.7.4.7 User impacts

Given the duration of an RFI event, the impacts to the GRB and DCPR downlinks can be determined. By understanding the timeline for data distribution over the GRB and DCPR downlinks, the RFI event durations are correlated to a loss of data products. This concept is shown in Figure 4.7-26, which uses bars to depict GRB product transmissions overlaying a hypothetical one-minute RFI event. During the RFI event, it is assumed that there is 100% downlink packet loss. For those product transmission periods that are shorter than the RFI duration, the product is lost. For those products having a portion of the transmission period coincident with the RFI event, the product is assumed to lose a proportional amount of data. Using the impact to ABI data in Figure 4.7-26 as an example, 10% of the full-disk data is lost, 20% of the CONUS image is lost, and two mesoscale images are lost.

GRB is transmitted continuously over the RF downlink. The transmission of data is prioritized to meet the product latencies established in the GOES-R ground segment, functional and performance specifications (F&PS). These product refresh rates are shown in Table 4.7-8. In terms of interference, the products are assumed to be transmitted continuously over this interval. Therefore, data loss within this interval causes degradation of a product. Data loss occurring throughout

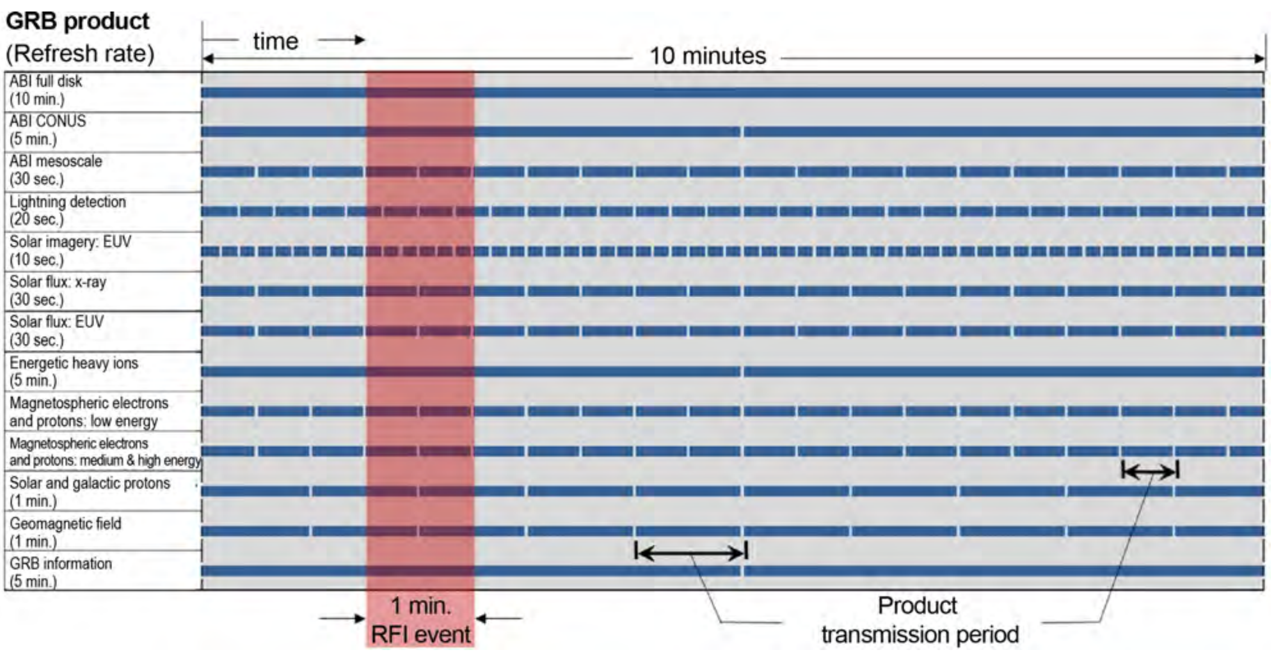


Figure 4.7-26. GRB transmission timeline.

Table 4.7-8. GRB downlink product loss during various RFI events.

GRB Product	10 sec. (%)	Number products lost	1 min. (%)	Number products lost	10 min. (%)	Number products lost	1 hour (%)	Number products lost	4 hour (%)	Number products lost	24 hour (%)	Number products lost
Full Disk Radiance (mode 4)	3	—	20	—	100	32	100	192	100	768	100	4,608
CONUS Radiance (all mode)	3	—	20	—	100	32	100	192	100	768	100	4,608
Mesoscale Radiance (mode 6)	33	—	100	2	100	320	100	1920	100	7,680	100	46,080
Lightning Detection	50	—	100	3	100	30	100	180	100	720	100	4,320
Solar Imagery: EUV	100	1	100	6	100	60	100	360	100	1,440	100	8,640
Solar Flux: X-ray	33	—	100	2	100	20	100	120	100	480	100	2,880
Solar Flux: EUV	33	—	100	2	100	20	100	120	100	480	100	2,880
Energetic Heavy Ions	3	—	20	—	100	2	100	12	100	48	100	288
Magnetospheric Electrons and Protons: Low Energy	33	—	100	2	100	20	100	120	100	480	100	2,880
Magnetospheric Electrons and Protons: Medium and High Energy	33	—	100	2	100	20	100	120	100	480	100	2,880
Solar and Galactic Protons	17	—	100	1	100	10	100	60	100	240	100	1,440
Geomagnetic Field	17	—	100	1	100	10	100	60	100	240	100	1,440
GRB Information	3	—	20	—	100	2	100	12	100	48	100	288
Total lost products	—	1	—	21	—	578	—	3,468	—	13,872	—	83,232

(Table header: GRB product loss; RFI event duration spans all duration columns.)

this interval results in product loss. Radiance data shown in the table is actually composed of 16 different products corresponding to different spectral bands. Based on the assumption that data is being transmitted continuously for a given product over the refresh period, the expectation is that all bands will experience similar impacts. The ABI sensor is configured to operate in different modes, and the modes producing imagery at the highest frequency were chosen for this analysis.

Those cells showing 100% represent all products lost during the RFI event and are followed by a total number of products that would have been transmitted over that RFI event interval. It is unlikely that an event will begin coincident with the beginning of a product refresh period, so the number of full products lost will be n−1 for any event. The remaining data lost will likely be dispersed between the preceding and successive data products.

Survey responses from Project 1 (see Table 4.7-9) identified the GRB product types that GRB users obtain from the downlink. These responses reveal that, with the exception of the 557th Weather Wing in Omaha, Nebraska, all users rely on data that is distributed at relatively low product refresh times, largely driven by the GLM product. Missing one report due to RFI could then cause significant delays in receiving data if users need to wait for the next data transmission.

DCPs operate in one of two modes, self-timed or random. In self-timed mode, the sensors are configured to report on a specific channel, time, and period. The channel and reporting window allocations are managed by NOAA. The number of DCPs that are reporting in self-timed or random mode are summarized in Table 4.7-10. Since approximately 97% of DCPs report at least on an hourly basis, longer-duration RFI events can result in multiple consecutive report losses.

Table 4.7-9. GRB product use by site.

GRB data use by site	
Sites	**GRB meteorological data use**
Fairmont, WV	None
Suitland, MD	All
Wallops Island, VA	None
Cape Canaveral, FL	All
Anchorage, AK (Elmendorf)	Unknown
Honolulu, HI (Hickam)	All
Honolulu, HI (NOAA)	All
Omaha, NE	ABI
Houston, TX	All
Huntsville, AL	All
College Park, MD	All
Anchorage, AK (NOAA)	Unknown
Kansas City, MO	ABI, SEISS, GLM, EXIS
Miami, FL	ABI, GLM
Norman, OK	ABI, GLM
Boulder, CO	All
Monterey, CA	All

Table 4.7-10. DCP system summary.

Reporting period	Number of DCPs	Percent of total	Number of daily messages
5 minutes	158	0.43	45,504
6 minutes	531	1.44	127,440
10 minutes	32	0.09	4,608
12 minutes	40	0.11	4,800
15 minutes	600	1.63	57,600
30 minutes	163	0.44	7,824
1 hour	34,217	92.78	821,208
3 hours	372	1.01	2,976
4 hours	13	0.04	78
12 hours	235	0.64	470
Random	520	1.41	N/A
TOTAL	36,881	—	1,072,508

Figure 4.7-27 depicts a potential one-minute RFI event overlaid on a portion of the DCPR channels. Each bar represents a DCP reporting window, and an event intersecting a reporting window is assumed to cause the full report loss. DCPs transmit a small amount of data, and partial loss of a product is not considered. This example corresponds to a loss of 28 products, but this is not fully representative of the DCPR downlink, as it contains over 175 active reporting channels. The DCPR channel loading is shown in Figure 4.7-28, which shows the percentage of time DCPs are actively reporting on a given channel.

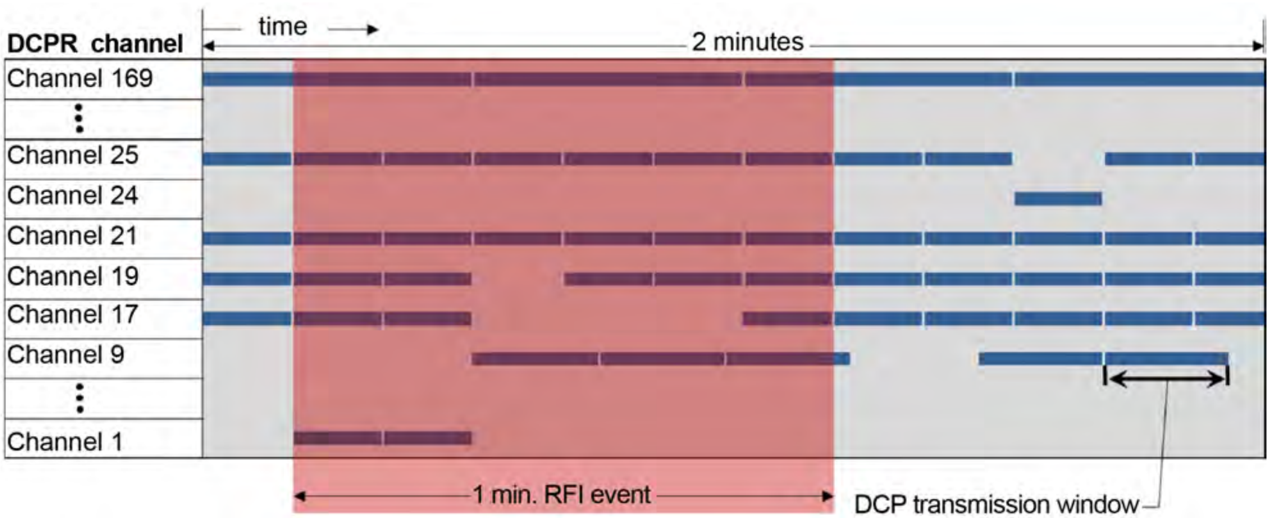


Figure 4.7-27. DCP transmission.

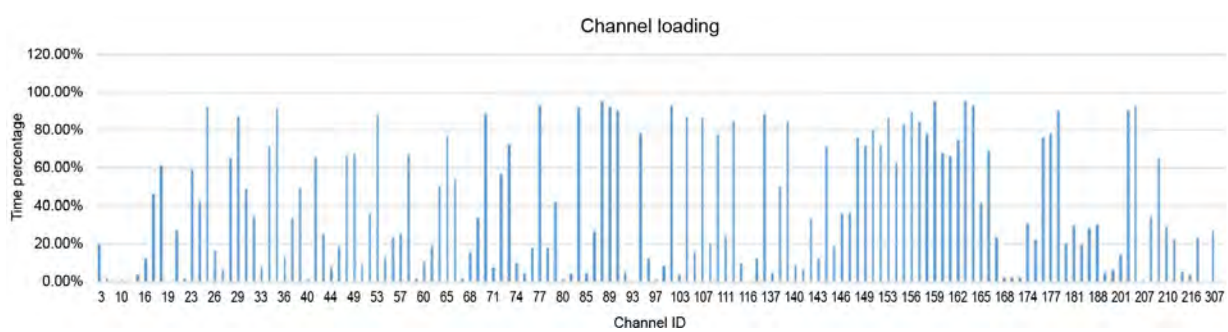


Figure 4.7-28. Percentage of time DCPs are actively transmitting on a given channel.

In random mode, the sensors generate and transmit reports based on an external trigger event, such as a river level gage exceeding a set threshold. As of June 2019, 33 DCS channels were allocated to sensors reporting in random mode. Since random sensor reporting is event-triggered, it is not possible to determine how many messages would be received each day. Although random sensors make up only 1.4% of total DCPs, those sensors are expected to be triggered under critical circumstances requiring some level of intervention by resource managers. The random DCPs in the United States are operated by approximately 63 different organizations located in 31 states (CA, AK, MT, ID, CO, UT, OR, WA, AL, WV, KY, OH, LA, MN, NY, PA, NC, FL, TX, AZ, OK, ND, MA, NH, TN, VA, HI, NV, GA, FL, MS).

The total number of DCPs operated by the DRGS user sites being considered during Project 7 was also determined. Given the DCP ID, the reporting period and transmit window can be used to determine the number of reports received in a given time period for each of these groups. With this information, the number of reports lost during a given RFI event can be calculated. This information is given in Table 4.7-11.

Table 4.7-11. DCPR downlink data loss during RFI events.

Organization	All	USACE	Cincinnati division	St. Louis/ Vicksburg district	Mobile district	Sacramento district	USGS	BLM/ NFIC	BOR
Reports per hour	34,348	2,600	669	579	137	236	11,084	893	572
RFI duration	Average number reports lost during RFI (total)								
10sec./0.0028hr.	95	7	2	2	0	1	31	2	2
1min./0.02hr	572	43	11	10	2	4	185	15	10
10min./0.17hr.	5,725	433	112	97	23	39	1,847	149	95
1hr./1.00hr.	34,348	2,600	669	579	137	236	11,084	893	572
4hr./4.00hr.	137,393	10,400	2,676	2,316	548	944	44,437	3,572	2,288
24hr./24.00hr.	824,358	62,400	16,056	13,896	3,288	5,664	266,024	21,432	13,728

4.7.4.7.1 Data availability

The susceptibility of data loss due to RFI occurring at a DRGS or GRB downlink site is dependent on the data sources available while a user is attempting to transfer data. For a user operating DRGS receivers, backup sources are available via DADDS/LRGS and HRIT/EMWIN. For GRB users, NOAA supports comprehensive L1b and GLM data distribution from only one other source, PDA. Table 4.7-12 is a list of Project 7 DRGS and GRB sites, along with existing alternate data sources.

Table 4.7-12. Direct broadcast service use and alternate data sources at Project 7 sites.

Sites	Direct broadcast service use	Existing alternate data sources	
Fairmont, WV	GRB	—	—
Suitland, MD	DRGS	DADDS/LRGS	—
	GRB	—	—
Wallops Island, VA	DRGS	DADDS/LRGS	—
	GRB	—	—
Cincinnati, OH	DRGS	HRIT	LRGS
Columbus Lake, MS	DRGS	LRGS	—
Rock Island, IL	DRGS	HRIT	LRGS

Table 4.7-12. cont.

Table 4.7-12. Direct broadcast service use and alternate data sources at Project 7 sites.

Sites	Direct broadcast service use	Existing alternate data sources	
Sacramento, CA	DRGS	HRIT	LRGS
St. Louis, MO	DRGS	HRIT	LRGS
Vicksburg, MS	DRGS	HRIT	LRGS
Boise, ID (BOR)	DRGS	HRIT	LRGS
Boise, ID (NIFC)	DRGS	HRIT	LRGS
Sioux Falls, SD	DRGS	HRIT	LRGS
Cape Canaveral, FL	GRB	—	—
Anchorage, AK (Elmendorf)	GRB	—	—
Honolulu, HI (Hickam)	GRB	—	—
Omaha, NE	GRB	PDA	—
Omaha, NE (USACE)	DRGS	HRIT	LRGS
Houston, TX	GRB	PDA	—
Huntsville, AL	GRB	PDA	—
College Park, MD	GRB	PDA	—
Anchorage, AK (NOAA)	GRB	PDA	—
Kansas City, MO	GRB	PDA	—
Miami, FL	GRB	PDA	—
Honolulu, HI (NOAA)	GRB	—	—
Norman, OK	GRB	PDA	—
Boulder, CO	GRB	PDA	—
Monterey, CA	GRB	PDA	—

It should be noted that there are no feasible alternative data sources for Fairmont, West Virginia, and Wallops Island, Virginia. These sites do not use the L1b and GLM products that could otherwise be obtained from the alternate source. The GRB data is downlinked for the purposes of optimizing the satellite-to-ground RF link at those sites, and this data is unavailable at other geographic locations.

Based on the results from Project 5, the availability of the alternate distribution systems are shown in Table 4.7-13. The PDA and HRIT values indicate measured operational availability, but the LRGS/DADDS values are based on operational estimates. The GRB and DRGS receiver systems are based on design specifications for availability of the GOES-R ground segment, which is 99.98%. Assuming that

Table 4.7-13. Alternate data source availability.

Data source system	Availability, A_s (percent)
ESPDS–Product Distribution and Access (PDA)	99.44
High Rate Information Transfer (HRIT)	99.33
DCS Administrative and Data Distribution System (DADDS)	99.90
Local Readout Ground Station (LRGS)	99.90
GOES Rebroadcast (GRB)	99.96
Direct Readout Ground Station (DRGS)	99.96

the receivers have a comparable availability, two systems acting in series will have a transmit-receive system availability of 99.96%.

Using system availability, the data availability can be determined by representing each alternate as a parallel data source, shown conceptually in Figure 4.7-29. The data availability is calculated by subtracting the product of source unavailabilities from 1. The data availability and the data availability when RFI mitigations are put in place is shown in Table 4.7-14. For those sites that do not have a backup source, loss of direct broadcast results in total loss of data availability if no RFI mitigating actions are taken, corresponding to 0.00%. It is assumed that the user has implemented provisions to automatically transition to backup data sources in the event of failure of a source or multiple sources. This LRGS system provides automated transition to alternate data sources in the event of multisource failure.

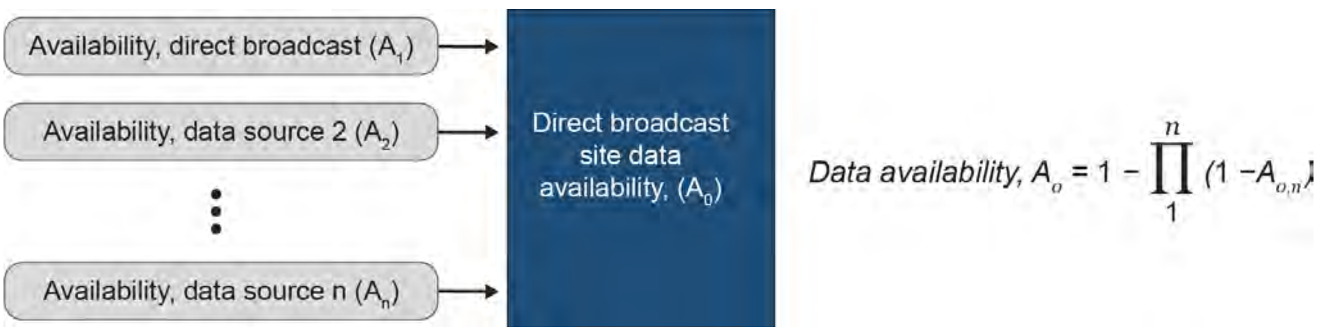


Figure 4.7-29. Data availability dependency on source availability.

Table 4.7-14. Data availability based on percentage of RFI mitigation.

Sites	Direct broadcast service use	Existing alternate data sources		Data availability (percent)		
				100% RFI mitigation	95% RFI mitigation	No RFI mitigation
Fairmont, WV	GRB	—	—	99.960	94.962	0.00
Suitland, MD	GRB	—	—	99.960	94.962	0.00
Wallops Island, VA	GRB	—	—	99.960	94.962	0.00
Cape Canaveral, FL	GRB	—	—	99.960	94.962	0.00
Anchorage, AK (Elmendorf)	GRB	—	—	99.960	94.962	0.00
Honolulu, HI (Hickam)	GRB	—	—	99.960	94.962	0.00
Honolulu, HI (NOAA)	GRB	—	—	99.960	94.962	0.00
Omaha, NE	GRB	PDA	—	99.9998	99.972	99.440
Omaha, NE (USACE)	DRGS	HRIT	—	**	**	**
Houston, TX	GRB	PDA	—	99.9998	99.972	99.440
Huntsville, AL	GRB	PDA	—	99.9998	99.972	99.440
College Park, MD	GRB	PDA	—	99.9998	99.972	99.440

Table 4.7-14. cont.

Table 4.7-14. Data availability based on percentage of RFI mitigation.

Sites	Direct broadcast service use	Existing alternate data sources		Data availability (percent)		
				100% RFI mitigation	95% RFI mitigation	No RFI mitigation
Anchorage, AK (NOAA)	GRB	PDA	—	99.9998	99.972	99.440
Kansas City, MO	GRB	PDA	—	99.9998	99.972	99.440
Miami, FL	GRB	PDA	—	99.9998	99.972	99.440
Norman, OK	GRB	PDA	—	99.9998	99.972	99.440
Boulder, CO	GRB	PDA	—	99.9998	99.972	99.440
Monterey, CA	GRB	PDA	—	99.9998	99.972	99.440
Suitland, MD	DRGS	DADDS/LRGS	—	99.99996	99.995	99.90
Wallops Island, VA	DRGS	DADDS/LRGS	—	99.99996	99.995	99.90
Columbus Lake, MS	DRGS	LRGS	—	99.99996	99.995	99.90
Cincinnati, OH	DRGS	HRIT	LRGS	99.9999997	99.99997	99.9993
Rock Island, IL	DRGS	HRIT	LRGS	99.9999997	99.99997	99.9993
Sacramento, CA	DRGS	HRIT	LRGS	99.9999997	99.99997	99.9993
St. Louis, MO	DRGS	HRIT	LRGS	99.9999997	99.99997	99.9993
Vicksburg, MS	DRGS	HRIT	LRGS	99.9999997	99.99997	99.9993
Boise, ID (BOR)	DRGS	HRIT	LRGS	99.9999997	99.99997	99.9993
Boise, ID (NIFC)	DRGS	HRIT	LRGS	99.9999997	99.99997	99.9993
Sioux Falls, SD	DRGS	HRIT	LRGS	99.9999997	99.99997	99.9993
**Omaha, NE (USACE) was not covered in the analysis.						

4.7.4.7.2 Data transfer impacts

The expected downtime that will occur over a given period of time can be calculated based on the percentage of RFI mitigation implemented. Comparing these values with the baseline, where 100% of the RFI is mitigated (i.e., pre-spectrum sharing), the impacts to RFI can be determined. These results are shown on a site-by-site basis in Table 4.7-15.

Table 4.7-15 exemplifies the benefit of multiple data sources when reliability of the direct broadcast downlink may be degraded. The GRB sites are the least resilient to loss of direct broadcast data, primarily because of the lack of alternate sources. In cases where GRB and DCS downlink sites will be relying on an alternate data source, it will be delayed due to latency induced by the alternate source. For GRB sites relying on a PDA alternative, the data may be delayed up to five seconds. For DRGS users relying on DADDS or LRGS, the data may be delayed up to five seconds. And for those LRGS sites relying on HRIT, the data may be delayed up to 21 seconds. While it is assumed these delays are acceptable under rare circumstances when the direct broadcast service is unavailable, it may not be acceptable under normal operations, especially during critical events when timely access to data can prevent loss of life and economic impacts.

Table 4.7-15. RFI event duration and periodicity at Project 7 sites.

Sites	Direct broadcast service use	Expected downtime (every 30 days)			
		100% RFI mitigation	95% RFI mitigation	90% RFI mitigation	75% RFI mitigation
Fairmont, WV	GRB	17.3 min.	36.3 hr.	72.3 hr.	7.5 days
Suitland, MD	GRB	17.3 min.	36.3 hr.	72.3 hr.	7.5 days
Wallops Island, VA	GRB	17.3 min.	36.3 hr.	72.3 hr.	7.5 days
Cape Canaveral, FL	GRB	17.3 min.	36.3 hr.	72.3 hr.	7.5 days
Anchorage, AK (Elmendorf)	GRB	17.3 min.	36.3 hr.	72.3 hr.	7.5 days
Honolulu, HI (Hickam)	GRB	17.3 min.	36.3 hr.	72.3 hr.	7.5 days
Honolulu, HI (NOAA)	GRB	17.3 min.	36.3 hr.	72.3 hr.	7.5 days
Omaha, NE	GRB	5.81 min.	12.2 min.	24.3 min.	60.6 min.
Houston, TX	GRB	5.81 sec.	12.2 min.	24.3 min.	60.6 min.
Huntsville, AL	GRB	5.81 sec.	12.2 min.	24.3 min.	60.6 min.
College Park, MD	GRB	5.81 sec.	12.2 min.	24.3 min.	60.6 min.
Anchorage, AK (NOAA)	GRB	5.81 sec.	12.2 min.	24.3 min.	60.6 min.
Kansas City, MO	GRB	5.81 sec.	12.2 min.	24.3 min.	60.6 min.
Miami, FL	GRB	5.81 sec.	12.2 min.	24.3 min.	60.6 min.
Norman, OK	GRB	5.81 sec.	12.2 min.	24.3 min.	60.6 min.
Boulder, CO	GRB	5.81 sec.	12.2 min.	24.3 min.	60.6 min.
Monterey, CA	GRB	5.81 sec.	12.2 min.	24.3 min.	60.6 min.
Suitland, MD	DRGS	1.04 sec.	2.2 min.	4.3 min.	10.8 min.
Wallops Island, VA	DRGS	1.04 sec.	2.2 min.	4.3 min.	10.8 min.
Columbus Lake, MS	DRGS	1.04 sec.	2.2 min.	4.3 min.	10.8 min.
Cincinnati, OH	DRGS	0.007 sec.	0.875 sec.	1.74 sec.	4.35 sec.
Rock Island, IL	DRGS	0.007 sec.	0.875 sec.	1.74 sec.	4.35 sec.
Sacramento, CA	DRGS	0.007 sec.	0.875 sec.	1.74 sec.	4.35 sec.
St. Louis, MO	DRGS	0.007 sec.	0.875 sec.	1.74 sec.	4.35 sec..
Vicksburg, MS	DRGS	0.007 sec.	0.875 sec.	1.74 sec.	4.35 sec
Boise, ID (BOR)	DRGS	0.007 sec.	0.875 sec.	1.74 sec.	4.35 sec.
Boise, ID (NIFC)	DRGS	0.007 sec.	0.875 sec.	1.74 sec.	4.35 sec.
Sioux Falls, SD	DRGS	0.007 sec.	0.875 sec.	1.74 sec.	4.35 sec.
Omaha, NE (USACE)	DRGS	**	**	**	**
**Omaha, NE (USACE) was not covered in the analysis.					

This data also shows that relatively small changes in the RFI mitigations implemented can have drastic impacts on expected downtimes. With 95% RFI mitigation, the expected downtime increases by 125 times; with 90% RFI mitigation, outages increase 250 times; and with 75% RFI mitigation, downtime is increased by 625 times.

4.7.4.7.3 User risk assessment

Project 6 developed a method to evaluate user risk by quantifying the likelihood and impact to data loss for a given user. This section seeks to reevaluate those metrics based on data that has been made available through other SPRES projects. In particular, it addresses the likelihood of ducting events resulting in data loss developed during Project 7 along with the system availability metrics that were determined during Project 5. This data will be used to reevaluate the probability of data loss at each user's site. The overall risk to a user will be calculated using the product of probability and impact.

4.7.4.7.3.1 Likelihood of data loss

During Project 6, four factors were evaluated to arrive at a score indicating the likelihood of impactful data loss for each user's site. The factors evaluated were user latency requirements, data source redundancy, service used to obtain DCS or GRB data, and susceptibility to anomalous propagation. In Project 7, the likelihood of data loss is based on data availability. Data availability combines the effects of source redundancy, direct broadcast service use (DCPR or GRB), and anomalous propagation into a single metric when an RFI mitigation percentage is selected. For this analysis, 95% RFI mitigation was chosen.

The latency added to data transfer was obtained during Project 5 for direct broadcast as well as the redundant data sources used in the event of a downlink failure. All of these systems meet the user-defined requirements as categorized in SPRES Project 1, where the minimum user latency requirement was designated as less than one minute. However, during weekly SPRES meetings, users indicated that latencies on the order of tens of seconds can have adverse impacts on operations. If the data used by these direct broadcast sites is closely examined, it is apparent that all Project 7 GRB users, with the exception of the NOAA site in Anchorage, Alaska, use GLM and space weather products that have product refresh rates as low as one second. In addition, DCP users considered during Project 7 all receive data from randomly reporting DCPs. The expectation is that since these messages are triggered by environmental factors in order to alert users to a developing critical condition, data latency is of high importance. Fairmont, Wallops, Suitland, and Sioux Falls are exceptions because they do not actually use the data. However, they are tier 1 providers, and because they act as the backup data source for all DRGS and GRB users studied in the SPRES project, it is assumed that low latency is of the utmost importance at these sites.

On average the alternate data sources are able to meet the users' needs despite the fact that they may be below 10 seconds. PDA is the backup source for GRB, and on average it transfers files to users in five seconds. The LRGS, a backup to all DRGS systems, is capable of providing data to users in five seconds. However, the performance of these sources varies, and there are outliers where data may take on the order of minutes to transfer to users. If RFI was expected to occur at high rates because appropriate mitigations were not implemented, then the performance of the alternate data sources and the performance outliers would become more prevalent, and latency may have to be included in the likelihood of data loss. However, if the sites are relying on backup data sources only 5%–6% of the time (because the other 94%–95% of the time RFI is mitigated), it is expected that latency induced during data transfer can be neglected.

In order to associate risk with data availability, the GRB ground system design availability of 99.988% was used. Assuming the receiver has a similar availability, the total availability of the GRB transmit/receive system is 99.976%, equating to approximately 10.4 minutes of downtime every 30 days. Users operating in a system configuration that provided 99.976% data availability or higher were given a low-risk score of 1. Users operating with a data availability between 99.976% and 99.971%, the equivalent of up to a 20% increase in product loss (12.4 minutes of downtime), were given a risk score of 2. Any site with data availability lower than 99.971% was given a high-risk rating of 3. The availability risk scores are shown in Table 4.7-16, along with the score for likelihood of data loss.

Table 4.7-16. Likelihood of data loss.

Sites	Direct broadcast service use	Existing alternate data sources		Data availability (percent) 95% RFI mitigation	Likelihood of data loss rating
Suitland, MD	GRB	—	—	94.96	3
Wallops Island, VA	GRB	—	—	94.96	3
Anchorage, AK (Elmendorf)	GRB	—	—	94.96	3
Honolulu, HI (Hickam)	GRB	—	—	94.96	3
Suitland, MD	DRGS	DADDS/LRGS	—	100.00	1
Wallops Island, VA	DRGS	DADDS/LRGS	—	100.00	1
Rock Island, IL	DRGS	HRIT	LRGS	100.00	1
Fairmont, WV	GRB	—	—	94.96	3
St. Louis, MO	DRGS	HRIT	LRGS	100.00	1
Boise, ID (BOR)	DRGS	HRIT	LRGS	100.00	1
Boise, ID (NIFC)	DRGS	HRIT	LRGS	100.00	1
Sioux Falls, SD	DRGS	HRIT	LRGS	100.00	1
Cape Canaveral, FL	GRB	—	—	94.96	3
Honolulu, HI (NOAA)	GRB	—	—	94.96	3
Columbus Lake, MS	DRGS	LRGS	—	100.00	1
Sacramento, CA	DRGS	HRIT	LRGS	100.00	1
Vicksburg, MS	DRGS	HRIT	LRGS	100.00	1
Cincinnati, OH	DRGS	HRIT	LRGS	100.00	1
Omaha, NE	GRB	PDA	—	99.97	2
Omaha, NE (USACE)	DRGS	HRIT	LRGS	**	**
College Park, MD	GRB	PDA	—	99.97	2
Anchorage, AK (NOAA)	GRB	PDA	—	99.97	2
Norman, OK	GRB	PDA	—	99.97	2
Monterey, CA	GRB	PDA	—	99.97	2
Kansas City, MO	GRB	PDA	—	99.97	2
Miami, FL	GRB	PDA	—	99.97	2
Boulder, CO	GRB	PDA	—	99.97	2
Huntsville, AL	GRB	PDA	—	99.97	2
Houston, TX	GRB	PDA	—	99.97	2

**Omaha, NE (USACE) was not covered in the analysis.

4.7.4.7.3.2 Impacts resulting from data loss

For the purposes of impact analysis, it was assumed that interference caused loss of data and the user-stated impact from Project 1 was realized. It is conceivable that there could be a severity scale associated with the level of RFI experienced. It could be intermittent, causing packet loss in a GRB downlink, with the result being blackout areas in ABI imagery, for instance, rather than complete product loss. DCP reports contain small amounts of data, and any interference experienced coincident with a sensor reporting transmission is likely to be a complete loss of data for that DCP reporting window.

There were two methods used to determine the potential impacts to data loss at a given node. One method considered the U.S. economic impacts, and the second considered user data loss impact statements provided during Project 1.

Economic impacts

To determine the economic impacts to data loss, an attempt was made to associate each site with industry sectors serviced by that user. Standard NAICS codes were associated with user sites so that economic data could be obtained from the Bureau of Economic Analysis to understand the size of the industry and its relative contribution to the U.S. gross domestic product (GDP). It is expected that the types of data being provided by many of the organizations investigated during the SPRES Project help industries operate more efficiently. For instance, if the Bureau of Reclamation (BOR) is managing water supplies over a given geographic area, it is improving the efficiency of agricultural industry through increased production and irrigable acreage. While BOR is not wholly responsible for the $133 billion agricultural sector of the U.S. GDP, it may help to improve the efficiency with which that industry operates, and fractions of a percent can yield substantial gains in terms of increased revenue. Based on the total value of all market sectors supported by a given site, the market sector impact was categorized as high (>$10 trillion), moderate ($6–$10 trillion), or low (<$6 trillion). Table 4.7-17 shows the NAICS market sectors supported by each site, as well as the risk of impact to the national economy. The DoD components (*) that do not directly contribute to the national economy through dissemination of data to private market sectors were rated as high GDP impact because they offer the stability necessary for the continued function of the economy.

Table 4.7-17. Economic impact scores.

Sites	Direct broadcast service use	GDP impact	Area of responsibility	Economic impact score
Fairmont, WV	GRB	Moderate	National	2.5
Suitland, MD	GRB	High	National	3
Wallops Island, VA	GRB	High	National	3
Cape Canaveral, FL	GRB	High	Local	2
Anchorage, AK (Elmendorf)	GRB	High	National	3
Honolulu, HI (Hickam)	GRB	High	National	3
Honolulu, HI (NOAA)	GRB	Moderate	Regional	2
Omaha, NE	GRB	High	National	3

Table 4.7-17. cont.

Table 4.7-17. Economic impact scores.

Sites	Direct broadcast service use	GDP impact	Area of responsibility	Economic impact score
Houston, TX	GRB	Low	Local	1
Huntsville, AL	GRB	Low	National	2
College Park, MD	GRB	High	National	3
Anchorage, AK (NOAA)	GRB	Low	Regional	1.5
Kansas City, MO	GRB	Moderate	National	2.5
Miami, FL	GRB	Moderate	National	2.5
Norman, OK	GRB	High	National	3
Boulder, CO	GRB	Moderate	National	2.5
Monterey, CA	GRB	High	National	3
Suitland, MD	DRGS	High	National	3
Wallops Island, VA	DRGS	High	National	3
Columbus Lake, MS	DRGS	Moderate	Regional	2
Cincinnati, OH	DRGS	Moderate	Regional	2
Rock Island, IL	DRGS	High	National	3
Sacramento, CA	DRGS	Moderate	Regional	2
St. Louis, MO	DRGS	High	Regional	2.5
Vicksburg, MS	DRGS	High	Regional	2.5
Boise, ID (BOR)	DRGS	High	Regional	2.5
Boise, ID (NIFC)	DRGS	Moderate	National	2.5
Sioux Falls, SD	DRGS	Moderate	National	2.5
Omaha, NE (USACE)	DRGS	**	**	**
**Omaha, NE (USACE) was not covered in the analysis				

In addition to supporting multiple market segments, each site may have a specific area of responsibility (AoR) requiring it to collect, process, and disseminate data within a specific geographic region. An example is the Corps of Engineers, which has eight divisions covering the United States, with each division segmented into multiple districts. Some service local areas, whereas others have a regional responsibility or have data users distributed nationally. Each site was assigned a high (national), moderate (regional), or low (local) impact based on its AoR. Together, the GDP and AoR impacts were given a value of 1 (low), 2 (moderate), or 3 (high), and then averaged to determine the potential economic impact of data loss at a particular site.

Based on the responses, the user impact statements were classified in one of four groups: loss of life and property, loss of property, industry impacts, and business impacts. The impacts were rated numerically based on the following scale: loss of life (3), loss of property (2.2), commerce impacts (1.7), and business impacts (1). Business impacts were related to a specific user's ability to perform its mission, whereas commerce impacts related to economic market sectors that would be impacted by data loss. For example, data use by the Aviation Weather Center to develop products for commercial flight operations would be an example of a commerce impact, and a particular airline that integrates DCP or GRB data into day-to-day business operations would be considered a business impact.

Table 4.7-18 shows the overall impact to data loss at a given site based on user impact statements and the economic impact scores from Table 4.7-17.

User risk

The risk of RFI at the direct broadcast downlink sites is the product of the likelihood of data loss in Table 4.7-16 and the impact to data loss in Table 4.7-18. Those overall site risks are shown in Table 4.7-19. The impact of data loss scores is fixed, assuming that a user's mission does not change. However, the likelihood of data loss can be tailored to reduce the overall risk to an

Table 4.7-18. Overall impact scores for data loss at Project 7 sites.

Sites	Direct broadcast service use	Economic impact score (E)	User impacts	User impact score (I)	Impact to data loss ave. (E,I)
Suitland,MD	GRB	3	Life	3	3
Wallops Island,VA	GRB	3	Life	3	3
Anchorage, AK (Elmendorf)	GRB	3	Life	3	3
Honolulu, HI (Hickam)	GRB	3	Life	3	3
Suitland, MD	DRGS	3	Life	3	3
Wallops Island, VA	DRGS	3	Life	3	3
Rock Island, IL	DRGS	3	Life	3	3
Fairmont, WV	GRB	2.5	Life	3	2.75
St. Louis, MO	DRGS	2.5	Life	3	2.75
Boise, ID (BOR)	DRGS	2.5	Life	3	2.75
Boise, ID (NIFC)	DRGS	2.5	Life	3	2.75
Sioux Falls, SD	DRGS	2.5	Life	3	2.75
Cape Canaveral, FL	GRB	2	Life	3	2.5
Honolulu, HI (NOAA)	GRB	2	Life	3	2.5
Columbus Lake, MS	DRGS	2	Life	3	2.5
Sacramento, CA	DRGS	2	Life	3	2.5
Vicksburg, MS	DRGS	2.5	Property	2.2	2.35
Cincinnati, OH	DRGS	2	Property	2.2	2.1
Omaha, NE	GRB	3	Life	3	3
Omaha, NE (USACE)	DRGS	**	**	**	**
College Park, MD	GRB	3	Life	3	3
Anchorage, AK (NOAA)	GRB	1.5	Life	3	3
Norman, OK	GRB	3	Life	3	3
Monterey, CA	GRB	3	Life	3	3
Kansas City, MO	GRB	2.5	Life	3	2.75
Miami, FL	GRB	2.5	Life	3	2.75
Boulder, CO	GRB	2.5	Life	3	2.75
Huntsville, AL	GRB	2	Property	2.2	2.1
Houston, TX	GRB	1	Property	2.2	1.6
**Omaha, NE (USACE) was not covered in the analysis.					

Table 4.7-19. Risk to RFI at direct broadcast sites.

Sites	Direct broadcast service use	Likelihood of data loss (L)	Impact to data loss (I)	Overall user risk
Suitland, MD	GRB	3	3	9.0
Wallops Island, VA	GRB	3	3	9.0
Anchorage, AK (Elmendorf)	GRB	3	3	9.0
Honolulu, HI (Hickam)	GRB	3	3	9.0
Fairmont, WV	GRB	3	2.75	8.3
Cape Canaveral, FL	GRB	3	2.5	7.5
Honolulu, HI (NOAA)	GRB	3	2.5	7.5
Omaha, NE	GRB	2	3	6.0
Omaha, NE (USACE)	DRGS	**	**	**
College Park, MD	GRB	2	3	6.0
Anchorage, AK (NOAA)	GRB	2	3	6.0
Norman, OK	GRB	2	3	6.0
Monterey, CA	GRB	2	3	6.0
Kansas City, MO	GRB	2	2.75	5.5
Miami, FL	GRB	2	2.75	5.5
Boulder, CO	GRB	2	2.75	5.5
Huntsville, AL	GRB	2	2.1	4.2
Houston, TX	GRB	2	1.6	3.2
Suitland, MD	DRGS	1	3	3.0
Wallops Island, VA	DRGS	1	3	3.0
Rock Island, IL	DRGS	1	3	3.0
St. Louis, MO	DRGS	1	2.75	2.8
Boise, ID (BOR)	DRGS	1	2.75	2.8
Boise, ID (NIFC)	DRGS	1	2.75	2.8
Sioux Falls, SD	DRGS	1	2.75	2.8
Columbus Lake, MS	DRGS	1	2.5	2.5
Sacramento, CA	DRGS	1	2.5	2.5
Cincinnati, OH (USACE)	DRGS	***	***	***
Vicksburg, MS (USACE)	DRGS	***	***	***

**Omaha, NE, Cincinnati, OH, and Vicksburg, MS (USACE) sites were not evaluated in the analysis.
***Cincinnati, OH (USACE) and Vicksburg, MS (USACE). The risk to RFI at the direct broadcast downlink sites is the product of "likelihood of data loss" in Table 4.7-16 and 4.7-18, however, the Cincinnati and Vicksburg sites were not calculated to quantify the Risk to RFI.

acceptable level. This could be accomplished by increasing the RFI mitigation percentages (increasing the exclusion zone boundary, for instance) or implementing a backup data source for those sites that do not have redundant sources available.

4.7.4.7.4 Potential for correlated RFI

The exclusion zones covering the Mid-Atlantic region GOES sites have significant overlaps. The exclusion zone for Wallops Island intersects exclusion zones for College Park, Suitland, and Norfolk. It is possible that atmospheric conditions for these sites are highly correlated because of their close proximity to each other. This correlation in atmospheric conditions could lead to simultaneous increases in RFI levels at each site, which could lead to outage conditions that produce significant failure modes for GOES data distribution.

Investigations show that correlated outages at Wallops and Suitland would produce significant disruptions in DCS data distribution to a large number of users. Figure 4.7-30 shows how DCS data is turned into data products that are made available to users. DADDS data products depend on data generation at either WCDAS or NSOF. HRIT and NOAAPort users similarly depend on data flowing through those two sites. If DCS reception is interrupted at WCDAS and NSOF concurrently, then data will not be available for DADDS, HRIT, or NOAAPort users.

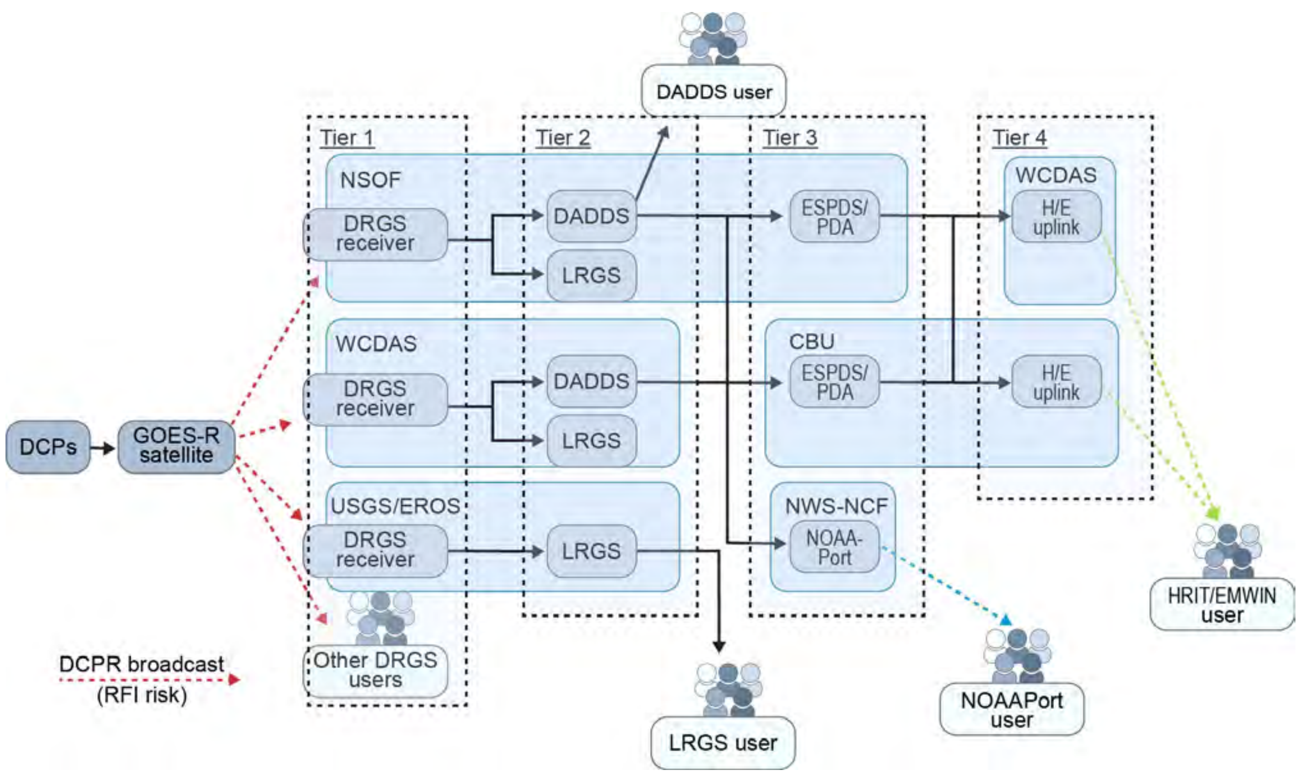


Figure 4.7-30. DCS data service dependencies.

Correlated RFI between NSOF and WCDAS occurs during anomalous propagation conditions. The measurements made from radiosonde locations in Dulles and Wallops Island, Virginia, were leveraged to identify the possibilities of such events. It was assumed that the atmospheric conditions at Suitland, Maryland, are represented by the radiosonde measurements at Dulles. All measurements were used to represent the refractive environment of these locations for 2018–2019.

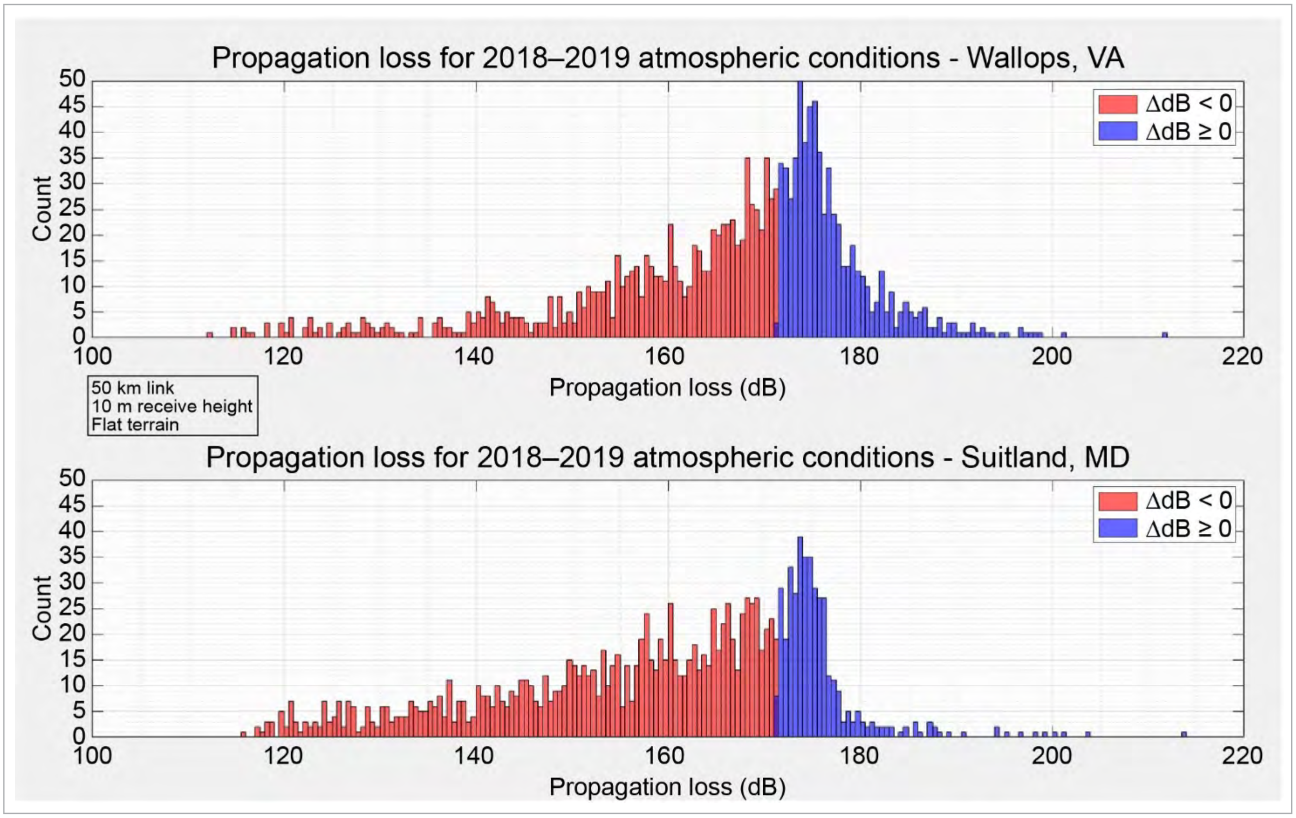


Figure 4.7-31. Histograms of propagation loss at Wallops Island and Suitland due to standard atmospheric and anomalous propagation conditions.

To model the propagation environments, all refractivity profiles were passed to the APM, and propagation loss statistics were obtained with respect to flat terrain. A standard atmospheric environment (linear refractivity profile) was assumed as the baseline case to allow for comparisons with all refractivity profiles produced. Therefore, differences in propagation loss between all refractivity profiles across a two-year period and a standard atmospheric case were used as the metric to identify correlated RFI events. Figure 4.7-31 displays two propagation loss histograms, with the colors representing the differences in dB across all refractivity profiles at Wallops Island (top plot) and Suitland (bottom plot). Differences less than 0 dB (red) are due to anomalous propagation events at each location, whereas differences greater than 0 dB (blue) represent standard atmospheric and anomalous propagation conditions when the GOES receiver is located within a skip zone. A skip zone is a region where radio transmission cannot be received because of tropospheric refraction.

It was determined that across the two-year period, given a duct at Wallops Island, the probability of a duct at Suitland is approximately 78%. In addition, given a duct at Suitland, the probability of a duct at Wallops Island is approximately 61%. Furthermore, conditional probabilities can also be used to represent the likelihood of propagation loss reductions across the two sites. The following represents the probability that the propagation loss reduction at Suitland is greater than 0, 10, 20, 30, and 40 dB given the propagation loss reduction at Wallops is 10, 20, 30, and 40 dB:

1. The probability that the propagation loss reduction at Suitland is greater than 0 dB given that the Wallops Island propagation loss reduction is:
    a. Greater than 10 dB = 31.96%
    b. Greater than 20 dB = 18.97%
    c. Greater than 30 dB = 10.82%
    d. Greater than 40 dB = 4.92%

2. The probability that the propagation loss reduction at Suitland is greater than 10 dB given that the Wallops Island propagation loss reduction is:
    a. Greater than 10 dB = 16.58%
    b. Greater than 20 dB = 10.68%
    c. Greater than 30 dB = 6.46%
    d. Greater than 40 dB = 3.95%

3. The probability that the propagation loss reduction at Suitland is greater than 20 dB given that the Wallops Island propagation loss reduction is:
    a. Greater than 10 dB = 7.38%
    b. Greater than 20 dB = 5.13%
    c. Greater than 30 dB = 3.30%
    d. Greater than 40 dB = 1.69%

4. The probability that the propagation loss reduction at Suitland is greater than 30 dB given that the Wallops Island propagation loss reduction is:
    a. Greater than 10 dB = 4.36%
    b. Greater than 20 dB = 3.09%
    c. Greater than 30 dB = 2.25%
    d. Greater than 40 dB = 1.26%

5. The probability that the propagation loss reduction at Suitland is greater than 40 dB given that the Wallops Island propagation loss reduction is:
    a. Greater than 10 dB = 2.67%
    b. Greater than 20 dB = 2.04%
    c. Greater than 30 dB = 1.48%
    d. Greater than 40 dB = 0.91%

The two years of radiosonde data indicate a large number of correlated RFI events between WCDAS and NSOF. This greatly impacts the DADDS data products, which rely on data generation from these two locations. Given the correlated RFI events due to LTE downlink deployments in the 1675–1680 MHz band, outage conditions that ultimately interrupt the distribution of GOES data are likely.

4.7.5 Potential RFI mitigations and protection methods

4.7.5.1 Dynamic exclusion zones

The study analyzed the potential use of dynamic protection criteria for maximizing spectrum sharing. Conceptually, dynamic protections would adapt the size (and possibly shape) of an exclusion zone based on the propagation conditions. Dynamic protections would provide for consistent protections of a GOES receiver (i.e., maintain a constant interference threshold) while allowing LTE carriers to adapt their operations to dynamic propagation conditions and maximize their geographic area and populations served, subject to maintaining compliance with the threshold.

Without a dynamic exclusion zone, downlink spectrum sharing in the 1675–1680 MHz band must choose between sufficient protections of GOES downlink operations and attaining high spectrum reuse. The exclusion zone analysis indicates significant RFI, geographic, and population coverage variations due to ducting at many locations, especially those along the Atlantic and Gulf coasts. If low interference risk is the primary goal, then protection criteria would be set at high confidence levels (i.e., ≥95th percentile). While this affords interference protection, it results in inefficient spectrum sharing under less severe conditions. For example, if static exclusion zones are set at the

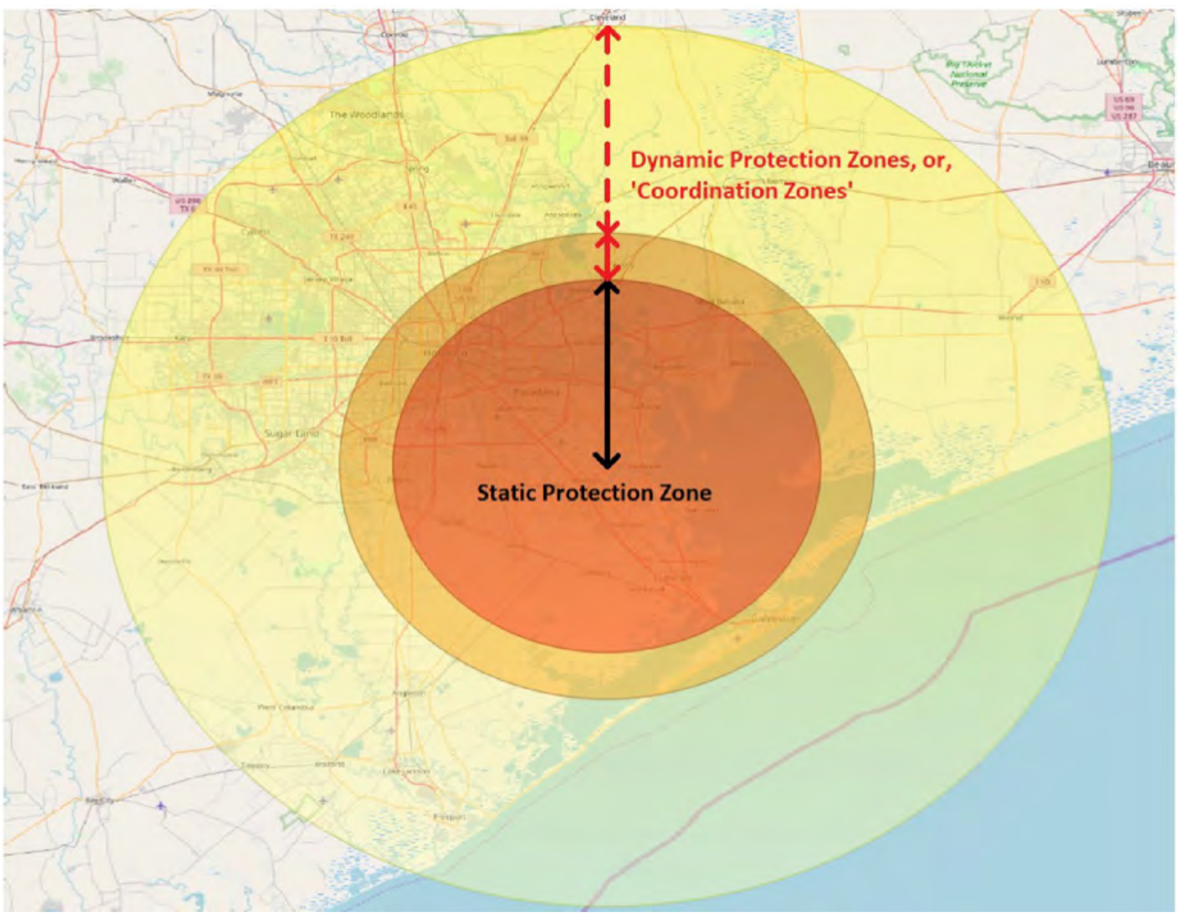


Figure 4.7-32. Example of dynamic and static coordination zones.

95th percentile, they will be overly conservative 94% of the time. If, however, the desire is for high spectrum reuse, then protection criteria would be set at a lower level. For example, setting the static exclusion zones at the 75th percentile provides significant reuse but results in interference to GOES systems 25% of the time. Neither of these outcomes is acceptable.

With a dynamic exclusion zone, a static zone could theoretically be established at the lower percentile under nominal operating conditions. When anomalous propagation conditions arise, the RF systems would adapt their operations to maintain RFI levels below the established threshold. Figure 4.7-32 illustrates the concept.

While conceptually attractive, a practical implementation of dynamic protections is not feasible for the 1675–1680 MHz band when sharing with downlink LTE, for the following reasons:

- GOES systems do not have the ability to adapt their downlinks. DCP and GRB data is broadcast to all users, so adapting the downlink to overcome RFI for one particular user is not possible without replacing the current satellites and ground systems with a totally different architecture.
- LTE systems may have the ability to adapt, but this requires complex mechanisms.
    - For downlink sharing, an LTE operator could reduce transmit power and/or increase antenna downtilt, but this reduces service to users, who would need to be offloaded to another band. Thus the operator in the 1675–1680 MHz band would need to maintain operations in other bands to absorb affected users.
    - Further, the LTE carriers need mechanisms for identifying which towers are causing interference and adapting their operations within a large region to maintain compliance with the interference threshold. As described in Project 10, evaluating causes, identifying mitigations, and verifying their effectiveness requires a complex measurement and mitigation system that is impractical.
    - Even if a system could be built, the time required from detection to mitigation is likely to be on the order of hours. Given that propagation conditions are dynamic, solutions based on observations would be hours old and not likely to be appropriate for current conditions.

It is highly unlikely that a dynamic sharing scheme would even be acceptable to the LTE operators, given their desire to provide reliable service to their users.

4.7.5.2 LTE resource block adjustment and MSAM

This project analyzed the removal of the upper resource block of an LTE signal operating adjacently and co-channel to NOAA's GOES satellite downlink DCS receive signals/channels. Removing this resource block may eliminate or reduce co-channel and possibly adjacent-channel interference. The intermodulation noise caused by high-gain amplification, 5 MHz and 10 MHz LTE interfering signals, DCS traffic, and pilot channels was examined. Further discussions are covered in Section 3.3.9.

In addition, an FDR analysis was completed using the microcomputer spectrum analysis models (MSAM) tool developed by the NTIA. This analysis does not consider narrowband internet of things or 5G technologies.

The NTIA MSAM FDR calculator computes FDR as the sum of the on-tune rejection (OTR) and off-frequency rejection (OFR). Key inputs are receive and transmit extrapolation slopes, receiver selectivity points, emission mask samples, and the transmit −3 dB bandwidth.

4.7.5.2.1 DCS receiver specifications and selectivity

Microcom is the primary DCS receiver manufacturer. The company's receivers have two receive paths, one for traffic channels and the other for pilots. Detailed receiver information was not available for traffic channels, and a theoretical selectivity curve was created. However, characteristics from a measured passband filter were used to create a pilot selectivity curve.

When the DCS receiver was designed, interference below DCS frequencies was not a concern and a ±1.25 MHz/40 dB passband filter was used after various stages of down conversion. DCS traffic was placed in the upper section of the 2.5 MHz passband filter, where it filtered out the lower edge of GRB signal at 1681.15 MHz with an upper frequency tuned to around 1681.1 MHz and lower edge around 1678.6 MHz.

For a single 300 bps DCS traffic channel operating at the lowest DCS frequency, 1679.701 MHz, a selectivity curve was created through MATLAB based on GOES DCPRS Certification Standard Version 2.0. The pilot's selectivity curve was based on measured passband filter characteristics.

In GOES DCPRS Certification Standard Version 2.0, the receive filter is defined as a 427 tap finite impulse response, square root raised cosine filter, a roll-off factor of 1.0, and an oversampling rate of 53.3333 samples/symbol. A magnitude response was generated where a normalized frequency of 1.0 corresponded to 8 kHz. In Figure 4.7-33, a normalized frequency of 0.038 and −20 dB was converted to a selectivity point of 304 Hz (0.038 x 8 kHz) and a power level of 37 (17–[–20]) dB.

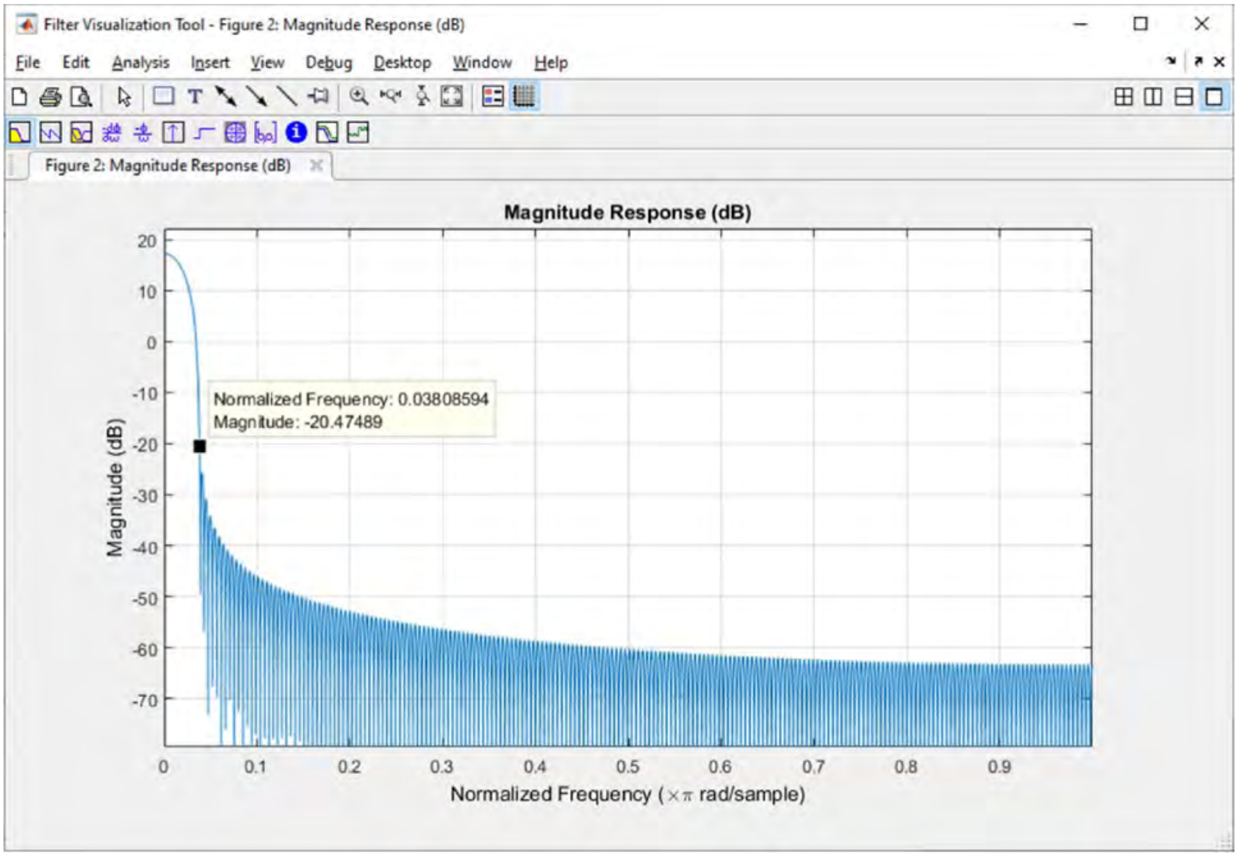


Figure 4.7-33. Magnitude response of a DAMS-NT receiver filter with a normalized frequency of 8 kHz samples per second.

Table 4.7-20 represents the selectivity curve points for a traffic channel. Following 60 dB, the curve was determined by a 20 dB extrapolation slope of the MSAM tool.

Table 4.7-20. Selectivity curve based on DCPRS CS2.

Delta frequencies (kHz)	Selectivity
±0.8	62
±0.3	37
±0.15	3
0	0

The receiver downconverts DCS signals to 5 MHz band and is filtered through a passband filter. Figure 4.7-34 shows a screenshot of the 5 MHz passband filter that was used to generate a pilot selectivity curve for the pilots.

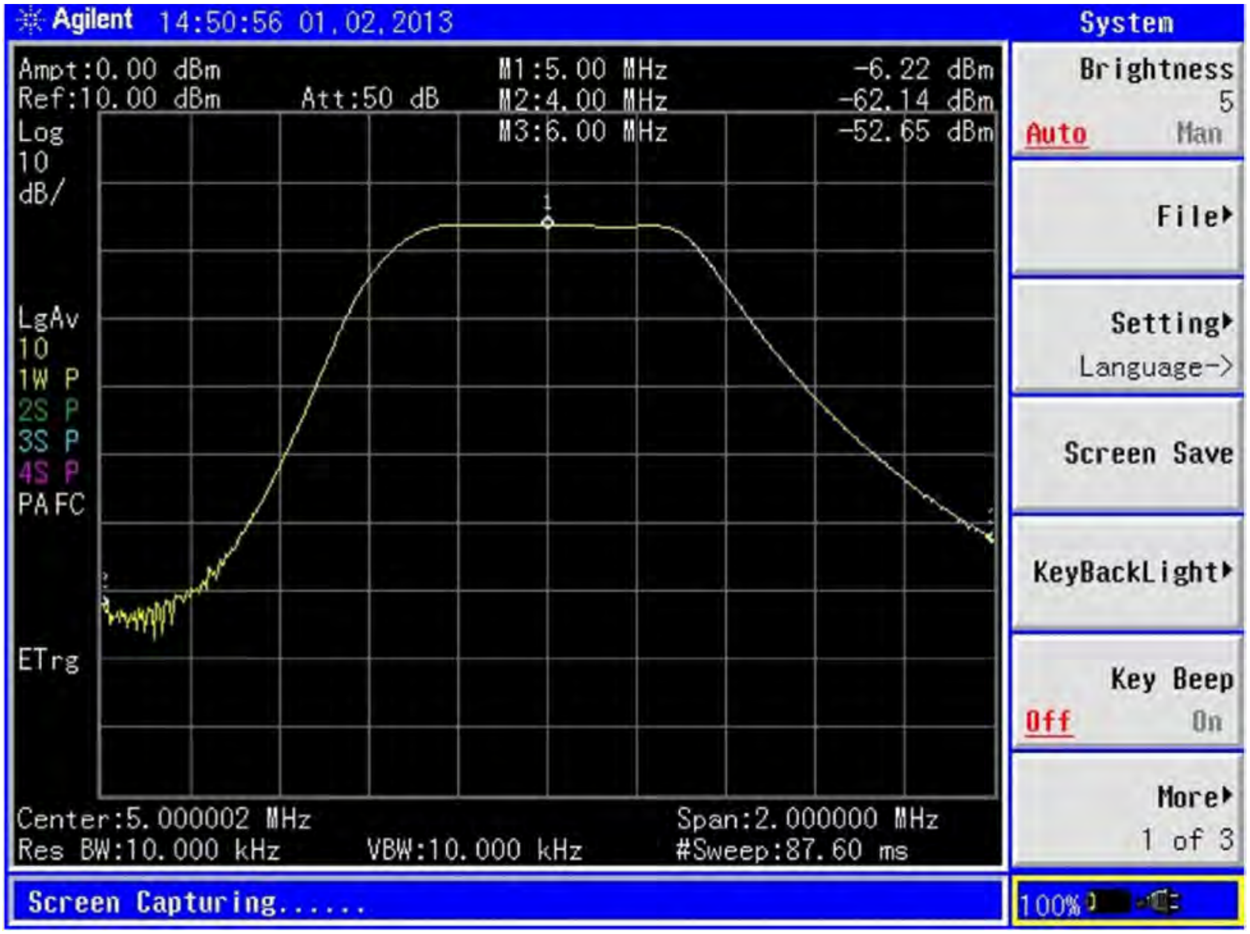


Figure 4.7-34. Passband characteristics as displayed through a spectrum analyzer.

Table 4.7-21 lists the selectivity points used to represent the pilot selectivity based on Figure 4.7-34.

Table 4.7-21. Pilot selectivity sample points based on a passband filter.

Delta frequencies (kHz)	Selectivity
−780	60
−350	3
0	0
330	3
900	50

4.7.5.2.2 LTE transmission specifications and emission points

Analysis of 5 MHz and 10 MHz LTE signals at high power (2000 W) and low power (40 W) levels was completed. FCC, 3GPP, and ITU-R have not defined a maximum power level for the 1675–1680 MHz band. However, FCC regulations for 1670–1675 MHz, 47 CFR §27.50(f), defined the maximum power as 2000 W EIRP. For unwanted emissions, FCC regulation 47 CFR §27.53(k) for 1670–1675 MHz, emissions outside the licensee's frequency band is attenuated below transmitter power (P) by at least 43 + 10log(P) dB, and this corresponds with 3GPP[24] limits of a base station maximum spurious emission as −13 dBm/MHz.

As an example, consider a 5 MHz LTE signal with a 3 dB bandwidth of 4.5 MHz. Figure 4.7-35 shows the emission mask with the 3 dB points at ±2250 kHz and a channel bandwidth of ±2500 kHz. If the LTE signal has an EIRP of 2000 W (63 dBm), and an average power of 56.5 dBm/MHz, the emission mask attenuation factor is 69.5 dB (56.5 dBm/MHz – [−13 dBm/MHz]). In the 1675–1680 MHz band, the 5 MHz LTE signal center frequency and 3 dB points correspond to 1677.5 MHz, 1675.25 MHz, and 1679.75 MHz, respectively.

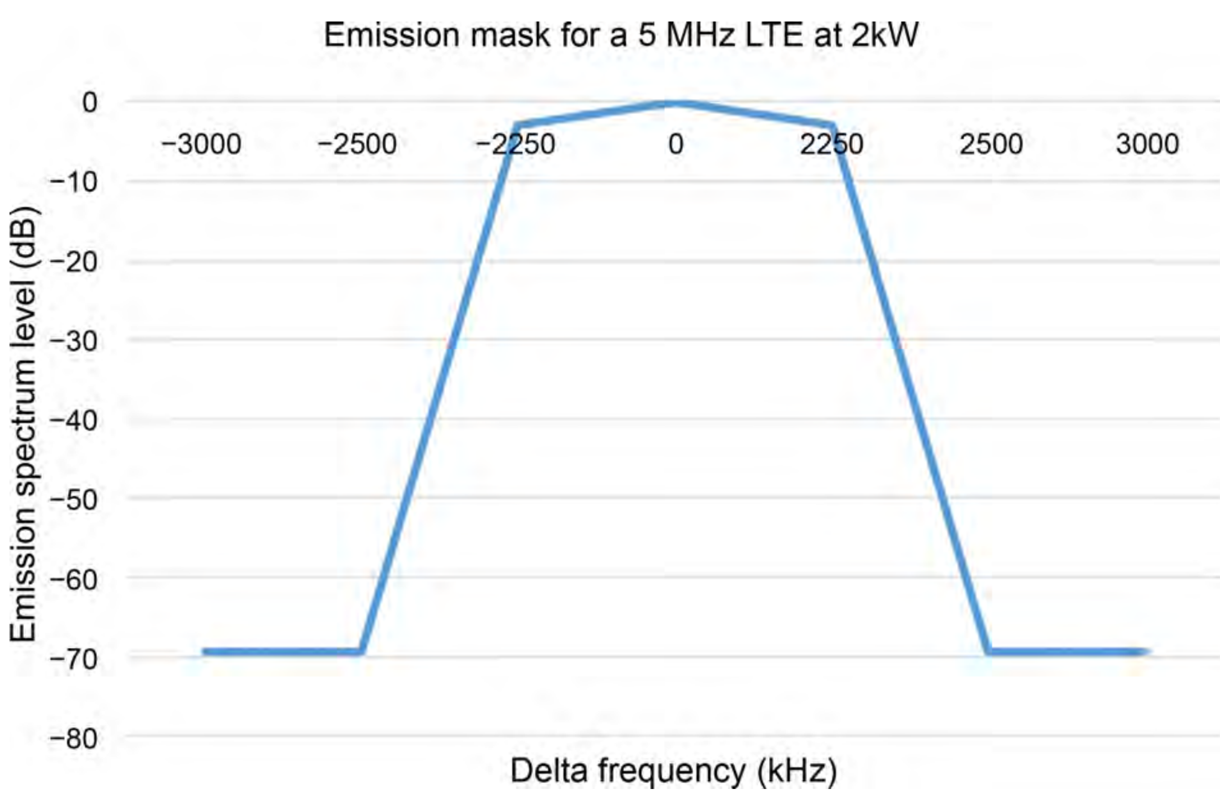


Figure 4.7-35. Emission mask for a 5 MHz LTE signal with 3 dB points at ±2250 kHz.

[24]European Telecommunications Standards Institute, "Evolved Universal Terrestrial Radio Access (E-UTRA): Base Station (BS) Radio Transmission and Reception," 3GPP TS 36.104, version 16.04.0 (Sophia Antipolis, France, 2019), table 6.6.4.1.1.1-1 ("BS Spurious emission limits, Category A").

Reducing overlap with GOES-R DCS

The 5 MHz LTE signal described overlaps the DCS channel by 50 kHz (1679.70–1679.75 MHz), creating RFI risk. One method to reduce the signal overlap is through removal of an LTE resource block (RB). LTE resource blocks are 180 kHz each. Reducing the LTE upper 3 dB frequency by 180 kHz results in a new upper 3 dB frequency of 1679.570 MHz and a new center frequency of 1677.41 MHz. This provides separation between the LTE signal and the DCS signal (lower edge) of 130 kHz (1679.70 MHz–1679.570 MHz).

4.7.5.3 Field strength limits and monitoring

4.7.5.3.1 Field strength benefits

Field strength RFI protection criteria can potentially simplify GOES earth station protection compared to alternative methods (see Table 4.7-22):

- Geographic exclusion or exclusion zones and limits on maximum transmitted power do not capture specific propagation, and they are derived from modeling. This approach requires “reasonable engineering assumptions” and represents a best estimate of expected interference prevention conditions. The complexity and uncertainties associated with sharing the 1675–1680 MHz band do not allow for well-defined exclusion zones. While sensitivity analyses indicate that results are somewhat tolerant of variations in LTE tower locations and depend primarily on a combination of emitter density, their proximity to the GOES station, and terrain, significant deviations from the implementations studied here could produce sufficient differences in RFI outcomes.

Table 4.7-22. Alternate RFI protection criteria considerations.

RFI definition	Performance	Implications to future LTE changes	Enforcement
LTE locations/ exclusion zones and power limits	Difficult to accurately predict LTE locations because of factors such as GOES antenna patterns and clutter; limited by model accuracy to achieve low RFI probability. Significant risk to GOES if models are not accurate.	Limited flexibility for LTE operator changes for new technologies. Possible limitations for GOES evolution.	Easy to enforce (LTE locations and transmitter characteristics).
Measured interference	Difficult to accurately predict RFI because of factors such as GOES antenna patterns and clutter; limited by model accuracy to achieve low RFI probability.	Maximizes LTE build-out options and technology evolution. GOES evolution limited by legacy system.	Difficult to enforce; need to separate RFI from desired signals; need access to receiver IF and/or receiver BER metrics.
Field strength	Moderate ability to predict RFI at monitoring antenna (e.g., clutter-loss uncertainties). LTE operator incurs risk if predicted RFI underestimates measured results; would need to adjust deployment plan.	Maximizes LTE build-out options and technology evolution. GOES evolution limited to field-strength threshold.	Easy to enforce (RF power measurement at a specified location).

- Interference thresholds that specify maximum RF energy into a system's IF are difficult to predict for GOES receivers because this requires complex antenna patterns associated with directional antennas, local terrain, etc.
- Field strength rules enforce a total power density at the antenna location. They define maximum acceptable power regardless of LTE deployment and transmitted power. Field strength rules may provide greater flexibility for evolution of GOES system and LTE deployment. The main benefit of field strength limits is that they allow flexibility in LTE deployments while still providing required protection to GOES systems.

Using a combination of multiple RFI protection criteria would have advantages, depending on the location of the LTE towers. If the LTE tower is far from the NOAA site, then a conservative geographic exclusion/exclusion zone is the easiest to use. If the LTE tower is close to the NOAA site, then a field strength limit provides the carrier the maximum flexibility to use the spectrum. Thus, field strength limits along with protection/coordination zones serve as good mechanisms for band sharing.

4.7.5.3.2 Field strength protection approach

4.7.5.3.2.1 Interference mechanisms

The field strength protection approach needs to protect against co-channel and adjacent-channel interference mechanisms (Figure 4.7-36). The approach must also include both linear and non-linear interference mechanisms. The approaches need to account for the monitoring receiver and the NOAA receiver having different selectivity and overload properties.

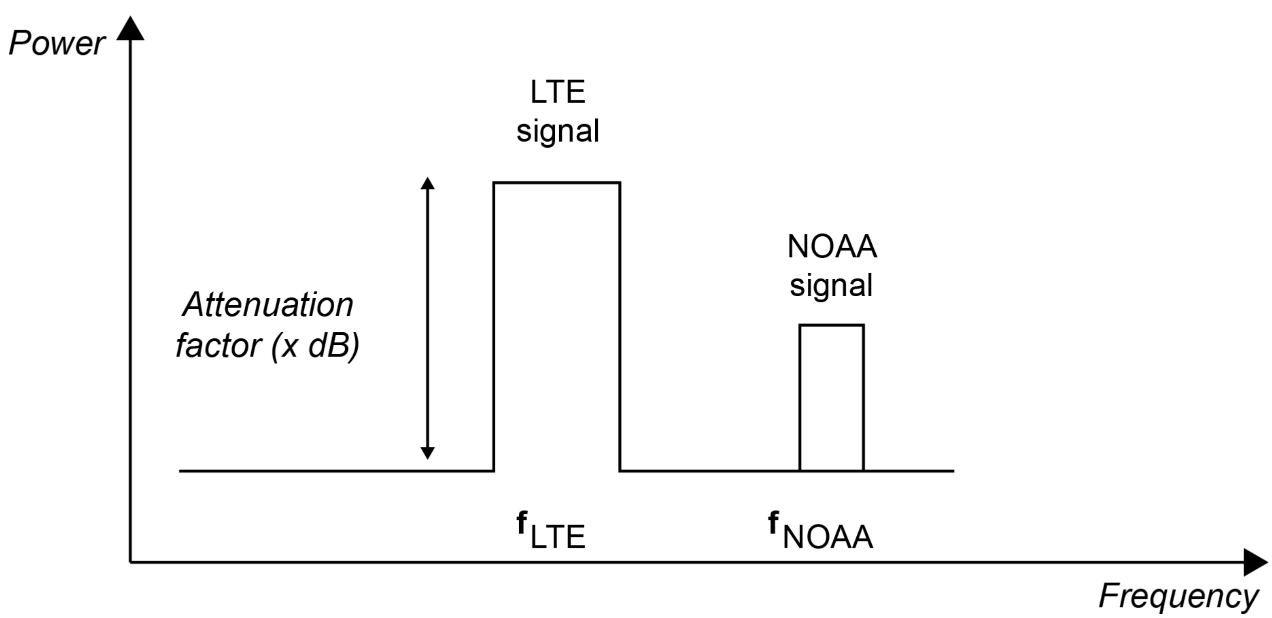


Figure 4.7-36. The field strength protection criteria need to account for co-channel and adjacent-channel interference mechanisms.

The interference to the NOAA signal is:

$$I = Pt + Gt + Lp(d) + Gr + FDR(\Delta f)$$

where

I = Interfering signal level at the victim receiver (dBm)

Pt = Power of the interfering transmitter (dBm)

Gt = Antenna gain of interfering transmitter in direction of victim receiver (dBi)

Lp(d) = Path loss between interfering transmitter and victim receiver (dB)

Gr = Antenna gain of victim receiver antenna in direction of interfering transmitter (dBi)

FDR(Δf) = Frequency-dependent rejection of the interfering signal by the victim receiver (dB). The FDR term includes non-linear effects, signal bandwidth effects, transmit mask effects, and receiver selectivity effects.

The interference is likely the sum of many LTE transmitters added together. The above equation accounts for this if the LTE-related parameters are assumed to be the sum value that represents the aggregate interference value. (See Appendix J, section J.3, for additional information.)

4.7.5.3.2.2 NOAA frequency measurement (I1)

The first field strength measurement made by the monitoring system is at the NOAA signal frequency. The monitor signal bandwidth is equal to the NOAA signal bandwidth. The monitoring system antenna gain is Gm (dBi). It is assumed that the spectrum monitor receiver selectivity and linearity are ideal. Hence, the intermodulation/overload power generated within the monitor receiver due to the LTE signal is negligible.

The predicted measured I1 power is determined by the LTE transmit mask power (down by X dB relative to the in-band LTE signal) at the NOAA signal frequency:

$$\text{Predicted value: } I1 = Pt - X + 10*\log10(BWNOAA/BWLTE) + Gt + Lp(d) + Gm$$

By using the above interference equation, the inferred interference with the NOAA receiver is:

$$\text{Inferred interference } I = I1 - Gm + Gr - 10*\log10(BWNOAA/BWLTE) + X + FDR(\Delta f)$$

If the NOAA receiver were ideal, the FDR value is equal to –X+10*log10(BWNOAA/BWLTE); hence, the I1 equation simplifies to:

$$\text{Ideal inferred interference } I = I1 - Gm + Gr$$

This simplified approach (which neglects overload and selectivity) could be used. However, it is likely that the NOAA receivers have overload issues; hence, the ideal inferred interference I is not used in the proposed approach.

4.7.5.3.2.3 LTE frequency measurement (I2)

The second field strength measurement made by the monitoring system is at the LTE signal frequency. The monitor signal bandwidth is equal to the LTE signal bandwidth. The monitoring system antenna gain is Gm. It is assumed that the spectrum monitor receiver selectivity and linearity are ideal. Hence, intermodulation/overload power generated within the monitor receiver due to the LTE signal is negligible.

The predicted measured I2 power is the LTE signal power:

$$\text{Predicted measured value: } I2 = Pt + Gt + Lp(d) + Gm$$

By using the above interference equation, the inferred interference with the NOAA receiver is:

$$\text{Inferred interference } I = I2 - Gm + Gr + FDR(\Delta f)$$

4.7.5.3.2.4 Examples

The following examples show how the dual measurement field strength protection approach meets these goals. In this approach, measurement 1 is at the NOAA signal frequency and checks for the LTE signal mask value. Measurement 2 is at the LTE signal frequency and checks for NOAA receiver overload (due to the LTE signal). If the LTE signal and NOAA signals were at the same frequency, then only a single measurement would be needed. The field strength approach must detect whether:

- The propagation loss to the LTE transmitter is less than expected.
- The LTE signal EIRP (power, gain, propagation) is higher than expected.
- The LTE transmission mask attenuation factor is less than expected.
- A combination of these conditions.

Example 1 has a low LTE Tx mask where the LTE mask is worse than anticipated and the LTE signal power is as anticipated. The transmitter mask mechanism would create higher interference than expected. The measurement at the NOAA signal frequency would detect this problem. The measurement at the LTE frequency would not detect this problem.

Example 2 has a high LTE Tx mask and high LTE Tx power. The LTE mask is better than anticipated and the LTE signal is higher than anticipated. The overload mechanism would create higher interference than expected in the NOAA receiver. The measurement at the NOAA signal frequency would not detect this problem. The measurement at the LTE frequency would detect this problem.

4.7.5.3.3 Field strength monitoring implementation

The following describes how the field strength measurements are performed (Figure 4.7-37). The monitoring antennas are at the same height above ground as the NOAA dish feed so that the NOAA system and monitor system see the same signals. Two monitoring systems are used to eliminate LTE signal shadows created by the NOAA dish antenna. The monitors are separated by more than 45° in azimuth from the dish. The field strength values are the largest of the two values measured by each monitor. The monitoring antennas are located 10–20 m from the dish feed so that the NOAA system and monitor system see the same signals. The monitoring antennas are located away from the buildings in the environment to minimize building shadowing effects.

The monitoring antenna type is a discone (~0 dBi) antenna. The goal is to have uniform azimuth coverage. Potentially, dual-polarization, stacked-dipole antennas similar to the RFIMS antennas (~10 dBi) could be used because they offer high gain along the horizon. These antennas are currently not commercially available.

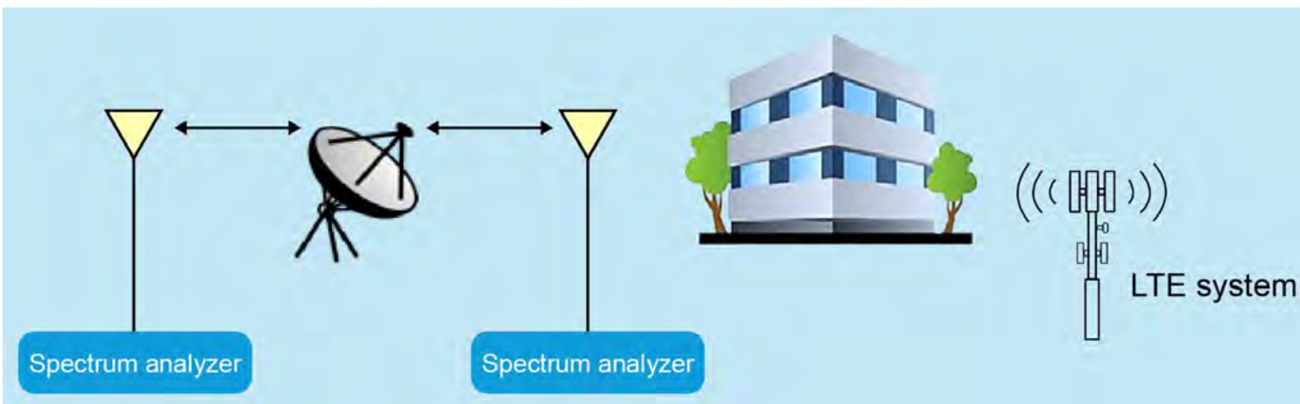


Figure 4.7-37. Two monitoring antennas are used to minimize the NOAA dish shadowing effects. The monitoring antennas are also located away from the buildings in the environment.

4.7.5.3.4 NOAA antenna gain model

A critical feature of the field strength protection criteria is the NOAA antenna gain pattern. The field strength protection approach makes the assumption that the NOAA antenna gain pattern is not a function of angle along the horizon, and/or that the interference comes from many angles (aggregate interference) and any NOAA antenna gain differences tend to average out. Hence, a specific NOAA antenna gain value needs to be determined.

The NOAA antenna pattern at the horizon directions is a complex function of angle that depends on the specific dish/feed type and the antenna pointing angles (elevation and azimuth). During the SPRES project, SSC developed a NOAA antenna sidelobe model that is based on measured 9.1 m antenna gain data provided by NOAA. The following figures show the NOAA antenna pattern versus azimuth for different antenna pointing angles. Also shown is the average gain, which is calculated in receiver power and not in dB. This average overall azimuth along the horizon represents the expected value to be used for aggregate interference calculations. Figure 4.7-38 shows the modeled NOAA antenna gain pattern versus angle for a pointing elevation of 30.07° and a pointing azimuth of 130.5°. There are significant changes in the gain versus angle, especially in the back angles (300° azimuth) where the dish creates a shadow. The average gain is −11 dBi.

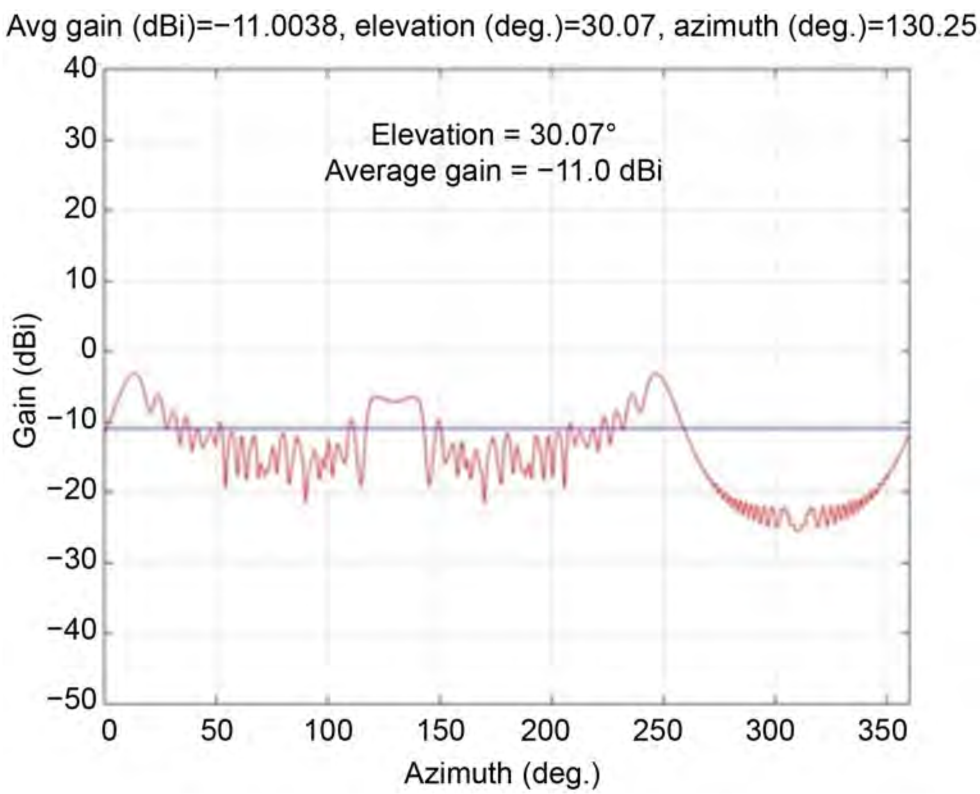


Figure 4.7-38. Modeled NOAA gain versus azimuth (30.07° elevation pointing angle) has a −11 dBi average gain value.

Figure 4.7-39 shows the modeled NOAA antenna gain pattern versus angle for a pointing elevation of 20.07° and a pointing azimuth of 30.25°. There are significant changes in the gain versus angle, especially in the back angles (210° azimuth) where the dish creates a shadow. The average gain is −9.7 dBi.

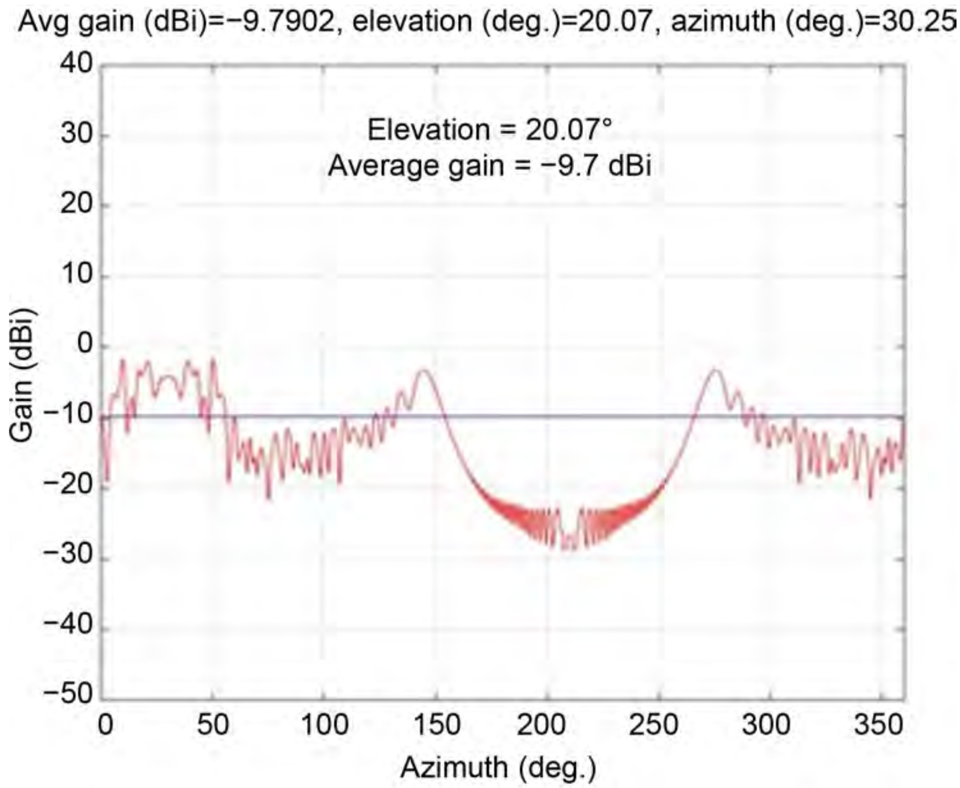


Figure 4.7-39. Modeled NOAA gain versus azimuth (20.07° elevation pointing angle) has a −9.7 dBi average gain value.

Figure 4.7-40 shows the modeled NOAA antenna gain pattern versus angle for a pointing elevation of 46.07° and a pointing azimuth of 179.25°. There are significant changes in the gain versus angle. The average gain is −10.8 dBi.

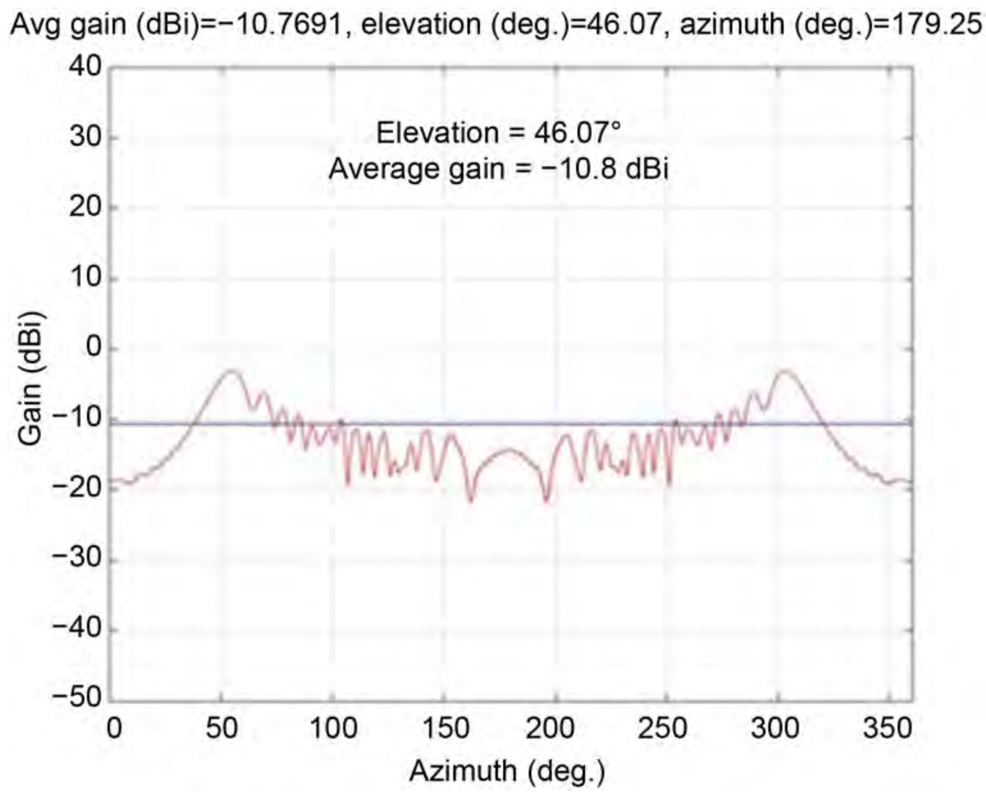


Figure 4.7-40. Modeled NOAA gain versus azimuth (26.07° elevation pointing angle) has a −10.8 dBi average gain value.

The average antenna gain in these three antenna pointing angles is nearly the same value. Hence, using a −10 dBi NOAA antenna gain value is a reasonable choice.

There is a risk that the population centers at some locations might be aligned with the NOAA antenna gain angles that are above −10 dBi. Thus, the final Gr values potentially need to be site-specific (if the population centers are likely to be located at high NOAA sidelobe azimuths).

4.7.5.3.5 Example field strength limits

Table 4.7-23 shows some example field strength limits for the NOAA DCS and GRB signals. The aggregate RFI threshold values are the same values used in the geographic exclusion zones. This is the net maximum power within the NOAA signal bandwidth (based on all interference mechanisms). The FDR values are examples. The specific FDR values need to be NOAA site/equipment specific. The NOAA antenna gain (Gr) is −10 dBi, as described above. The LTE transmit mask (X=50 dB) is based on the Ligado/Alion FCC fillings. The field strength limits consist of the two values:

- I1 measured with NOAA signal bandwidth at NOAA signal frequency
- I2 measured with LTE signal bandwidth at LTE signal frequency

Table 4.7-23. Example field strength value limits for DCS and GRB.

GOES service	I–Aggregate RFI threshold (dBm)	NOAA bandwidth (MHz)	LTE bandwidth (MHz)	FDR (dB)	Gr (dBi)	Gm (dBi)	X (LTE transmit mask) (dB)	I1–NOAA frequency limit (dBm)	I2–LTE frequency limit (dBm)
DCS	−128.2	0.4	5	−55*	−10	3	50	−127.1	−66.1
GRB	−113.8	11	5	−35*	−10	3	50	−119.3	−72.7
*Contingent upon each receive system.									

4.7.6 Study recommendations on spectrum sharing in the 1675–1680 MHz band

The following are recommendations for protection criteria and measures for the 1675–1680 MHz band.

4.7.6.1 Band sharing

Use of the band for LTE uplink operations is the only feasible means of band sharing. Downlink sharing (FDD or TDD) requires large protection areas for each Federal GOES ground station, which would exclude significant populations from LTE service in this band. For uplink operations, RFI risks are still present to the GOES receive stations but are greatly reduced. The reduction of exclusion zone sizes, even under anomalous propagation conditions, necessitates less of a restriction on LTE carriers. This conclusion is supported by models that calculated the maximum protection distances to be 61 km and 299 km for uplink and downlink operations, respectively, providing protection 95% of the time.

4.7.6.2 Protection criteria and mechanisms

Feasible protection and mitigation measures for band sharing must be static. While dynamic mitigations that adapt with anomalous propagation conditions are conceptually interesting, practical solutions do not exist. The GOES rebroadcast system cannot implement dynamic mitigations without a complete overhaul of the space and ground segments, which would not happen before GOES-NEXT replaces GOES-R (circa 2035). The commercial users may have the ability to adapt transmissions, but the large-scale reduction in service in the 1675–1680 MHz bands would require that millions of users be migrated to alternative services. It is unlikely that commercial carriers would be willing to accept such disruptions and take on the responsibility to carry them out in a suitable timeline. Further, developing, deploying, and maintaining a monitoring system that is able to accurately determine which commercial transmitters need to cease operation is infeasible. At best, all transmitters within a pre-defined protection area would be required to cease operations during heightened RFI conditions.

The use of field strength limits along with protection/coordination zones is recommended as a basic mechanism for band sharing. The complexity and uncertainties associated with sharing the 1675–1680 MHz band do not allow for well-defined exclusion zones. The analysis presented here required that some assumed LTE implementation be used as a basis of analysis. While sensitivity analyses indicate that results are somewhat tolerant of variations in LTE tower locations and depend primarily on a combination of emitter density, their proximity to the GOES station, and terrain, significant deviations from the implementations studied here could produce significant differences in RFI outcomes.

The combination of field strength limits and protection/coordination zones provides a process for pre-deployment assessments and an absolute metric for enforcement. The exclusion zones would require that the commercial user demonstrate that a proposed operation will not materially increase risks that aggregate RFI will exceed the defined field strength limit. This analysis should include all existing and approved emissions in the band, along with agreed-upon assumptions similar to those used in this study (e.g., transmit power levels, duty cycles, propagation models, etc.). A field strength provides an understandable and enforceable metric. The field strength predictions produced in pre-deployment analyses would eliminate the need to model GOES system details; those details are already inherent in the derived field strength limit. Further, enforcement via monitoring is simplified using a field strength measurement, as discussed in the next section.

4.7.6.3 Enforcement mechanisms

Enforcement should be accomplished via the pre-deployment analyses and with real-time monitoring of field strength levels. Field strength monitoring should be established at each Federal GOES ground station to record and characterize potential interference events. The monitoring system must be able to distinguish between interference from commercial users and interference from other sources (e.g., mechanical noise). This data is vital in determining the cause of the interference event. GOES users should also maintain logs of interference events, including their duration, immediate impact (i.e., data delay and loss), and ultimate impact (e.g., loss in mission performance).

Mitigation rules should also be included in the proceedings. Many GOES users rely on low latency and high reliability of satellite rebroadcast data to ensure their missions and operations provide accurate and timely reports. The impacts include economic losses, environmental damage, and loss of life. The mitigation rules should establish time limits on interference. These time limits should include the following metrics:

1. A maximum rate and duration of short-term interference events.

2. A maximum rate and duration of long-term interference events.

The duration and frequency of occurrence place compliance limits on commercial systems sharing the spectrum and necessitate that they establish the mechanisms for mitigating interference in a timely manner when it occurs.

4.7.6.4 Auction license areas

Licenses should be auctioned such that the number of licenses within a given exclusion zone is minimized. This is necessary to minimize discrepancies during pre-deployment analyses of the planned RF environment for each site. It will also minimize uncertainties regarding how much interference is being received from the different operators should an interference event occur.

Project 10 results concluded that limitations associated with identification and geolocation of interference sources is not feasible. Given that some exclusion or exclusion zone would permit interference only under strong anomalous propagation conditions, the prevailing type of interference to GOES would be an aggregation of many low-power LTE signals. The low signal power of any single emission relative to the overall aggregate interference power inhibits reliable decoding of the emitter identification information. Refraction from anomalous propagation conditions, along with the potential for interference from transmitters spread across a large area, makes geolocation of interfering signal sources similarly infeasible.

If a spectrum monitoring and enforcement system cannot attribute interference to specific LTE transmitters, then permitting multiple LTE carriers to operate within proximity to a given GOES ground station would increase the difficulty for planning and mitigation. Planning would need to ensure that all carriers' planned deployments and operations are evaluated prior to approving any added use of the spectrum within a protection/coordination zone. Since it is unlikely that a monitoring system could attribute interference to a specific set of emitters, the system would have difficulty determining how much interference is attributed to a given operator. Thus, minimizing the number of operators in the protection/coordination zone is important for reducing interference risk and enabling better mitigation when interference does occur.

Figure 4.7-41 shows the relationship between exclusion zones for WCDAS and cellular market areas (CMAs). The large exclusion zone associated with DCS protection against LTE downlink use for the small-cell scenario intersects 49 different CMAs for the polygon zone, and 84 for the circular zone.

Figure 4.7-41. Relationship between WCDAS exclusion zones and cellular market areas.

The smaller exclusion zone associated with LTE uplink use intersects two CMAs. Using the larger business enterprise areas (BEAs) for an auction, as shown in Figure 4.7-42, creates fewer licenses: 14 and 20 BEAs intersect the downlink polygon and circular exclusion zones, respectively, while a single BEA encompasses the uplink exclusion zone.

Figure 4.7-42. Relationship between WCDAS exclusion zones and business market areas.

4.8 Project 8: Anomalous Propagation Interference to Critical NOAA Sites

Project 8 looked at the impact of anomalous propagation (AP) of wireless broadband signals over long distances into Federal Met-Sat ground stations. AP reduces the propagation loss of over-the-horizon radio paths (in effect allowing terrestrial sources from a much further distance from the Met-Sat ground station to cause unacceptable levels of interference when such conditions occur), which would have significant impact to sharing conditions for the 1675–1680 MHz band. Past spectrum sharing studies largely ignored AP (ducting) effects because ducting occurs only a fraction of the time,[24] and because of the complexity of the ducting phenomena and the lack of information on ducting propagation loss statistics.

4.8.1 Study objectives

Because anomalous propagation is one of the least-studied phenomena that may play a role in the RFI Modalities and Risks topic area of the SPRES objectives, the AP study was initiated at the start of the program, leaving room for any additional work needed to better address the Mitigation Options and Feasibilities topic area later in the program. The study analyzed the potential impact of anomalous propagation on LTE downlink spectrum sharing with GOES ground stations in the 1675–1680 MHz band. Specific objectives were as follows: (1) determine the importance of anomalous propagation interference to GOES receive stations; (2) develop Federal GOES ground station/downlink protection requirements under anomalous propagation conditions; and (3) analyze methods to mitigate potential interference under anomalous propagation conditions.

4.8.2 Assumptions

The study focused on co-channel spectrum sharing and interference assessments in the 1675–1680 MHz band. For this study, LTE downlinks were assumed to operate in the 1675–1680 MHz band along with GOES satellite downlinks. LTE tower locations and characteristics were identical to those used in the Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 5 study. A 9.1 m representative GOES earth station antenna pattern was used and extrapolated for site-specific antenna sizing. A range of duct sizes and strengths were analyzed based on information derived from radiosonde data; duct sizes were assumed to extend the same distance in all directions.

4.8.3 Methodology

The project focused on predicting and modeling tropospheric ducting effects on radio frequency (RF) signal propagation, which is believed to be the dominant anomalous propagation phenomena. Ducting occurs when temperature and humidity profiles in the atmosphere have strong gradients, a situation that causes RF signals to refract at duct boundaries and become trapped rather than dissipate. As a result, signal energy levels remain stronger across longer distances than occurs under nominal propagation conditions.

[24]Often these AP events are brought about by meteorological conditions associated with temperature and humidity profiles. The times when AP occurs often are the times when obtaining weather satellite data is most critical.

From the 32 SPRES locations, 10 sites were selected for AP analysis. Ducting characteristics were derived for each of the 10 GOES ground stations using historical radiosonde data collected from nearby radiosonde launch locations. The radiosonde data was used to determine the index of refraction versus height at each location. The refractive index profiles were provided as input to the U.S. Navy Advanced Propagation Model (APM), which accounts for both ducting and terrain to predict signal propagation characteristics. APM is a hybrid ray-optic and parabolic equation (PE) model that uses the complementary strengths of both methods to construct an accurate composite model. RFI was characterized statistically to assess the risk of occurrence.

Three years of radiosonde data analyzed near 10 Federal sites (Wallops Island, Virginia; Norman, Oklahoma; San Diego, California; Houston, Texas; Miami, Florida; Boulder, Colorado; Monterey, California; Fairmont, West Virginia; Huntsville, Alabama; and Anchorage, Alaska) showed the ducting occurrence probability as high. Five of these sites (Wallops Island, Norman, Houston, Miami, and Huntsville) exceeded a 5% occurrence rate.

To determine what propagation loss values are relevant to the interference to a Federal GOES satellite ground station, a first-order calculation was made and is shown in Table 4.8-1. It is assumed that the LTE transmitter has a 25 W transmitter and a 15 dBi (800 W or 58 dBm EIRP) antenna. The GOES receiver antenna is assumed to have −10 dBi antenna gain toward the LTE transmitter, and noise temperature of 25 K (or 14 dB-K).(See Appendix J, section J.2, for additional information.)

As shown in Table 4.8-1, if the LTE transmitter to GOES antenna propagation loss is greater than 158.6 dB, then a single LTE transmitter will cause insignificant (−6 dB INR) interference. If the LTE

Table 4.8-1. Estimated propagation loss* needed to avoid interference from a single LTE transmitter (Tx) (158.6 dB) and from multiple LTE transmitters (198.6 dB).

Item	Interference from single LTE tower	Aggregate interference from many LTE towers
LTE Tx BW (MHz)	10.0	10.0
LTE Tx power (W)	25.0	25.0
LTE Tx power (dBm)	44.0	44.0
LTE Tx antenna gain (dBi)	15.0	15.0
Propagation loss (dB)	169.6	209.6
GOES Rx antenna element gain (dBi)	−10.0	−10.0
GOES signal bandwidth (MHz)	5.0	5.0
Frequency-dependent rejection (dB)	0.0	0.0
Aggregate factor (dB)	0.0	40.0
Interference power in GOES bandwidth (dBm)	−123.6	−123.6
GOES receiver noise figure (dB)	0.4	0.4
GOES noise floor (dBm)	−117.6	−117.6
I/N (dB)	−6.0	−6.0
Desired I/N (dB)	−6.0	−6.0

*Link budget is based on a 5 MHz LTE signal with no guard bands.

transmitter to GOES antenna propagation loss is greater than 198.6 dB, then a large number of LTE transmitters (10,000) will cause insignificant (−6 dB INR) interference to occur. These two propagation loss values (158.6 dB and 198.6 dB) provide reference values to evaluate the propagation condition's impact to the GOES ground station.

Figure 4.8-1 shows the propagation loss probability distributions (PDF and CDF) for the Wallops Flight Facility GOES ground station characterized at four different distances. There is a reduced mean and increased variance of the PDF and CDF functions due to the significant occurrence of ducting propagation events over the three-year period.

Figure 4.8-2 shows the propagation loss versus range for many different types of ducts. Elevated ducts have the highest amount of frequency variations, and low-altitude ducts are less susceptible to range and frequency-dependent effects.

At the Wallops Island site (Figure 4.8-3), the significant ducting conditions based on the radiosonde data (CDF 0%–1% and CDF 1%–5%) have higher interference levels compared to the non-ducting events (CDF 25%–50%). This is consistent with terrain not being critical in the Wallops Island area.

The allowable interference to the Federal ground station is −112.7 dBm assuming an interference-to-noise (I/N) goal of −6 dB. If a fixed exclusion size were used to compensate for AP, this calculation indicates it would need to be approximately 250 km in size to keep commercial LTE downlink interference below −112.7 dBm 95% of the time, and >500 km to eliminate all interference risk.

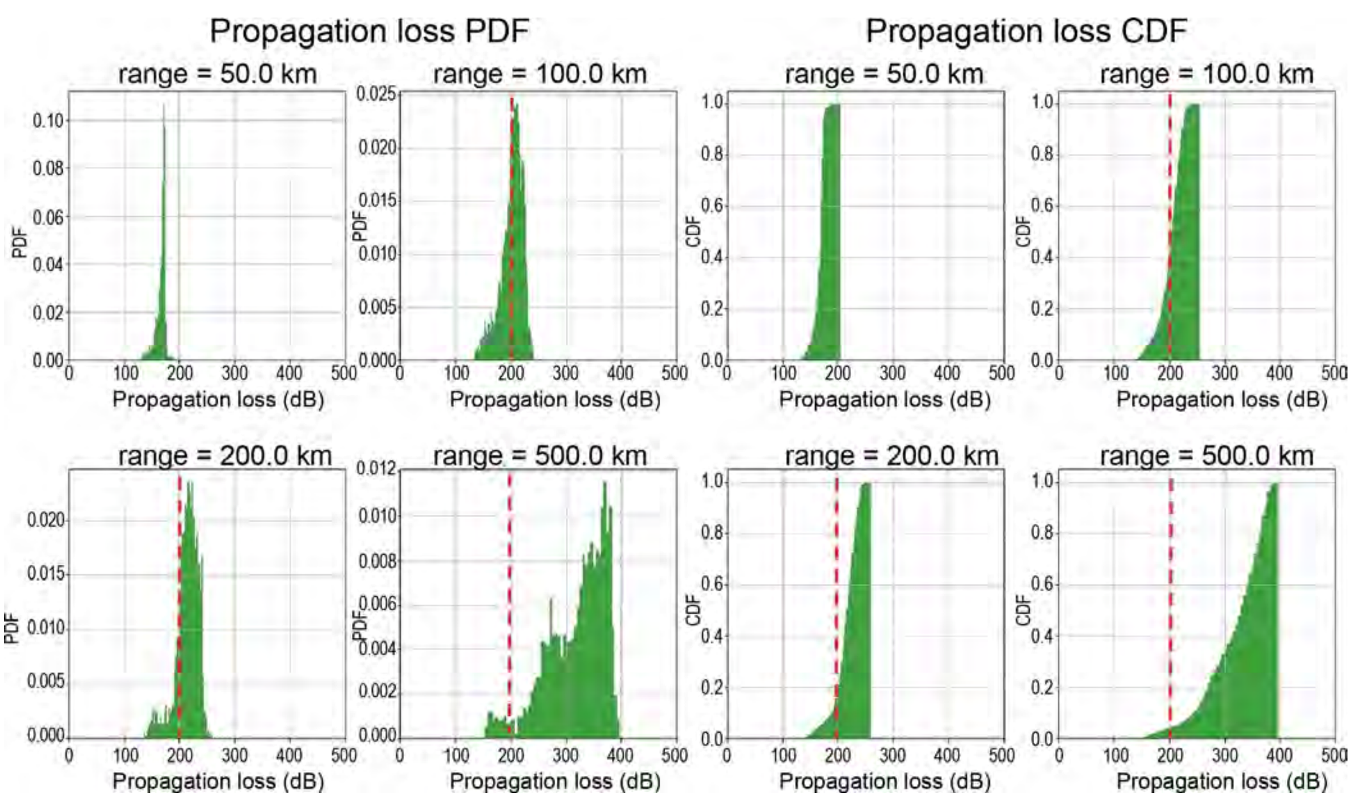


Figure 4.8-1. Propagation loss probability distributions (PDF and CDF) characterized at four different distances from the Wallops Island GOES ground station.

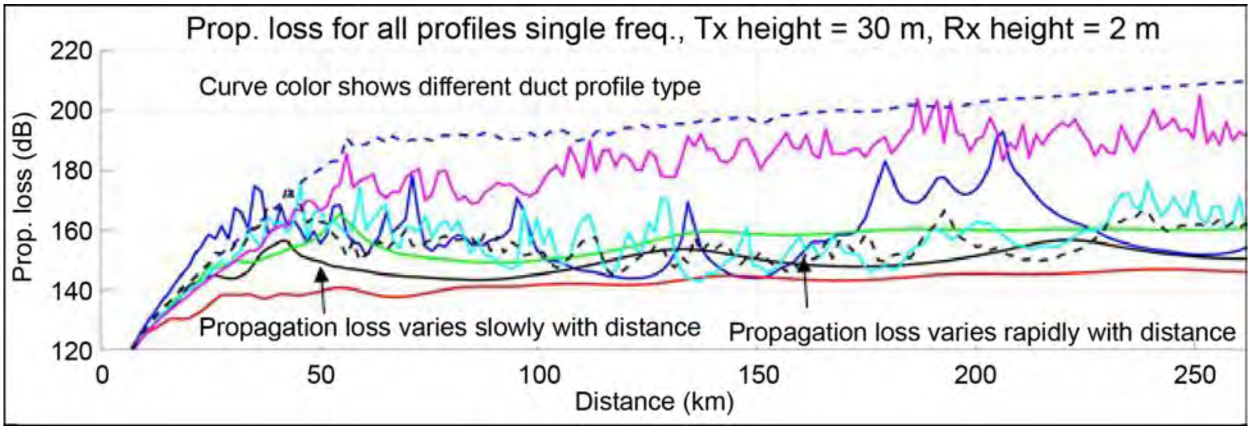


Figure 4.8-2. Propagation loss versus distance for different ducting profiles shows that some profiles have propagation loss that varies significantly with distance.

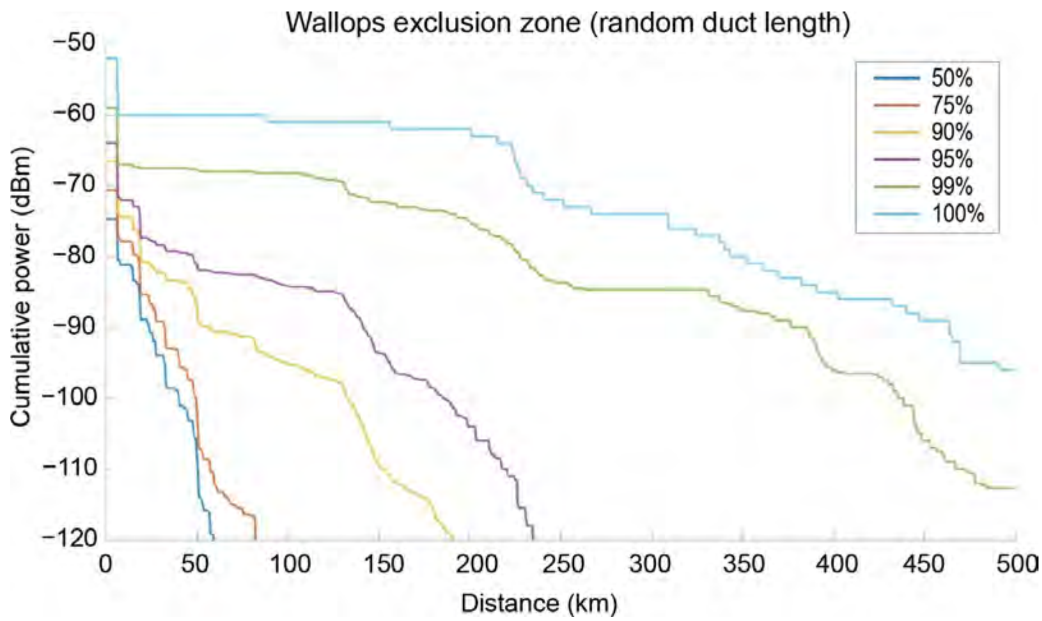


Figure 4.8-3. Received power at Wallops Island site versus exclusion distance, including Monte Carlo selection of duct profile, terrain effects, and large-scale duct size for different occurrence probabilities.

Mitigations

A variety of mitigation approaches were considered, as shown in Table 4.8-2. These approaches were identified by examining each parameter in the RFI analysis to determine how the parameter value could be reduced. The first two mitigation approaches improve the time spectrum-sharing capability by turning certain LTE users off during high ducting periods. Dynamic exclusion zones use circular or sectorial exclusion zones where all users in these regions are switched off. Specific contribution exclusion assumes that each user's RFI impact can be estimated and only the highest-RFI-impacting LTE users are turned off during high ducting periods. The remaining approaches (low-sidelobe ground station antenna, increasing ground station clutter, increasing ground station antenna gain, and reduced LTE transmit EIRP) are adjustments to the ground station or the LTE users to improve the spatial spectrum-sharing capability.

Table 4.8-2. Potential RFI mitigation approaches.

Interference mitigation approach	Interference mitigation approach description	Effectiveness
Low-sidelobe ground station antenna	Modify the ground station antenna to reduce its sidelobe levels.	High
Increased ground station clutter	Modify the ground station clutter (add walls and buildings) to block the interfering signal from entering the ground station antenna.	Low
Increased ground station antenna gain	Increase the ground station antenna's boresight gain.	Low
Reduced LTE transmit EIRP	Reduce the LTE transmitter power and/or antenna gain.	Low
Dynamic exclusion zones	Exclude LTE operation within a certain geographic region surrounding the ground station based on the current ducting conditions.	High
Specific contribution exclusion	Exclude LTE operation based on an RFI impact ranking based on the current ducting conditions.	Low

The impact of different RFI mitigation approaches can be estimated so that a cost-benefit analysis can be performed on each RFI mitigation approach. The primary RFI mitigation impact is to reduce the exclusion distance, which increases the number of LTE users the shared spectrum can support. As a baseline, the previous Wallops Island site RFI analysis—which includes a Monte Carlo selection of the duct profile, terrain effects, clutter propagation loss, and a probabilistic duct size (see Figures 4.8-3, and −4)—is considered.

Figure 4.8-4 shows the received power for six receiver power curves (at different occurrence probabilities) from the previous analysis with the impact of different RFI mitigation levels (10 dB, 20 dB, and 40 dB). The spatial spectrum-sharing mitigation approaches will tend to reduce the interference power linearly with the improvement amount. For example, if the ground station sidelobe levels were reduced by 10 dB, then the total received power would be reduced by

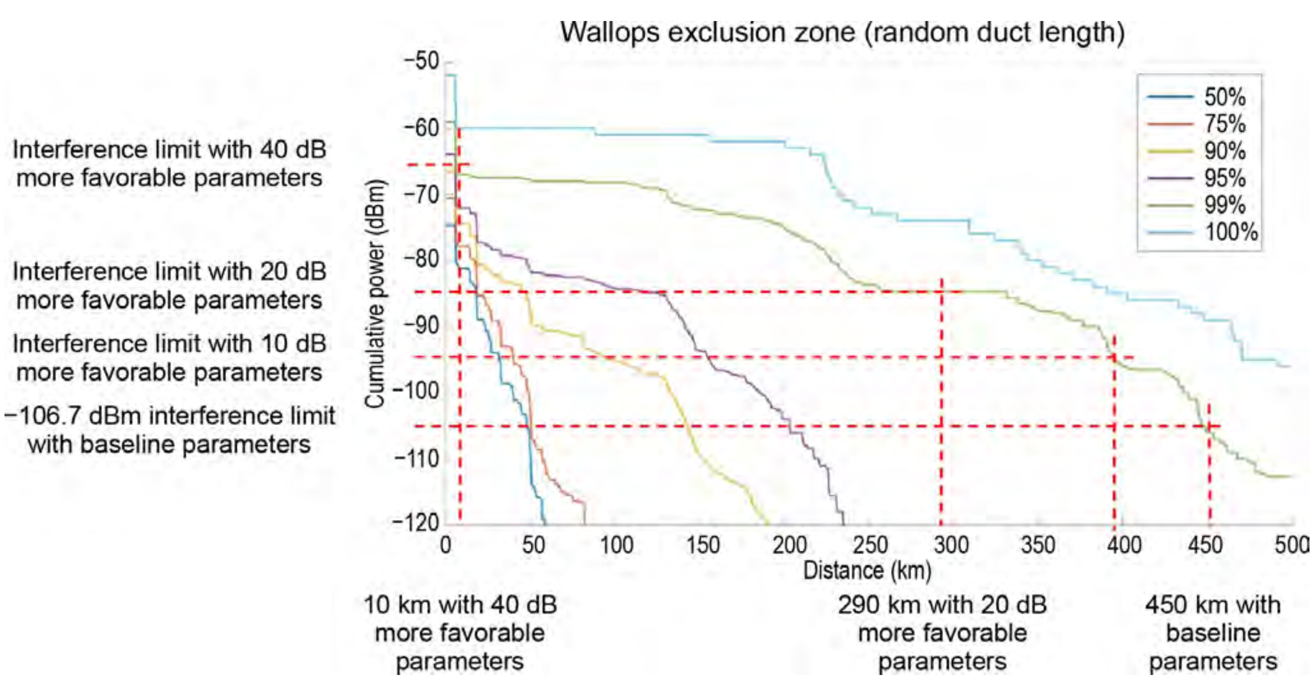


Figure 4.8-4. Received power at Wallops Island site versus exclusion distance for different occurrence probabilities with different levels of system RFI improvement.

10 dB. For convenience of analysis, it is assumed that the mitigation approach raises the interference threshold by the same amount as the receiver power reduction. Hence, a 20 dB reduction in the ground station antenna sidelobes would change the exclusion from 450 km to 290 km (at 99%). A 10 dB mitigation approach would have small practical value (changing the exclusion distance from 450 km to 390 km). A 40 dB mitigation approach would have a significant improvement (reducing the exclusion distance from 450 km to 10 km at 99%).

Low-sidelobe ground station antenna mitigation approach

A potential RFI mitigation approach is the low-sidelobe ground station antenna mitigation approach, in which the ground station antenna is modified to reduce its sidelobe levels, as indicated in Figure 4.8-5. To have significant impact, the antenna sidelobe gain needs to be reduced by 20–40 dB. The typical approaches include tapering the feed pattern that illuminates the reflectorand adding shrouds to the edge of the reflector. These methods alone are believed to provide only 10–20 dB of sidelobe reduction.

Active cancellation systems are also used to eliminate RFI from reflector antenna systems. One example is the radio astronomy community, which uses an active, digital cancellation RFI

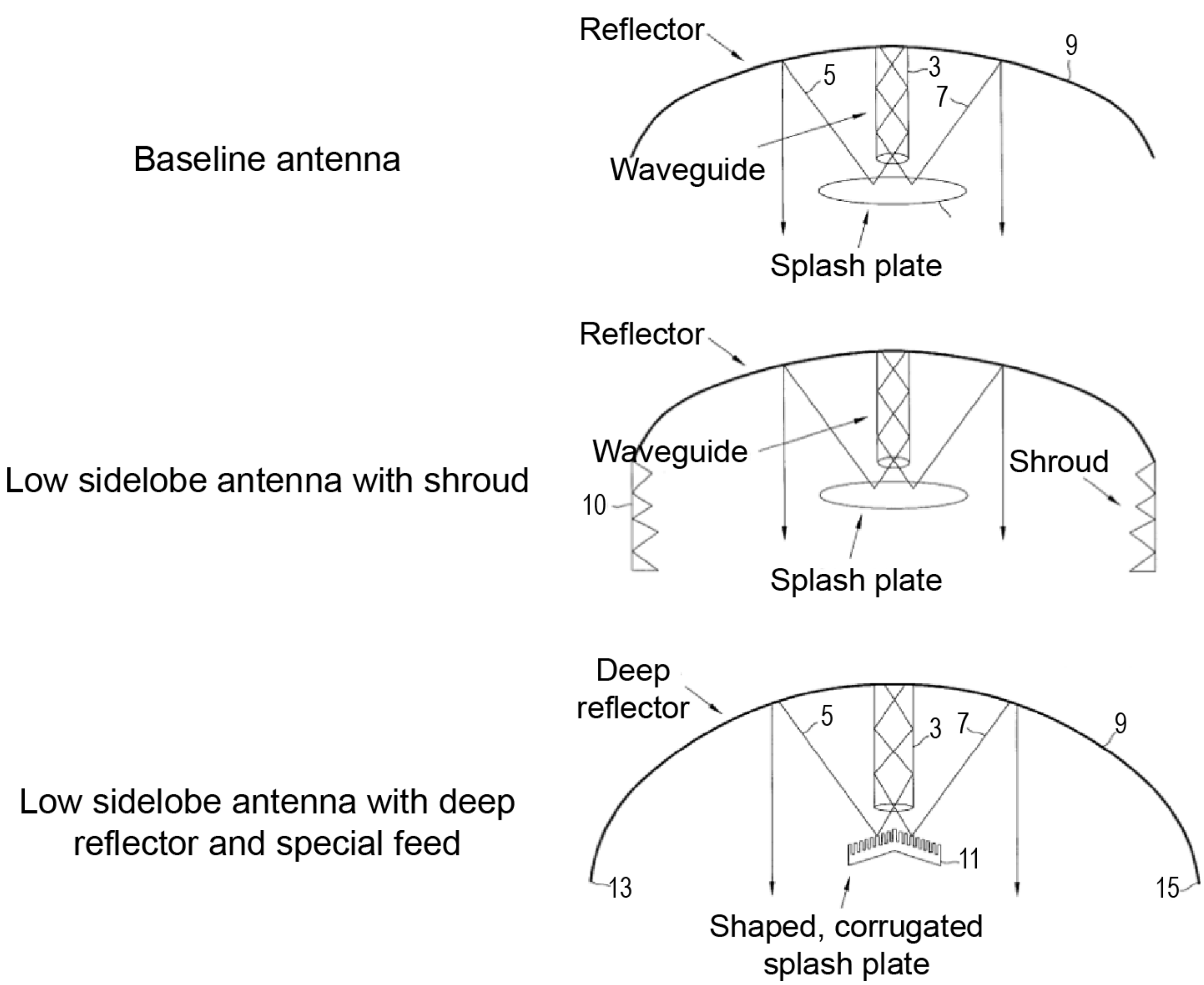


Figure 4.8-5. Typical low-sidelobe antenna approaches use shrouds, deep reflectors, and special feeds.

mitigation approach.[25] The solution used by the radio astronomers involves out-of-band-emisssions parsing the received signal through a large number of narrow digital filters, discarding outputs from those affected by interference, and coherently integrating the results. This approach is effective for integrating an envelope signal but would not be applicable to digital communications signals. A second, more applicable example is provided by a past NOAA project involving investigation of an active cancellation approach for an L-band spectrum-sharing application.[26] In this project, a contractor developed a simulation of a Satellite Downlink Interference Filtering and Monitoring System (SDIFMS). This simulated system mitigates interfering signals to NOAA satellite ground stations from wireless user transmitters (such as handheld smartphones and other devices), including eliminating aggregate LTE interference from multiple, simultaneous interferers. The interferers can be below the noise level.

In addition, the SDIFMS monitors and identifies the interference. Cyclostationary-based signal detection and classification algorithms support the identification of signals buried under the noise floor. The SDIFMS uses a circular array of monitoring antennas (surrounding the NOAA satellite downlink antenna) that continuously sense the interference signals. The sampled interference signals are digitally processed to coherently subtract them out of the desired NOAA satellite downlink signal. The number of monitor antennas (4–20) is scalable depending on the number of interfering signals.

The cyclostationary detector uses unique correlation peaks at different cyclic frequencies and can be used to discriminate between NOAA and LTE signals. Compared with other techniques such as energy detector and auto-correlation detector, detection and classification are known to have excellent theoretical performance, but implementation is extremely complex and challenging. Feasibility is therefore unknown and would require additional study.

4.8.4 Findings

Anomalous propagation

When ducting occurs, the commercial wireless broadband system to GOES ground station propagation loss at long distances is much lower (50 dB or more) because the loss function decreases slowly with range. The large reductions in propagation loss that occur with ducting could create significant increases in interference power at a GOES ground station as compared to nominal propagation conditions. The inclusion of large numbers of LTE towers within a ducting region can generate significant interference levels from base-station transmitters at long distances from the GOES ground station, requiring mitigation methods to be implemented across large geographic regions.

Overall Project 8 findings show that ducting can have a significant impact on RFI risks. In non-ducting conditions, exclusion zones of 50–100 km are sufficient. Strong ducting conditions,

[25]RFI 2016: Coexisting with Radio Frequency Interference, Socorro, NM, October 17–20, 2016, http://www.cvent.com/events/coexisting-with-radio-frequency-interference/event-summary-636cf7581cb6418fb0e80544527822d0.aspx.

[26]Shared Spectrum Company, "L-band Radio Frequency Interference Filtering Phase I SBIR Project," Project 2840, NOAA Contract No. WC-133R-16-CN-0065 (2016).

however, can lead to significant aggregate RFI risks (i.e., greater than 5% risk of interference) even with exclusion distances exceeding 500 km.[27] The risks were driven by duct spatial size, duct strength, LTE tower density, and terrain effects.

The ducting spatial size, expressed primarily in terms of geographic distance, is a dominant factor that affects the amount of interference to the ground stations. The ducting spatial size is based on large-scale weather patterns. Ducting spatial size is not well-characterized in scientific literature and was estimated in this project by using refractivity profile correlations among different radiosonde stations in a given region. Analyses of radiosonde data indicated strong ducts can extend well beyond 100 km (in one case, up to 1,000 km). When ducting conditions are included, exclusion zones up to hundreds of kilometers may be needed. Spectrum sharing would be impractical with the use of such large permanent exclusion zones to protect Federal GOES ground stations. Instead, sectored dynamic exclusion zones should be considered with a method to activate affected exclusion segments during ducting events.

Given the large exclusion distances that would be required to mitigate RFI risks, static spectrum sharing with downlinks based on exclusion zones appears not to be a feasible approach. Static exclusion zones required to reduce RFI risks to less than 5% will be large and encompass many heavily populated areas, significantly reducing the spectrum value to a wireless service licensee. Some form of adaptive sharing, such as a dynamic exclusion technique, is required.

Mitigations

A variety of mitigation approaches were considered; of these, the reduction of GOES earth station antenna sidelobes and the use of dynamic exclusion zones appeared promising.

The development of a combined passive (shrouds, deep reflectors, and special feeds) and active (low antenna sidelobe equivalency) cancellation approach is likely able to provide 40 dB of sidelobe level reduction, which would provide significant operational improvement.

The study investigated the ability to detect the onset of anomalous propagation and selectively mitigate RFI by signaling to carriers to deactivate towers, dynamically altering the exclusion zone. Anomalous propagation detection may be possible by monitoring for RF signal amplitude changes in the local region. A monitoring station could measure the transmissions from other users or signals from a dedicated set of beacons. Signal sources used for ducting detection would need to be geographically dispersed to avoid location-specific propagation nulls that can occur with ducting. Additionally, the monitor would need to know the position of signal source so that the geographic extent of the ducting-induced RFI can be determined. The study further showed that a dynamic mitigation system may benefit from dividing the surrounding region into sectors to determine the RFI contribution from each sector and then applying mitigation techniques to select sectors. This approach could enable some commercial utilization of the spectrum while achieving the required level of RFI mitigation but would also entail the loss of spectrum use for potentially hours at a time, multiple times per year, in sectors near some locations.

[27]Results are as reported for Project 8, and should be considered preliminary here. They were subsequently updated in Project 7.

4.8.5 Areas for further study

While determining the duct strength from radiosonde data is well known, determining duct size and variability with distance has not been well characterized in scientific studies. This study estimated duct size based on statistical correlations of adjacent radiosonde readings. While the approach provides a general approximation of duct sizes, higher-fidelity characterizations are warranted because the duct size and shape critically impact the interference levels. Measurements should be made of the ducting features using a network of ground-based beacons.

Similarly, the temporal characteristics of ducting are not well characterized in scientific literature. Current radiosonde data is collected twice daily, providing limited insight into the dynamic nature of ducts. The study conducted here looked at a snapshot in time for each duct based on the corresponding radiosonde readings; it did not investigate time-varying aspects of ducts. While the time dynamics are unlikely to affect the RFI risk assessments of the study, they would affect mitigation system requirements. The time required for a duct to form and dissipate would influence the response-time requirements of mitigation systems that employ anomalous propagation detection. Similarly, the rate and extent to which ducts (and propagation conditions) change and evolve throughout the ducting event would influence mitigation system requirements.

4.9 Project 9: Interference Thresholds for GOES-R Receivers

Introduction

A key challenge to the establishment of a sharing scheme has been examining how spectrum sharing between dissimilar technologies can be implemented without leading to an environment where RFI commonly occurs. Use of the 1675–1680 MHz band for terrestrial mobile broadband is inherently different from the existing use of this band for satellite downlinks for meteorological aids, because the proposed signals are thousands of times stronger than the existing satellite transmissions in this band. To address that challenge, Project 9 seeks to examine two types of RFI characteristics in order to determine the feasibility of using these characteristics to aid in sharing spectrum between Advanced Wireless Service (AWS) carriers and GOES satellite broadcast receivers. The first type of characteristics, AWS RFI thresholds, pertains to the GOES satellite broadcast receiver. RFI thresholds are the maximum RFI power above which GOES satellite broadcast receivers will suffer degraded or lost data. The second type of characteristic, carrier identification (CID)[28] information, is attributed to an offending AWS transmitter. CID is a signal which is embedded into a video or data that describes its origin.

Project 9 approaches this goal by analyzing the spectrum-sharing benefits of using AWS carrier identification and developing the bit error rate (BER) or frame error rate (FER) threshold above which Federal GOES-R satellite broadcast receivers will suffer degraded or lost data.

[28] For the purpose of this report, "carrier identification" uses the acronym CID. The use of "cell ID" is more specific to base stations, and is so noted in the report.

Study objective

Project 9 primarily supports the SPRES program objective area RFI Modalities and Risks, and begins to address some of the Mitigation Options and Feasibilities. The objectives of this project are (1) to develop the interference level thresholds above which Federal GOES-R satellite downlink receivers will suffer degraded or lost data, and (2) to assess whether the use of AWS CID provides benefits to spectrum sharing and what, if any, limitations are associated with such use.

Assumptions

The study used the following assumptions as a starting point, some of which were investigated for more conclusive evidence:

1. Project 9 sought to investigate the variations between ITU and measured thresholds and to detail the differences. This should lead to a better understanding of NOAA concerns and the spectrum use of the AWS carrier.

2. In examining past RFI incidents at WCDAS, the signature of the in-band signals assumed to be causing RFI closely matches that transmitted by Ligado Networks (5 MHz bandwidth, 1670–1675 MHz band, etc.). As a result of the RFI incidents, Ligado reduced its transmitted power levels to prevent future such events. As Ligado was not in revenue service, this did not impact its business.

3. In future potential incidents involving LTE carrier-induced RFI, when carriers are in revenue service, they would likely be less willing to shut down transmitters (or even to implement less restrictive actions) in response to a request from WCDAS or any other impacted ground station, because their customers would be directly impacted.

4. As a limitation to the future use of CID as part of a mitigation method, the LTE tower/transmitter density will be much higher than what was examined in the past RFI incidents with Ligado.

Methodology

RFI threshold measurements were conducted on receiver systems commonly used for the DRGS/DCPR, GRB, and HRIT/EMWIN GOES-R Series signals. It was not possible to test all fielded receivers, including software-defined radios (SDRs), which may be particularly susceptible, because of time and access limitations. The thresholds for DRGS/DCPR were measured by injecting RFI while the receive system received the DCPR signal at the minimum sensitivity level. DCPR has no typical operating level because of variations in channel power output from the satellite, which changes with channel loading. The thresholds for HRIT and GRB were measured by injecting RFI while the systems received their signals at typical operating levels, since these signals are stable and transmitted at a fixed power. BER was recorded during RFI threshold testing, as reported by receiver equipment, or derived from similar signal quality metrics.

The potential benefits and limitations of CID were evaluated by assessing the effectiveness of efforts to mitigate incidents of RFI to the NOAA WCDAS site, which has been sharing spectrum with a fixed wireless system since 2011. The Wallops site has experienced multiple RFI events despite the existence of a significant exclusion zone. Furthermore, the study evaluates the likelihood of continued or increased incidence of RFI to GOES downlink sites, based on known current or planned locations of towers near GOES downlink sites, should they begin to transmit in 1675–1680 MHz. Finally, the study assessed the use of CID (to date) as an approach to improve effectiveness of RFI mitigation at GOES downlink sites.

Findings

Measured interference thresholds

The DCS DRGS/DCPR downlink is the primary impacted GOES-R signal among the three downlinks measured due to partial overlap of the signal with LTE in 1675–1680 MHz. Periods of heavy loading of the DCS system, often occurring around the top of the hour, cause the DRGS signal power level to decrease for each channel, increasing susceptibility to interference due to reduced margin. As a result, DRGS receivers require protection under all conditions considered.

The secondary concern is RFI to the GRB downlink due to out-of-band (OOB) energy from LTE operations in 1675–1680 MHz. The GRB is less susceptible to interference than DCS because of three factors: (1) frequency separation from the shared band, (2) the GRB signal is at constant power, and (3) the DVB-S2 signal has >15 dB of coding gain but is still affected by RFI from 1675–1780 MHz and was found to require protection in most cases, even from LTE uplinks.

The tertiary interference concern is RFI to the HRIT/EMWIN due to OOB energy from LTE in 1695–1710 MHz and 1675–1680 MHz. The HRIT/EMWIN signal's >10 MHz separation from the 1675–1680 MHz signal and relative proximity to 1695 MHz indicate it will be more affected by OOB energy from terrestrial emissions in the upper band. HRIT/EMWIN thresholds were measured at operational power levels.

Benefits and limitations of having CID information

Project 9 investigated the possibility of a benefit to spectrum sharing from the use of CID information. The CID provides the identity of the carrier/base station and does not interpret any other content such as individual users. If the concept works, CID information offers an opportunity for automating RFI mitigation processes by rapidly identifying the offending carrier.

It is important to understand that there are limitations to making practical use of CID information that make it of very limited utility in the RFI scenarios projected for sharing this band with LTE. In a scenario where multiple signals are being received, the process can decode the CID for only one signal at a time and only when there is a sufficiently large delta of power level among the aggregation of signals. If there are multiple signals present, only the strongest signal will be decoded. Also, a likely scenario is multiple signals with similar power levels, in which case no CIDs would be decoded.

Recommendations

- Research better filtering techniques to lessen the impact of out-of-band RFI.
- Investigate other types of RFI sources beyond LTE (64 QAM).
- Deploy spectrum monitoring systems to other high-visibility locations (e.g., National Hurricane Center in Miami, Florida).
- If Sensor Data downlink at WCDAS is activated, utilize carrier ID decoding capabilities to mitigate the potential RFI situation.

4.9.1 Evaluate the benefits to spectrum sharing of AWS carrier identification information

Carrier identification: Definition and potential use

Mobile wireless communication signals integrate a carrier and base-station identification component that is embedded within the video or data transmission. One purpose is to identify base station transceivers or sectors within a specific network. The identification component of the RF signal is alternately referred to as "carrier identification" (CID) or "cellular identification." By using a spectrum analyzer with CID decoding add-ons or custom decoding by software, one can use the decoded CID to identify the transmitter of an RF signal.

When RFI to GOES downlink signals (caused by commercial broadband wireless signals) occurs, it can have harmful effects on the ability of the victim system to reliably transport data. Obtaining the CID of an interfering signal may offer the ability to facilitate rapid mitigation of the RFI. Note that extraction of the CID does not involve decoding any other part of the signal or its content, thus avoiding privacy issues. Without a way to rapidly identify the base station operator source of RFI, it can be difficult to mitigate the impacts in a timely fashion. Decoding the CID of the interfering signal, in combination with proper CID reference information, would identify the source of the interfering signal and allow the responsible provider to immediately take action to reduce or eliminate the interference as long as the signal received is clear and readable.

Approach to CID

This evaluation consisted of the following determining factors for the benefit to spectrum sharing of CID decoding:

- Establish the value of GOES data that is transmitted in and adjacent to the 1675–1680 MHz spectrum band (completed in project #1).
- Describe efforts to date to mitigate RFI in proximity to a significant GOES downlink site without using CID.
- Describe efforts to date to monitor spectrum near WCDAS, detect potentially interfering signals and decode the CID to identify and locate the source of the received signals.
- Describe limitations of techniques to obtain CID, and the use of CID to mitigate RFI.

4.9.1.1 Rationale for considering CID implementation

A principal reason to employ CID decoding is to support quick-reaction mitigation strategies. Ultimately, the more rapidly the RFI source to GOES downlinks is identified and the interference resolved, the less data loss occurs; this can result in reduced impact to both the social and the economic welfare of meteorological users. Assessment of the value of GOES data was accomplished in SPRES Project 1.

4.9.1.2 Spectrum monitoring and current CID decoding results

In a separately contracted NOAA study in 2016, Alion employed a spectrum monitoring capability at WCDAS to detect potentially interfering signals. The system is referred to as Versatile RF Automated Monitoring System (VRAMS). Initial data collection was used to determine whether the RF envelope of received signals was similar to the known signature of Ligado's 5 MHz digital video broadcast–horizontally polarized (DVB-H) transmission in the 1670–1675 MHz band. For received signals where this was found to be the case, such signals were assumed to be transmitted by Ligado.

Demonstrated capabilities

The VRAMS was adapted for that study to decode the CID of a received Ligado DVB-H signal, both efficiently and with high confidence. CIDs in DVB-H signals are mandatory elements carried in the signal's transmission parameter signaling (TPS) bits, as stated in DVB-H service standards. With knowledge of where the CID data bits are located within DVB-H modulated signals, the VRAMS signal processing capabilities were extended to rapidly decode the CID of such signals received at WCDAS. Once decoded, the CID value is compared to a list of CIDs for all Ligado transmitters (provided to NOAA by Ligado under their coordination agreement), as well as additional data (e.g., location) about each transmitter. This decoded CID is used to clearly determine the identity and location of the transmitter producing the signal in question.

In the 2016 study, Alion stated that VRAMS could be configured to send email notifications when a DVB-H signal is captured, when a CID is successfully decoded, and when CID cannot be found. VRAMS could also be configured not to send another message for a specified number of minutes or hours, so as to reduce redundant email notifications.

Results of CID decoding

Table 4.9-1 is an excerpt of data from the VRAMS monitoring system at WCDAS covering the period July 11–22, 2017, of the 1670–1675 MHz log.

The excerpt selected in Table 4.9-1 illustrates the large variety and dispersion of transmitters in a day. It is important to note that a received signal with a successfully decoded CID may not necessarily be the actual source producing RFI to a GOES downlink, and also that the CID relationship to location may not be correct. Through site visits by NWS technicians, it was learned that most of the transmitters are operating at reduced power (35–45 W) as compared to the authorized power

Table 4.9-1. Excerpt from the VRAMS monitoring system at WCDAS.*

Ligado Networks Receiver Log								
Date	Julian Day	Start Time (hh:mm:ss)Z	Stop Time (hh:mm:ss)Z	Duration (hh:mm:ss)	Peak Power at Antenna, dBm	Transmitter Location	Distance to WCDAS (mi)	Comment
7/11/2017	192	00:23:37	00:24:21	00:00:44	-111	Midland 1	1,522.6	< 1 min
7/11/2017	192	00:53:19	00:54:04	00:00:45	-106	Midland 1	1,522.6	< 1 min
7/11/2017	192	01:45:37	01:47:14	00:01:37	-109	Midland 1	1,522.6	
7/11/2017	192	02:17:46	02:27:34	00:09:48	-111	Midland 1	1,522.6	
7/11/2017	192	02:27:51	02:28:54	00:01:03	-111	Midland 1	1,522.6	
7/11/2017	192	03:09:38	03:10:19	00:00:41	-110	Midland 1	1,522.6	< 1 min
7/11/2017	192	03:16:50	03:17:27	00:00:37	-110	Midland 1	1,522.6	< 1 min
7/11/2017	192	03:42:33	03:45:17	00:02:44	-111	Midland 1	1,522.6	
7/11/2017	192	00:30:56	00:31:40	00:00:44	-106	Minnesota 2	1,032.6	< 1 min
7/11/2017	192	02:40:11	02:40:55	00:00:44	-110	Nashville 1	613.0	< 1 min
7/11/2017	192	03:15:50	03:16:35	00:00:45	-110	Nashville 1	613.0	< 1 min
7/11/2017	192	01:25:32	01:26:16	00:00:44	-106	New Jersey 1	168.5	< 1 min
7/11/2017	192	00:26:36	00:27:41	00:01:05	-111	Tampa 3	768.3	
7/11/2017	192	03:14:52	03:15:34	00:00:42	-111	Tampa 3	768.3	< 1 min
7/12/2017	193	14:58:01	14:58:48	00:00:47	-109	Not Listed	No XMTR Listed	< 1 min
7/12/2017	193	14:59:01	14:59:48	00:00:47	-105	Tampa 4	802.7	< 1 min
7/12/2017	193	15:00:01	15:00:48	00:00:47	-109	Boston 2	334.3	< 1 min
7/12/2017	193	15:01:01	15:01:17	00:00:16	-111	Kansas City 2	1060.0	< 1 min
7/15/2017	196	02:03:44	02:04:25	00:00:41	-110	Richmond 1	108.4	< 1 min
7/15/2017	196	13:14:32	13:21:44	00:07:12	-112	Richmond 1	108.4	
7/15/2017	196	13:22:12	13:23:22	00:01:10	-111	Richmond 1	108.4	
7/19/2017	200	04:05:27	04:08:04	00:02:37	-109	Wilmington 1	113.6	
7/20/2017	201	12:59:33	13:01:14	00:01:41	-110	Midland 1	1522.6	
7/20/2017	201	01:23:46	02:10:23	00:46:37	-111	Richmond 1	108.4	
7/20/2017	201	02:10:42	02:11:23	00:00:41	-111	Charleston WV 1	332.7	< 1 min
7/20/2017	201	02:11:47	02:12:45	00:00:58	-111	Jacksonville 1	610.7	< 1 min
7/20/2017	201	02:13:08	02:15:22	00:02:14	-111	Tampa 4	802.7	
7/20/2017	201	02:15:45	02:16:32	00:00:47	-111	Boston 2	334.3	< 1 min
7/20/2017	201	02:16:52	02:17:22	00:00:30	-111	Kansas City 2	1060.0	< 1 min
7/20/2017	201	03:14:46	03:15:28	00:00:42	-110	Richmond 1	108.4	< 1 min
7/20/2017	201	03:15:46	03:16:28	00:00:42	-110	Not Listed	No XMTR Listed	< 1 min
7/20/2017	201	03:23:33	03:32:18	00:08:45	-111	Wilmington 1	113.6	
7/20/2017	201	03:45:48	03:58:15	00:12:27	-111	Philadelphia 1	143.2	
7/20/2017	201	04:41:10	05:13:05	00:31:55	-109	Wilmington 1	113.6	
7/20/2017	201	08:41:13	09:11:40	00:30:27	-111	Wilmington 1	113.6	
7/20/2017	201	10:35:05	10:55:45	00:20:40	-107	Midland 1	1522.6	
7/20/2017	201	12:49:18	12:52:45	00:03:27	-108	Midland 1	1522.6	
7/20/2017	201	12:53:04	12:53:37	00:00:33	-111	Minnesota 2	1032.6	< 1 min
7/20/2017	201	12:54:03	12:54:44	00:00:41	-110	Midland 1	1522.6	< 1 min
7/20/2017	201	12:55:04	12:56:52	00:01:48	-108	Minnesota 2	1032.6	
7/22/2017	203	02:39:30	02:40:09	00:00:39	-111	Boise 1	2074.8	< 1 min

*Entries represent potential interfering signals detected by VRAMS. The color coding in the "Transmitter location" column represents distance rings (in miles) from the transmitter to WCDAS: red, 0–110; orange, 110–175; yellow, 175–235; green, 235–290; light blue, 290–400; dark blue, 400–600, purple, 600–900; gray, 900–1600; white, 1600–2500.

levels of 500–2000 W, which correlates with the low power levels received at Wallops. However, information from VRAMS can be used to correlate a monitored signal and CID to evidence of impacts of harmful interference on GOES data. Beyond the CID, more data (e.g., spectral captures, time stamps, etc.) would need to be packaged to confirm and correlate RFI.

Although some of the data in Table 4.9-1 was not verified as to the tower's location (tower IDs were changed without notifying NOAA), it does show that there are frequent ducting events at WCDAS. Note that the distances shown were provided by Ligado. The accuracy of CID values and mapping of CIDs to transmitter locations were not independently confirmed during this activity. It is believed that the CID values detected as shown in the table were out of date and associated with other locations. The information implied such signals could propagate beyond the 300-mile cutoff agreed upon in the Ligado-WCDAS RFI mitigation protocol, but more detailed studies in Project 8 uncovered physical limitations to ducting conditions that would make inland sources or sources beyond 500 km very unlikely. This study did demonstrate that a reporting system could be implemented to identify incidents where thresholds are exceeded, but it would require a verifiable standard to be applied to the CIDs. In addition, while the interaction process established in the agreement between the two entities (WCDAS and Ligado) was relatively simple, the results included lengthy outages that would be unacceptable for both parties. This process would require automation to facilitate rapid notification of NOAA and the relevant commercial provider of RFI incidents and the RFI source.

LTE network density

As was noted above, transmissions from Ligado's towers greater than 300 miles from the NOAA earth stations may have caused RFI to the GOES-NOP SD downlink. This presents an important limitation of CID decoding—the inability to decode when multiple signals with similar amplitudes are present. It is reasonable to assume that the risk of this scenario occurring varies proportionately with the number of towers. It is also reasonable to assume that the transmitter density in the context of LTE is likely to be much higher than what was demonstrated here.

For example, Figure 4.9-1 displays several business economic areas (BEAs) (a BEA is an demographic statistic used to identify license areas) and the potential buildout of cell phone towers in the AWS-3 bands. Although this network buildout is not complete yet, one can see that there are already 1,911 base stations within 150 miles of WCDAS. This can be compared to less than 200 sites for Ligado throughout the U.S.:

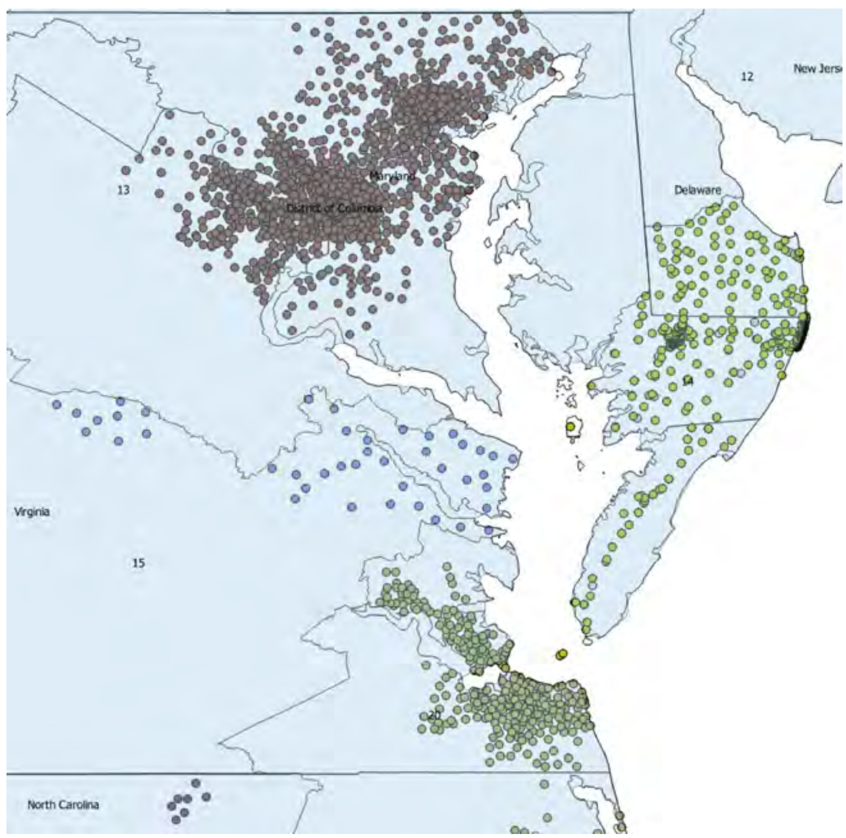


Figure 4.9-1. Potential AWS-3 cell phone towers in select BEAs.

- BEA 13, named Washington-Baltimore DC-MD-VA-WV-PA, 1,205 towers (brown dots) 10 MHz

- BEA 14, named Salisbury MD-DE-VA, 343 towers (bright green dots) 5 & 10 MHz
- BEA 20, Norfolk-Virginia Beach-Newport News, VA-NC, 320 towers (dark green dots) 10 MHz
- BEA 15, Richmond-Petersburg VA, 43 towers (blue dots) 10 MHz

Limitations of obtaining CID and effect on usefulness

It has been demonstrated that the CID of the Ligado existing DVB-H broadcast signal in 1670–1675 MHz can be decoded effectively when certain conditions are in place. However, the need for such conditions in order to be effective places practical limitations on both the process of decoding the CID and its usefulness in mitigating RFI. (Note: While there has been successful decoding of many of the received signals at WCDAS, there have been instances when the CID could not be decoded due to overlapping aggregate signals.)

4.9.2 GOES-R receiver field testing

This subtask of Project 9 focused primarily on characterizing RFI from the frame of reference of signals from commercial wireless broadband carriers interfering with the downlink signals at NOAA's GOES receive sites. This was done by measuring the interference thresholds above which Federal GOES-R series satellite broadcast receivers would suffer degraded or lost data.

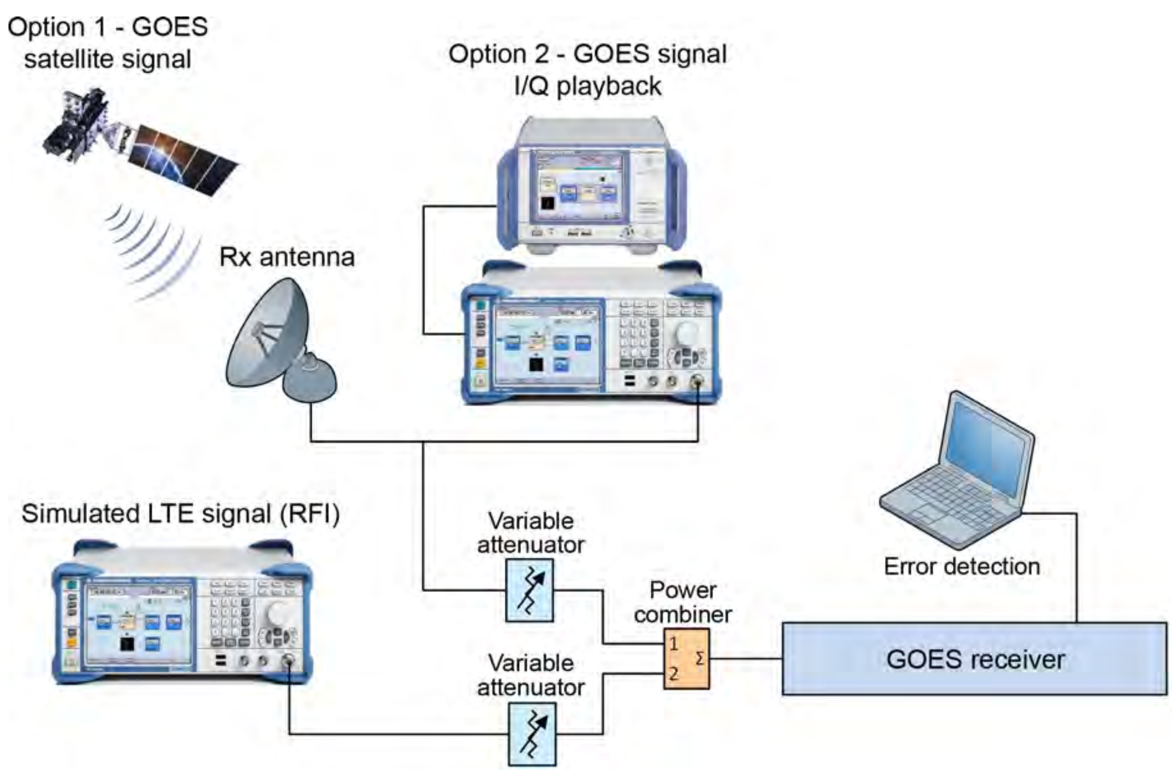
GOES-R GRB, DCPR, and HRIT/EMWIN receiver manufacturer specifications were classified and grouped by receiver sensitivity and expected RFI thresholds. Among the manufacturers contacted about receiver specifications are Microcom, Novra, Orbital Systems, RT Logic, Quorum, and Signal Engineering. Manufacturers were asked about whether open- or closed-loop tests with their equipment could be conducted, either in a laboratory or at a mutually convenient and cost-effective location. Via telephone and email, points of contact from WCDAS (Wallops Island, Virginia), the NOAA Center for Weather and Climate Prediction (NCWCP, College Park, Maryland), and Microcom Environmental (Hunt Valley, Maryland) were presented with initial requests to test interference thresholds. Upon initial agreement, follow-up technical questions regarding receiver system configurations were distributed via email to the sites to further clarify the feasibility of testing. Finally, test plans were shared, along with official requests to approve testing. WCDAS, NCWCP, and Microcom all gave official permission for testing.

Test plan

Team members experienced with receiver testing and characterization used the following procedures to validate and verify GOES-R receiver interference thresholds (see Figure 4.9-2 for a representative test configuration):

1. Establishment of an RF link between the transmitter and receiver, simulating typical operations.

2. Injection of variable levels of RFI from an LTE signal generator. Interference waveforms for each of the four test scenarios were developed using Matlab.



Fgure 4.9-2. Diagram of typical receiver threshold test setup.

3. Measurement of power output, sensitivity, and susceptibility to interference with the various interference scenarios (see Table 4.9-2).

4. Determination of interference threshold above which data degradation or loss occurs.

Table 4.9-2. FDD LTE interference scenarios used.

Scenario	Subtask	Details	Signal type
LTE in 1675–1680 MHz band	9.2	5 MHz bandwidth, 25 resource blocks (fully loaded), 64 QAM	Base station downlink
LTE in 1675–1680 MHz band	11.2b	5 MHz bandwidth, 25 resource blocks (fully loaded), 64 QAM	User equipment uplink

Interference threshold tests were performed by combining RFI with the GOES signal before feeding it into the receiver under test. Four fully loaded LTE simulated signals were applied as the RFI source, according to the scenarios outlined in Table 4.9-3. The scenarios in the table specify the frequency bands of the LTE signals, the SPRES subtasks that they satisfy, the LTE resources and modulation of the signals, and whether the LTE signals are configured for base station downlink or user equipment uplink.

Table 4.9-3. DCPR sensitivity test results.

Minimum DCPR power at LNB input		
Data rate (bps)	dBm/BWDCPR	dBm/kHz
300	−141	−135
1200	−137	−138

4.9.2.1 DCS Data Collection Platform Return direct broadcast signal

The most vulnerable GOES-R L-band signal is the DCPR satellite downlink signal, which is received by DRGS, because it would be overlapped in frequency (in-band) if the 1675–1680 MHz band is shared with commercial land-based transmitters. This situation is somewhat analogous to the interference experienced at WCDAS to the legacy GOES Sensor Data (SD) downlink signal at 1673.4–1678.6 MHz due to overlap with Ligado emissions in the 1670–1675 MHz band. It was previously noted that the GOES satellite transponder operates at fixed power. If only a few DCP ground units are sending data to the satellite, the transponder retransmits those signals with higher signal power and noise floor. If there are hundreds of ground units sending data simultaneously, the transponder distributes the power equally to all units and the entire spectrum is lower in amplitude and in noise floor (i.e., signal-to-noise ratio remained constant). This attribute was noted from observing spectrum analyzer displays over long time periods.

As a result of the preliminary findings, it was determined that interference threshold testing should be performed when the satellite was heavily loaded and the noise floor was lowest. When unloaded, the satellite transmitter noise floor could mask RFI that was as much as 10 dB higher than with the satellite transponder fully loaded.

4.9.2.1.1 Test methods and test equipment configuration for DCPR/DRGS

Several methods were utilized to develop a repeatable test signal that could be used for determination of system sensitivity and RFI thresholds. The test signal was minimized so that error correction was fully utilized and there were no errors in the test message. The test messages were 30 seconds in length for data rates of both 300 bps and 1200 bps. For each 30-second DCPR playback, LTE RFI was injected into the receiver and the RFI power level was increased until corrupt or missing text was observed in the decoded message. Then the maximum RFI signal power levels at the antenna low-noise block (LNB) before data loss were noted in a log and recorded as the RFI threshold. Two methods were used:

1. Method A used a ground transmitter that sent the minimum signal to the satellite that could be received by DRGS with no message errors. (The Microcom DRGS receive system was using a factory-developed software program that recorded the corrected bit errors.)

2. Method B recorded a simulated signal from a factory-supplied DCP transmitter and played it back at the same level that produced the minimum received signal or "sensitivity" in Method A. The playback signal power was duplicated by sending the signal through a vector signal generator at fixed output power, as shown in Figure 4.9-3. This method became the standard for DRGS testing because transmitting through the satellite in Method A added too much variability to the signal power due to satellite loading.

The DRGS receiver selected for testing was the Microcom Dual Pilot Control Module (DPCM) and DAMS-NT DigiTrak DRGS receiver located at Microcom Environmental in Hunt Valley, Maryland. Multiple configurations are shown in Figure 4.9-3. The determination of the receiver sensitivity was conducted without the third vector signal generator shown in the bottom left hand corner

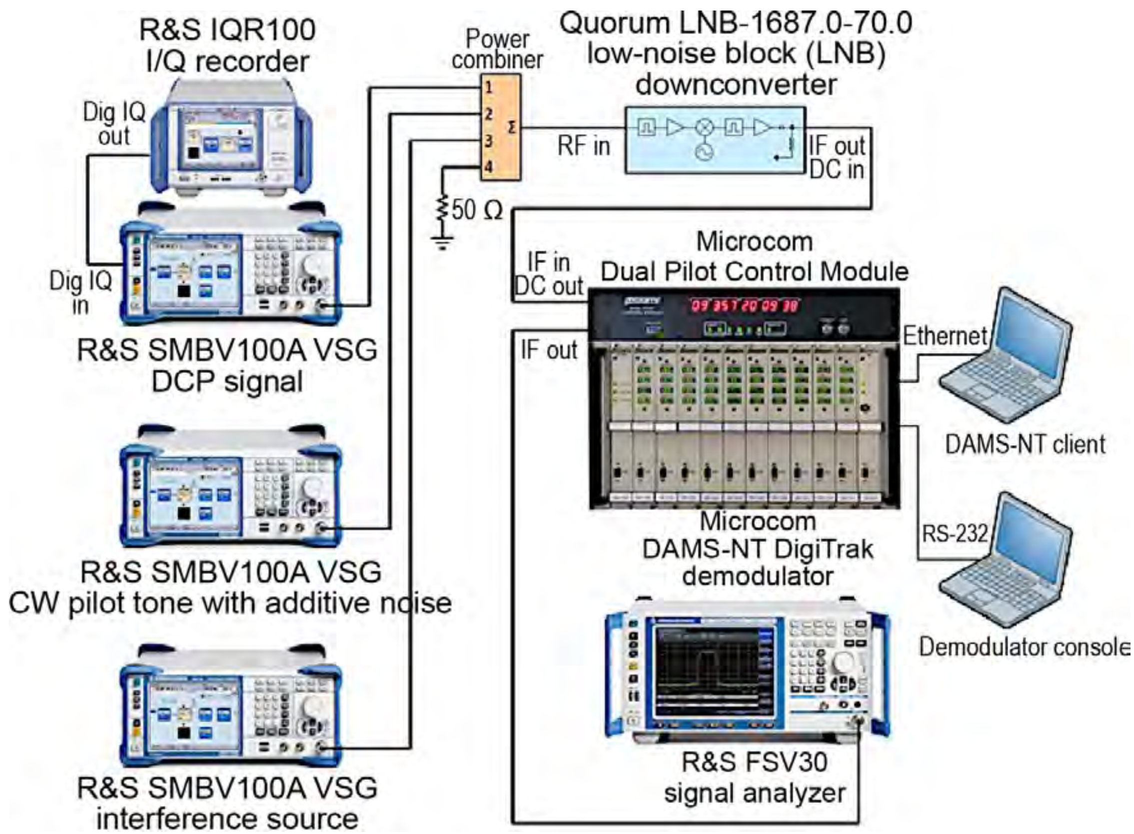


Figure 4.9-3. Equipment configurations for DCPR testing.

and terminal 3 of the power combiner terminated in a 50-ohm load. The full configuration in Figure 4.9-3 was utilized to determine the Microcom DPCM and DigiTrak receiver RFI threshold for the data rates of 300 bps and 1200 bps. The lowest RFI power level of the two data rates was selected as the RFI threshold. Testing was done on the lowest channel (301) of the DCPR band for the 1675–1680 MHz RFI tests. Note that the backup pilot tone signal at the bottom of the DCPR band was completely overlapped and useless under RFI testing for 1675–1680 MHz. Therefore, only the primary pilot tone was implemented for this phase of testing where there was no overlap from the 1675–1680 MHz RFI source.[29]

The Microcom DigiTrak receiver can output the following data items about a received signal to a terminal console via serial cable using factory-supplied software:

- Decoded message text
- Bit error count
- Average effective isotropic radiated power (EIRP) relative to pilot
- Signal-to-noise ratio (SNR)
- Good phase count
- Phase error

The above data items were recorded during the test and subsequently analyzed to determine the RFI power levels at which data was lost, as indicated by corrupt or missing text in the decoded

[29] DCPR operation requires interference-free reception of the pilot tone.

message. The total bits in each message were calculated from three times the good phase count, which was then used to determine bit error rate (BER). BER was found by dividing the number of bit errors by the total bits. However, most DCPR messages are less than 10 seconds, and the fastest data rate is 1200 bps, so there is an insufficient sampling of data to determine whether the required 10^{-6} bit error rate is achieved.

4.9.2.1.2 Sensitivity measurements for DCPR

The summary of sensitivity test results is presented in Table 4.9-3. The equivalent DCPR power level at the input to the antenna low-noise block (LNB) downconverter (output from antenna feed) was found by subtracting the total cable, combiner, and IQ playback implementation loss from the signal generator output power. The power levels at the LNB input are presented in the table as total channel power in dBm (per DCPR bandwidth of 300 Hz or 1200 Hz, for 300 bps and 1200 bps data rates, respectively), as well as power spectral density in dBm/kHz for easy comparison with threshold results. Data loss occurs when corrupt or missing text is observed in the decoded message.

4.9.2.1.3 Interference threshold and BER measurements for DCPR

A vector signal generator (VSG) was used to play back the recorded DCPR signal at the RF frequency for channel 301 or 565. The power level of the RF signal was set and displayed on the

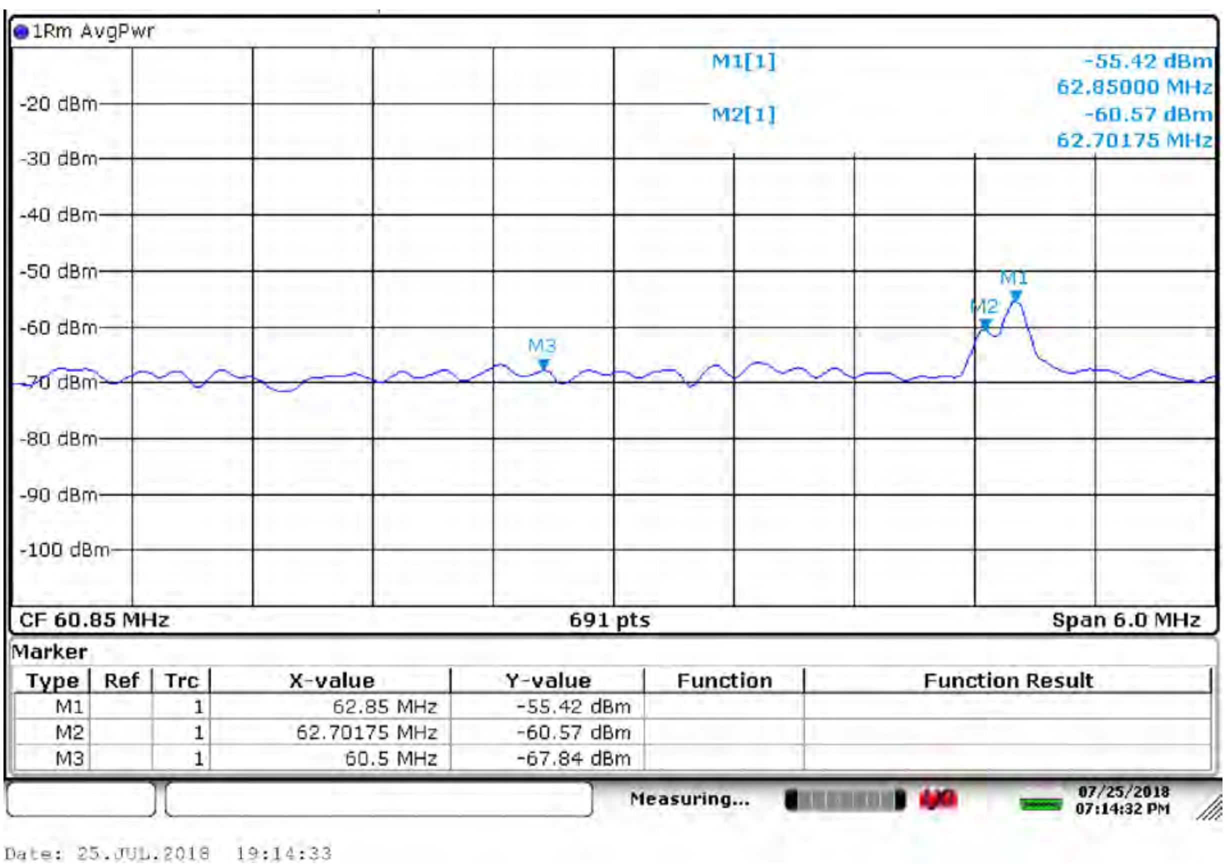


Figure 4.9-4. DCS channel 301 signal and primary pilot tone without RFI.
Note: Marker 1 (M1) is the DCS primary pilot tone, marker 2 (M2) is the DCS channel 301 signal, and marker 3 (M3) is centered on the RFI signal.

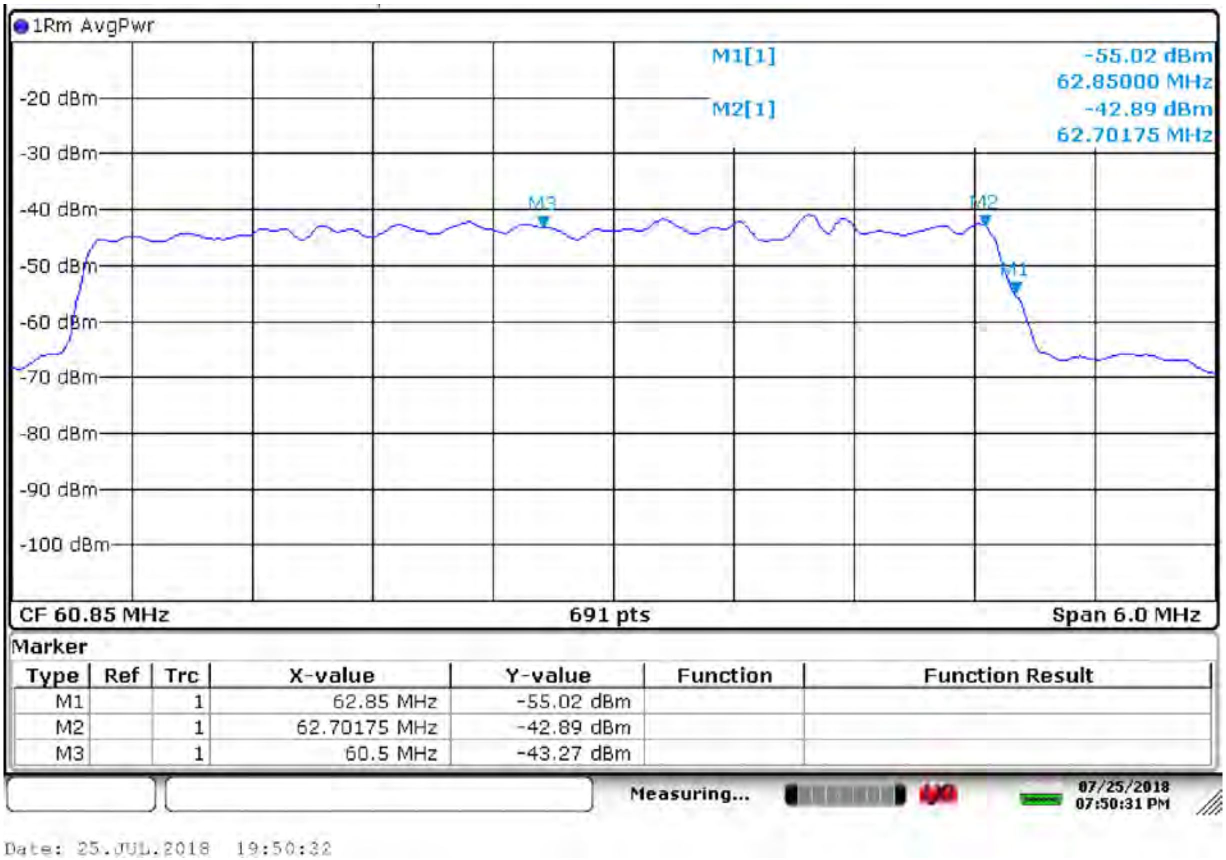


Figure 4.9-5. DCS channel 301 signal and primary pilot tone with RFI.
Note: Marker 1 (M1) is the DCS primary pilot tone, marker 2 (M2) is the DCS channel 301 signal, and marker 3 (M3) is centered on the RFI signal.

front panel screen of the VSG. The test was performed by combining RFI with the DCPR signal before feeding it into the antenna LNB.

Note: The DCPR downlink frequency band is 1679.7–1680.1 MHz. The guard band in LTE channels greater than 1.4 MHz is defined as 10% of the available channel bandwidth. The 1675–1680 MHz LTE has an occupied bandwidth of 4.5 MHz, 1675.25–1679.75 MHz.

Figures 4.9-4 and 4.9-5 show examples of the receiver's intermediate frequency (IF) output spectrum on the signal analyzer display, without RFI and with RFI, respectively.

Table 4.9-4 presents a summary of the threshold test results along with the corresponding BER values observed during each test. The RFI power levels at the input to the antenna LNB are presented in the table as total channel power in dBm (with LTE bandwidth of 5 MHz), as well

Table 4.9-4. Summary of DCPR channel interference threshold and BER results.

Interference type	DCPR data rate (bps)	Maximum RFI power at LNB input			BER
		dBm/BW$_{LTE}$	dBm/kHz	dBW/100 Hz	
5 MHz LTE BS downlink (1675–1680 MHz)	300	−110	−147	−187	8.97E-03
	1200	−110	−147	−187	2.71E-02
5 MHz LTE UE uplink (1675–1680 MHz)	300	−115	−152	−192	9.49E-03
	1200	−115	−152	−192	2.54E-02

as power spectral density in both dBm/kHz and dBW/100 Hz for easy comparison with sensitivity results and ITU thresholds, respectively. The ITU thresholds are −198.8 dBW/100 Hz no more than 20% of the time (long term) and −193.6 dBW/100 Hz no more than 0.025% of the time (short term) (Draft Revision to ITU Rec. SA.1163). In the worst case, at 5 MHz LTE uplink, test results were 6.8 and 1.6 dB higher than the long- and short-term ITU thresholds, respectively. (See Appendix J, section J.1.2, for clarifications.)

Table 4.9-5. Summary of DCPR pilot interference threshold results.

Interference type	Pilot tone	Maximum RFI power at LNB input		
		dBm/BW_{LTE}	dBm/kHz	dBW/100 Hz
5 MHz LTE BS downlink (1675–1680 MHz)	Primary	−82	−119	−159
	Secondary	−82	−119	−159
5 MHz LTE UE uplink(1675–1680 MHz)	Primary	−84	−121	−161
	Secondary	−85	−122	−162

During testing of DCPR, it was noted that signals in the adjacent band (1675–1680 MHz) could corrupt the primary pilot tone. This was noted for an FM signal as well as an LTE signal. Both the FM signal and LTE signal increased the phase jitter of the pilot tone. Table 4.9-5 presents a summary of the pilot threshold test results. Data presented in this table is only for the LTE signal used as the RFI source. The DCPR channels have a lower RFI threshold than the pilot tones; therefore, the DCPR channel threshold should be used. (See Appendix J, section J.1.2, for clarifications.)

4.9.2.1.4 Results of DCPR testing

Given that an LTE base station may be transmitting 100% of the time, 24 hours a day, seven days a week, Table 4.9-4 indicates that the single RFI threshold for DCPR should be −115 dBm/5 MHz power at the input to the LNB amplifier. The antenna size and feed configuration will vary, but the input RFI threshold is a constant, not-to-exceed value.

Later discussions in this report will show that the problem is further compounded as long-distance RFI (originating from hundreds to one thousand miles away) due to anomalous propagation can be present at the antenna for extended time periods (up to 8–10 hours a day).

4.9.2.2 High Rate Information Transmission/Emergency Manager Weather Information Network

The next GOES-R satellite downlink tested was HRIT/EMWIN, which is utilized throughout the Western Hemisphere.[30] Measurements were performed to determine the system sensitivity and interference threshold of the Microcom DAMS-NT DigiRIT HRIT receiver at Microcom Environmental in Hunt Valley, Maryland.

[30] HRIT is an international standard, used by multiple nations. The combined HRIT/EMWIN signal is unique to the Western Hemisphere.

The threshold tests were performed with the HRIT signal at its typical received signal level, and SNR with a 1.2 m antenna, because the downlink signal is output from WCDAS at constant power (not affected by satellite loading).

Prior to performing sensitivity and threshold measurements, a recording of the HRIT signal from GOES-R was captured in order to replay the recording for each iteration of the test. The Microcom DAMS-NT DigiRIT HRIT receiver was connected to a 3.6 m antenna for a clean signal with optimum SNR. A signal analyzer with an in-phase and quadrature (I&Q) recorder was connected to the receiver intermediate frequency (IF) output, and a client computer was connected to the receiver via Ethernet.

For test purposes, two minutes of the HRIT signal I&Q was captured with the I&Q recorder, and, at the same time, data from the received signal was decoded into a file using the DAMS-NT client software. This captured data file was then compared with the replayed I&Q signal in each test scenario.

4.9.2.2.1 Interference threshold and BER measurements for HRIT/EMWIN

Measurements were performed to determine the interference threshold of the Microcom DigiRIT receiver. A vector signal generator (VSG) was used to play back the recorded HRIT IF signal, translated up to the original RF frequency transmitted by the GOES satellite. The power level of the RF signal was set and displayed on the front panel screen of the VSG. The test equipment was configured as shown in Figure 4.9-6. Sensitivity measurements were done, as in DRGS, with the lower left-hand VSG disconnected and terminal 2 of the power combiner terminated. The threshold tests were performed by combining RFI from the second VSG with the HRIT signal before feeding it into the antenna LNB.

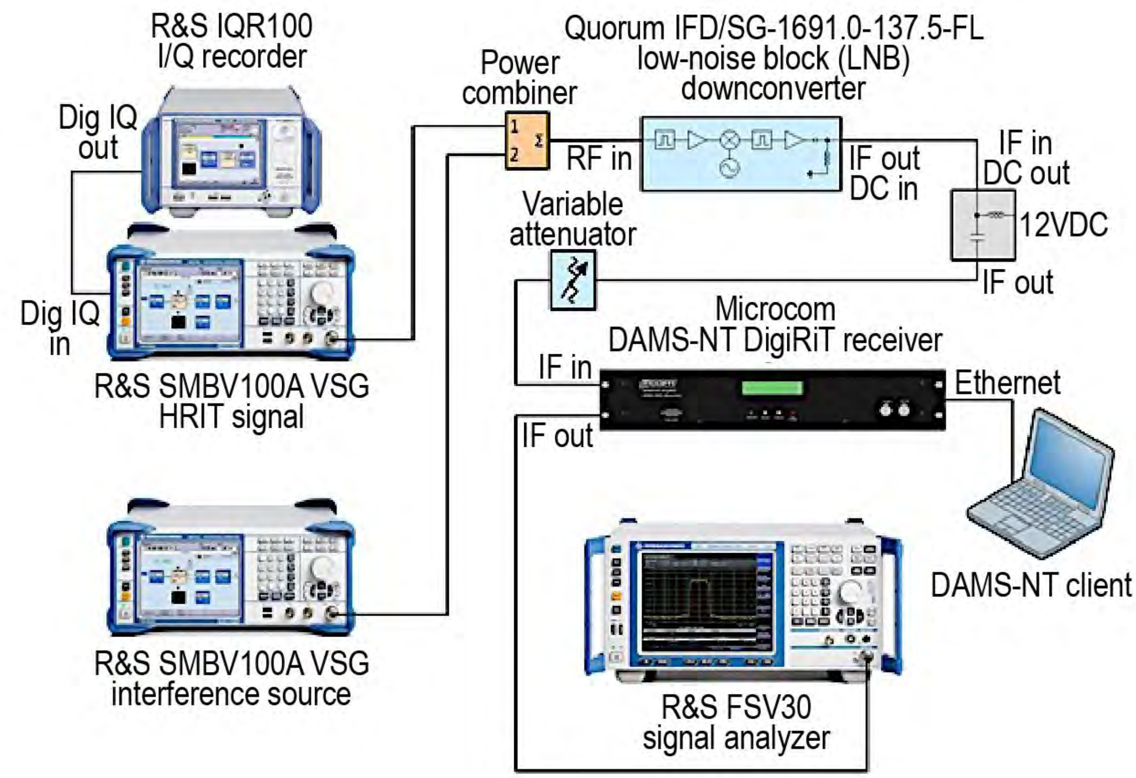


Figure 4.9-6. HRIT threshold measurements.

Note: The HRIT downlink center frequency is 1694.1 MHz with an occupied bandwidth of 1.205 MHz, ranging from 1693.4975–694.7025 MHz. The guard band in LTE channels greater than 1.4 MHz is defined as 10% of the available channel bandwidth and equally split at each end of the band. The 1675–1680 MHz LTE has an occupied bandwidth of 4.5 MHz, ranging from 1675.25 to 1679.75 MHz. Therefore, the 1675–1680 MHz LTE signals are out-of-band for HRIT.

The following figure shows a selection of the HRIT spectrum from the receiver IF pass-through port, as seen on the signal analyzer during the tests. Figure 4.9-7 is the live GOES signal and the HRIT signal with 5 MHz LTE downlink interference in 1675–1680 MHz band at −54 dBm equivalent power level at antenna feed, which caused uncorrectable RS blocks. The blue trace is only the live GOES satellite signal as received by the 1.2 m antenna. In the blue trace, from left to right, is DCPR, GRB, telemetry/command, and HRIT (far right). The black trace is the 5 MHz LTE on the far left and HRIT test signal on the far right.

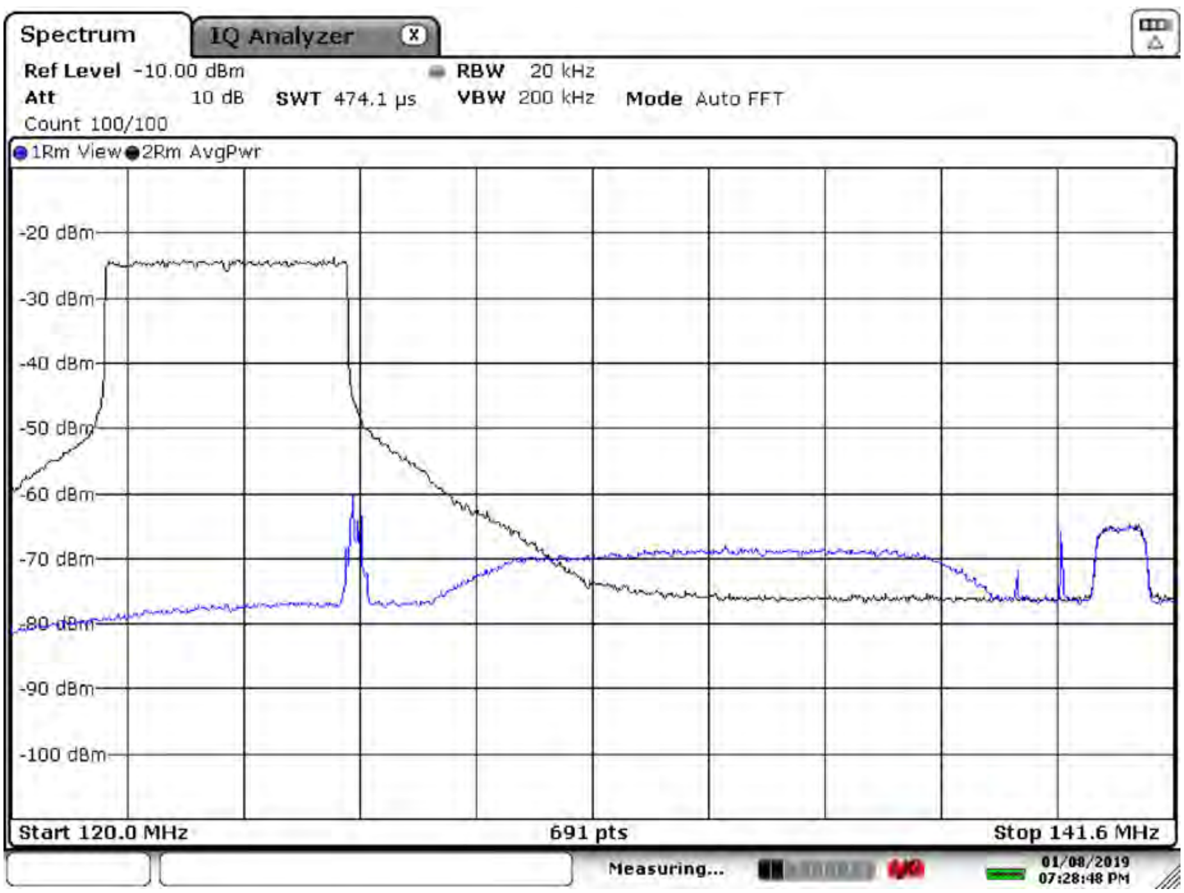


Figure 4.9-7. HRIT signal with 5 MHz LTE DL interference in 1675–1680 MHz band.

Microcom proprietary software for this test (referred to as DAMS-NT client software) measured and displayed the following:

- Total frames
- Error frames
- Frame error rate (FER)
- Total Reed-Solomon (RS) blocks

- Good RS blocks
- Corrected RS blocks
- Uncorrectable RS blocks
- Corrected RS bits
- RS Viterbi bit error rate (BER)
- Pre RS bit errors
- Pre RS BER
- Post RS bit errors

The data items listed above were recorded during the test and subsequently analyzed to determine the RF power levels at which data was degraded, as indicated by corrected RS blocks, and when data was lost, as indicated by uncorrectable RS blocks.

4.9.2.2.2 Results for HRIT/EMWIN RFI threshold and BER measurements

Table 4.9-6 presents a summary of the threshold test results along with the corresponding BER values observed during each test. The RFI power levels at the LNB are presented in the table as total channel power in dBm (per LTE bandwidth of 5 MHz), as well as power spectral density in both dBm/kHz and dBW/MHz for easy comparison with sensitivity results and ITU thresholds, respectively. The ITU thresholds are −158.1 dBW/MHz no more than 20% of the time (long term) and −153.6 dBW/MHz no more than 0.011% of the time (short term) (Preliminary Draft Revision to ITU Rec. SA.1161). The ITU thresholds are lower because they are calculated using the minimum required carrier-to-noise power spectral density ratio (C/N_0) of similar receivers worldwide. However, our threshold tests were specific to Microcom DigiRIT in Hunt Valley and were performed with the HRIT signal at its typical operating received signal level and corresponding C/N_0, not the minimum. The BER for the onset of degradation is zero because no errors occur until RFI increases above the threshold. Refer to trip report in appendices for raw test data.

Table 4.9-6. Summary of HRIT/EMWIN interference threshold and BER results.

Event	Interference type	Maximum RFI power at LNB input			BER
		dBm/BW_{LTE}	dBm/kHz	dBW/MHz	
Onset of degradation	5 MHz LTE BS downlink (1675–1680 MHz)	−60	−97	−97	0.00E+00
	5 MHz LTE UE uplink (1675–1680 MHz)	−60	−97	−97	0.00E+00
Data loss occurs	5 MHz LTE BS downlink (1675–1680 MHz)	−55	−92	−92	6.09E-03
	5 MHz LTE UE uplink (1675–1680 MHz)	−55	−92	−92	5.10E-03

The antenna size and feed configuration will vary, but the input RFI threshold is a constant not-to-exceed value at the LNB. The RFI threshold for adjacent-band interference to HRIT/EMWIN, from a 5 MHz LTE signal in the 1675–1680 MHz band, is −60 dBm/5MHz.

Later discussions in this report connecting propagation issues and carrier identification (CID) will show that the problem is further compounded as long-distance RFI (from hundreds to one thousand miles) can be present at the antenna for extended time periods (up to 8–10 hours a day).

4.9.2.3 GRB downlink testing

The GRB downlink receive sites selected for testing were WCDAS in Wallops Island, Virginia, and NCWCP in College Park, Maryland. Threshold tests were performed by injecting interference while the GRB signal was at its typical operating level, not reduced to its sensitivity level. The reason for testing at typical operating level was that the GRB downlink signal is output at a constant power that is not affected by satellite loading and the signal is received by high-gain fixed antennas.

The GRB receiver tested at WCDAS was the RT Logic Model T400. Testing for system sensitivity, thresholds for degradation, and thresholds for lost data were all possible with this system. The GRB receiver tested at NCWCP was the Quorum GRB-200 receiver. However, the Quorum GRB-200 does not report whether error correction is taking place, which would indicate the onset of degradation. Degradation threshold testing was not possible at this location.

The GRB signal is split into two data streams, and each stream is transmitted with a different polarization: left- or right-hand circular polarization (LHCP and RHCP). In this report, the worst-case level from measurements of either polarization is presented as the RFI threshold level.

4.9.2.3.1 WCDAS GRB receiver testing

The GRB receiver tested at WCDAS was the RT Logic Model T400 connected to the HR4 16.4 m antenna. The antenna feed and LNB downconverter receives GRB from the GOES satellite at RF center frequency of 1686.6 MHz, amplifies and separates the RHCP and LHCP signals, and downconverts them to the IF center frequency of 66.6 MHz. The RHCP and LHCP signals are sent over two separate transmission cable paths to a matrix switch and patch panel, which allows the signals to be connected to multiple receivers and test equipment. The GRB signal utilizes two types of error correction code, one within the other: an inner code, which is low-density parity-check (LDPC), and an outer code, which is Bose-Chaudhuri-Hocquenghem (BCH). Typically, BCH attempts to correct frames that are uncorrectable by LDPC. Complete data loss occurs when BCH frames are uncorrectable.

The losses were measured for the test equipment cables, splitter/combiners, connectors, and adapters used during testing. The RF gains/losses from the input to the 16.4 m LNB to the IF patch panel could not be directly measured. According to WCDAS personnel, the station tries to establish the antenna interfacility link (IFL) gains and losses such that the level that is on the output of the LNB downconverter is what is presented to the demodulator. This approach takes into account the dynamic power ranges of the various IFL components (such as the downconverters, fiber converters, switch, etc.), and it may be different for different types of antennas. Therefore, the gain from antenna LNB input to IF patch panel was derived with a simple link budget calculation by knowing the power output and gain from the GOES satellite (as specified in GOES-R DD1494), the antenna gain at WCDAS (as specified in the NESDIS Antenna and RF Systems Capabilities Handbook), and the power measured on the signal analyzer used for the tests.

4.9.2.3.1.1 Interference threshold and BER measurements for GRB at WCDAS

Measurements were performed to determine the interference threshold of the RT Logic T400 receiver. The test was performed by combining RFI with the GRB signal before feeding it into the T400. The test equipment was configured as shown in Figure 4.9-8. The vector signal generator was used to create the LTE interference signal at the IF frequency.

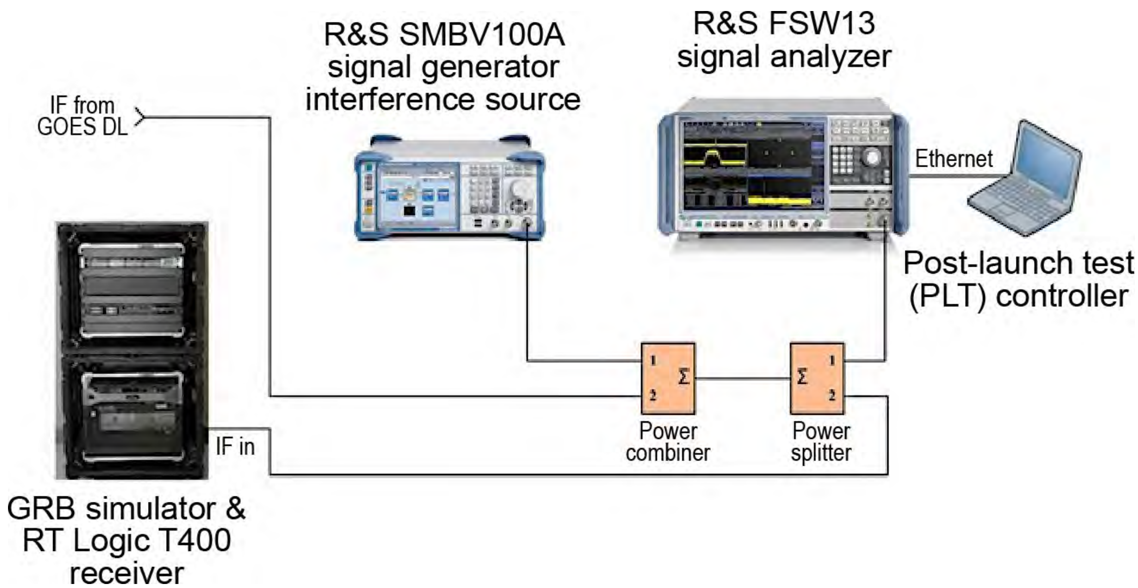


Figure 4.9-8. GRB interference threshold measurement test equipment configuration.

The T400 front-end processor (FEP) software was configured to display the following data frame statistics:

- Total frames
- Uncorrectable LDPC frames
- Corrected LDPC frames
- Corrected LDPC bits
- Uncorrectable BCH frames
- Corrected BCH frames
- Corrected BCH bits

The post-launch test (PLT) software and signal analyzer were configured to measure energy per bit-to-noise power spectral density ratio (E_b/N_0) (which in this case is actually energy per bit-to-noise plus interference power spectral density ratio [$E_b/(N_0 + I_0)$]). These data items were recorded during the test and subsequently analyzed to determine the levels at which data was degraded, as indicated by corrected frames, uncorrectable frames, and decrease in $E_b/(N_0 + I_0)$.

The RT Logic T400XR software interface can output the following data items about a received signal:

- E_b/N_0
- FER for LDPC frames
- FER for BCH frames
- BER can be calculated as a function of E_b/N_0 or $E_b/(N_0 + I_0)$

The following figure shows a selection of the GRB IF spectrum (set at 1620 MHz) as seen on the signal analyzer during the tests. The large lobe, in the center of the waveform, is the GRB signal. The narrow signal to the left is the DCPR band, easily shown in the blue trace. The signals to the right are GOES telemetry and HRIT. Figure 4.9-9 shows the GRB signal with 5 MHz LTE UE UL interference in the 1675–1680 MHz band (seen here at IF 55–60 MHz, to the left of the GRB signal). The equivalent interference power at the antenna LNB input was −64 dBm/5MHz during this measurement.

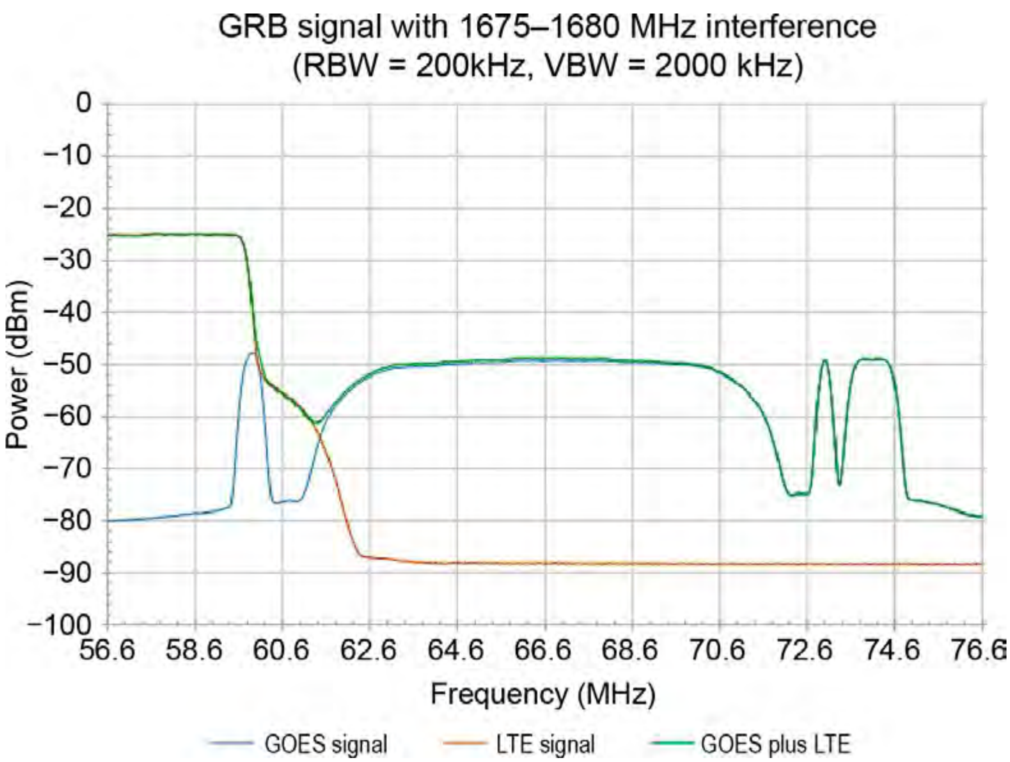


Figure 4.9-9. GRB signal with 5 MHz LTE interference in the 1675–1680 MHz band.

4.9.2.3.1.2 Results for GRB RFI threshold and BER measurements at WCDAS

The equivalent RFI power at the antenna LNB input was found by taking the power output from the signal generator and subtracting the total gain from the antenna LNB input to the signal generator. Next, the following adjustments were included:

- 2.5 dB subtraction for link margin
- 2.3 dB subtraction for implementation loss

    - Link margin and implementation loss based on Interface Requirements Document for the GOES-R System Space Segment to GRB Service (417-R-IRD-0002 ver. 2.8)
- 4.2 dB subtraction for GRB end-of-life transmit power difference
    - Difference between:
        - Typical satellite EIRP: 64.7 dBmi (GOES-R DD1494)
        - Minimum satellite EIRP at edge-of-coverage and end-of-life: 60.5 dBmi (per GRB Downlink Specifications for Users, Rev. C)

The onset of degradation occurs at the first instance of corrected LDPC frames and no uncorrectable frames. Typically, BCH (outer code) attempts to correct frames that are uncorrectable by LDPC (inner code). Complete data loss occurs when BCH frames are uncorrectable. The interference threshold can be interpreted as the maximum RFI power at the antenna LNB input at which the GRB signal can still be successfully received.

Table 4.9-7 presents a summary of the threshold test results along with the corresponding BER values observed during each test. The RFI power levels at the LNB input are presented in the table as total channel power in dBm (per LTE bandwidth of 5 MHz), as well as power spectral density in dBW/100 Hz, so they may be compared to ITU thresholds with the same units. The BER for the onset of degradation is zero because no errors occur until RFI increases above the threshold. Refer to trip report in appendices for raw test data.

Table 4.9-7. Summary of GRB interference threshold and BER results for WCDAS.

Event	Interference type	Polarization	Maximum RFI power at LNB input		BER
			dBm/kHz	dBW/MHz	
Onset of degradation	5 MHz LTE BS downlink (1675–1680 MHz)	RHCP	−104	−181	0.00E+00
		LHCP	−89	−166	0.00E+00
	5 MHz LTE UE uplink (1675–1680 MHz)	RHCP	−90	−167	0.00E+00
		LHCP	−87	−164	0.00E+00
Data loss occurs	5 MHz LTE BS downlink (1675–1680 MHz)	RHCP	−66	−143	2.96E-04
		LHCP	−68	−145	5.68E-05
	5 MHz LTE UE uplink (1675–1680 MHz)	RHCP	−65	−142	2.40E-04
		LHCP	−64	−141	1.29E-03

The ITU thresholds are −198.8 dBW/100 Hz no more than 20% of the time (long term) or −193.6 dBW/100 Hz no more than 0.025% of the time (short term) (Draft Revision to ITU Rec. SA.1163). The ITU thresholds are lower because they were calculated using the minimum required carrier-to-noise power spectral density ratio (C/N0) of similar receivers worldwide. However, these threshold tests were specific to RT Logic T400 at WCDAS and were performed with the GRB signal at its typical operating received signal level and corresponding C/N0, not the minimum.

The table shows that the RFI threshold levels higher than −90 dBm/5MHz for the 5 MHz LTE signal and −102 dBm/15MHz for the 15 MHz LTE signal will begin to degrade the GRB signal at WCDAS. These levels apply to the 16.4 m antennas at WCDAS and CBU.

4.9.2.3.2 GRB receiver testing at NCWCP in College Park, Maryland

The GRB receiver tested at NCWCP was the Quorum Model GRB-200 connected to a 6.5 m antenna. The antenna feed and LNB downconverter receives GRB from the GOES satellite at RF center frequency 1686.6 MHz, amplifies and separates the RHCP and LHCP signals, and downconverts them to the IF center frequency 140 MHz. The RHCP and LHCP signals are sent over two separate IF coax cables, each to a four-way power splitter, which allows the signals to be connected to both the GRB-200 and an antenna controller/spectrum analyzer. The GRB-200 demodulator has two 140 MHz IF inputs, for RHCP and LHCP.

The losses were measured for the test equipment cables, splitter/combiners, connectors, and adapters used during testing. The RF gain of the Quorum antenna LNB downconverter could not be directly measured, and the typical gain of 60 dB was used from the Quorum antenna LNB specifications.

4.9.2.3.2.1 Interference threshold and BER measurements for GRB at NCWCP

Measurements were performed to determine the system sensitivity of the Quorum GRB-200. The test was performed by combining RFI with the GRB signal before feeding it into the GRB-200. The test equipment was configured as shown in Figure 4.9-10. The vector signal generator was used to create the LTE interference signal at the IF frequency.

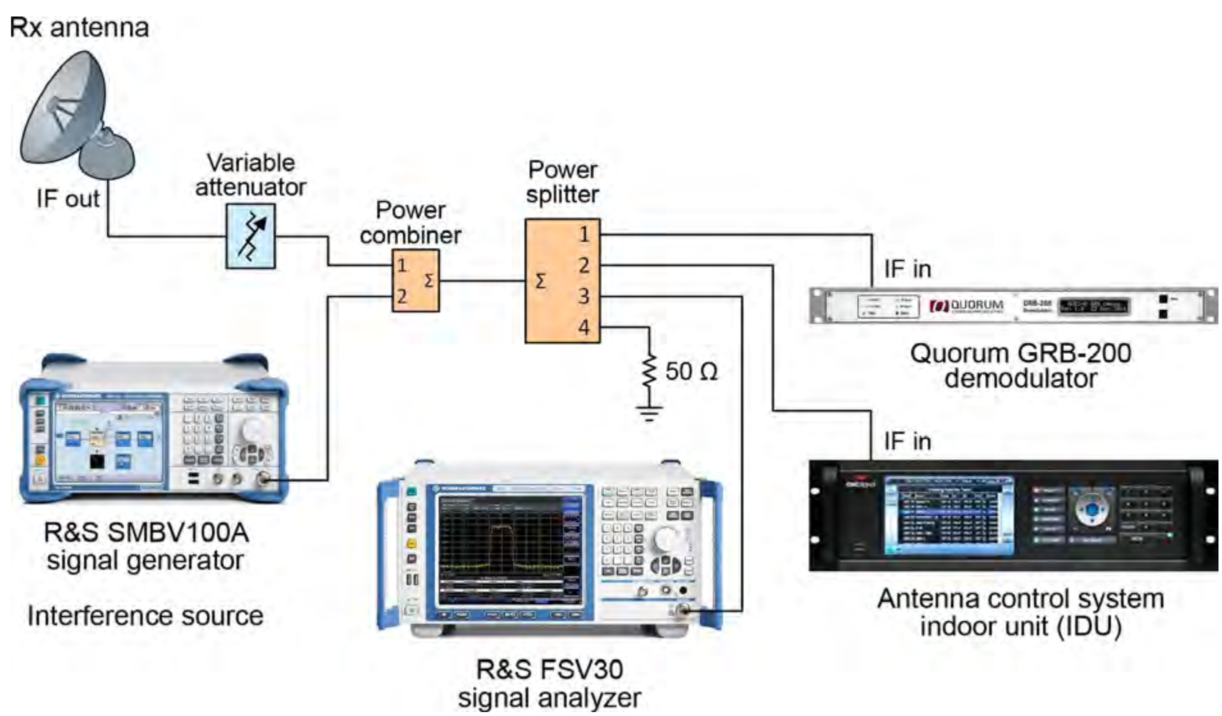


Figure 4.9-10. Interference threshold measurement test equipment configuration at NCWCP.

The GRB-200 displayed the following data items about the signal on the receiver front panel:

- Received signal strength indicator (RSSI)
- Data frames received per second
- Uncorrectable frames per second
- Energy per symbol-to-noise power spectral density ratio (ES/N0), (which in this case is actually energy per symbol-to-noise plus interference power spectral density ratio [ES/(N_0+I_0)])

The signal analyzer was configured to measure the following items:

- Channel (or carrier) power of the GRB signal at IF
- Noise plus interference power spectral density (N_0+I_0) of the system noise floor

These data items were recorded during the test and subsequently analyzed to determine the levels at which data was lost, as indicated by uncorrectable frames and decrease in $E_S/(N_0+I_0)$. Carrier-to-noise, plus interference power spectral density ratio [$C/(N_0+I_0)$], was calculated based on the measured values. $E_b/(N_0+I_0)$ was calculated from both $C/(N_0+I_0)$ and $E_S/(N_0+I_0)$. BER can be calculated as a function of E_b/N_0 or $E_b/(N_0+I_0)$.

4.9.2.3.2.2 Results for GRB RFI threshold and BER measurements at NCWCP

The GRB-200 does not report whether error correction is taking place on the front panel, which would indicate the onset of degradation. It reports only uncorrectable frames, which indicate that data is already lost. Without this information, it was not possible to compare degradation threshold results from the RT Logic T400 at WCDAS with the results of the Quorum GRB-200 at NCWCP.

The equivalent RFI power at the antenna LNB input was found by taking the power output from the signal generator, adding the difference between antenna LNB input and signal generator, and subtracting the antenna LNB gain. Next, the following adjustments were included:

- 2.5 dB subtraction for link margin
- 2.3 dB subtraction for implementation loss
    - Link margin and implementation loss based on Interface Requirements Document for the GOES-R System Space Segment to GRB Service (417-R-IRD-0002 ver. 2.8)

- 4.2 dB subtraction for GRB end-of-life transmit power difference
    - Difference between:
        - Typical satellite EIRP: 64.7 dBmi (from the GOES-R Federal Equipment Spectrum Certification)
        - Minimum satellite EIRP at edge-of-coverage and end-of-life: 60.5 dBmi (per GRB Downlink Specifications for Users, Rev. C)

Table 4.9-8 presents a summary of the threshold test results along with the corresponding BER values observed during each test. The RFI power levels at the LNB input are presented in the

Table 4.9-8. Summary of GRB interference threshold and BER results for NCWCP.

Interference type	Polarization	Maximum RFI power at LNB input when data loss occurs		BER
		dBm/BW_LTE	dBW/100 Hz	
5 MHz LTE BS downlink (1675–1680 MHz)	RHCP	−68	−145	1.62E-06
	LHCP	−70	−147	3.22E-08
5 MHz LTE UE uplink (1675–1680 MHz)	RHCP	−68	−145	4.54E-08
	LHCP	−72	−149	2.44E-11

table as total channel power in dBm (per LTE bandwidth of 5 MHz), as well as power spectral density in dBW/100 Hz, so they may be compared to ITU thresholds with same units. The ITU thresholds are −198.8 dBW/100 Hz no more than 20% of the time (long term) or −193.6 dBW/100 Hz no more than 0.025% of the time (short term) (Draft Revision to ITU Rec. SA.1163). The ITU thresholds are lower due to the fact they were calculated using the minimum required carrier-to-noise power spectral density ratio (C/N_0) of similar receivers worldwide. However, our threshold tests were specific to Quorum GRB-200 at NCWCP and were performed with the GRB signal at its typical operating received signal level and corresponding C/N_0, not the minimum. Refer to trip report in appendices for raw test data.

The above table shows that if the RFI threshold level is higher than −72 dBm/5MHz for the 5 MHz LTE signal, it will cause loss of frames for the GRB signal at NCWCP and similar sites. These levels apply to the 6.5 m antennas commonly used at other GRB sites.

4.10 Project 10. RFI Monitoring Analysis for 1675–1680 MHz Band

4.10.1 Introduction

4.10.1.1 Project objectives

Project 10 evaluates alternative methods for detecting and mitigating interference to GOES ground stations from potential commercial LTE system configurations. The project supports two SPRES program objective areas: RFI Modalities and Risks, and Mitigation Options and Feasibilities. The project has two main objectives:

- Evaluate the possibility of employing carrier identification sharing to detect and mitigate LTE base station signals.
- Perform a trade study and engineering analysis of RFI monitoring capabilities and technical specifications for protection of NOAA GOES-R ground stations, especially Wallops Command and Data Acquisition Station (WCDAS).

The monitoring system trade study evaluates and analyzes the following key factors and characteristics:

- Candidate RFI monitoring and mitigation technologies.
- Existing and future monitoring system automation approaches and architectures (e.g., cloud-based) for minimizing impact to operations.
- Technical characteristics associated with each approach.
- Current and future monitoring and mitigation capabilities (such as reconfiguring the LTE system within minutes of the monitoring system detecting a problem).
- NOAA data management systems for possible centralized or cloud applications.

4.10.1.2 Project approach

Project 10 efforts spanned four primary technical tasks. The four tasks evaluated specific aspects of a monitoring and mitigation system. Each task investigated alternative methods and technologies. A trade study evaluated options for monitoring, data management, and system automation in the context of alternative end-to-end monitoring systems.

The first task evaluated various techniques for identifying specific LTE emitters for RFI detection and mitigation. The project investigated techniques such as extracting the downlink identification (ID) from the LTE signal; LTE signal pattern analysis using autocorrelation; and geolocation methods to detect interfering emitters by their bearing and distance from the ground station. The study assessed technique performance under aggregate interference conditions as well as RFI from a single interferer.

The second task performed engineering analyses of RFI monitoring capabilities for NOAA ground stations. The study evaluated alternative carrier ID (CID) technologies as well as the architectures (e.g., hardware, data processing infrastructure) required for their implementation. Analyses included omnidirectional and directional antenna approaches; signal processing for detection and classification; and single versus multiple distributed antennas. The task evaluated the potential for integration into GOES-R ground sites with an emphasis on WCDAS.

The third task assessed monitoring system automation capabilities. The automation study included RFI prediction and detection; signal classification and emitter identification; and time required to detect RFI and identify the source. It also evaluated factors associated with automated reporting of RFI events to government and LTE operators.

The fourth task evaluated potential data management systems for recording and mitigating RFI events. The study characterized the data to be distributed and the means for its distribution. It assessed a range of alternatives including storage and management at each ground station, use of a cloud-based system, and a centralized data management system using traditional dedicated servers.

The project conducted a trade study using five alternative architectures composed of different monitoring, automation, and data-management features. The study evaluated technical, operational, and performance risks to assess the relative value of each alternative. The trade study included sensitivity analyses to determine any change to the ranking of options, with slight changes in how the various criteria were scored or weighted.

4.10.1.3 Relationship to other SPRES projects

Project 10 relied primarily on outputs from several other SPRES projects. Project 6 provided GOES site characteristics and existing data distribution architectures. These were used to determine the types of equipment at each GOES site as well as potential constraints for installing an RF monitoring system. The project used data from Projects 8 and 11 to characterize the expected RFI environments in which the monitoring system would need to operate.

4.10.1.4 Summary of findings

This project evaluated the possibility of employing carrier identification sharing to detect and mitigate LTE base-station signals, and performed a trade study and engineering analysis of RFI monitoring capabilities and technical specifications for NOAA ground station protection.

Carrier ID: Carrier ID is designed for nearby cell identification and is based on strong signal, low interference (high SNR) assumptions. Successful detection of carrier ID is low for aggregate interference conditions because the majority of events are low signal power and/or high interference (low SNR). Hence, using carrier ID likely has little benefit as a stand-alone capability, but may be good augmentation of other approaches such as spectrum power measurements. The carrier ID feature is not expensive, so benefit may outweigh incremental cost.

Critical monitoring system factors: There are multiple goals driving the RFI monitoring system design (detection sensitivity, attribution, amplitude uncertainty, cost, and complexity). RFI attribution offers significant value, especially for the identification of repeated interference cases/sources. RFI monitoring attribution would be critical if dynamic LTE mitigations are adopted by the carriers and if RFI monitoring information is used by the LTE operators. NOAA should establish capability and technical objectives for an RF monitoring system along with expected operating concept, and in particular should determine LTE operators' ability (or likelihood) of implementing dynamic mitigations.

RF monitoring design depends on auction approach: Large FCC auction geographic license ar- eas reduce RFI monitoring requirements because of the difficulty in assessing attribution and establishing mitigation among multiple carriers. License areas are less of a factor for uplink sharing than downlink sharing because downlink sharing has much larger protection areas, which would require dynamic mitigation (small uplink protection areas could be static).

RFI measurement uncertainty: The NOAA ground station antenna uncertainties create large uncertainty in the estimated RFI amplitude measured by a stand-alone monitoring system. The issue creates RFI risk for NOAA or less spectrum for the LTE operators.

RFI monitoring solutions: There is a large solution space (with costs that range from tens of thousands to several million dollars per site) that can consist of different definitions of a "good" system. A "best" solution depends on the sharing rules and system operating concept.

COTS solutions: Commercial off-the-shelf (COTS) products meet many of the goals at a significantly lower cost than custom solutions. COTS-based solutions will require some modification, such as high-gain antenna and extended data management features. NOAA should evaluate the COTS monitoring system performance. A "try before buy" assessment could be done at low cost by deploying the system at a NOAA site for several months. The evaluation would provide insights into the overall monitoring system requirements as well as the COTS software's capabilities and shortfalls.

RFIMS: An RFIMS-based solution provides much higher performance (sensitivity, angle of arrival, and data management) compared to COTS products. RFIMS doesn't include some important capabilities and would require modification to support aggregate interference measurement, amplitude uncertainty calibration, and correlation with GOES modem errors. Something similar to the RFIMS antenna design would be useful in many monitoring approaches. NOAA should consider acquiring a detailed RFIMS antenna design package and IP rights[31] to promote competition and reduce long-term acquisition costs.

RFI monitoring operations: Monitoring system operations will require a significant staff, regardless of the approach. It takes significant labor and expertise to operate (configuration, system maintenance, and troubleshooting) a distributed spectrum measurement system. The additional tasks of evaluation of data, determining cause, and establishing mitigations requires multiple staff.

4.10.2 Monitoring and mitigation system technologies

4.10.2.1 Study factors

4.10.2.1.1 The operating environment

The technical analysis began by considering the types of RFI that the system would need to detect and mitigate. LTE deployment approaches and the corresponding nature of RFI conditions determine the technologies and architectures. It is reasonable to expect that LTE systems will be deployed such that interference risks are low. Interference cases would therefore occur intermittently and under three different conditions:

- A misconfigured LTE transmitter that produces RFI from a single emitter.
- A rogue, non-LTE transmitter that produces RFI from a single emitter.
- Anomalous propagation, which produces aggregate RFI from many low-power LTE transmitters or interference from a single distant LTE transmitter.

In the case of a misconfigured emitter, the monitoring and mitigation system will need to detect and identify only a single transmitter (assuming that the band is used for LTE downlinks). The signal is likely to be weak since the tower would be sited in a location where interference to the GOES ground station is unexpected. Furthermore, the signal source would be in a fixed location. If the transmitter can be identified, then only a single LTE carrier would need to be notified to mitigate the RFI.

[31] Since the time of this project, the RFIMS contract has obtained for NOAA all IP rights (i.e., full government purpose rights).

A rogue, non-LTE transmitter could be an unauthorized user, a harmonic/intermodulation signal created by a valid transmitter at another frequency, or man-made noise. The RFI characteristics from anomalous propagation are likely to be very different than the first case. Project 8 results indicate that ducting will be a frequent occurrence at many locations, especially along the East and Gulf coasts (see Project 8). Ducting would allow signals to travel much farther due to lower signal attenuation conditions created by surface ducts and result in RFI from many (tens to hundreds) of LTE towers. Each signal would be weak and potentially below the interference threshold, but the aggregate effects from many low-power signals would generate a total interference power that exceeds the interference threshold. The signal sources may all come from a common direction or may come from many/all directions, depending on the nature of the duct. Offending LTE towers could be associated with multiple LTE carriers, resulting in a potentially complex mitigation problem.

The nature of ducting events also affects technology and system evaluations. Ducting events can propagate potentially interfering signal levels for periods of minutes to hours. The data shows that ducting events grow, dissipate, and last from tens of minutes to hours; can increase RFI strength from individual signals by more than 10 dB; and can have highly variable power within the event window.

It is also possible that an RFI event could simultaneously affect multiple GOES sites. Figure 4.10-1 shows preliminary exclusion zones of a number of sites along the East Coast derived from Project 11

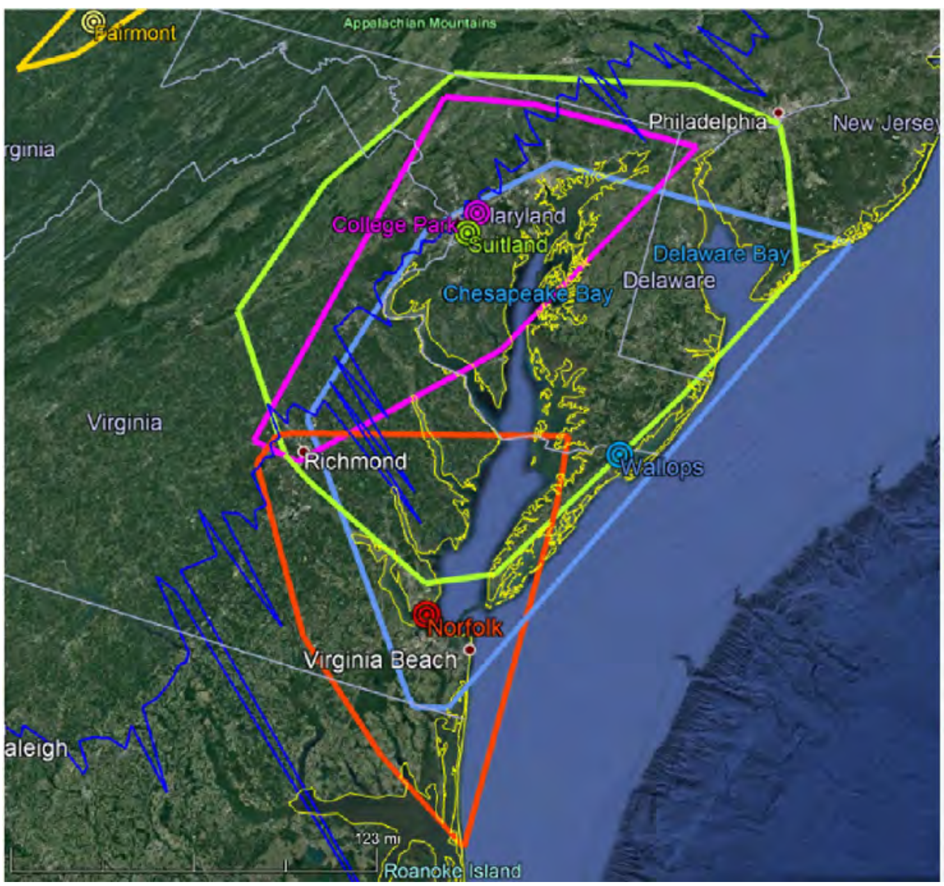


Figure 4.10-1. RFI impact assessments from Mid-Atlantic GOES earth stations using Project 11 data show significant correlation that indicates high risk of simultaneous RFI events at Wallops Island (light blue), Suitland (green), College Park (purple), and Norfolk (red).

data. The figure shows significant exclusion zone overlap from multiple GOES sites. An RFI event within the Baltimore-DC-Richmond corridor could simultaneously disrupt operations at NSOF, WCDAS, National Weather Service (NWS) in College Park, and U.S. Navy Norfolk. It may therefore be important to correlate RFI events within a given region.

In summary, there are is a wide range of RFI signal types that might be present in the 1675–1680 MHz SPRES band. These signals could be intermittent, last for hours, or last for days. These signals include:

- Single LTE transmitter at >5 km distance from NOAA site.
- Single non-LTE (e.g., FM or GMSK) modulation, pulsed modulation transmitter >5 km distance from NOAA site.
- Single non-LTE (e.g., FM or GMSK) modulation, pulsed modulation transmitter >50 km distance from NOAA site (due to ducting).
- Single non-LTE modulation from a moving aircraft.
- Broadband man-made noise from NOAA site equipment <100 m from NOAA site.
- Multiple intermittent transmitters with different modulations and/or from different transmitter locations.
- Aggregate interference from 20 LTE sources, >10 km from NOAA.
- Aggregate interference from 50 ducting LTE sources, >100 km from NOAA.

These RFI characteristics form the basis for evaluating technologies, capabilities, and system architectures considered in this study. They influence the types of detection, classification, and identification techniques that would be effective. Anomalous propagation in particular provides insight regarding the time required for detection and mitigation in those RFI environments.

4.10.2.1.2 System goals

The candidate RFI monitoring and mitigation system needs to meet the following high-level goals:

Maximize NOAA's ground link system availability. The most important goal is to protect the operation of the NOAA satellite downlinks from LTE interference. To achieve this, the RFI monitoring system needs high RFI detection sensitivity. This sensitivity needs to be well below a level that would cause loss of service to the NOAA downlink. Suggested specific sensitivity levels are discussed in Section 2.3.1. The sensitivity is a critical system tradeoff factor because it is difficult and costly to obtain.

The system needs to respond (provide alerts) quickly to an interference event so that mitigation efforts can be started promptly. This RFI monitoring response time of fractions of a second would not provide much value because reasonable RFI mitigation actions (adjusting the LTE system parameters) would likely take minutes to hours to accomplish. Our initial investigation shows that a cloud-based architecture could meet sub-second data access times. Thus, obtaining rapid RFI monitoring response times of a few seconds to 10 seconds is easily obtained with a practical RFI monitoring system, and the response time is not a critical system trade.

Minimize NOAA's monitoring operations costs. Another important goal is to minimize NOAA's cost to operate the RFI monitoring system. This includes operating the monitoring system, repairing the monitoring system, understanding the interference events, and interacting with the carriers. Many of these tasks could require specialized RF, software, and other technical skills. This is especially true because of the distributed nature of the problem (there are a large number of sites throughout the U.S.). In general, automating signal detection, alerting when events occur, and notifying the affected parties are straightforward tasks that are common to the COTS monitoring products available now. Automating signal classification, especially with the multiple signal types described in the previous section, is not readily available. Thus, automation of as many RFI monitoring tasks as possible is a critical system trade.

Maximize the spectrum sharing between NOAA and the carrier. Maximizing the spectrum available to the carrier is an important system goal. An RFI monitoring system that has a large uncertainty in measuring RFI events will waste spectrum because a low interference threshold value will have to be used to ensure that the significant events are recorded. Measurement uncertainty occurs due to multiple factors: (1) errors in compensating for the NOAA antenna pattern gain values relative to the monitoring antenna gain values, (2) equipment calibration, and (3) polarization effects. These are difficult-to-obtain features; hence, measurement uncertainty is a critical system trade.

Another way the RFI monitoring system affects sharing efficiency is the ability to determine the transmitter(s) causing interference to support mitigation activities. The interference to the NOAA site is likely to be caused by ducting; hence, the interference will be unpredictable, sudden (occur rapidly, within minutes), and irregular. If the RFI monitoring system can determine the interference source properties (transmitter identification using the carrier ID function, the fraction of interference power from each transmitter when aggregate interference occurs, the transmitter's location, of the transmitter's line of bearing), then the RFI monitoring system information can be used by the carrier to mitigate the problem.

Figure 4.10-2 shows an RFI monitoring approach that does not determine the interference source properties. This approach provides an estimate of the total interference power at the NOAA receiver. This approach is appropriate if a single carrier is deployed in the region, and the carrier did not dynamically (within minutes or hours) adapt its LTE network features to compensate for ducting conditions. Instead, the carrier used a static, large exclusion zone to deploy the LTE network.

Figure 4.10-3 shows an alternate RFI monitoring approach, which would determine the individual interference from each LTE transmitter or from LTE transmitters belonging to a specific carrier. This approach also provides an estimate of the total interference power at the NOAA receiver. This approach is appropriate if there are multiple carriers in the region, or if the carrier deployed an adaptive LTE network to adapt its LTE network features to compensate for ducting conditions. This RFI monitoring approach enables the carriers to use dynamic, small exclusion zones to deploy the LTE network.

Transmitter source properties, however, are difficult to obtain. Properties such as the transmitter identification (using the carrier ID function) require the ability to demodulate the signal. Determining the direction or location of the RFI source requires advanced signal processing or

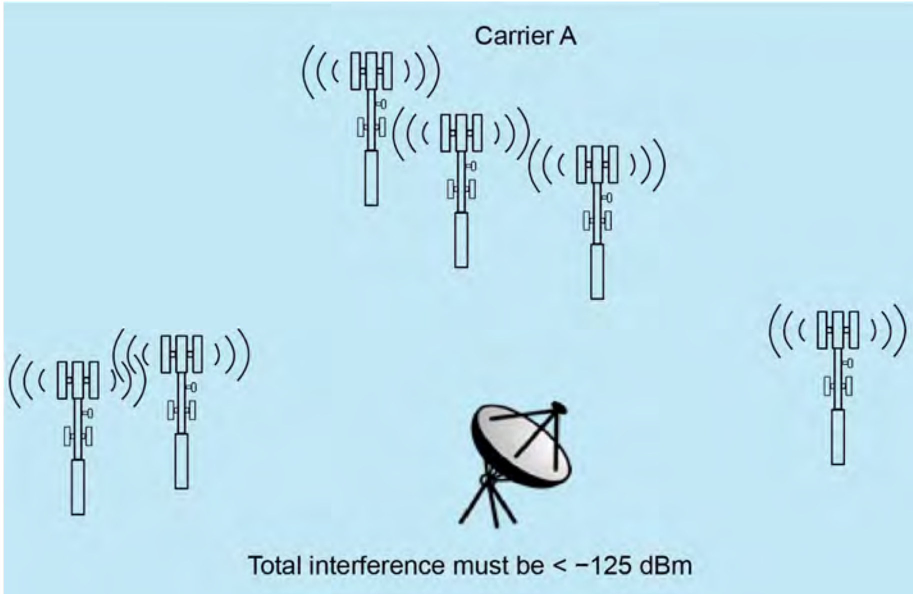


Figure 4.10-2. One potential RFI monitoring goal is to determine the total interference at the NOAA receiver.

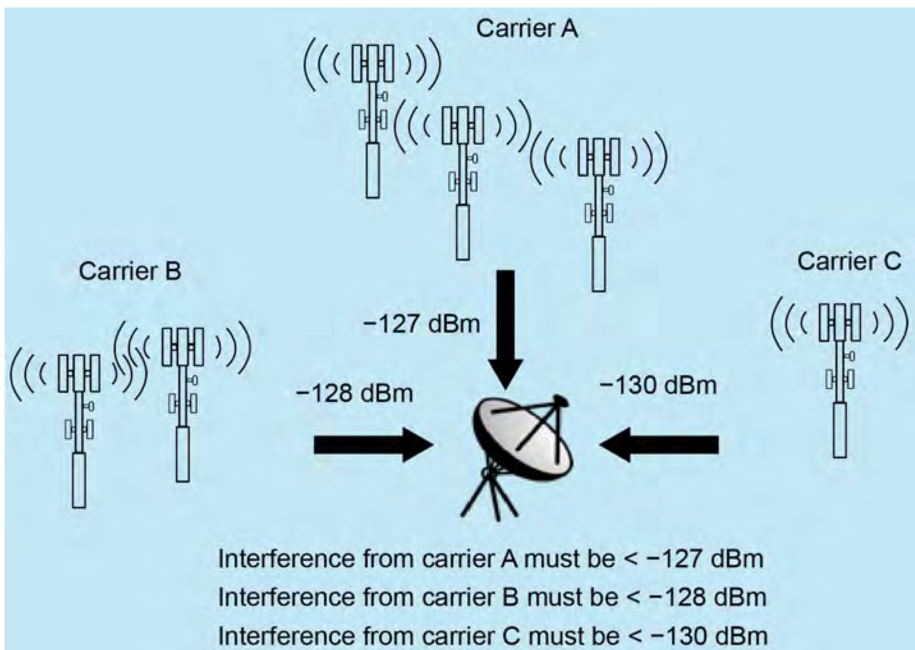


Figure 4.10-3. An alternative RFI monitoring goal is to determine the interference at the NOAA receiver from each RFI transmitter (or from each carrier).

increases the complexity of the monitoring system hardware and software. Similarly, attributing the fraction of interference power from each transmitter or carrier requires increased hardware and/or software components over the prior monitoring system. Further, the characteristics of the interference signals may limit the ability to determine these advanced properties, as is discussed in later sections. The trade study factors these considerations into the analysis.

The RFI detection probability and false-alarm rates also affect spectrum-sharing effectiveness and efficiency. Inherent limitations of monitoring systems will influence sharing capabilities. Some monitoring approaches may allow high-sensitivity detection and mitigation before RFI reaches levels that cause harm to GOES data operations. The level at which a monitoring system can detect RFI is influenced by system designs as well as background RF signals and noise. Detection thresholds would need to be set at low false-alarm rates to avoid unnecessary alerts. Further, monitoring systems must also be able to distinguish between interference types such as LTE versus noise from other sources to avoid implementing LTE mitigations that are not required and do not solve the problem.

4.10.2.1.3 Exclusion zones

Potential Data Collection Platform (DCP) and GOES Rebroadcast (GRB) exclusion zones include:

- Suitland DCS exclusion zone for LTE uplink
- Suitland DCS east exclusion zone for LTE downlink
- Suitland DCS west exclusion zone for LTE downlink
- Cellular market areas (CMA) (various colors)

The large exclusion zones associated with LTE downlink use in 1675–1680 MHz impact many CMAs, including 22 different CMAs that intersect the Suitland DCS downlink exclusion zone. The smaller exclusion zones associated with LTE uplink deployments cross fewer CMAs, including three CMAs that intersect the Suitland DCS uplink exclusion zone. Point of reference: Advanced Wireless Service Auction 3 (AWS-3) data sets show multiple carriers are within the polar operational environmental satellites (POES) coordination zone.

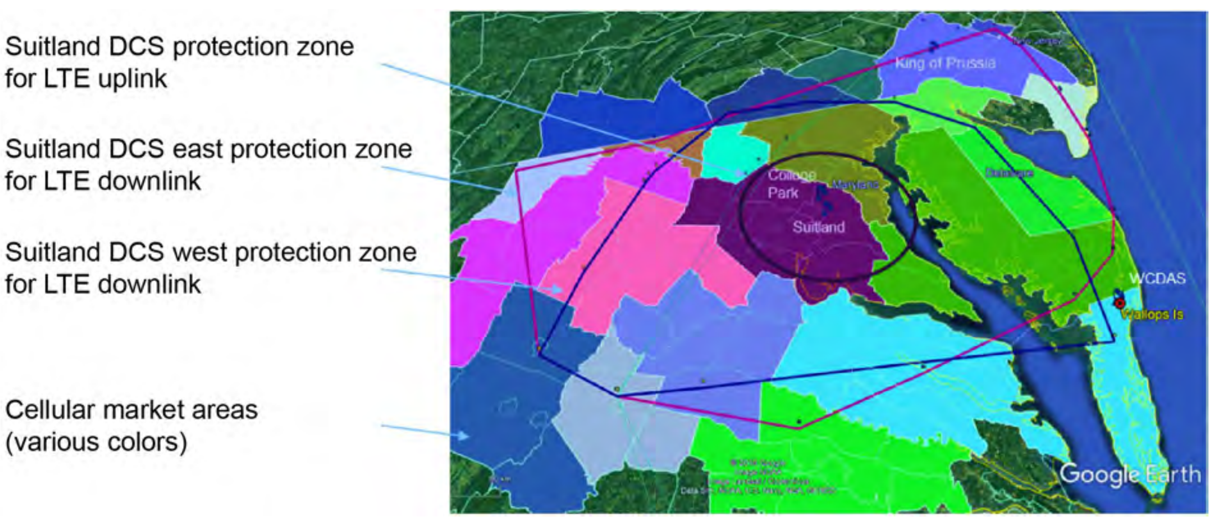


Figure 4.10-4. Potential DCS and GRB exclusion zones based on Project 7 analysis.

Figure 4.10-5 shows that multiple CMAs in a protection area drive attribution performance and mitigation complexity.

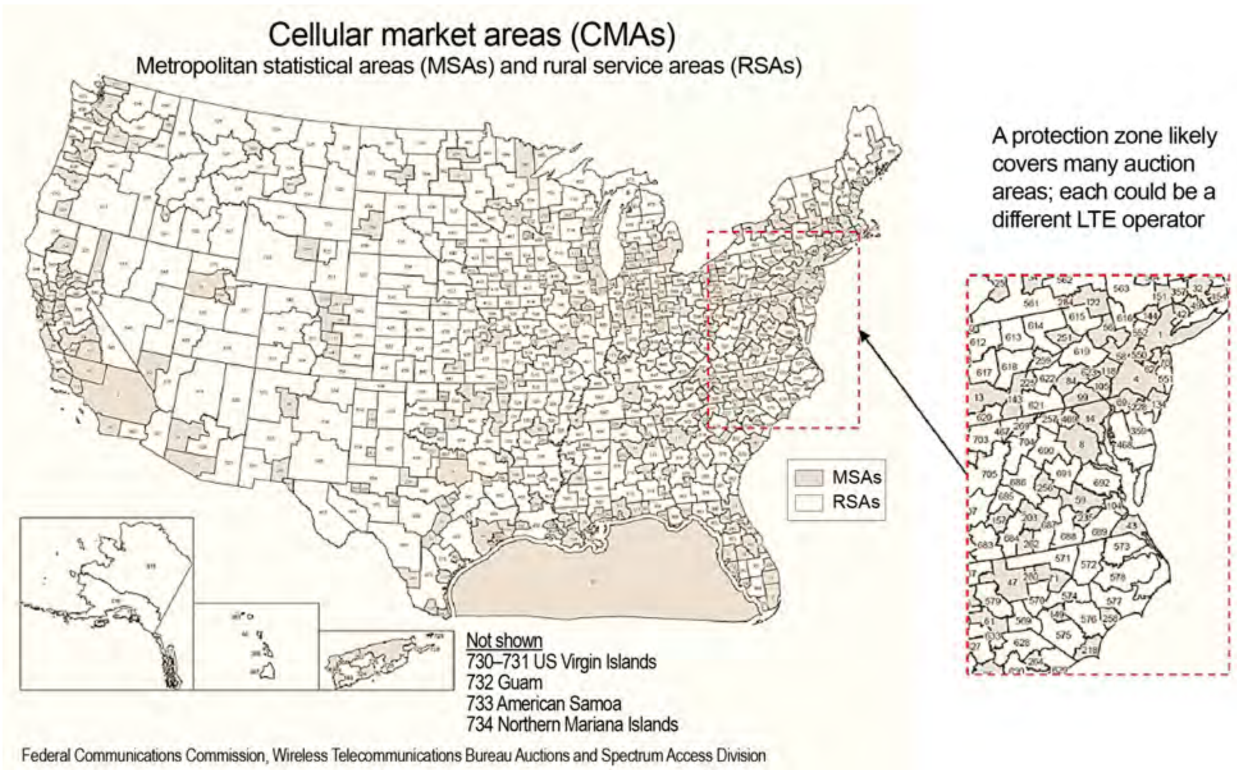


Figure 4.10-5. An exclusion zone likely covers many auction areas; each could be a different LTE operator.

4.10.2.1.4 System architecture

An RF monitoring and mitigation system for protecting GOES downlink operations against interference from LTE systems using the 1675–1680 MHz band has many architectural, operational, and technical factors that determine effectiveness. This project specifically investigates three aspects of the system: RF monitoring, system automation, and data management. Each of these is analyzed independently in the following sections.

These three aspects, however, are interdependent and cannot be effectively evaluated independent of each other. The value of one option in one of the areas depends on the overall system goals and the features instantiated by options in the other areas. For example, the type and amount of data collected by a monitoring subsystem will determine which data management and automation capabilities may be preferred. The trade study analysis that follows the individual evaluations therefore defines alternative systems with a range of operational concepts and incorporates different capabilities for implementing them.

Figure 4.10-6 depicts a notional/reference architecture that maps monitoring and mitigation system capabilities to functions. The monitoring subsystem needs to detect and classify the signal, and may also need to identify the interference source (equipment and/or operator). Data management is responsible for handling the data produced by the monitoring subsystem so that

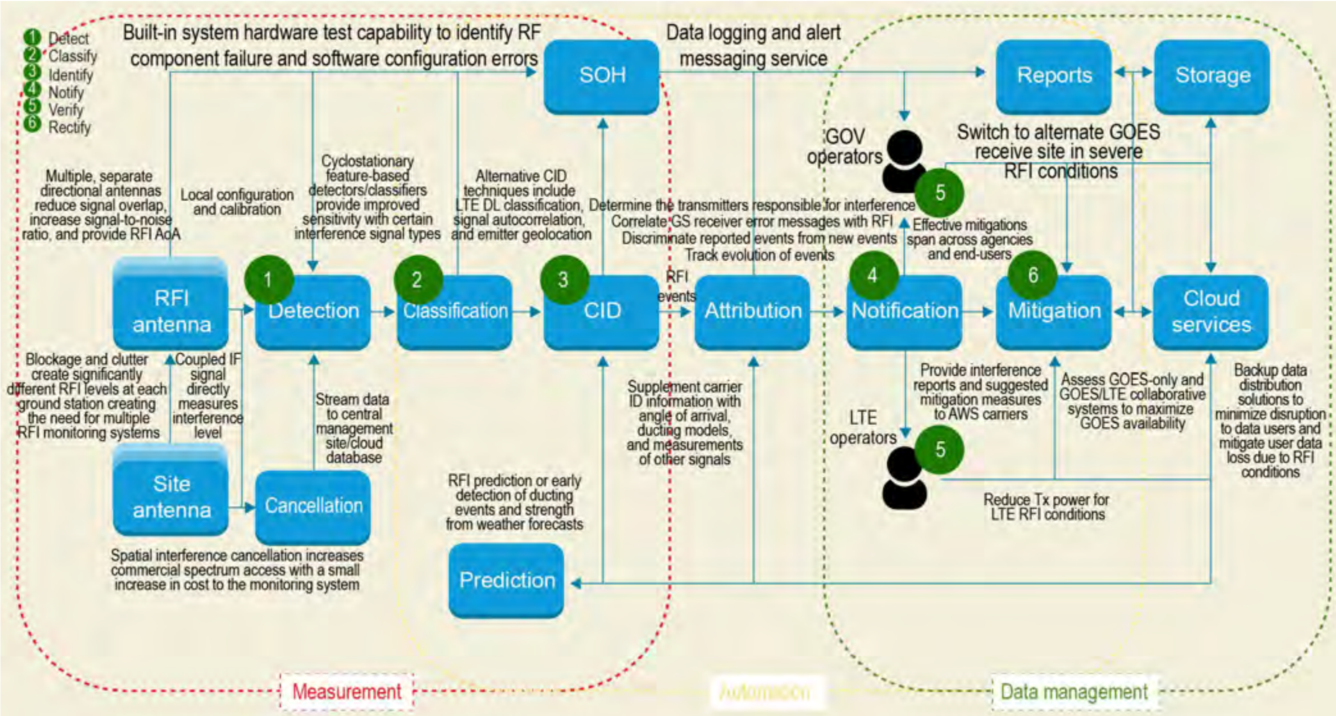


Figure 4.10-6. RF monitoring system consists of three major components: measurement, automation, and data management.

NOAA and possibly LTE operators can be notified. Data may also provide information for developing solutions for rectifying the RFI. System automation spans monitoring and data management, identifying which functions can be machine-driven and which functions require (or benefit from) human intervention.

RFI monitoring and mitigation system

In Figure 4.10-7, the green circles represent the main functions of the RFI monitoring and mitigation system.

1. Detect is the ability of the RFI monitoring and mitigation system to detect an RFI event.

2. Classify is the ability of the RFI monitoring and mitigation system to classify the detected RFI event into LTE or non-LTE signal.

3. Identify is the ability of the RFI monitoring and mitigation system to identify the location and source of the RFI event.

4. Notify is the ability of the RFI monitoring and mitigation system to notify a government or LTE operator of the RFI event.

Figure 4.10-7. Six main functions of the RFI monitoring and mitigation system.

5. Verify is the ability of the RFI monitoring and mitigation system to determine the responsible party of the RFI event.

6. Rectify is the ability of the RFI monitoring and mitigation system to enable the mitigation of the RFI event.

Figure 4.10-8 depicts a notional/reference architecture that maps monitoring and mitigation system capabilities to functions. The monitoring subsystem needs to detect and classify the signal, and may also need to identify the interference source (equipment and/or operator). Data management is responsible for handling the data produced by the monitoring subsystem so that NOAA and possibly LTE operators can be notified. Data may also provide information for developing solutions for rectifying the RFI. System automation spans monitoring and data management, identifying which functions can be machine-driven and which functions require (or benefit from) human intervention. For the 1675–1680 MHz band, this architecture overlays interference mitigation (black dotted line), with extensive collaboration. It assumes that the carrier's LTE equipment can support dynamic (within minutes) changes to its operation configuration and that the carrier is using the NOAA RF monitoring and mitigation system to determine the interference source parameters.

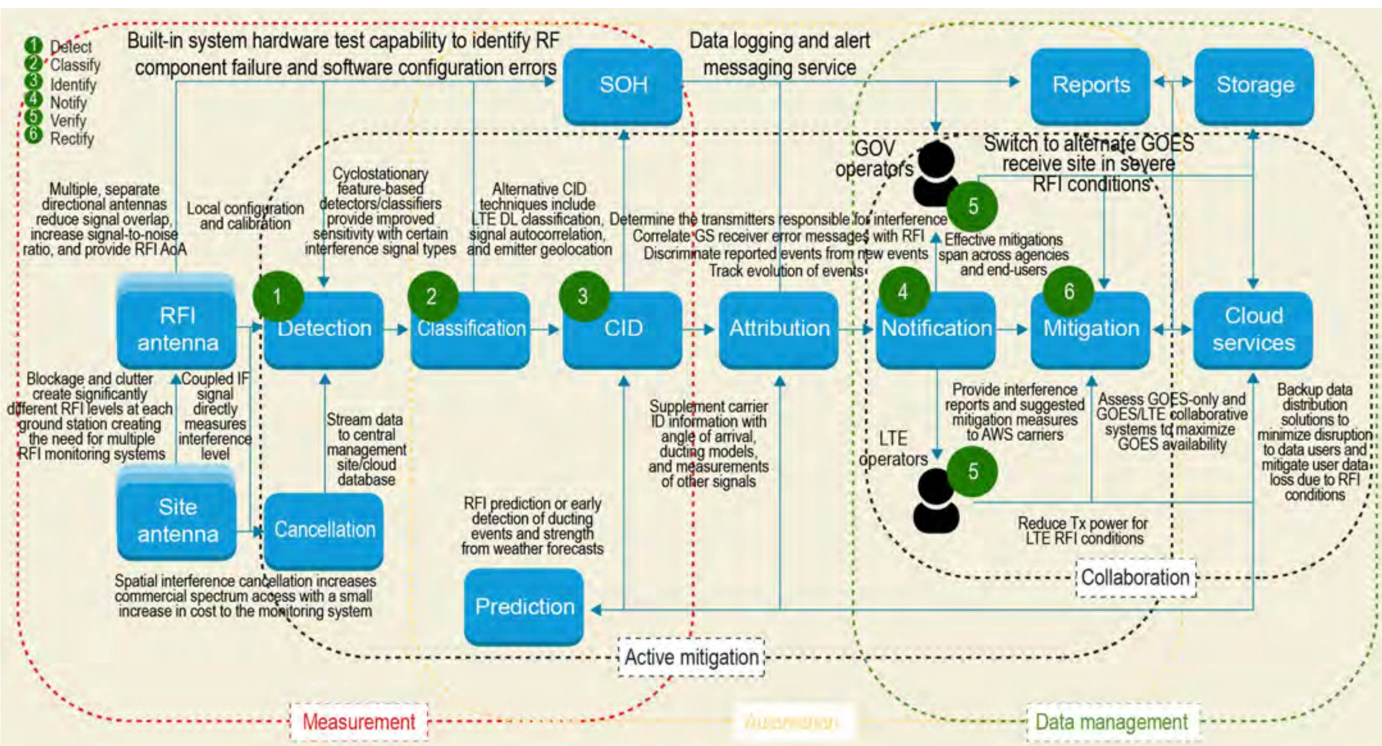


Figure 4.10-8. Notional architecture with active mitigation and collaboration capabilities added.

Table 4.10-1 provides definitions of all the capabilities in the notional architecture.

Table 4.10-1. Notional architecture capability definitions.

System capability	Definition
RFI antennas	The ability of the system to provide separate, multiple directional antennas to reduce signal overlap, to increase signal-to-noise ratio (SNR), and to provide RFI AoA.
Detection	The ability of the system to detect an RFI event.
Classification	The ability of the system to classify the detected RFI event into LTE, non-LTE, or other signals.
Identification	The ability of the system to identify the location and source of the RFI event.
Attribution	The ability of the system to determine the transmitters responsible for the interference, to correlate GS receiver error messages with RFI to discriminate reported events from new events, and to track evolution of events.
Notification	The ability of the system to provide alerts to government and LTE operators, to provide interference reports, and to suggest mitigation measures and plans.
Active mitigation	The ability of the system to provide rapid detection and automated mitigation for different RFI events (local versus geographic, by carrier versus by NOAA, tower power control versus site switchover, etc.), and mitigations spanning across agencies and end users.
Collaboration	The ability of the system to enable coordination between NOAA and LTE carriers to separately or jointly mitigate RFI events in various regions during ducting conditions to maximize GOES availability.
Cloud services	The ability of the system to provide web access services and backup data distribution solutions to minimize disruption to data users and to mitigate user data loss due to RFI conditions.
Storage	The ability of the system to provide adequate short-term storage and long-term archiving for all related RFI event data.
Reporting	The ability of the system to generate RFI event reports, SOH reports, security reports, diagnostics, and analytics reports.
State of health (SOH)	The ability of the system to provide SOH of the system hardware via test, local configuration and calibration, and repair.
Prediction	The ability of the system to predict RFI events based on history.
Cancellation	The ability of the system to provide spatial interference cancellation to increase commercial spectrum access with a small increase in cost to the monitoring system.
Site antenna	The ability of the system to provide coupled IF signal directly to site antenna to measure interference level.

4.10.2.2 Carrier ID performance

The carrier ID[32] capability determines the transmitter ID of LTE signals. The carrier ID performance level is critical to the monitoring design because the carrier ID provides a cost-effective method to identify the RFI source and to help mitigate the problems. If carrier ID works well, then the monitoring system could rely on this mechanism as the fundamental method to detect and characterize RFI. If carrier ID does not work well, then supplemental signal detection and classification approaches must be used.

LTE deployment approaches and the corresponding nature of RFI conditions determine the effectiveness of emitter ID technologies. Conventional LTE carrier ID methods extract the carrier ID

[32] Cell ID is not the same as carrier ID. Cell ID is what is called PCI (combination of PSS+SSS). Carrier ID is PLMN ID. This analysis is approximately true for reception of either message type.

information from an LTE signal's system information block (SIB). The SIB is embedded in the LTE protocol frame and is extracted by synchronizing a receiver in time and frequency to the signal of interest and decoding the SIB. Decoding requires a minimum signal power relative to other background signals and noise (i.e., the signal-to-interference-plus-noise ratio, or SINR).

Insights from Project 8 and experience with LTE protocols and signal processing show that a conventional approach to carrier ID may not work well for NOAA's intended purpose. Most interference cases are unlikely to produce sufficient SINR to demodulate the SIB and enable emitter identification. Interference is most likely to occur under non-standard propagation conditions. With weak ducting, RFI comes from several emitters that exist just beyond an exclusion zone and consists of several low-power signals. With strong ducting, RFI comes from many (hundreds) of emitters across a potentially large geographic area. The received power histogram in Figure 4.10-9 produces low SNR values for many of the LTE signals. The low SINR results from the fact that each signal for which cell ID information is to be extracted is one of many low-power, co-channel signals.

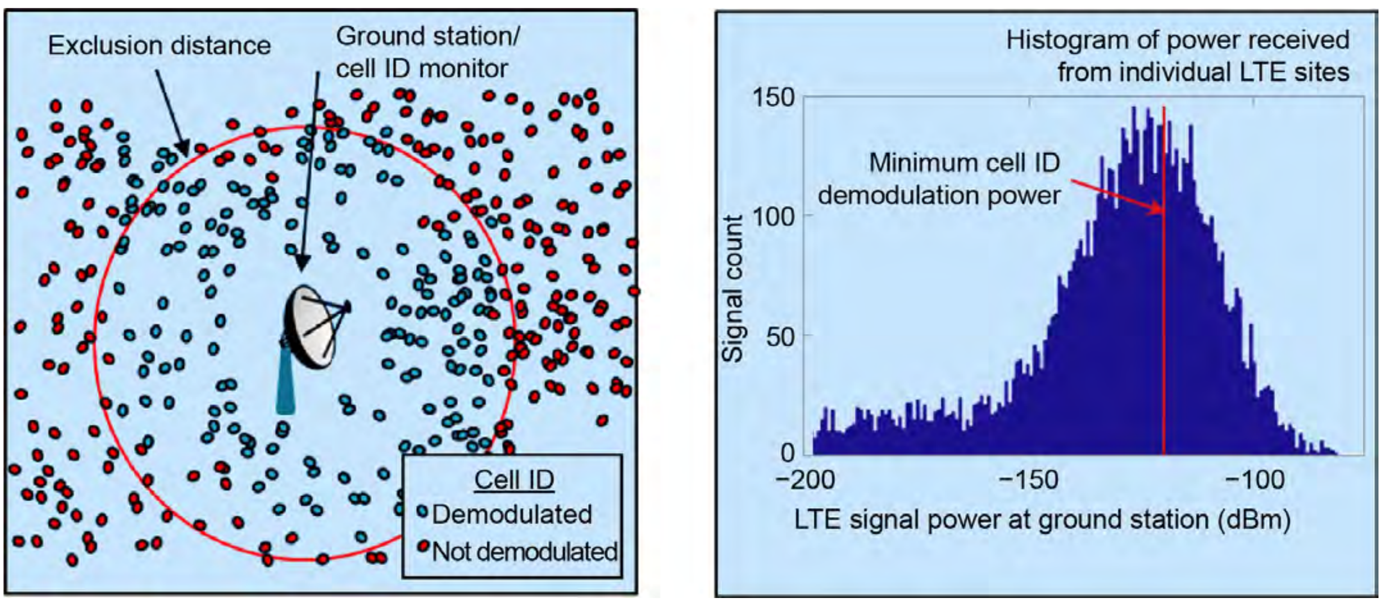


Figure 4.10-9. The carrier ID spectrum-sharing approach issues.

Project 10 evaluated the ability to identify individual interference sources under a range of propagation environments and LTE deployment scenarios. This included data from the Project 8 anomalous propagation analysis, which is the most likely mode of interference. This data defines the power of each individual LTE signal received at the ground station. A model was developed to determine the expected number of overlapping LTE signals and calculate the resulting SNR for each signal. Details of the analysis can be found in Appendix H. The analysis quantified the likelihood of successful carrier ID to be approximately 0.05% across several different cases, including standard atmosphere (non-ducting) conditions.

Carrier ID conclusions

The analysis shows that extracting the carrier ID from interfering LTE signals has limited potential in the expected interference environments. Extracting the carrier ID from an LTE downlink transmission requires that the receiver process several signals to extract the SIB1 message containing the carrier ID. 3GPP standards and LTE signaling assume that a receiving device (e.g., an LTE handset) would see only a few downlink signals. The receiver would furthermore seek to find the strongest signal, which would have strong SNR (and therefore low interference levels). The environment predicted by Project 8 analysis indicates that the likely interference conditions consist of many low-power LTE signals. Each signal would have low SNR, which makes carrier ID extraction difficult. The simulations performed in this project show that the probability of extracting carrier ID is less than 1%, even in non-ducting cases.

The analysis assumes that LTE deployments would be such that no LTE towers would cause high power interference (e.g., via the use of exclusion zones). Logically, LTE deployments would be permitted only if they do not cause interference to a GOES system under some range of propagation conditions. As with Citizens Broadband Radio Service (CBRS) spectrum sharing, commercial deployments will be established such that they do not interfere for some high percentage of cases (e.g., 95%). Other than rare occurrences of rogue or misconfigured emitters, interference would therefore occur only when LTE signal power levels rise at the GOES receiver due to changes in atmospheric conditions that reduce atmospheric attenuation beyond the planned levels. These can occur due to temperature and humidity variations as well as due to the formation of ducts. Under weak attenuation changes, low levels of interference may come from a few towers, while ducting can produce high levels of interference from hundreds of towers. Project 8 analysis indicates that the East Coast and Gulf Coast of the U.S. encounter frequent anomalous propagation due to atmospheric ducting that could often produce significant RFI. Other regions in the U.S. experience much lower occurrences and severity of anomalous propagation. In either case, the dominant nature of the RFI would be the aggregation of many low-power LTE signals, which results in low SNR for each signal and makes carrier ID extraction unlikely.

4.10.2.3 Monitoring system approaches

The study investigated the broader range of spectrum monitoring trades and technologies in addition to the carrier ID approach discussed in the previous section.

4.10.2.3.1 Monitoring sensitivity trade

Table 4.10-2 shows different monitoring system sensitivity level capabilities that the system could be designed to provide and the value (potential action when this level was reached). The selection of the minimum monitoring level significantly impacts the monitoring system's antenna gain

Table 4.10-2. Value of different sensitivity capabilities.

Potential sensitivity capability	Value
Harmful interference (bit error rate limit)	Create urgent request to carrier to stop transmitting.
Interference protection criteria (1/3 link margin)	Provide warning to carrier to modify their operations.
0 dB INR: impact limit	Provide update to carrier on potential issue (potentially provide early warning of ducting events).
−10 dB INR: policy limit	Collect statistics and trends (potentially provide early warning of ducting events).

and signal processing. The “harmful interference limit” is when the interference starts to cause data loss and errors. The next lower sensitivity level is the “interference protection criteria,” which is when the interference accounts for one-third of the satellite downlink margin. The “impact limit” is when the interference is equal to the receiver noise level. The “policy limit” is the agreed-on interference that the LTE system is designed to cause, which is nominally −10 dB INR.

To illustrate, example values can be determined assuming that the received satellite signal was −90 dBm, the receiver noise floor was −117.6 dBm, and satellite signal modulation must be 15 dB above the signal plus interference to avoid harmful interference. In this case, the link margin is 12.6 dB (−90 dBm −15 dB + 117.6 dBm).

- The harmful level is −105.7 dBm (this is approximately 15 dB below the signal level and removes all of the margin).
- The interference protection criteria level is −110.1 dBm (approximately equal to −90 dBm −15 dB −12.6 dB/3).
- The impact limit is −117.6 dBm (equal to the noise).
- The policy limit is −127.6 dBm (10 dB below the noise).

Figure 4.10-10 shows the increasing level of difficulty in obtaining lower sensitivity levels, and even more so in obtaining transmitter identity and location information relative to detecting interference. Combining the objectives of obtaining low sensitivity, transmitter identity, and location information greatly increases the monitoring system complexity and cost. The importance of achieving this combined goal is potentially not worth the cost. Obtaining detailed transmitter information at the policy sensitivity limit would be useful for determining trends on the LTE system operations, while obtaining detailed transmitter information at the harmful interference sensitivity limit would be critical in immediately mitigating critical problems impacting NOAA operations.

Difficulty →

R = requirement
O = objective

		Monitoring system objective			
		High detection probablility	Identify signal type	Determine angle of arrival	Determine transmitter location
Sensitivity requirement	Harmful interference (BER limit)	R	R	R	O
	Interference protection criteria (1/3 link margin)	R	R	R	O
	0 dB INR – impact limit	R	O	O	O
	−10 dB INR – policy limit	O	O	O	O

↓ Difficulty

Figure 4.10-10. Monitoring sensitivity requirements and monitoring system objectives.

4.10.2.3.2 Antennas type trade

Variations in monitoring antenna configurations have system size, cost, and complexity impacts. Table 4.10-3 shows that antenna selection depends on system goals, expected interference, and the system budget. There are commercial spectrum monitoring systems that use each of these approaches. There is no obvious best antenna choice for the NOAA problem, and the entire system needs to be considered for this selection.

Table 4.10-3. Antenna configuration trade.

Antenna design alternative	Pros	Cons
Omni antenna	• Easy installation • Low cost	• Low sensitivity
Digital beamforming using an array of omni azimuth antennas	• Provides AoA • Improved sensitivity	• High cost • Large antenna footprint • Might not work with aggregate interference • Requires digital beamforming
Array of directional antennas	• Provides AoA • Highest sensitivity • Works with aggregate interference	• High cost • Large size
Distributed array of TDOA antennas	• Provides transmitter geolocation or AoA depending on the geometry	• Medium cost due to backhaul and multiple widely spaced antennas • Low sensitivity (especially with AoA)

The key antenna trade factor is sensitivity. The following quantifies the directional antenna sensitivity benefit. Figure 4.10-11 shows the monitoring scenario. The monitoring system uses a separate antenna to estimate interference power that is input to the ground station antenna. The GOES satellite has an equivalent isotopically radiated power (EIRP) of approximately 60.3 dBm and free space path loss to a typical site of 189.7 dB. The ground station has an antenna gain of 39 dBi, which provides a power level of −90.4 dBm at the antenna feed. The noise power with a 5 MHz signal bandwidth and 25.1 K front-end noise figure is −117.6 dBm. The incident interference power at the ground station has variable power at ground station feed. The ground station antenna gain is approximately −10 dBi toward the source of the interference. The monitoring antenna gain toward the interference is 0 dBi to 20 dBi, depending on the monitoring system design.

An effective monitoring system needs to detect RFI before it affects GOES data reception. Figure 4.10-12 illustrates the benefit that increased sensitivity or gain provides for a monitoring system. The figure plots the received interference and desired signal power into the monitoring and satellite ground station antenna versus the incident interference power for omni and directional monitoring antennas. The horizontal purple curve shows the −90.4 dBm GOES satellite signal power at the antenna feed. The horizontal brown curve shows the satellite receiver and monitor receiver −117.6 dBm noise power. The sloped red curve shows the interference power into the NOAA ground station receiver. If the incident interference power is −120 dBm (measured with an omni antenna), then the interference power into the NOAA receiver will be −130 dBm (due to the −10 dBi antenna gain). The interference power into the monitor receiver is higher due to the omni 0 dBi or the 20 dBi

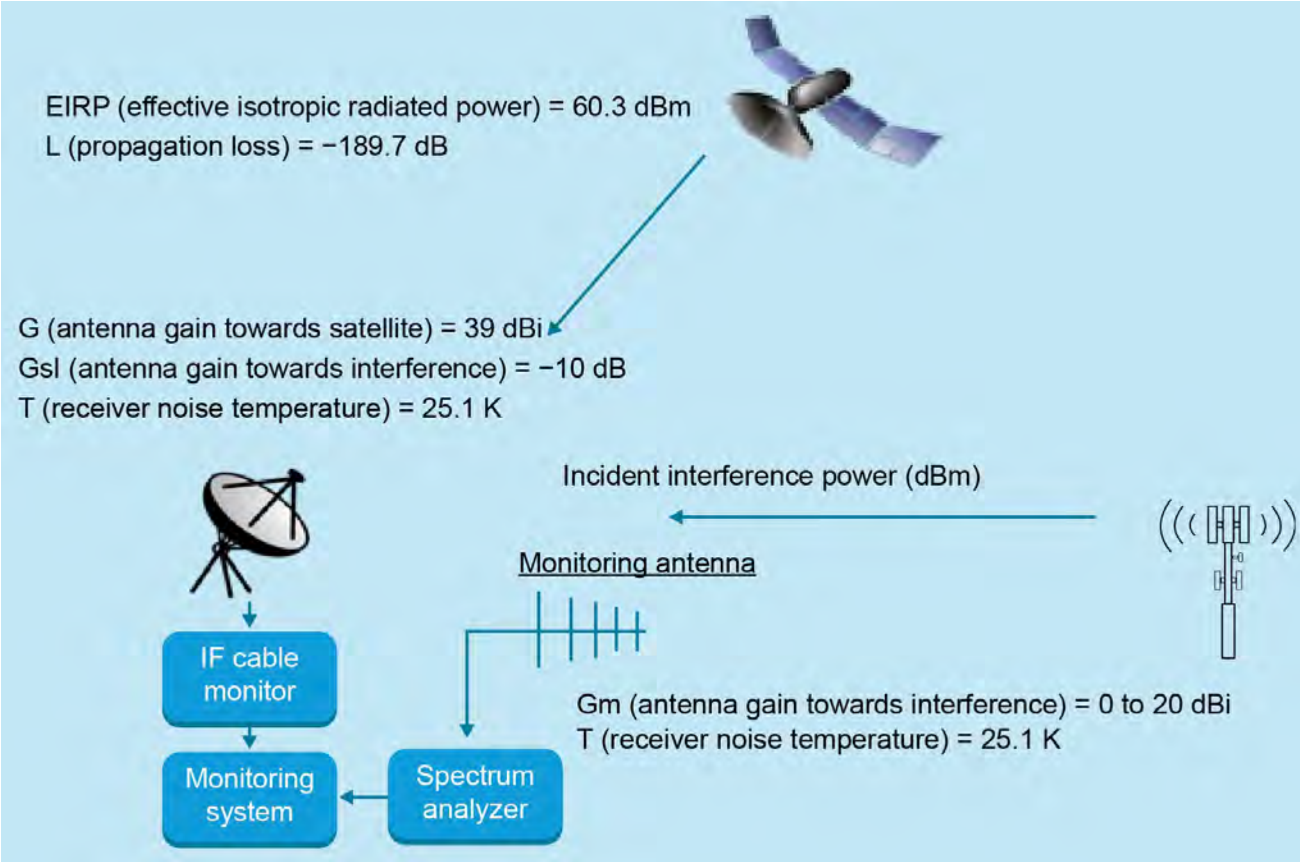


Figure 4.10-11. Monitoring system scenario example.

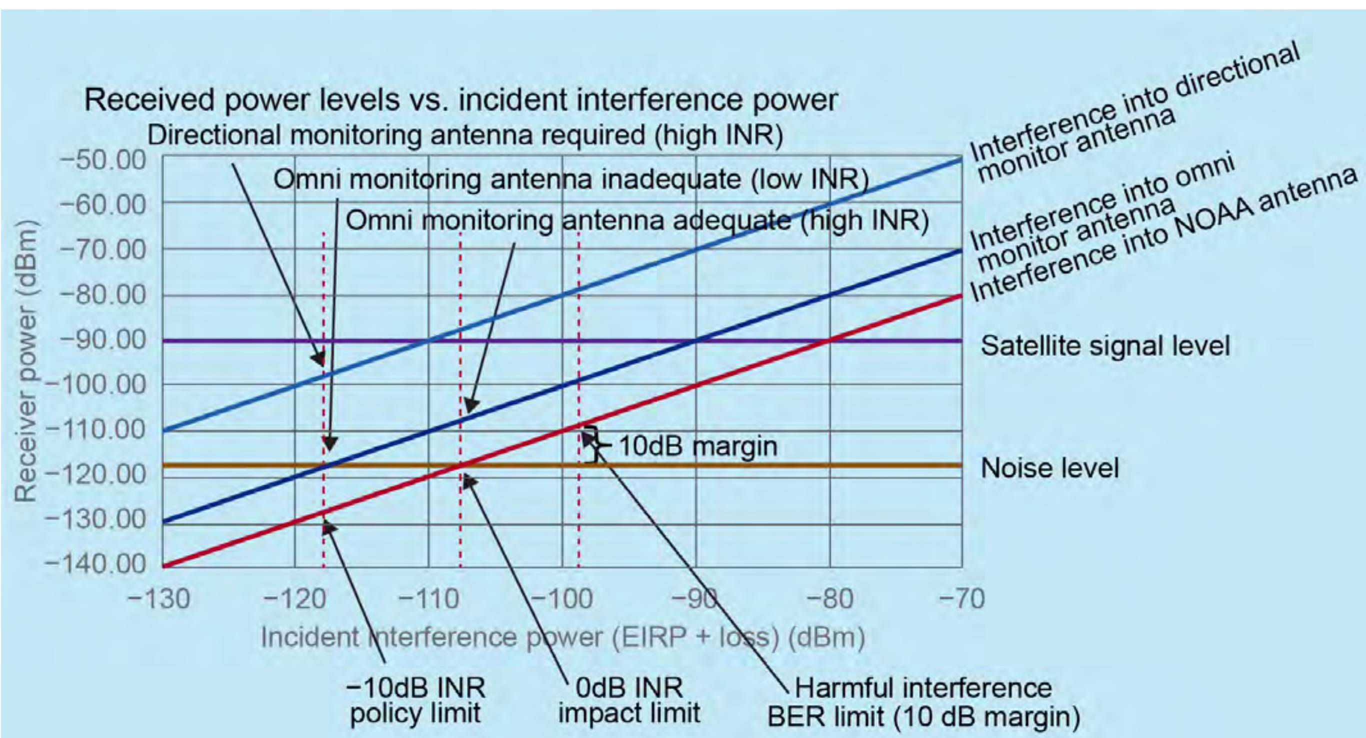


Figure 4.10-12. Received interference and desired signal power into the monitoring and satellite ground station antenna versus the incident interference power for omni and directional monitoring antennas.

monitor antenna gain. Thus, if the RFIMS requirement of −10 dB interference-noise ratio (INR) detection is applied to the 1675–1680 MHz band monitoring system, then directional monitoring antennas must be used.

The three red dashed vertical lines show different potential sensitivity capability levels (policy limit, impact limit, and harmful interference). If the monitoring system goal was to detect interference at the −10 dB INR policy limit, then the 0 dBi monitoring antenna gain system would have to operate on the interference signal, which is same power level as the noise level. This operation would be problematic, especially with aggregate interference, because the signal would be too weak for classification and for angle of arrival (AoA) determination. To avoid this problem, a 20 dBi directional monitoring antenna should be used to boost the interference signal level well above the noise.

If the monitoring system goal was to detect interference at the impact limit or the harmful interference limit, then the 0 dBi monitoring antenna gain system would operate on the interference signal, which is 10 dB or more above the noise level. This operation would be successful because this is a high enough signal level for classification and for AoA determination.

4.10.2.3.3 Polarization trades

All of the above antenna approaches need to consider the monitoring system polarization. The monitor antenna polarization should be aligned with the RFI source polarization to avoid polarization mismatch losses and uncertainties in estimating the RFI amplitude. A wide variety of LTE/5G polarization strategies and antennas (+/−45° slant, horizontal, or vertical) are likely to be deployed.[33] Thus, an omni-directional system will likely consist of a two-channel system that contains a dual polarization antenna. All of the above antenna approaches could:

- Ignore the polarization effects and assume that the polarization effects are random, will vary during an event, and are not critical. This would provide significant antenna, receiver, and signal processing cost savings.
- Implement a dual-polarization monitoring antenna, and use RF switches to alternatively sample each polarization. This would provide significant receiver and signal processing cost savings.
- Implement a dual-polarization, dual-channel monitoring system to continuously measure both polarizations. This approach doubles the receiver and signal processing costs.

As will be seen in the following section, using a separate monitoring antenna to estimate the interference at the NOAA receiver introduces significant measurement uncertainty. Thus, depending on the relative weight of cost and complexity, ignoring the polarization effects may be the best option.

[33] 5G Americas, "Advanced Antenna Systems for 5G," *5G Americas White Papers* (August 2019), https://www.5gamericas.org/wp-content/uploads/2019/08/5G-Americas_Advanced-Antenna-Systems-for-5G-White-Paper.pdf; CommScope, "2HH-33A-R4 8-port Multibeam Antenna," accessed May 12, 2020, https://www.commscope.com/catalog/antennas/pdf/part/96840/2HH-33A-R4.pdf.

4.10.2.3.4 Monitor/IF signal calibration trade

It is critical to calibrate the RFI strength at the NOAA receiver IF signal to the RFI level measured with an external monitor for accurate transmitter attribution. Figure 4.10-13 shows the measured and modeled satellite ground station antenna gain versus azimuth of a typical 1675 MHz satellite ground station antenna. There is more than 10 dB of gain variability with angle. For example, if there were two equal RFI sources at 25° azimuth and 150° azimuth, the RFI monitoring system would estimate that the RFI sources had identical impact. However, the 25° azimuth RFI source would have more than 10 dB impact compared to the other RFI source.

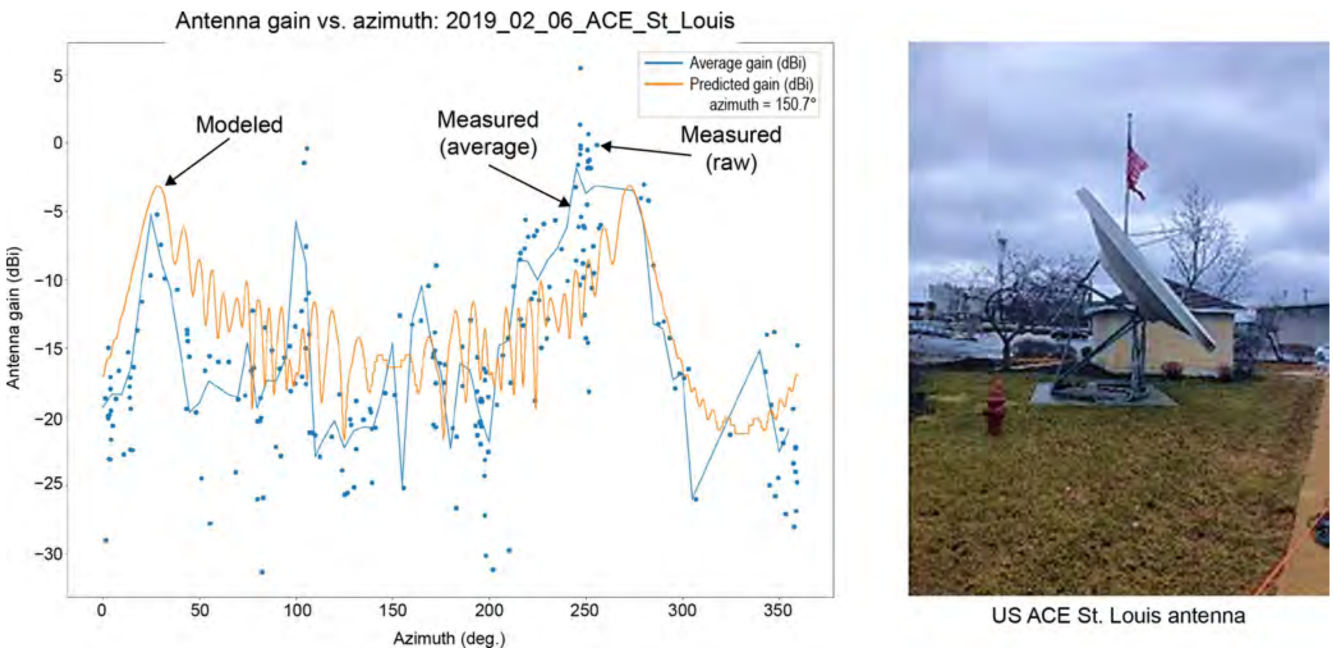


Figure 4.10-13. Measured and modeled satellite ground station antenna gain versus azimuth shows high variability with angle.

This uncertainty between the RF monitoring predictions and the actual interference is one of the most significant RF monitoring issues. Analysis of the exclusion zone sizes using the maximum NOAA gain values and the modeled NOAA antenna gain pattern should be performed to see the impact on the amount of spectrum available to the carriers. Also, the specific RF monitoring system AoA method should be analyzed to determine its accuracy with both single RFI and aggregate RFI conditions.

4.10.2.3.5 NOAA receiver IF signal monitoring trade

One RFI detection approach monitors the GOES receiver IF signal for RFI. This option uses the GOES ground station antenna(s) for monitoring and attains RF signals directly from the GOES receiver. The signals contain the GOES downlink signals in addition to the interfering signals. The monitoring system must use filtering and signal processing techniques to extract the interfering signals from the combined signal. One technique is to extract the interfering signal components by using samples of the interfering signal recorded on an external omni antenna.[34] While the

[34]The signals recorded with the omni antenna will contain negligible signal power from the GOES downlink due to factors such as mismatches in polarization between the GOES signal and monitoring antenna.

GOES antenna amplifies the GOES signal more than the LTE signal, the omni antenna primarily detects the LTE signal. This approach has limitations in sensitivity relative to other options and is unlikely to provide beneficial performance when aggregate interference is present. It is likely to have high integration costs because it interfaces physically and electronically directly with the GOES ground station.

The issue here is feeding the digitized IF spectrum and other measurements that indicate interference into a computer monitoring system via the GOES local area network (LAN). This would require data to transit the GOES security boundary, which is currently not enabled by NOAA's security policy. This solution would therefore require a security solution to be reviewed and approved to enable monitoring data to transit the GOES LAN for remotely monitoring the system. This approach directly associates interference events (NOAA modem errors) to external monitoring (best transmitter attribution). The investigation is to trade separate monitor antenna versus ground station IF coupled signal. Separate monitor antennas enable directional antennas to improve interference detection while coupled IF signal directly measures the interference level. Table 4.10-4 provides a summary of this trade.

Table 4.10-4. IF coupled signal trade.

Design alternative	Pros	Cons
Coupled IF signal	• Low cost • Measures the interference level directly	• Limited sensitivity (interference is masked by satellite signal) • Requires NOAA security approval
Separate antennas: signal subtraction/ cancellation	• ~20 dB sensitivity improvement • Improves interference detection	• Expense

4.10.2.3.6 COTS spectrum monitoring hardware trade

A spectrum monitoring system should measure the spectrum to at least the sensitivity level of the intended receiver. Most modern receivers have a low noise figure (NF) (<5 dB), which is a much lower NF than a spectrum analyzer's NF. A typical spectrum analyzer has an NF of 20–30 dB that will unacceptably mask many weak signals that would impact a sensitive radiosonde receiver. Many spectrum analyzers have preamplifiers[35] to overcome this problem, but the intermodulation performance with the preamplifier enabled is very low. These intermodulation problems are caused by strong LTE downlinks, TV stations, land mobile radio (LMR) systems, and other high-power transmitters near the measurement location, which overdrive the spectrum analyzer amplifiers. Overdriving the amplifiers causes noise in the signal band of interest. Typically, the manufacturers do not provide preamplifier intermodulation performance values with the amplifier enabled because of the low performance. The manufacturers do offer bandpass filters to reduce this problem, but these filters usually do not cover the desired signal bandwidth. Shared Spectrum Company's experience shows that the only way to make sensitive spectrum surveys is to use a band-specific, high-performance cavity filter followed by a high-performance, low-noise preamplifier, followed by the spectrum analyzer.

[35] A typical test and measurement preamplifier: "Schwarzbeck BBV 9745 Broadband Preamplifier," EMC Shop, accessed May 13, 2020. https://www.theemcshop.com/emc-rf-preamplifiers/1878-schwarzbeck-bbv-9745-broadband-preamplifier.html.

A spectrum monitoring system (Figure 4.10-14) should use a cavity bandpass filter, a preamplifier, and a spectrum analyzer (or dedicated receiver). The filter rejects out-of-band signals to prevent intermodulation noise to be created in the preamplifier or the spectrum analyzer. An example system would use a custom-built 1650–1700 MHz cavity filter and a Mini-Circuits ZX60-P103LN+ preamplifier with <1 dB NF and high (38.7 dBm) third-order intercept point (IP3). A Tektronix RSA306B spectrum analyzer or similar collects spectrum trace data under PC control. This type of system provides sensitive (<5 dB NF) spectrum measurements, which is required for protecting the satellite ground station receiver. Using just a spectrum analyzer will result in high noise levels or spurious intermodulation signals that will invalidate the results, creating high risk for monitoring failure.

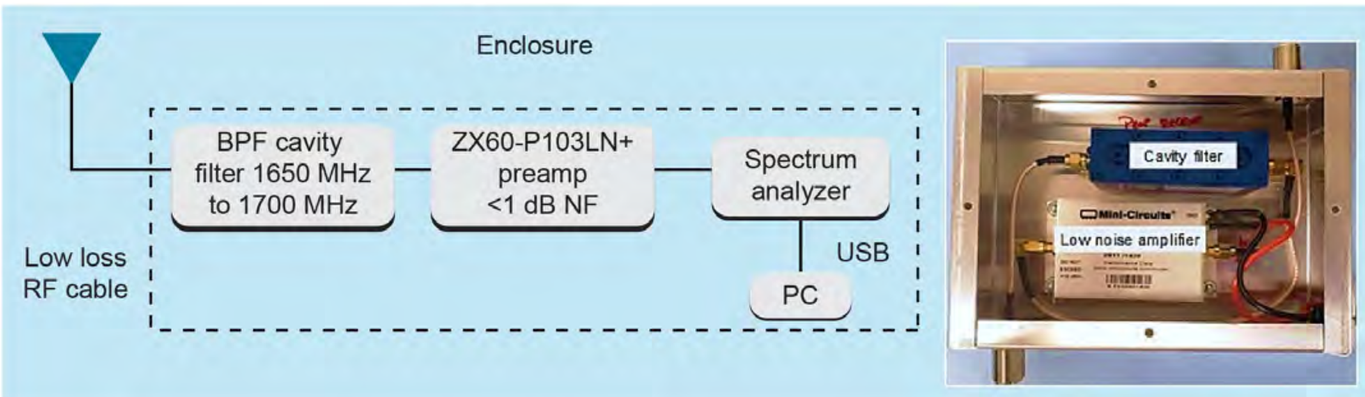


Figure 4.10-14. The monitoring system should use a cavity bandpass filter and amplifier to provide sensitive (<5 dB NF) spectrum measurements, even in high-signal environments.

4.10.2.3.7 Signal classification technique trade

A few signal classification methods are possible for the RF monitoring system and are provided in Table 4.10-5. Fast Fourier transform (FFT)-based classification provides the basic capability at low cost but requires high (≈0 dB) SNR. This approach provides basic signal information such as signal bandwidth, power, and time characteristics. Modulation-based classification inspects the signal modulation (e.g., quadrature phase-shift keying [QPSK]), pilot tones, or other signal characteristic(s) that identify the signal type. Known signal types can be classified by using COTS receiving equipment; other signals (e.g., broadband noise generated by machinery) can be identified using methods such as machine-learning classifiers. Modulation-based techniques require sufficient signal margin (above noise/interference) to demodulate the signal, which can be >10 dB SNR. Feature-based classifiers use advanced signal-processing methods to inspect signals and classify them based on the extracted features. Cyclostationary processing inspects

Table 4.10-5. Signal classification techniques.

Design alternative	Pros	Cons
FFT-based signal classification	• Low cost	• Requires high (~10 dB) SNR
Modulation-based signal classification	• High performance	• Requires high (~10 dB) SNR • High signal processing required
Feature-based signal classification	• Supports sub-noise detection • High development non-recurring engineering (NRE)	• High signal processing required

repetitive (cyclic) patterns in a signal to enable identification. Cyclostationary methods can operate in low SNR environments, but they can take significant time periods (tens of seconds) to reliably classify RFI signals.

4.10.2.3.8 RFI source attribution techniques trade

While signal classification identifies the signal type, attribution methods seek to identify the RFI signal source (i.e., the specific transmitter). Several potential methods such as SIB1 decoding, autocorrelation, and geolocation were reviewed in the study. Table 4.10-6 summarizes the benefits and drawbacks of each method.

Overall, extracting the carrier ID from the SIB1 message is unlikely to be useful as a stand-alone technique for attributing LTE-based interference to a particular source.

Geolocation methods use directional information from monitoring receivers to locate a signal source. As discussed above, several of the antenna options provide information regarding the azimuthal direction from which a signal originates. This information can be combined with other information to locate or identify the signal source. One alternative augments signals received at the GOES system with information from other sensors distributed throughout the region,[36] providing the ability to geolocate a signal source. Additional information could come from a database of registered users and their locations, allowing the detection information (direction, signal powers, and signal type) to be cross-referenced with the user information. Geolocation-based identification is likely to impose complexity on the monitoring system but could also provide improved mitigation performance.

Table 4.10-6. RFI source attribution techniques.

Design alternative	Pros	Cons
SIB decoding/ demodulation	• SIB is embedded in the LTE protocol frame and is extracted by synchronizing a receiver in time and frequency to signal.	• SIB decoding requires a minimum SINR that is unlikely to be achieved under most RFI conditions.
Geolocation	• Directional sensing provides bearing to interferer. • Directional sensing from antennas distributed throughout a region can provide geolocation. • Directional/geospatial information can be augmented with database registry to identify the emitter.	• Requires updates of database. • Baseline performance (both sensitivity and accuracy) to attribute interference to the actual source. • Potential false information from signals affected by multipath or ducting.
Autocorrelation	• Uses patterns in the LTE signal to determine the emitter ID without decoding the signal. • Generally works on low SINR. • Can ID many signals simultaneously.	• High system complexity. • Cost.

Autocorrelation methods use known signal patterns unique to a given transmitter to identify the signal source. Unique patterns could be control-channel information containing emitter ID information or segments of data transmitted with a signal. Autocorrelation is used by LTE systems

[36]These antennas would be part of the monitoring system.

for extracting some information associated with SIB1. Autocorrelation can work on low-power signals and can be applied to RF samples containing many signals.

Unfortunately, the complexity of an autocorrelation capability for RF monitoring prevents it from being a practical consideration. A primary drawback is attaining correlation signals with which to process the signals pulled from the monitoring system. Using autocorrelation for the LTE signal in effect is similar to decoding the SIB1 signal. Using autocorrelation for other RFI types (e.g., machine-made noise) is not practical.

4.10.2.3.9 Monitoring system deployment for GOES-R limitations

The study considered issues associated with deploying or integrating the monitoring system at the non-DoD Federal GOES ground stations. Factors focused on the ability to add monitoring antennas on or near the GOES antenna(s) at each site based on site-specific information collected in Project 6 site survey activities.

Integration potential and limitations varied by site but tended to fall into some general categories. Several Federal GOES sites are located on large Federal Government properties or university campuses, which may allow for monitoring systems that use distributed antenna arrays. Antenna restrictions are likely determined by other on-property structures, considerations for aviation activities, and interagency coordination. Some sites such as the Tennessee Valley Authority site are located on rooftops with limited on-site space. These sites would require acquisition of tower locations (e.g., commercial building rooftops or privately owned land) for array-based monitoring systems.

An attempt was also made to determine the issues related to integrating the RFI monitoring system to WCDAS and GOES-R downlink systems at the applicable Federal ground stations. This included determining the security, operational, and technical limitations of coupling the IF signal to determine the actual signals input to the receiver and polling the modem BER/frame error reporting to determine actual interference events.

Monitoring systems that wish to integrate with GOES components will also encounter additional system security efforts. GOES system integration may include access to the GOES receiver IF, GOES receiver BER or signal strength statistics, or injecting data into the GOES LAN for data distribution. Systems extracting the IF or receiver performance metrics are likely to have straightforward security needs because they do not inject data into the GOES system. Distribution of the performance data may need protection. Solutions that leverage the GOES LAN, however, will need to implement NOAA network security measures.

Table 4.10-7 provides a summary of RFI monitoring system deployment considerations for non-DoD Federal GOES ground stations.

4.10.2.4 Automation approaches

Table 4.10-7. Summary of RFI monitoring system deployment considerations for non-DoD Federal GOES ground stations.

Facility name	Location	Total GOES Rx	GOES antenna separation	Blockage/ clutter	Notes
NWS Alaska Region Office	Anchorage, AK	1	N/A	N/A	Space for tower; antennas near hilltop.
Aviation Weather Center	Kansas City, MO	3	tens of meters	None	Space for tower; may be rooftop location on operations building.
Bureau of Reclamation	Boise, ID	2	tens of meters	None	May be space on nearby multistory building; no room for on-site tower.
Earth Resources Observation and Science Center	Sioux Falls, SD	4	hundreds of meters	Buildings	Space for tower; may be rooftop location on operations building; site is almost 400 acres.
Fairbanks CDAS	Fairbanks, AK	1	N/A	N/A	Space for tower; antennas near hilltop; approximately 6,000-acre site.
NASA SPoRT	Huntsville, AL	2	10 meters	None	Space for tower; site on large Federal installation; may be limited by aircraft operations and other on-site users.
National Hurricane Center	Miami, FL	3	tens of meters	None	Space for tower; may be a rooftop location on operations building; site on university campus that may impact tower installation.
National Interagency Fire Center	Boise, ID	1	N/A	None	May be space on nearby one-story building on-site.
National Ocean Service	Chesapeake, VA	1	N/A	N/A	No tower allowed on the operations building roof; site in a small industrial park; may be nearby space off-site.
National Weather Service	Seattle, WA	1	N/A	N/A	Dish located on rooftop that may have space for monitoring system; located on large Federal installation.
Center for Weather and Climate Prediction	College Park, MD	3	tens of meters	None	May be roof top space on adjacent operations building; site on large Federal installation adjacent to very large university campus.
Satellite Operations Facility	Suitland, MD	5	tens of meters	None	Dish is located on rooftop that may have space for monitoring system; site on large Federal installation that may be limited by other users on-site.
NWS Pacific Region Office	Ford Island, HI	1	N/A	N/A	Dish is located on rooftop that may have space for monitoring system; site on large Federal installation; may be limited by aircraft operations and other on-site users.
Space Weather Prediction Center	Boulder, CO	3	tens of meters	None	May be rooftop space on adjacent operations building; site on large Federal installation; may be limited by other users on-site.

Table 4.10-7. cont.

Table 4.10-7. Summary of RFI monitoring system deployment considerations for non-DoD Federal GOES ground stations.

Facility name	Location	Total GOES Rx	GOES antenna separation	Blockage/ clutter	Notes
Spaceflight Meteorology Group Johnson Space Center	Houston, TX	2	20 meters	None	Space for tower; site on large Federal installation; may be limited by other users on-site.
Storm Prediction Center	Norman, OK	3	tens of meters	None	May be rooftop space on adjacent operations building; site on very large university campus; may be limited by other users on-site.
Tennessee Valley Authority	Knoxville, TN	1	N/A	N/A	May be rooftop space; dish is located on rooftop in congested downtown location; may be space on another nearby TVA building.

Automating the monitoring and mitigation system is important for minimizing the impacts of RFI events. Measurement data indicate that interference from atmospheric changes can increase in a matter of minutes, last for minutes to hours, and then disappear. Providing automated system functions that enable mitigation at the onset of interference events may greatly increase GOES system availability.

Table 4.10-8 shows automation areas for the NOAA monitoring and mitigation system. The table focuses on the basic function of a monitoring and mitigation system. Many of these functions appear to be readily automated, but the verification, mitigation, and rectification functions may require human involvement.

Table 4.10-8. RF monitoring and mitigation functions that may be automated.

Automation area	Discussion
Detection and classification	• Detection and classification are readily automated. • Need to discriminate new events/signals from ongoing events/signals. • Track evolution of events (e.g., as propagation conditions change).
Identification/attribution	• Carrier ID is readily automated. • Geolocation may require combining data from multiple monitoring stations with a database of emitters. • May require use of propagation models.
Notification	• Send alert (and supporting data) to NOAA spectrum manager or control center. • Send alert (and supporting data) to LTE carrier/operator. • Data may need to be stored in or retrieved from data archive.
Verification	• Confirming event information likely requires human intervention, but perhaps with automated toolchain (e.g., computer-based models and simulations). • May need to correlate ground station receiver performance data (e.g., error messages) with monitoring system information.
Mitigation and rectification	• Developing a mitigation solution likely requires human intervention, but perhaps with automated toolchain (e.g., computer-based models and simulations). • NOAA and LTE personnel may need to interact for developing a mitigation solution and determining its effectiveness. • Will need ability to reconfigure LTE operations once propagation conditions return to “normal.”

Detection and classification functions are readily automated. Current automated spectrum monitoring systems[37] perform many of the needed functions such as automated signal survey and classification, scheduled alarms, flexible tasking, and data logging for data analysis. An RF monitoring system should be able to build these capabilities into a design with low risk.

The effort required for automating the emitter identification process varies with the technique to be applied. Carrier ID capabilities are easily adopted and integrated into a monitoring system. Geolocation capabilities can also be automated but would require custom software that combines data from multiple receivers and correlates geolocation data with a database of emitters in the suspected area. The process may also involve the use of propagation models to establish further evidence in determining the likely interference source.

Notification is readily automated. The NOAA spectrum manager or control center responsible for mitigation would receive an automated alert that would potentially include event data. The data may include RF signal captures, classification results, and information regarding emitter identification. The specific information provided depends on the intended use, which could be verification of the automated decisions (e.g., classification and identification) or developing a mitigation. Similarly, alerts sent to the LTE operators can be automated, and the content will depend upon the role played by the LTE carrier in developing a mitigation solution.

Verification, mitigation, and rectification will likely be driven by human actions. The decisions produced by the preceding functions will need to be checked to ensure their veracity. For example, signal classifiers have limited accuracy, which typically depends on the SNR.[38] Typical classification performance is 94% correct classification with a 10 dB SNR.

Similarly, developing a mitigation solution will likely require human judgment, and the LTE operator will want to be sure that the actions have the least impact on customers. Developing a mitigation solution will require the use of computer-based tools, so automation of the toolchain and data processing may be beneficial.

Once the mitigation solution is implemented, NOAA and the LTE operator will need to verify its effectiveness in reducing interference. This process will likely include continued analysis of monitor data as adjustments are made to the LTE system, which would essentially repeat the steps in Table 4.10-8 until a solution is attained.

Finally, if the interference event was caused by anomalous propagation, the LTE carrier will want to return the LTE configuration back to a nominal operating state as soon as possible after the condition clears.

[37] Keysight Technologies, "N6820ES Signal Surveyor 4D Software," n.d., accessed May 12, 2020, http://literature.cdn.keysight.com/litweb/pdf/5991-2242EN.pdf.

[38] Yi Shi, Kemal Davaslioglu, Yalin E. Sagduyu, William C. Headley, Michael Fowler, and Gilbert Green, "Deep Learning for RF Signal Classification in Unknown and Dynamic Spectrum Environments," *IEEE International Symposium on Dynamic Spectrum Access Networks* (2019), 1-10, https://doi.org/10.1109/DySPAN.2019.8935684.

The carrier will need the feedback provided by the monitoring stations to ensure that LTE system reversions would not trigger interference events. This again repeats the process of monitoring and providing information to human decision-makers.

4.10.2.4.1 Report creation trade

Collaborative operation of the monitoring system requires interaction between NOAA and the carrier operators to provide interference reports and suggested mitigation measures to AWS carriers. Other reporting capabilities are required to discriminate reported events from new events, create historical and statistical reports, and log and report data. High data backhaul costs favor local data processing, while collaborative operations favor central data processing. Table 4.10-9 lists the pros and cons of the different identified notification approaches.

Table 4.10-9. Report creation trade.

Design alternative	Pros	Cons
Locally generated reports	• Individual RFI event reports • Includes detection results • Include SOH • Discriminate reported events from new events	• Limited notification and mitigation capabilities
Centrally generated reports	• Consolidated RFI data reports • Includes system availability • Includes security report • Includes mitigation reports • Generate archived RFI event statistical reports • Create historical and statistical reports • Track evolution of events	• Requires web services/portals for commanding, requests, mitigation plans, CID update, system/security status, and notifications management • Requires high data BW • Requires large storage • Introduces latency

4.10.2.4.2 Notification trade

Table 4.10-10 lists the pros and cons of the different identified notification approaches. The “no-send notification” would require an operator to review data and determine if an RFI event is occurring. This is generally not useful but is provided here for completeness. At the other extreme is sending notifications of every event. While this increases awareness, it would overload network traffic and likely cause data overload for anyone trying to analyze the data. The remaining options provide different approaches for consolidating and filtering reports. “Event-based” consolidates reporting of detections that are part of the same event. The “rule-based’ approach will provide notifications to users based on sets of rules. For example, an analyst may need data on every detection event while other system operators may need information only under certain conditions: someone responsible for NWS systems would want to know only about events affecting NWS systems, and LTE operators would want to know only about events associated with their operating regions. A baseline set of rules may be established based on each user’s roles and responsibilities, but configurable notifications would allow users to establish additional rules to facilitate data processing that is more effective. Combining these three approaches provides an optimal solution.

Table 4.10-10. Notification trade.

Design alternative	Pros	Cons
No-send notification	• Lowest network overhead, since no notifications are being sent to operators	• Operators may not immediately be able to respond to events
All RFI events sent	• Reduced operator error • Reduced chance of missing an event	• Highest network overhead; operator may be overrun with event notifications, causing errors
Configurable notifications	• Most flexible option • User can query only specific types of events for notification • Based on interference level	• Most prone to operator error • Most complex to implement • Requires developing an interface for configuring notifications
Event-based	• Correlates ground station receiver error messages with RFI monitoring results	• One notification at a time
Rule-based	• Processes RFI events based on preconfigured notification thresholds and rules for filtering • Minimizes excessive alarms via configurable software filter • Configurable notification filter so as not to saturate operators with continual RFI events	• Requires database stores and retrieves notification thresholds and rules • Introduces latency • Notification filter performed only by a central service

4.10.2.4.3 Mitigation plan trade

Rapid detection and mitigation of RFI is crucial for avoiding critical GOES service disruptions. Interference prediction may also be viable. Automation needs will impact technology and architecture requirements. The monitoring system must provide sufficient information about the interference condition so that mitigations can be implemented. Mitigations may include changes to LTE systems as well as changes to GOES operations to prevent data loss. A mitigation system could use these capabilities to proactively implement mitigations, which could include changes in the LTE network as well as changes to GOES operations to prevent data loss. While a carrier should manage mitigation plans to reduce the risks to NOAA, a coordinated mitigation capability may be required in various regions for effective mitigations that could span across agencies and end users. Table 4.10-11 lists the pros and cons of the different mitigation approaches.

Table 4.10-11. Mitigation trade.

Design alternative	Pros	Cons
Submitted by carrier	• Provide proposed plan of action to eliminate the interference • Provide proof that the interference has been alleviated • Submit and view mitigation plans for RFI event	• May require changes to carrier operations • Associate to only one RFI event • Stored only in central storage • Address only local mitigation
Submitted by NOAA	• Stored in central and local storages • Associate to one or more RFI events • Update history • Submit and review mitigation plans for RFI event • Mitigations may require regional or national coordination	• May require changes to NOAA operations • Severe RFI events may require switch over to alternate/backup ground station reception • May require GOES downlinks to acquire data through means other than direct broadcast

4.10.2.4.4 COTS spectrum-monitoring software

The use of COTS versus custom software factors significantly in the architectures. Often, custom code is preferred because COTS does not always perform as advertised, nor does it integrate well with other COTS. As such, the optimal solution is often a hybrid one. For example, custom application services may be combined with COTS web framework. Table 4.10-12 lists the pros and cons of the different monitoring software approaches.

Table 4.10-12. Monitoring software trade.

Design alternative	Pros	Cons
Use COTS software	• Low cost • Minimum development time risk • Make necessary configuration changes • Minimal customized software associated with communications, management, and control of system	• Potentially does not meet NOAA's needs • COTS equipment that follows standard maintenance/sustainment practices • Gap in current understanding of COTS • COTS evaluation revealed gap in functionality; increased software staff to overcome the shortfalls
Develop custom software	• Best aligned with NOAA's needs • Custom and COTS software CM to maintain the respective baselines and ensure traceability throughout the project lifecycles	• High NRE development and support costs • Lack of stability and robustness • Using more custom services (databases, search, etc.) creates greater dependencies

The NOAA spectrum monitoring problem is very similar to the general spectrum monitoring problem that exists for many applications. There exist multiple COTS spectrum monitoring software solutions that could potentially meet most of the NOAA spectrum monitoring requirements.

4.10.2.4.5 System automation to minimize impact to NOAA operations

As described in the previous sections, Project 10 evaluated existing and future monitoring system automation approaches and architectures (including cloud-based) to minimize impact to NOAA operations. Focus was placed on the following operational automation areas: monitoring report creation, determining the interference cause and party, notifying the interfering party, determining the suggestion of mitigation approach, and the switchover to alternate ground station reception. Our finding is that the monitoring system must provide sufficient information about the interference condition so that mitigations can be implemented. Mitigations may include changes to LTE systems as well as changes to GOES operations to prevent data loss. The next section evaluates the different designs that enable GOES network operations to adapt and minimize risk to end-user missions. This includes scoring factors such as labor/staffing costs, maintenance and operations costs, and sustainment costs for the different design alternatives described in Section 4.10.2.3 and scored in Section 4.10.3. Our conclusion is that the monitoring system operations will require a significant staff for a high system complexity (especially with an AoA system). The goal of a single, central operator is likely not feasible with a custom RFI monitoring system.

4.10.2.5 Data management architecture trades

Data management is an essential element of an RFI monitoring and mitigation system that extends from the point of data collection to the determination of mitigations as depicted previously in the reference architecture shown in Figure 4.10-6. The overall system capabilities and architecture define specific data management functions and approaches. A system that relegates management and control to each GOES ground station requires only local storage and minimal data distribution, while a system that centralizes management of all monitoring stations into one location requires larger amounts of data distribution and may have a range of data storage options (e.g., centralized or cloud). Regardless, data management involves data storage and archiving; data distribution and messaging; report and notification management; and data security.

Data storage includes warehousing data collected by the monitoring system as well as reporting data that presents processed information to a user or decision process. Storage is driven by the purpose(s) for which it is used and may need to be stored for short-term use or long-term analysis. Short-term storage may be most appropriate for initial signal processing data to support detection, classification, and identification functions. Functions requiring longer-term data storage include event verification and mitigation development. Analysts may wish to conduct studies over multiple events to identify and mitigate systemic issues (e.g., repeat offenders or situations leading to RFI), which would require access to archived data.

The characteristics of data to be stored vary as data moves from signal processing to analysis and reporting. Data volumes used for detection and classification differ with monitoring system capabilities and algorithm needs. State-of-the-art COTS systems can collect data up to 10 GB per second. The output of these algorithms such as received signal strength, signal bandwidth, signal type, and detection/classification confidence levels are much smaller (≈10 MB). This data supports identification, verification, mitigation, and long-term analyses.

Identification algorithm data input and output requirements vary as well. Carrier ID algorithms described in Section 2.2.1 replicate part of the LTE receiver, so each iteration of the process produces small amounts of data. Larger amounts of data may need to be stored over longer periods of time (minutes) to support carrier ID of low SNR signals, which may require processing of multiple SIB1 messages to attain the carrier ID. The data used for carrier ID determination can be discarded once the ID is determined.

Data storage requirements for geolocation-based identification depends on the geolocation approach. Geolocation providing bearing-only information produces fairly simple data that characterizes the direction of the signal source, while methods such as triangulation require data from multiple receiving stations to be stored and combined for processing. The data output from these more complex geolocation algorithms would also characterize the region in which the interference source is located; this may be a set of polygons characterized by the confidence that the emitter is in that region.

Storage capacity depends not only on the data production rate, but also on the required storage duration. As with all other data management requirements, storage of collected and processed measurement data depends on the desired system functionality. Storing raw measurement data for more than a few minutes or hours is probably necessary only when a detection is declared; the sample data may support verification and mitigation, or support longer-term analysis to better understand and avoid future RFI events. Similarly, verification and mitigation may require data used for geolocation of emitters. Processed data including detection, classification, and identification reports that include summary information of each event support verification and mitigation as well as long-term analysis, and would likely require archival storage.

4.10.2.5.1 Storage/archive trade

Alternative architectures drive storage/archival capabilities: for example, short-term storage at local site versus long-term archive at a central site. The type of data and retention period dictate the type/location of data storage. Storage costs grow with needs of storage (no up-front purchase of all storage) since data storage scales over time. As such, network utilization and storage is usually not a cost driver. It is prudent to try to co-locate data storage and processing in an attempt to minimize latency induced by data transfer protocols. Additional bandwidth can be acquired, but unless there is an advantage to separating storage and processing, it is generally advisable to keep them in close geographic proximity. Table 4.10-13 lists the pros and cons of the different data storage approaches.

Table 4.10-13. Storage trade.

Design alternative	Pros	Cons
Local storage	• Low latency • High network availability • Data available/managed by on-site personnel	• More difficult for SOC to access data • Inter-site event correlation is a manual process • More difficult notification, verification, and mitigation
Central storage	• Includes short-term storage for mitigation plans and long-term archive for reports • Simplifies data access and management	• Large storage depending on retention requirements • Public network dependency
Distributed storage	• Includes decisions in local storage • Includes archives for mitigation plans and reports	• Consistency across distributed databases • System partitioning • Public network dependency

Data distribution requirements depend on the physical architecture as well as on the functional solutions described above. The locations and types of storage used throughout the architecture define the data transfers that need to occur between functions. A distributed RFI monitoring and mitigation system emphasizes local storage because all (or most) functions happen locally. A system with centralized control may use a combination of local and centralized storage, which could include private or cloud-based storage.

A data distribution network for RFI monitoring and mitigation would likely need to be separate from any existing GOES data distribution network. RFI data could not use the GOES space-based segment for two critical reasons:

- Reversed data flows: GOES data flows from a central location to GOES ground stations, whereas RFI data would need to flow in the other direction.

- Performance and system impacts: Creating the reverse flow would require a different satellite transponder design. It would also require additional spectral bandwidth to avoid degrading GOES user data delivery such as latency. This additional bandwidth would presumably occur in the 1675–1680 MHz band and add to the issues associated with LTE sharing addressed in the SPRES study.
- Leveraging GOES terrestrial data distribution networks such as DADDS, Emergency Data Distribution Network (EDDN), Environmental Satellite Processing and Distribution System (ESPDS), and National Weather Service Telecommunications Gateway (NWSTG) encounters similar issues:
  Performance and system impacts: Adding data to existing networks may degrade performance such as latency or availability of GOES user data. Adding new data distribution functions to existing systems could also require resizing hardware or changing the design. Simply "scaling up" by adding new hardware (e.g., storage and routers) may not be possible.
- Different performance requirements: RFI monitoring system data management may have different requirements than GOES data distribution capabilities. These could include latency and availability as well as data security.
- Different topologies: The GOES data flow topology does not match the expected RFI monitoring data flow topology:
  - Reversed data flows: GOES data architectures are designed to move data from a processing location to end users, whereas an RFI monitoring system would move data from GOES ground stations to one or more locations responsible for system control and operation.
  - Different locations: RFI monitoring would occur at every non-DoD Federal GOES ground station, but GOES terrestrial networks do not necessarily go to every ground station.

Given these reasons, the architectures studied in this effort do not seek to use the GOES data distribution network. The trade study in Section 4.10.3 instead evaluates several types of architectures that include different storage options and overall system functionality.

4.10.2.5.2 Traffic load trade

The data management system traffic load trade applies to the wide area network (WAN) used to transfer data between the central document management system (DMS) and the remote monitoring sites. These sites are geographically segregated and checked, and likely rely on public internet to provide a WAN link, although NOAA operates private networks that interconnect various Federal agencies. There are two distinct data types that flow over the WAN: remote monitoring system control data and processed spectrum data. It is assumed that the on-site LAN will offer adequate infrastructure to support collection and distribution of RF and digital data over appropriate network infrastructure. The WAN traffic load will be impacted by two main factors: (1) the alternative selected, which dictates the level of data processing available at the remote and central sites, and (2) the configuration of the remote site data acquisition systems, such as resolution bandwidth and sweep rates. In fact, the selection of a monitoring system or data acquisition (DAQ) system configuration may be driven by WAN available bandwidth. Given that there is ability to centrally process and store data, the remote sites may be tailored to optimize the overall system and intervening network designs.

There are different methods for managing "high-volume traffic," including continuous signal characterization, process most events possible with list overflow, and ranked queue implementation. The optimal solution is often a hybrid of multiple options to gracefully degrade system/network performance during high volumes of interference-event detections. The rationale is that processing all signals would require too many resources; using ranked queue reduces the number of dropped detections; and dynamic thresholding is configurable. Table 4.10-14 lists the pros and cons of the different traffic load management approaches.

Table 4.10-14. Traffic load trade.

Design alternative	Pros	Cons
Process all events	• Captures most events possible	• Requires too many resources
Drop detections	• Requires fewer resources	• May miss some events
Ranked list	• Reduces number of dropped detections and focuses on significant interferences	• Complex
Dynamic thresholding	• Configurable	• Complexity may exceed benefits
Continuous signal characterization	• Capture most events possible	• Requires too many resources • Prioritizing events is necessary
Save and process on demand	• Configurable	• Requires more compute and network resources

Data management also includes dissemination and storage of interference event reports and notifications as well as mitigation solution development. The architectural assumptions behind system operations (i.e., who is responsible and what data is required?) drive the data-management requirements for these functions.

Collaborative operation of the monitoring system requires interaction between NOAA and the carrier operators to provide interference reports and suggested mitigation measures to AWS carriers. Other reporting capabilities are required to discriminate reported events from new events, create historical and statistical reports, and log and report data. High data backhaul costs favor local data processing, while collaborative operations favor central data processing.

4.10.2.5.3 RFI monitoring system management trade

The monitoring system can be managed by personnel on-site, centrally managed by NOAA, or owned and operated by on-site personnel while allowing access to NOAA centrally managed monitoring and analysis tools. Distributed architectures help balance RF performance with automation performance.

Distributed architecture provides an acceptable compromise between system owners within NOAA and other Federal organizations. Table 4.10-15 lists the pros and cons of the different RFI monitoring systems management approaches.

Table 4.10-15. RFI monitoring system management trade.

Design alternative	Pros	Cons
On-premise NOAA System	• Processing done on site • Lower backhaul costs • NOAA maintains configuration control	• Increased on-site operator skills required • Hardware maintenance • Extended system boundaries
Centralized/cloud management	• Lower NOAA labor • Processing done on central location • Cloud enables operator access via web services, allowing NOAA to interface from any location with internet access • Cloud offer high availability, flexible provisioning, scalability, and reduced hardware maintenance and tech refresh costs	• Higher backhaul costs • Increased NRE development • Cloud interoperability is limited • Security risks due to greater external exposure • API development for system management/ data access
Distributed	• Processing allocated between local and central sites • Predictable central load • Moderate BW requirements	• Complexity of distributed system management

4.10.2.5.4 Local configuration trade

Active mitigation requires remote access/control to change local site configurations. This may be done via remote cloud-based management/control and configuration of local sites as well as built-in hardware test capability to identify RF component failure and software configuration errors. This leveraged Project 6 to identify ground station configurations and design trades (e.g., IF coupling and integration limitations). Table 4.10-16 lists the pros and cons of the different local configuration approaches.

Table 4.10-16. Local configuration trade.

Design alternative	Pros	Cons
Local calibration	• Includes test equipment item, calibration frequency, date last calibrated, and date of next scheduled calibration	• COTS equipment that follows standard maintenance/sustainment practices
Built-in hardware test	• Identifies RF component failure and software configuration errors	• COTS equipment that follows standard maintenance/sustainment practices
Software configuration errors	• Makes necessary software configuration changes	• Requires configuration control over test scripts
Cloud-based configurations	• Remote management, control, and configuration of local sites	• Periodic compatibility checks with vendor infrastructure changes

4.10.2.5.5 RFI event consolidation trade

Labeling event records reduces notifications as RFI events records with the same label need not be sent. Event consolidation reduces the amount of messaging between processing/storage sites. Both help increase automation levels for RFI event attribution, notification, mitigation, and record generation. Table 4.10-17 lists the pros and cons of the different RFI event consolidation approaches.

Table 4.10-17. RFI event consolidation trade.

Design alternative	Pros	Cons
Send each RFI event record	• Frequency of RFI event records does not merit increase in complexity for consolidation	• Less efficient managements of events
Label RFI event records	• Labeling provides more efficient management of events • Event records can have more than one label • Includes manual and automatic generation of labels for records	—
Consolidate similar RFI event records	• RFI events may be associated with a single source for an extended period of time	• Complex • Grouping does not consolidate events in the database • Events need to be linked/consolidated to both effectively describe what is causing the interference and efficiently store the events

4.10.2.5.6 Performance monitoring trade

The performance monitoring shall include the amount of interference to the NOAA ground stations and the amount of spectrum available to the commercial user. This included analysis of non-ducting conditions and ducting conditions. Augmented techniques were identified that may improve emitter ID performance in low SINR conditions. A baseline system model was established for determining performance (both sensitivity and accuracy to attribute interference to the actual source). Monitoring capabilities were added to model a low-level, a base, and a high-level RF monitoring system. Performance was evaluated using multiple LTE scenarios (large and small cell; time domain duplex [TDD] and frequency division duplex [FDD]) and RFI environments (ducting and non-ducting). Specifically, the study:

- Evaluated technology and design capabilities performance in multiple LTE scenarios and RFI environments.
- Traded RF performance with automation performance.

Effective monitoring system automation requires automation of many processes: signal detection, signal classification, emitter ID, correlation of measurements and interference events, report creation, alert notification, mitigation development, and mitigation effectiveness monitoring. Collecting monitoring data into a cloud would also enable greater prediction of RFI events and analysis of mitigation effectiveness for improving overall monitoring and mitigation system performance using cloud-native tools and services. Table 4.10-18 lists the pros and cons of the different performance monitoring approaches.

Table 4.10-18. Performance monitoring trade.

Design alternative	Pros	Cons
All metrics sent to central site	• Consistent view and resolution for all metrics in GUIs for all local sites • Unified location for viewing metrics	• Alerts and notifications originate from centralized location • BW requirements
Local site aggregates metrics locally	• Monitoring performance metrics on local site while minimizing BW between local and central sites	• Operators have primary responsibility for monitoring RFI events and collecting metrics from local site. • Latency
Central site queries local site for metrics (periodically)	• Monitoring performance metrics on local site while minimizing BW between local and central sites	• Operators have primary responsibility for monitoring RFI events and collecting metrics from local site • Latency
All metrics sent periodically to central site	• Configurable	• Complexity

4.10.2.5.7 Cloud use trade

One of the objectives of this trade study is to assess existing and future monitoring system automation approaches and architectures (e.g., cloud-based) for minimizing impact to operations. As such, NOAA data management systems were analyzed for any possible central or cloud-based monitoring configurations. For Project 3, one of the alternative architectures evaluated was a hybrid private/public cloud architecture that would allow multiple acquisition sites to store acquired “mission” data in the cloud. A similar architecture to support RFI event data and to enable a mitigation response to be coordinated among LTE operators as well as affected GOES sites and data users is considered in this project. Further, RFI predictions could be generated centrally and provide alerts to potentially affected entities (similar to other warnings, such as those for space weather). Cloud processing offers high availability, flexible provisioning, scalability, and reduced hardware maintenance and tech refresh costs. Mitigation may be done via remote cloud-based management/control and configuration of local sites, as well as through built-in hardware test capability to identify RF component failure and software configuration errors. Collecting monitoring data into a cloud would also enable greater prediction of RFI events and analysis of mitigation effectiveness for improving overall monitoring and mitigation system performance using cloud-native tools and services. Table 4.10-19 lists the pros and cons of the different cloud use approaches.

4.10.2.6 Potential monitoring system design alternatives

Five monitoring systems alternatives are identified and defined for decision analysis and resolution (DAR). The alternatives were developed based on NOAA’s guidelines and best practices. These include:

- Consider the pros and cons of the number of alternatives before proceeding with additional analyses to bound scope.
- Include an alternative that reflects continuation of the current course of action or status quo to show comparative cost/benefits of other alternatives over the system life.
- Ensure that the final set of alternatives is distinct and independent.

Table 4.10-19. Cloud use trade.

Design alternative	Pros	Cons
NOAA-owned	• Full control over system security • Predictable system performance • Opportunity to leverage existing underutilized assets • Potential to utilize existing network for data transport between sites	• Extends or creates new system boundaries • Complex integration, operation, and maintenance • Redundancy requirements • High initial cost • Overprovisioning hardware • Tech refresh
Cloud-based	• Lower hardware risk • Minimal impact to facilities • High availability built in • Reduced hardware maintenance • Scaling to meet mission needs • Rapid development • Reduced development/tech-refresh costs	• Need method of inheriting content security policy (CSP) security controls • Lack of experience incorporating CSP into operations • Vendor lock-in • Predicting costs

The alternatives include existing available systems (RFIMS and COTS), as well as customized systems, as shown in Table 4.10-20.

Table 4.10-20. Project 10 design alternatives.

Alternative	Name	Measurement	Automation	Data management	Architecture
Alt. 1	COTS software/omni/all COTS	COTS hardware/ software	COTS software	COTS software	Isolated
Alt. 2	COTS software/omni/custom software	COTS hardware/ software	Custom software	Custom software	Distributed
Alt. 3	COTS software directional/ custom software	COTS hardware/ software	Custom software	Custom software	Distributed
Alt. 4	COTS software/directional/ custom software/cloud-based	COTS hardware/ software	Custom software	Custom software	Centralized
Alt. 5	RFIMS	COTS/custom hardware/software	COTS/RFIMS custom software	COTS/RFIMS custom software	Distributed

4.10.2.6.1 Alt. 1: COTS hardware design alternative

This alternative is built around all COTS including a single omni antenna and COTS spectrum monitoring software. It uses a custom cavity filter and a preamplifier to obtain good sensitivity. It uses a commercial spectrum analyzer. It offers minimum NRE cost. All RFI event processing except notification is done locally. COTS software offers limited notification capability and limited RFI event mitigation capability. All RFI event processing is done locally.

In Figure 4.10-15, the green circles represent the main functions of the monitoring system:

- Detect is the ability of the RFI monitoring system to detect an RFI event.
- Classify is the ability of the RFI monitoring system to classify the detected RFI event into LTE or non-LTE signal.
- Identify is the ability of the RFI monitoring system to identify the location and source of the RFI event.
- Notify is the ability of the RFI monitoring system to notify a government or LTE operator of the RFI event.
- Verify is the ability of the RFI monitoring system to determine the responsible party of the RFI event.
- Rectify is the ability of the RFI monitoring system to enable the mitigation of the RFI event.

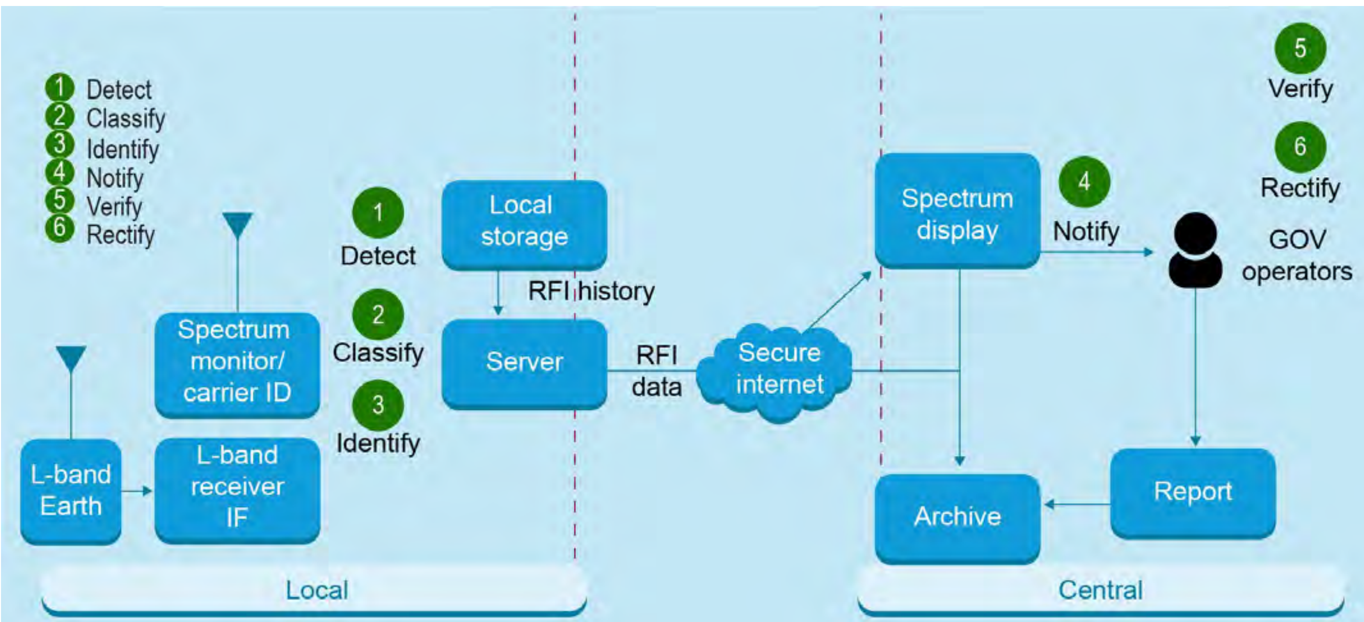


Figure 4.10-15. Alt. 1: COTS software.

The following are the unique Alt. 1 factors compared to the other designs:

- Is the lowest cost (hardware cost, software cost, labor-document, implement and test, operations/sustainment) because the system uses mostly existing commercial components.
- Has low "attribute RFI interference to source (AoA)" because it uses a single antenna and no time difference of arrival (TDOA) capability.
- Has low RFI detection sensitivity because it does not use directional antennas to increase the RFI signal energy.

4.10.2.6.2 Alt. 2: COTS hardware/custom software design alternative

Similar to Alt. 1, this alternative is built around a single omni antenna and COTS software spectrum monitoring software but has added custom software for automation and data management. It offers minimum NRE cost. All RFI event processing except notification is done locally.

The following are the unique Alt. 2 factors compared to the other designs:

- Has a relatively higher cost than Alt. 1 due to the development of added automation and data management custom software cost.
- Has low "attribute RFI interference to source (AoA)" because it uses a single antenna and no TDOA capability.
- Has low RFI detection sensitivity because it does not use directional antennas to increase the RFI signal energy.

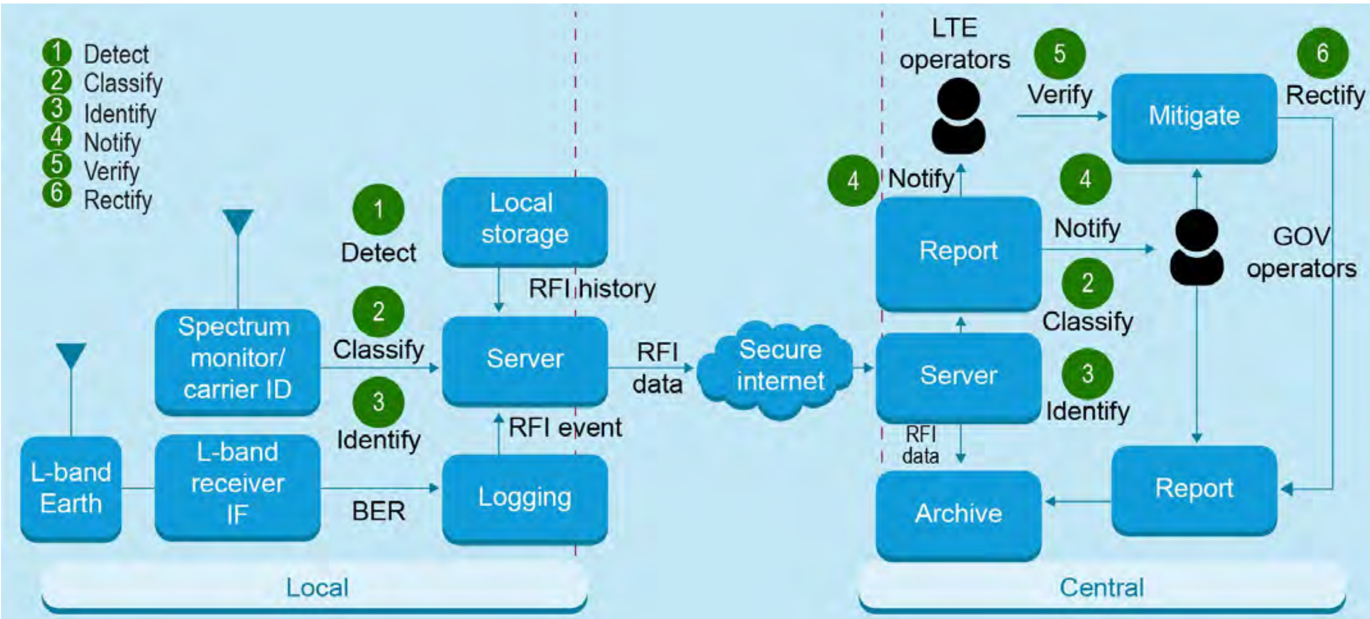


Figure 4.10-16. Alt. 2: COTS hardware with COTS software augmented with custom software.

4.10.2.6.3 Alt. 3: COTS hardware using directional antennas design alternative

This alternative is built around the same software as in Alt. 2 but with an array (approximately 10 antennas) of directional antennas replacing the omni antenna in Alt. 2. The directional antennas enable the AoA of aggregate interference to be determined. All RFI event processing is done locally, while notification is done centrally.

The following are the unique Alt. 3 factors compared to the other designs:

- Has a relatively higher cost than Alt. 1 due to the development of added automation and data management custom software cost.
- Has relatively higher "attribute RFI interference to source (AoA)" because it uses multiple directional antennas with TDOA capability.
- Has relatively higher RFI detection sensitivity than Alt. 1 and Alt. 2 because it uses directional antennas to increase the RFI signal energy.

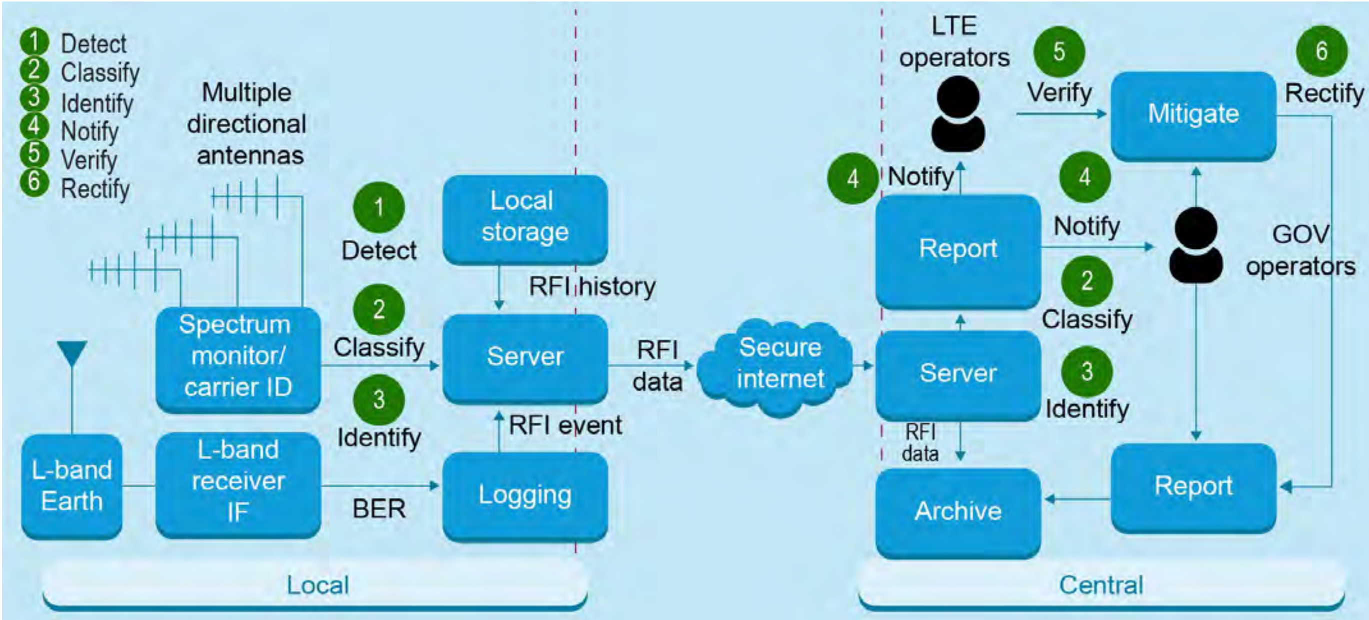


Figure 4.10-17. Alt. 3: COTS software with custom software and directional antennas.

4.10.2.6.4 Alt. 4: Cloud-based COTS hardware using directional antennas design alternative

Alt. 4 uses the same COTS hardware (up to 10 antennas) and COTS/custom software as in Alt. 3 but is a cloud architecture that would allow multiple acquisition sites to store acquired mission data in the cloud. This will enable a mitigation response to be coordinated among LTE operators as well as affected GOES sites and data users. Further, RFI predictions could be generated centrally and provide alerts to potentially affected entities (similar to other warnings such as those for space weather). Collecting monitoring data into a cloud would also enable greater prediction of RFI events and analysis of mitigation effectiveness for improving overall monitoring and

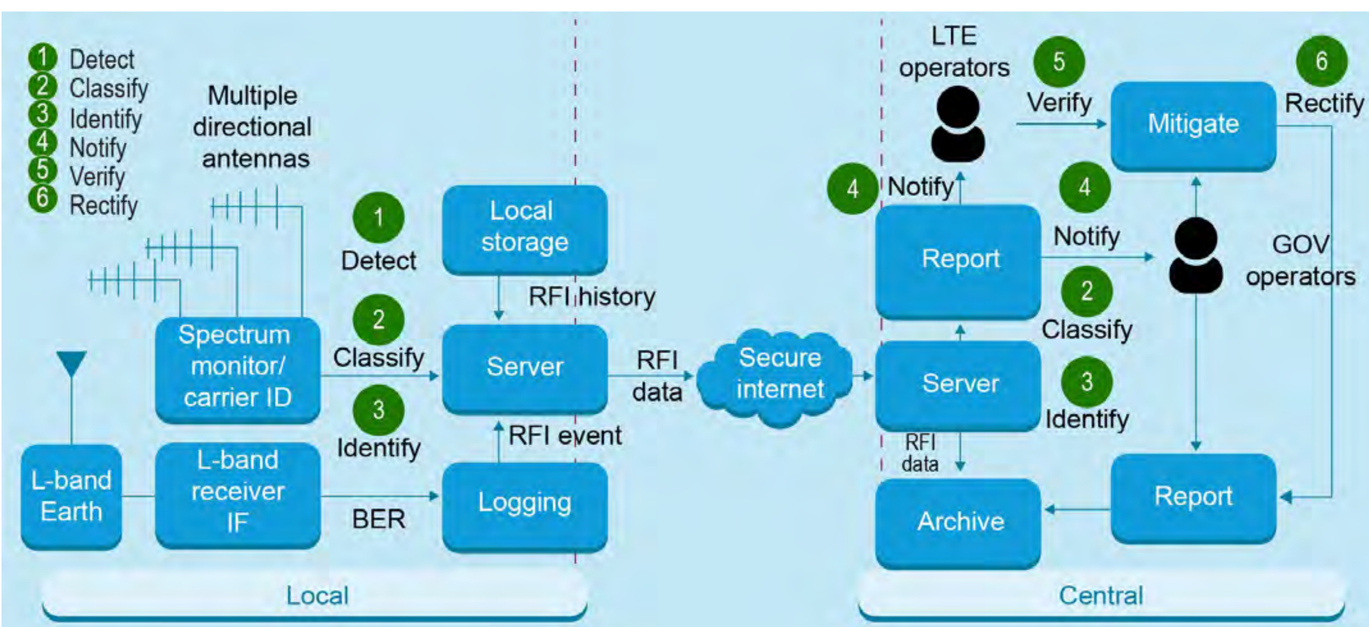


Figure 4.10-18. Alt. 4: Cloud-based architecture uses multiple directional antennas (with separate detectors), logging of the satellite L-band receiver errors, and comprehensive cloud-based data management software.

mitigation system performance using cloud-native tools and services. This, however, will require streaming data to a central management site/cloud database for centralized classification, identification, notification, and mitigation. Detection is done locally. Finally, this will enable remote cloud-based management/control and configuration of local sites.

The following are the unique Alt. 4 factors compared to the other designs:

- Provides enhanced monitoring, automation, and data management capabilities.
- Has relatively higher RFI detection sensitivity than Alt. 1 and Alt. 2 because it uses directional antennas to increase the RFI signal energy.
- Enables multiple acquisition sites to store acquired mission data in the cloud.
- Enables a mitigation response to be coordinated among LTE operators as well as affected GOES sites and data users.
- Enables central generation of RFI predictions to provide alerts to potentially affected entities (similar to other warnings such as those for space weather).
- Enables greater prediction of RFI events and analysis of mitigation effectiveness for improving overall monitoring and mitigation system performance using cloud-native tools and services.

4.10.2.6.5 Alt. 5: RFIMS: COTS/custom software/hardware design approach

Alt. 5 is based on the Radio Frequency Interference Measurement System (RFIMS)[39] developed by Harris. RFIMS employs custom hardware and software for distributed processing and data management. Detection, classification, and identification are done locally at the remote monitoring site (RMS), while notification and mitigation are done centrally at the centralized monitoring system.

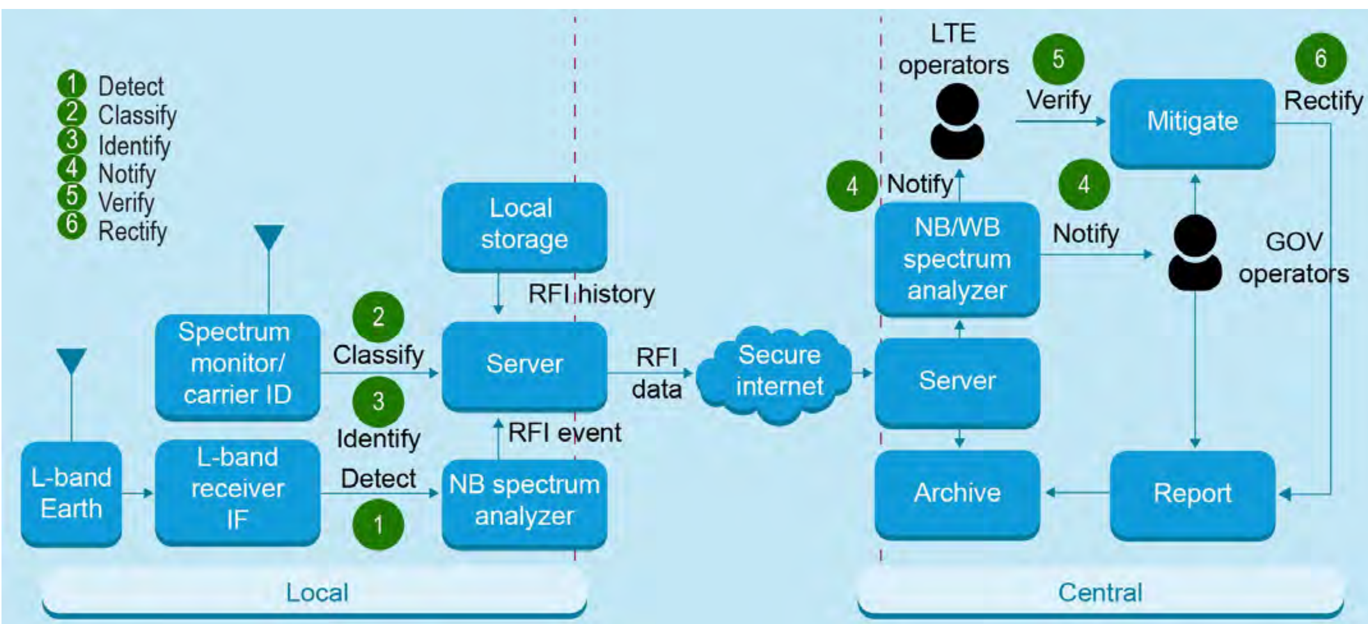


Figure 4.10-19. Alt. 5: RFIMS with a single high-performance sensor (with beamforming) providing minimum RF sensitivity versus elevation angle to meet mission need.

[39]RFIMS, System Design Description (SDD), Revision A, December 2018, Post-CDR Update.

The following are the unique Alt. 5 factors compared to the other designs:

- Provides enhanced monitoring, automation, and data management capabilities.
- Enables multiple acquisition sites to store acquired mission data in the cloud.
- Enables a mitigation response to be coordinated among LTE operators as well as affected GOES sites and data users.
- Enables detection of RF interference in real time.
- Capable of supporting remote software upgrades.
- Consolidates RFI event data from NOAA Federal earth station locations.
- Provides notifications of RFI event occurrence to wireless carrier in real time.
- Allows operators to analyze the consolidated RFI event data.
- Allows an operator at a single location to generate reports from the consolidated RFI event data.
- Allows operators to download technical data for selected RFI events from the remote earth stations.
- Has a single high-performance sensor providing minimum RF sensitivity versus elevation angle to meet mission need.
- Provides accurate LTE classification via physical examination of signal including frequency bandwidth and time duration and discovery reference signal.
- DRS extraction and peripheral component interconnect (PCI) correlation.
- Provides accurate LTE identification via DRS extraction and PCI correlation.
- Performs calculation to determine if interference is above harmful level based on RMS detection report, publically available ephemeris data, and known characteristics of Met-Sat dish/antenna.
- Has central monitoring via commercial cloud via Amazon Web Services versus on-premises NOAA system.
- Interfaces with NOAA Security Operations Center (SOC) for security information and event management (SIEM).
- Manages notification of interference events to minimize excessive alarms via configurable SW filter added to not saturate wireless carriers with excessive notifications based on similar RFI events.
- Provides web services portal for role-based interface to analysis tools and status.
- Provides short-term storage and long-term archive at central monitoring subsystem.

4.10.3 Trade study

The alternatives were evaluated using a decision analysis and resolution (DAR) process. Select capabilities were identified and further investigated in the measurement, automation, and data management areas. This included investigations of the strengths and weakness of the different potential alternatives for each of these capabilities. The evaluation criteria are similar to the seven categories provided in Project 3, and use the same descriptions in terms of risk. The score factors within each evaluation criteria were identified from the select capabilities traded above, especially in the technical, operations, and performance areas. The DAR results are notional and could easily be adapted (by adjusting the weights and evaluation criteria) once the RF monitoring system usage is determined by NOAA and the FCC.

Table 4.10-21. Score factors used in the evaluation criteria for each alternative.

Evaluation criteria	Weight (percent)	Score factors
Technical	20	• Monitor aggregate interference • Attribute interference to source • Integrate monitoring system to WCDAS and GOES-R • Account of complex/unknown sidelobes of GS antenna • Classify signal (LTE, non-LTE) • Correlate RFI measurements and interference events • Determine RFI source responsible for interference • Built-in system test • Message management • Storage/archive management • Statistics/reports management • Notification management • Spectrum data streaming
Schedule	10	• Justification/authorization • Procurement • Implementation/verification and validation
Operational	20	• Site-specific antenna and processor size limitations • Carrier ID classification • Estimate RFI interference level at NOAA receiver • Support real-time, spectrum analyzer mode • Built-in test of RF paths (antennas, cables, amplifiers, and receiver) • RFI prediction or early detection • Report creation • Identify RFI interference source • Notify interfering party (interact with AWS carriers) • Determine new RFI events vs. recent past RFI events • Isolated site management • Centralized management • Distributed management • Active mitigation • Collaboration
Security	10	• Identification and authentication • Auditing and logging • Access management • Physical protection • Support user role-based access
Cost	20	• Hardware cost • Software cost • Labor: document, implement, and test • Ops/sustainment cost
Scalability	5	• Scalability • Existing capacity

Table 4.10-382.

Table 4.10-21. Score factors used in the evaluation criteria for each alternative.

Evaluation criteria	Weight (percent)	Score factors
Performance	15%	• RFI detection sensitivity • RFI signal classification accuracy (many signal types) • False alarm rate • Processing latency • Antenna size/gain • NOAA receiver integration • Traffic load • Data exchanges between NOAA and the AWS carriers • Amount of human interaction • Storage size • Statistics/reports management • Accuracy • Latency • Availability

Table 4.10-22 provides a summary of the findings of key system capabilities and qualitative risk assessment of each, which directly relate to how the alternatives were scored.

Based on these findings, the following scores were used in the DAR analysis:

- Score = 1 for high risk: the capability is not met.
- Score = 2 for moderate risk: the capability is somewhat met.
- Score = 3 for low risk: the capability is fully met.

Table 4.10-22. Project 10 findings.

Research area	Spectrum monitoring research findings	Effect on risk and category
Carrier ID	• Long detection periods needed when multiple simultaneous carrier IDs (CIDs) are present, or during ducting conditions (low signal power and potentially multiple interferers)	↑ Performance
	• Probability of successful CID detection is low in aggregate interference conditions	↑ Performance
	• CID is useful to supplement spectrum power measurement automation	↓ Performance
	• CID information can provide critical identification and transmitter location information	↓ Performance
	• Adding CID capability to an RF monitoring system is not expensive	↓ Cost
	• It is difficult to decode the CID information in weak signal areas with heavy user data traffic	↑ Technical

Table 4.10-383.

Table 4.10-22. Project 10 findings.

Research area	Spectrum monitoring research findings	Effect on risk and category
Measurement	• A separate monitoring antenna (for CID) is needed to improve CID detection performance	↑ Operations
	• Using multiple directional monitor antennas improves system sensitivity	↓ Performance
	• Low INR sensitivity values add only incremental benefit	~ Performance
	• Design monitoring system around 10 dB satellite link margin	↓ Performance
	• Wide range of interference signals with different modulations and cumulative effects drives challenging monitoring system requirements	↑ Cost
	• Sensitivity, geolocation, and cost requirements drive antenna alternatives	↑ Cost
	• Correlating CIDs of interfering signals to GOES Rx IF signals will be difficult in most sites due to high clutter	↑ Technical
	• Measuring elevation angle of arrival (AoA) can aid in determining signal direction/source.	↓ Performance
	• Connecting RF monitoring system to GOES satellite downlink system requires NOAA IT security approval	↑ Security
Automation	• Create monitor reports: generate an event when RFI power exceeds a threshold	↓ Operations
	• Identify interference source based on modulation, BW, frequency, location, and TDOA	↓ Performance
	• Notify interfering party: minimize excessive alarms via configurable software filter	↓ Operations
	• Determine mitigation approach: associate a mitigation plan to one or more RFI events	↓ Performance
	• RF monitoring system could switch GOES reception to alternate site when harmful RFI is detected	↓ Performance
Data management	• Centralized database: acquire and transfer monitoring data to central management site/cloud	↑ Security
	• Distributed database: store data locally in a web-accessible database	↓ Performance
	• Active mitigation: requires access control to change local configurations	↑ Security
	• Active mitigation: requires spectrum data streaming service to SOC and/or LTE user	↑ Technical
	• Isolated site management: reflects what is being done at WCDAS today	~ Operations

4.10.3.1 RFI monitoring systems DAR form evaluation

A summary of the DAR form is shown in Table 4.10-23. Alt. 4 has the highest score in the analysis, with a 10.5% margin over Alt. 1, which has the second-highest score. The higher scores for technical, operational, and performance for Alt. 4 relative to Alt. 1 outweighed the lower scores for cost and schedule. Significant observations for each of the evaluation criteria are provided here.

Table 4.10-23. DAR form scores for collaborative monitoring scenario.

Evaluation criteria			Alt. 1: COTS software/ omni	Alt. 2: Custom software	Alt. 3: Directional	Alt. 4: Cloud	Alt. 5: RFIMS
Number	Criteria	Weight (percent)					
1	Technical	20	1.42	1.92	2.58	2.58	2.17
2	Schedule	10	3.00	1.00	1.00	1.00	2.00
3	Operational	20	1.55	2.18	2.18	2.30	1.91

Table 4.10-23. cont.

Table 4.10-23. DAR form scores for collaborative monitoring scenario.

Evaluation criteria			Alt. 1: COTS software/ omni	Alt. 2: Custom software	Alt. 3: Directional	Alt. 4: Cloud	Alt. 5: RFIMS
4	Security	10	1.40	3.00	3.00	3.00	3.00
5	Cost	20	3.00	2.00	1.00	1.75	1.75
6	Scalability	5	3.00	2.50	2.50	3.00	1.50
7	Performance	15	2.00	2.00	2.11	2.22	1.89
Overall weighted score			2.08	2.04	1.99	2.21	2.02
Margin (percent)			10.5	13.7	17.8	—	15.4

Technical risk

The directional (Alt. 3) and cloud (Alt. 4) alternatives scored significantly better than the others in terms of technical risk. This is largely due to the ability of directional antennas to measure aggregate noise and the ease with which NOAA can manage the network of monitoring systems using cloud-based tools. In addition, this was the only option considered that provided in-phase and quadrature (I/Q) data streaming for real-time mitigation of an RFI event using probabilistic causation.

Operational risk

Alt. 4 scored the highest from a DMS perspective because it facilitated active mitigation by making I/Q data available in real-time to NOAA and LTE operators during ongoing RFI events This allows LTE operators to identify outcomes of changes being made at the GOES downlink site during execution of mitigation processes.

Performance

From a DMS perspective, the COTS software/omni system localized the majority of processing and storage, and therefore data transfer errors and latency are minimal. However, in terms of minimizing data loss and detection accuracy for a given RFI event, the cloud alternative (Alt. 4) and directional alternative (Alt. 3) were considered the lowest risk. This is due to improved notification speed and ease of data access, which would allow the LTE provider to quickly identify the source of the interfering tower(s) and initiate mitigating actions.

4.10.3.2 Other evaluation scenarios

There is the potential that funding for a monitoring system could be tied to the value of the spectrum auction. In this scenario, the cost of the system is a less important factor when selecting a monitoring system, and other evaluation criteria are given more importance. This is accomplished by adjusting the weights for each of the evaluation criteria. In this scenario, cost weight was set to a value of zero, eliminating that evaluation criteria from consideration. Its 20% weight factor was distributed proportionally over technical, schedule, operational, security, and performance evaluation criteria using a multiplier of 1.27. Scalability was held fixed at 5% because this system scale is somewhat confined by the identified critical and important downlink sites. The results of changing the weights are shown in Table 4.10-24.

Table 4.10-24. DAR form scores with cost weight being set to zero.

Evaluation criteria			Alt. 1: COTS software/ omni	Alt. 2: Custom software	Alt. 3: Directional	Alt. 4: Cloud	Alt. 5: RFIMS
Number	Criteria	Weight (percent)					
1	Technical	25	1.42	1.92	2.58	2.58	2.17
2	Schedule	13	3.00	1.00	1.00	1.00	2.00
3	Operational	25	1.55	2.18	2.18	2.30	1.91
4	Security	13	1.40	3.00	3.00	3.00	3.00
5	Cost	0	3.00	2.00	1.00	1.75	1.75
6	Scalability	5	3.00	2.50	2.50	3.00	1.50
7	Performance	19	2.00	2.00	2.11	2.22	1.89
Overall weighted score			1.84	2.05	2.24	2.31	2.10
Margin (percent)			38.9	21.8	6.3	—	17.4

As can be seen in the last two rows of Table 4.10-24, Alt. 4 still scored the highest. Removing costs as a factor increased the margins for Alt. 1, Alt. 2, and Alt. 5. Alt. 1 becomes the lowest-ranked option because it scored lowest on many of the remaining criteria. Alt. 2 similarly dropped in rank. Alt. 3, however, shows a reduced margin relative to the baseline because the directional antennas provide increased technical and performance capabilities and the cost of those capabilities is not a factor in this assessment.

4.10.4 Conclusion

4.10.4.1 Introduction

SPRES Project 10 investigated potential RF monitoring systems for detection and mitigation of RFI events. This enforcement capability is an important part of spectrum sharing.

4.10.4.2 Carrier ID feasibility

The first goal was to evaluate the possibility of employing carrier identification sharing to detect and mitigate LTE base station signals. The carrier ID capability determines the transmitter ID of LTE signals. The carrier ID performance level is critical to the monitoring design because the carrier ID provides a cost-effective method to identify the RFI source and to help mitigate the problems. If carrier ID works well, then the monitoring system could rely on this mechanism as the fundamental method to detect and characterize RFI. If carrier ID does not work well enough, then supplemental signal detection and classification approaches must be used.

The carrier ID challenge for this application is that the LTE interference could be due to many (10 or more) weak LTE signals combined. In this case, the carrier ID signals would overlap, causing interference to the carrier

Extracting the carrier ID from an LTE downlink transmission requires that the receiver process several overlapping signals to extract the SIB1 message containing the carrier ID. 3GPP standards and LTE signaling assume that a receiving device (e.g., an LTE handset) would see only a few downlink signals. The receiver would furthermore seek to find the strongest signal, which would have strong SNR (and therefore low interference levels). The environment predicted by Project 8 analysis indicates that the likely interference conditions would consist of many low-power LTE signals. Each signal would have low SNR, which makes carrier ID extraction difficult. The simulations performed in this project show that the probability of extracting carrier ID is less than 1%, even in non-ducting cases.

The conclusion is that relying on the carrier ID approach exclusively to estimate the amount of interference to the NOAA receiver and to determine the responsible LTE transmitters is not feasible. However, the carrier ID information (when available) is useful, and it is worth adding the carrier ID capability to the RFI monitoring system. The additional cost to add the carrier ID capability is relatively small.

4.10.4.3 RFI monitoring trade study

The second goal was to perform a trade study and engineering analysis of the RFI monitoring capabilities and technical specifications for NOAA ground stations protection. The system needs to meet four high-level goals: (1) maximize NOAA's ground link system availability, (2) minimize NOAA's monitoring operations costs, (3) maximize the spectrum sharing between NOAA and the carriers, and (4) ensure cooperative relations between NOAA and the carriers. The monitoring problem was divided into three different areas: measurement, automation, and data management.

There are many critical RFI monitoring system trades, as shown in Table 4.10-25. These choices have a significant impact to the RF monitoring system. A COTS-based, omni-antenna monitoring system (at a cost of about $100,000 per site) would satisfy many of the requirements and would cost an order of magnitude less that custom solutions (more than $1 million per site). A custom solution is the only way to meet all of the potential requirements.

Table 4.10-25. Critical system choices/trades depend on how the RFI monitoring system is used.

Alternative	Discussion	System impact
Desired RFI detection sensitivity	• Very low detection levels (−10 dB INR: policy limit) provide more insight into regulatory compliance, but minimal operational benefits	• Impacts the need for directional monitoring antennas versus omni antennas (and the additional receivers and signal processing) • Greatly increases system size, power, and costs
RFI AoA determination	• Determining RFI AoA would help carriers mitigate interference problems	• Including AoA greatly increases system size, power, and costs
RFI measurement with aggregate RFI performance	• Determining RFI level with aggregate interference provides a more accurate estimate of the RFI level value	• Requires multiple parallel receiver chains approach instead of a beamforming architecture • Significantly increases system size

Table 4.10-25. cont.

Table 4.10-25. Critical system choices/trades depend on how the RFI monitoring system is used.

Alternative	Discussion	System impact
COTS versus custom hardware and software	• COTS hardware and software exist for basic spectrum monitoring and would meet many of the NOAA requirements • Custom hardware and software are required for directional antenna approaches and to meet many of the data management functions	• COTS solutions are an order of magnitude less expensive than custom solutions
Cloud-based architecture	• Cloud-based architecture is best suited for the data management functions, but not for the measurement and automation functions due to the high data collection rates	• Cloud-based systems potentially offer significantly reduced operational costs

Most of these trades are related to the measurement area and depend on how the RF monitoring system is used.

- If the spectrum is shared with multiple different carriers near each NOAA site, then it is necessary to subdivide the allowable RFI levels to different carriers. To monitor this more complex scenario, the higher-performance monitoring system alternatives (low sensitivity, RFI AoA determination, and RFI measurement with aggregate RFI performance) are necessary.
- If the carrier deploys a dynamic LTE system (where ducting, varying traffic loading, and other temporal effects are varied within minutes), then the RFI monitoring system would be a critical component to guide the carrier on how to adapt the LTE network. To monitor this more complex scenario, the higher-performance monitoring system alternatives (low sensitivity, RFI AoA determination, and RFI measurement with aggregate RFI performance) are necessary.

4.10.4.4 Decision analysis and resolution process

To narrow down the problem space, and to highlight system strengths and weaknesses, five RFI monitoring system alternatives were created. These alternatives span the trades shown in Table 4.10-25, and include an all-COTS approach, the RFIMS system, and others. The alternatives were evaluated using a DAR process. Select capabilities were identified and further investigated in the measurement, automation, and data management areas. This included investigations of the strengths and weakness for the different potential alternatives for each of these capabilities. Notional evaluation criteria (similar to the seven categories provided NOAA in Project 3) were used for illustrative purposes. The score factors within each evaluation criteria were identified from the select capabilities traded above, especially in the technical, operations, and performance areas. The DAR results are notional and could easily be adapted (adjust the weights and evaluation criteria) once the RF monitoring system usage is determined by NOAA and the FCC.

4.10.5 Next steps

Monitoring system requirements. NOAA should determine how the RF monitoring system is to be used (if the spectrum is shared with multiple different carriers near each NOAA site or if the carrier deploys a dynamic LTE system). The first factor would be determined by estimating the spectrum auction's license area sizes and the number of likely spectrum auction bidders. The second factor would be determined by discussions with the carriers. SSC believes that the carriers currently have no ability to support dynamic LTE system adaption.

Detailed COTS software evaluation. Study results show that COTS-based systems could provide significant monitoring capabilities. NOAA should purchase a COTS spectrum monitoring system and evaluate it as a low-cost way to verify capabilities and identify any gaps relative to requirements. Assessments should include detection and classification capabilities as well as data management options. NOAA should also evaluate the ability to extend existing capabilities with additional signal processing (e.g., classification algorithms) and data management features. The evaluation should be conducted at one or more GOES ground station sites for several months. This evaluation could be in parallel with the RFIMS evaluation that NOAA is already performing, providing a comparison of any gains that the RFIMS advanced antenna provides.

RFIMS antenna. It is recommended that NOAA conduct detailed assessment of RFIMS-based antennas for the expected LTE deployment and desired system capabilities. An RFIMS antenna system provides capabilities that are likely needed under any alternative design. The vertically aligned, stacked dipole antenna configuration has higher than 0 dBi gain along the horizon and lower gain at high elevations. For this assessment, it is recommended that NOAA consider acquiring a detailed RFIMS design and IP rights. Obtaining IP may promote competition and reduce long-term acquisition costs.

4.11 Project 11. LTE TDD Simulations and Passive Site Surveys

Introduction

Project 11 explored and compared the RFI potential of the use of the 1675–1680 MHz band for a range of LTE derivatives such as traditional cellular, small cell, and internet of things (IoT). Interference scenarios addressed in the study include frequency division duplex (FDD) downlink, FDD uplink, and time division duplex (TDD) operations in the 1675–1680 MHz band. Project 11 assumed normal propagation modes, while anomalous propagation effects are examined in Project 8. This project also identified alternative RFI mitigation techniques and quantified their RFI risk mitigation potential, as described in Section 3.3.

Objective

Project 11 supports two SPRES program objective areas: RFI Modalities and Risks, and Mitigation Options and Feasibilities. This study focused on the following objectives:

- Analyze risks and impacts of RFI produced from in-band and adjacent-band LTE services on GOES Federal earth station sites.

- Develop factors that drive protection requirements for GOES ground stations from the impact of interference as a result of the potential operation of LTE services in the 1675–1680 MHz band.
- Identify methods to mitigate possible RFI from LTE TDD and FDD services and quantify the RFI mitigation methods.

Assumptions

Project 11 used the following assumptions:

- Analysis primarily used LTE tower locations identical to those used in the CSMAC Working Group 5 study. However, CellMapper data was applied for a subset of Federal sites.
- Tower heights assigned based on morphology.
- UE distribution around each base station's sector to fully load the uplink.

Methodology

The study established a "baseline" FDD deployment for all Federal sites using cell tower databases and a consistent set of parameters to describe all the antennas of interest within a 200 km analysis radius of each GOES earth station. RFI for this baseline case was compared with results obtained from several alternative commercial LTE deployments to determine relative changes in RFI risks: LTE TDD, LTE for machines (LTE-M), narrowband internet of things (NB-IoT) in-band, NB-IoT guard-band, and NB-IoT stand-alone. The study then quantified the impact of RFI mitigation techniques applied to the LTE deployments. Mitigations include increased LTE base station antenna downtilt and replacement of large cells with small cells in densely populated areas. The mitigations were analyzed for a representative set of Federal sites, which were selected based on characteristics such as morphology, proximity to population centers, and terrain type. Initially, five Federal sites were considered, but mitigations with the greatest RFI reduction potential were applied to all remaining GOES earth stations.

Findings

Study results indicate deployments show similar RFI risks as functions of exclusion zone sizes surrounding the earth stations. The RFI produced from LTE downlinks dominates the RFI produced from the uplinks in TDD deployments but does not significantly change between FDD and TDD. The primary factors causing the downlink RFI dominance include the differences in EIRP between the downlink and uplink, due in part to the larger peak antenna gain; the larger peak antenna gain of the towers as compared to the user equipment (UE); and a lower propagation loss for the antennas mounted on the towers above terrain and clutter compared to the UEs, which have lower antenna heights above terrain and more clutter loss. The findings are consistent for the large-cell, small-cell, and IoT deployments.

Mitigations that reconfigure the downlink have the most impact in minimizing RFI risks. In particular, adjusting the downtilt or performing a small-cell substitution of offending LTE sectors were the most effective mitigations for most of the sites. While technically plausible, this approach is not considered viable nor likely to be accepted by the wireless carriers.

4.11.1 Modeling

This section describes the ground station antennas, models, and parameters used in the analysis, including RF propagation models and communication system parameters used.

4.11.2 GOES Federal site modeling

Antenna pattern

A critical interference factor is the ground station antenna gain toward the LTE transmitter. The GOES ground stations use reflector-type antennas that have very high gain in the boresight direction and much lower gain at other angles. These ground station antennas also have significant sidelobes that have significant gain at certain angles.

Measured GOES-R 9.1 m and 16.4 m antenna patterns provided by NOAA were used. For the other NOAA ground station antennas, which have different diameters than 9.1 m and 16.4 m, this study assumes that the antenna sidelobe values were independent of antenna diameter, which is consistent with the patterns that were obtained. The 9.1 m diameter antenna pattern was used for all ground station sites. In addition, polarization effects were accounted for by averaging the E-plane (electrical field) and H-plane (magnetic field) values, as shown in Figure 4.11-1. The boresight is given by the axis of maximum gain, indicated by the angle at 0°. The analysis uses the average of the E-plane and H-plane polarization values.

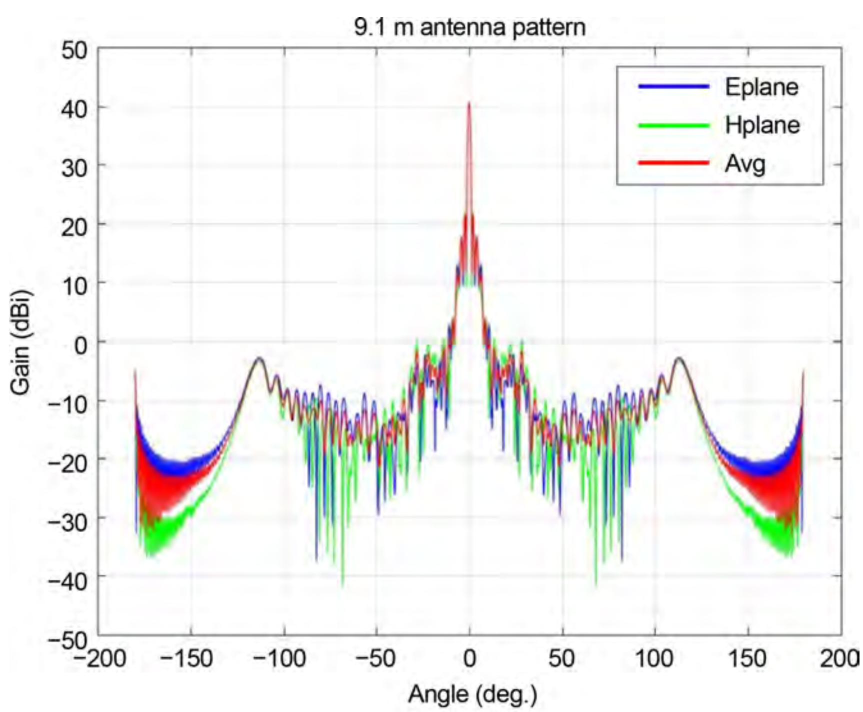


Figure 4.11-1. Simulated antenna pattern gain versus off-boresight angle for E-plane and H-plane polarizations.

4.11.3 Commercial system modeling

LTE tower distribution

The LTE base station (eNB) deployment data was obtained from the CSMAC Working Group 5 Randomized Real model. As CSMAC data was primarily based on a single carrier network, it needed to be augmented for locations where the carrier did not have a presence. For these locations, data from either CellMapper (verified from FCC databases) or AWS-3 deployments were used. The CSMAC data set includes 68,139 towers, as shown in Figure 4.11-2. Tower heights in the study were applied based on the morphology of the tower. Towers in dense urban, urban, suburban, or rural regions were assigned antenna mount heights of 25 m, 35 m, 45 m, or 55 m, respectively. The heights were assigned using demographics (U.S. census) and land-use (USGS) data of the surrounding area.

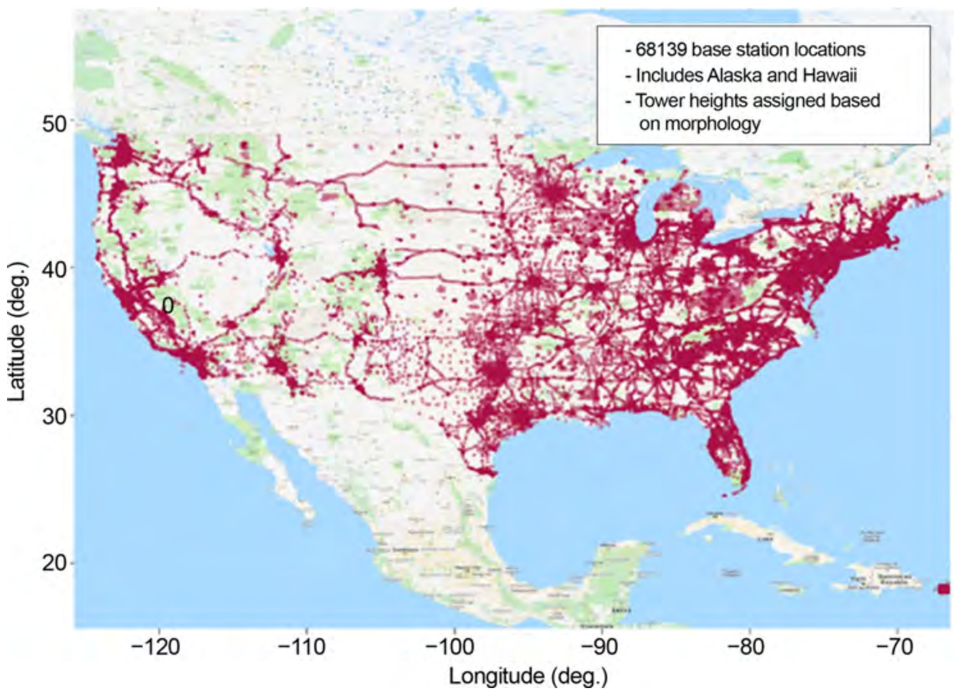


Figure 4.11-2. LTE tower locations based on the Randomized Real data set.

LTE small-cell distribution

Demographics data was used to determine the small-cell locations. Small cells act as potential replacements for large cells and are placed in the populated areas. Thus, the small cells will provide different coverage footprints based on demand. Small cells were not deployed in rural areas since small cells in this frequency range are usually placed only for more densely populated regions. To determine the morphologies, the population density was computed for each block group, and grids of different sizes were created for the given demographics type. The center of the grid acted as the small-cell location, and the following describes the grid sizes for dense urban, urban, and suburban areas:

- Dense urban: grid layout with a 0.5 km coverage radius
- Urban: grid layout with a 1 km coverage radius
- Suburban: grid layout with a 2 km coverage radius

Small cells were generated for regions in proximity to the GOES earth stations of interest, as displayed in Figure 4.11-3. For the 35 GOES earth stations analyzed in this study, there were a total of 116,826 small cells.

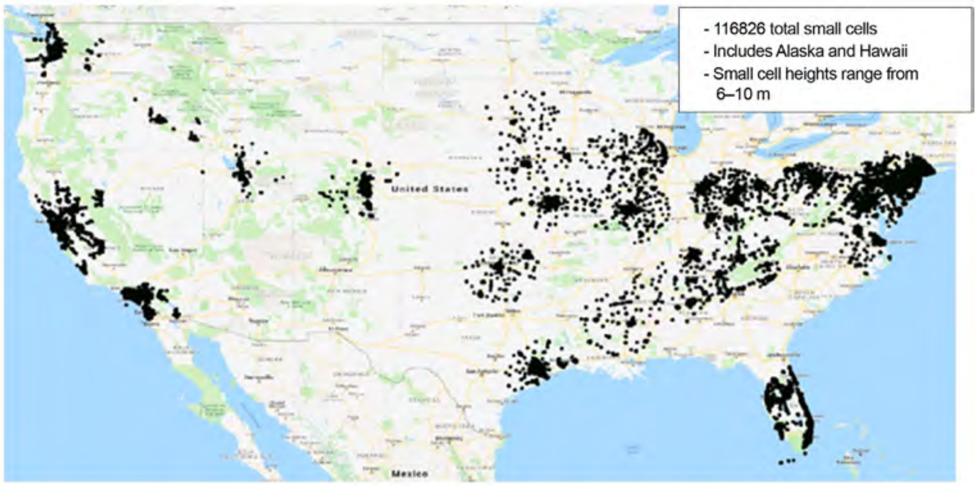


Figure 4.11-3. LTE small-cell locations in the proximity of selected GOES earth stations.

LTE system parameters

The LTE parameters used for analysis are presented in Tables 4.11-1 through 4.11-4. Power levels are maximum allowed per channel.

Table 4.11-1. LTE large-cell downlink system parameters used in analysis.

Parameter	Value	Discussion	Data source
eNodeB (eNB) antenna coordinates	Latitude, longitude	Primary analysis used the CSMAC database. CellMapper* data was also considered.	CSMAC Working Group 5 laydown and cell mapper
eNB EIRP (dBm)	63	—	2 kW/5 MHz limit from 47 CFR 27.50 for 1670–1675 MHz**
eNB antenna gain (dBi)	17.23	Maximum antenna gain from a directional antenna pattern used.	CelPlan patterns. Antennas manufactured by Kathrein
eNB antenna height (m)	25–55	eNB antenna heights of 25 m, 35 m, 45 m, and 55 m in dense urban, urban, suburban, and rural regions.	Representative of industry practice
Transmission bandwidth (MHz)	4.5	—	—
Downlink duty cycle for TDD (%)	60–75	Mitigation analysis will alter the downlink duty cycle for TDD.	—
Number of sectors/tower	3	Mitigation analysis will analyze a configuraton of two sectors per tower.	—

Table 4.11-1. cont.

Table 4.11-1. LTE large-cell downlink system parameters used in analysis.

Parameter	Value	Discussion	Data source
eNB out-of-band-emisssions (OOBE) mask (dBm/MHz)	−13	Default FCC OOBE level at transmitter output. Not adjusted for any filtering.	FCC-14-31A1 R&O***
Downlink maximum resource block (RB) utilization (%)	100	Assumed worst-case scenarios.	—
Downlink loading (%)	100	Assumed worst-case scenarios.	—

*CellMapper is a crowd-sourced service that provides a coverage mapping service as described in Section 4.2.9.
**https://www.law.cornell.edu/cfr/text/47/27.50 (See Section [f]).
***https://transition.fcc.gov/Daily Releases/Daily Business/2014/db0401/FCC-14-31A1.pdf. FCC-14-31A1 R&O states the OOBE suppression to be 43+10Log10(P) which translates to absolute power of −43dBW or −13 dBm.

To conduct the LTE large-cell analysis, 63 dBm EIRP in a 5 MHz band was used, as indicated in Table 4.11-1. The 63 dBm/5 MHz is taken from the maximum EIRP limit in 47 CFR 27.50 for the 1675–1680 MHz band. This power level is 4 dBm/5 MHz higher than the power level proposed by Ligado. Ligado proposed 32 dBW/10 MHz (equal to 59 dBm/5 MHz) in 1670–1680 MHz in FCC Modification Applications (DA 16-442) proceedings.[40]

The LTE small-cell parameters are assumed as indicated in Table 4.11-2.

Table 4.11-2. LTE small-cell downlink system parameters used in analysis.

Parameter	Value	Discussion	Data source
eNB coordinates	Latitude, longitude	Coordinates determined based on population density of regions.	—
eNB transmitter (EIRP) (dBm)	40	Lower EIRP compared to large-cell to account for smaller coverage area.	GSMA Small-Cell Deployment Guide
eNB antenna gain (dBi)	6	Antenna gain from an omnidirectional antenna pattern.	—
eNB antenna height (m)	6–10	—	GSMA Small-Cell Deployment Guide
Transmission bandwidth (MHz)	4.5	—	—
Downlink duty cycle for TDD (%)	60–75	—	—
Number of sectors/small cell	1	—	—
eNB OOBE mask (dBm/MHz)	−13	—	FCC-14-31A1 R&O
Downlink loading (%)	100	Assumed worst-case scenarios	—

The LTE large-cell and small-cell uplink parameters are assumed as indicated in Table 4.11-3.

To conduct the LTE-M analysis, most of the downlink parameters as indicated in Table 4.11-1 remained consistent. A single carrier could transmit at 63 dBm EIRP in a 1.4 MHz channel. LTE supports scalable carrier bandwidths from 1.4 MHz to 20 MHz, and the device bandwidth for LTE Category M (LTE-M) is limited to 1.4 MHz only. The 1.4 MHz limit originates from the 1.08 MHz for

[40]Federal Communications Commission, *Comment Sought on Ligado's Modification Applications*, DA-16-442, RM: 11-109, 12-340, 31 FCC Rcd 3802 (5) (Washington, DC, 2016), accessed May 12, 2020, https://www.fcc.gov/document/ligado-satellite-modification-applications.

Table 4.11-3. LTE large-cell and small-cell uplink system parameters used in analysis.

Parameter	Value	Discussion	Data source
User equipment (UE) coordinates	Latitude, longitude	Location randomized based on morphology and eNB antenna azimuth.	—
UE EIRP (dBm)	−37 to 23	UE EIRP follows a distribution curve such that the maximum EIRP is 23 dBm.	UE EIRP curves from the CSMAC Working Group 1 and 3 studies, maximim EIRP altered to 23 dBm
UE antenna gain (dBi)	2.15	Antenna gain from omnidirectional antenna pattern.	—
UE antenna height (m)	1.5	Typical UE antenna height, based on cellphone case.	—
UE OOBE (dBm/MHz)	−13	Assumed across the whole analysis bandwith.	FCC-14-31A1 R&O
Uplink duty cycle for TDD (%)	25–40	Uplink duty cycle will be altered in the mitigation analysis.	—
Uplink maximum resource block (RB) assignment	25	The three simultaneous UEs cannot exceed 25 RBs. Each resource block is 180 kHz wide.	—
Uplink loading (%)	100	The percentage of UEs that will simultaneously transmit.	—
Number of UEs/sector	Up to 3	UE distribution around each eNB sector to fully load the uplink	—

Table 4.11-4. LTE-M downlink and uplink configurations.

Parameter	1 LTE-M carrier	2 LTE-M carriers	3 LTE-M carriers	Discussion
Channel bandwidth (MHz)	1.08	2.16	3.24	1.08 MHz plus guard-band for 6 RBs in-band to obtain the 1.4 MHz limit
Number of UEs per channel bandwith	6	12	18	1 RB per UE

the six resource blocks (RB) in-band operation (each RB occupies 180 kHz) plus guard bands of 320 kHz total. The LTE-M uplink configuration also retained similar parameters, as shown in Table 4.11-3.

NB-IoT can be deployed in three ways: stand-alone operation, guard-band operation, and in-band operation, as shown in Figure 4.11-4.

To conduct full loading of the RBs in the NB-IoT in-band analysis, most of the downlink parameters as indicated in Table 4.11-1 remained consistent. However, in the 5 MHz channel, one or more of the 25 RBs can be configured as NB-IoT channels. In addition to the possible three non-IoT LTE UEs operating in the uplink 5 MHz channel, an additional one to four NB-IoT UEs (a tone size of 15 kHz per UE) were assigned for each of the 180 kHz RBs that were configured as NB-IoT carriers. Table 4.11-5 describes the UE configuration per NB-IoT carrier.

To perform the NB-IoT guard-band analysis, most of the downlink parameters as indicated in Table 4.11-1 remained consistent. Additionally, one or two NB-IoT channels may be added to the 25 RBs in the standard 5 MHz LTE channel in the guard-band space at either end of the LTE-occupied bandwidth. The uplink configuration used was identical to the scenario outlined for the NB-IoT in-band deployment.

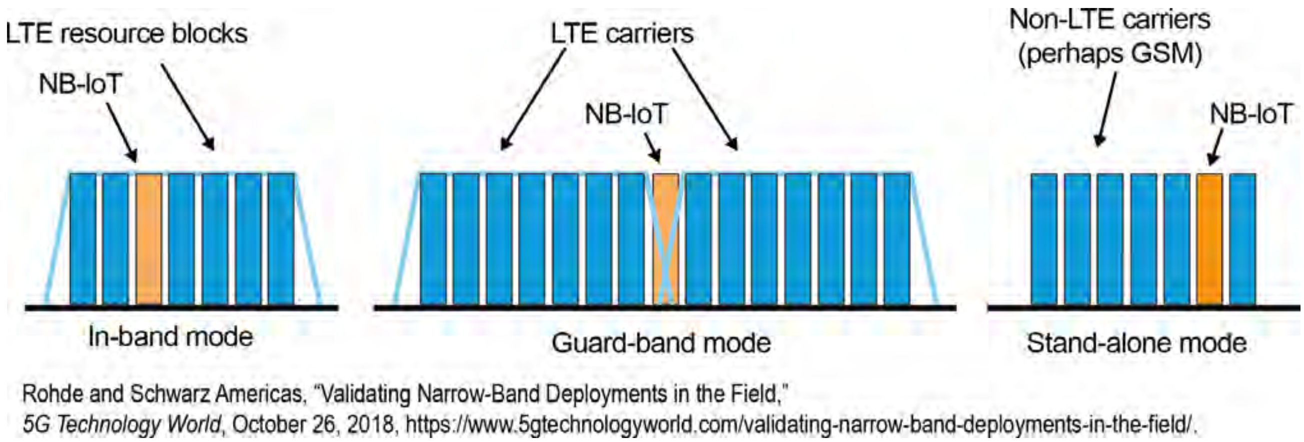


Figure 4.11-4. NB-IoT deployment modes.

Table 4.11-5. NB-IoT in-band and guard-band UE configuration per NB-IoT carrier.

Parameter	Non-IoT LTE UE	NB-IoT UE: 3 tones	NB-IoT UE: 6 tones	NB-IoT UE: 12 tones
Channel bandwith per UE (MHz)	1.44	0.045	0.09	0.18
Number of UEs per NB-IoT carrier	1	4	2	1

To execute the NB-IoT stand-alone analysis, most of the downlink parameters as indicated in Table 4.11-6 remained consistent. However, the occupied bandwidth of this deployment equates to the number of NB-IoT channels multiplied by 180 kHz. Six NB-IoT carriers were assumed in the analysis; therefore, the occupied bandwidth of the downlink equates to 1.08 MHz. In the uplink configuration, the UE coordinates were randomized in the same fashion as the LTE large-cell and small-cell deployments. One to four NB-IoT UEs were assigned for each of the 180 kHz RBs that were configured as NB-IoT carriers.

Table 4.11-6. NB-IoT stand-alone UE configuration per NB-IoT carrier.

Parameter	NB-IoT UE: 3 tones	NB-IoT UE: 6 tones	NB-IoT UE: 12 tones
Channel bandwith per UE (MHz)	0.045	0.09	0.18
Number of UEs per NB-IoT carrier	4	2	1

4.11.4 Propagation modeling

Propagation model

This study used the ITM point-to-point link predictions as it considers detailed terrain paths to determine the propagation loss. The variation of the signal is computed by considering atmospheric changes, terrain profiles, and free space.

Terrain data

The Shuttle Radar Topography Mission (SRTM) terrain data was used to create terrain profiles that were input into the ITM propagation model. For analysis in Hawaii and the continental United States (CONUS), the terrain resolution was approximately 30 m. The terrain resolution for analysis in Alaska was approximately 90 m.

Clutter model

In addition to the propagation loss obtained from the ITM, this study included an additional loss to account for buildings, trees, and other obstacles (clutter). U.S. Geological Survey (USGS) land cover data was used to apply the clutter model. The USGS land cover data is 30 m of resolution for all regions considered in this study. USGS data represents 32 different potential clutter categories (including three “no data” categories). These categories are based on the different clutter types in the surrounding area.

The clutter model consists of two values (transmitter clutter and receiver clutter). These two values are added together to get the total clutter loss. The clutter value at each location is a function of the antenna height and the land cover value. Clutter losses were applied based on the primary clutter category surrounding the earth station, and the primary clutter category between the interferer and the earth station.

4.11.5 Analysis approach

Bandwidth normalization

Base station transmission power level, eNB and UE OOB emission levels, and interference threshold levels are normalized to 1 MHz bandwidth. This approach eliminates the need to adjust the power levels individually for the bandwidth of the received signal.

The UE transmit power level is not normalized. Maximum Tx power level of 23 dBm EIRP is possible across any bandwidth from 180 kHz (1 PRB) to 5 MHz (25 PRBs), depending on path loss, modulation, and block error rate target inputs to the power control and resource allocation algorithms.

Adjacent channel analysis

Downlink NOAA signals that do not overlap the 1675–1680 MHz band can still be harmed by the OOBE from LTE emitters. OOBE is assumed to be −13 dBm/MHz across the whole analysis bandwidth. This is a “conducted” power level; therefore Tx antenna gain is added to it. OOBE is calculated as aggregate RFI at the NOAA earth station similar to co-channel emissions.

OOB RFI is compared to the interference threshold of −129 dBm/MHz, and the exclusion zone is evaluated in a way similar to that in the co-channel interference case. Adjacent-channel analysis is relevant only for sites without in-band downlink signals (i.e., signals outside 1675–1680 MHz).

4.11.6 Findings and results of analysis

This section describes the results obtained during the project for large-cell and IoT deployments. Appendix G describes the use case of an exclusion zone, in addition to differences in results when the earth station is pointing to GOES-East or GOES-West. Appendix G also presents the results for the LTE large-cell and IoT deployment.

The amount of aggregate RFI to a satellite ground station receiver from a distribution of LTE transmitters is dominated by the signal from the closest LTE transmitter. It was assumed that the spectrum-sharing approach between the ground station and the LTE network will require that no LTE towers are allowed within a certain exclusion zone distance. For convenience of analysis, a circular exclusion zone as shown in Figure 4.11-5 was assumed. The analysis used the CSMAC LTE deployment model for LTE tower locations and various emission characteristics. LTE tower locations from the CSMAC database properly represented the density of towers for a single carrier. Moreover, CellMapper data was considered but not used in the primary analysis, for a number of reasons, including (1) locations are not necessarily accurate, and (2) the data does not present the expected density of towers in the proximity of the earth stations. RF energy from LTE towers falling within the region bounded by the exclusion zone and maximum study radius of 200 km was aggregated to produce the total RFI power.

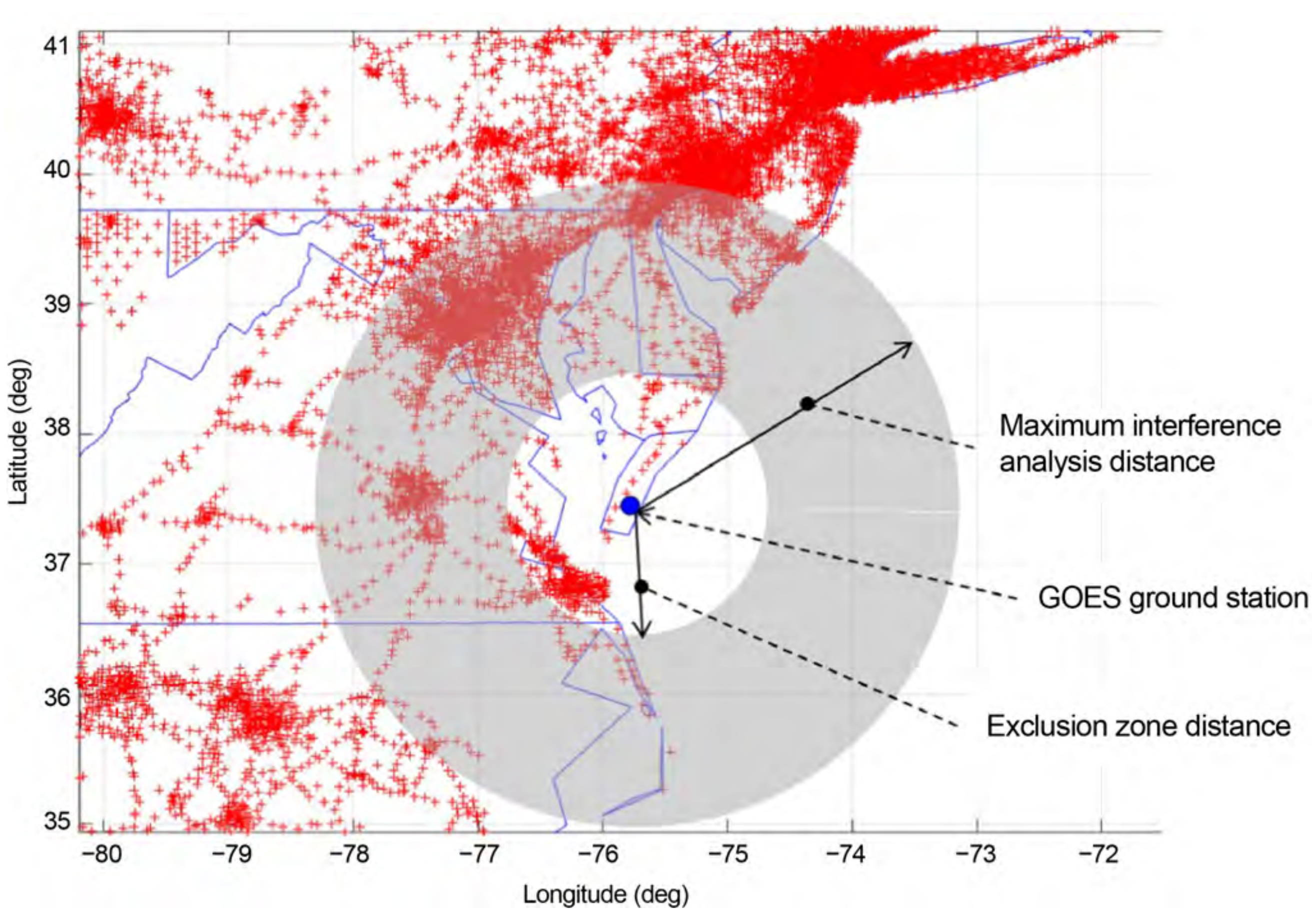


Figure 4.11-5. RFI analysis approach: determine cumulative LTE signal power at GOES ground station as a function of exclusion zone radius.

In general, to determine the degradation of the GOES receiver performance, aggregate RFI versus exclusion distance graphs are considered. The plots in Appendix G consist of six curves representing the co-channel and adjacent-channel results produced from a Monte Carlo analysis. Three percentiles are considered: the 5th, 25th, and the 50th percentiles present the potential outcomes. The CDF 5% curves have the highest interference power, whereas the CDF 50% curves have the lowest aggregate RFI.

Results produced will vary depending on the antenna size and whether the earth station is pointing to GOES-East or GOES-West. This is due to the distributed density of the LTE towers surrounding the GOES earth stations in addition to the geographical location of the earth station. Many interferers will be in the direction of the earth station's sidelobes. The density of interferers in the direction of these sidelobes drives the required size of the exclusion zone. For example, Figure 4.11-6 represents a 9.1 m pattern assumed for WCDAS when the earth station is pointing to GOES-East. In this scenario, the earth station has an antenna azimuth of approximately 179.25°. Considering a 200 km radius, the densest region of towers is located in Washington, D.C. The bearing from Wallops Island site to the center of Washington, D.C., is approximately 305°. From Figure 4.11-6, the gain at approximately 305° is originating from the significant portion of the sidelobes. Thus, it is expected that for the towers at the approximate distance from Wallops Island to Washington, the aggregate RFI contribution from the interferers in Washington will be more significant than in the case when the Wallops Island earth station

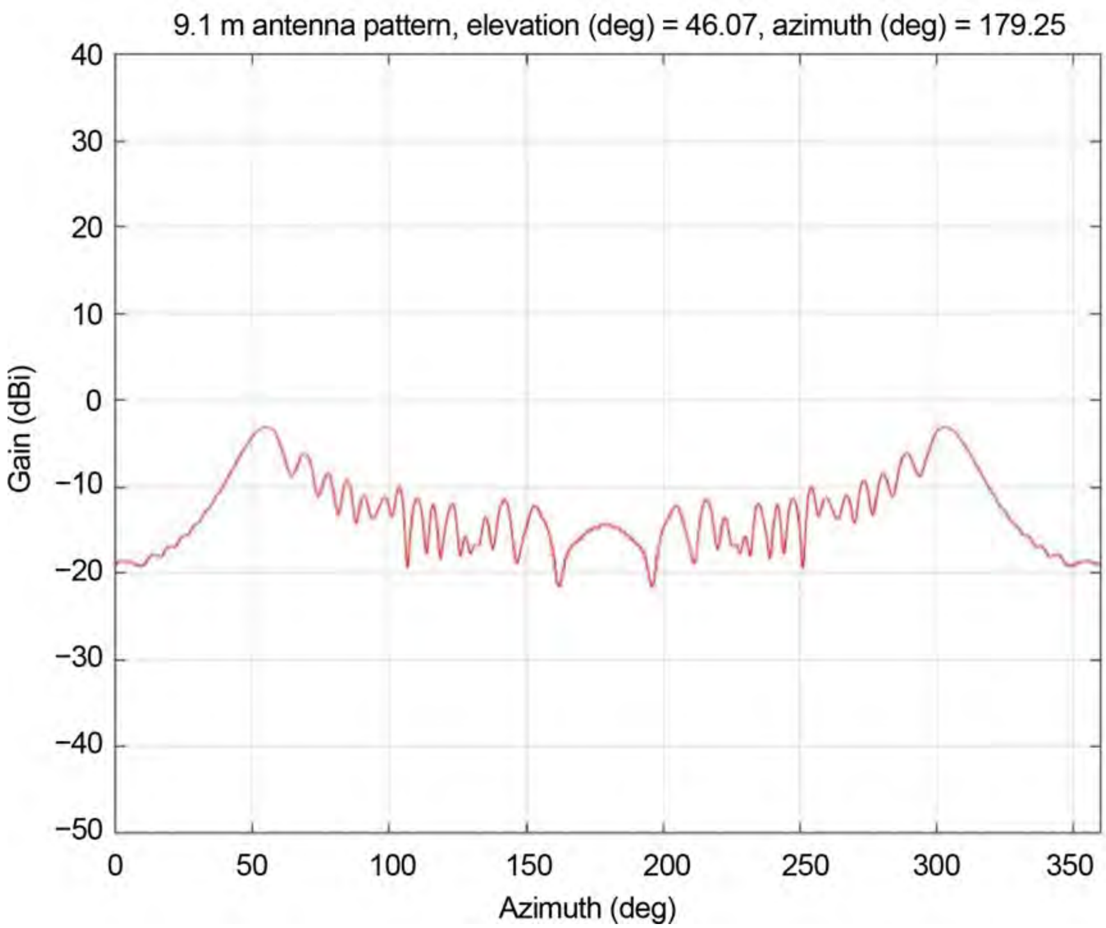


Figure 4.11-6. Simulated antenna pattern versus LTE signal source azimuth direction with the WCDAS satellite antenna elevation at 46.07° and azimuth at 179.25°.

is pointing to GOES-West. When pointing to GOES-West, the antenna azimuth is approximately 250.15°. Therefore, the gain of the earth station with respect to the interferers in Washington, D.C., will not be as significant, because the maximum values of the sidelobes are off-angle. In this case, the gain of the earth station will be approximately −10 dBi, which is about 6 dBi less than the maximum sidelobe gain.

Despite the potential differences in which the earth station is pointing at either GOES-East or GOES-West, the results observed from performing LTE TDD and FDD analysis will remain consistent between both scenarios.

A summary of the simulation results in Appendix G is shown in Table 4.3-9.

Table 4.11-7. Summary of exclusion distance for GOES-East and GOES-West.

Scenario	Earth station	Exclusion distance for GOES-East and GOES-West	Exclusion distance for FDD and TDD deployments
LTE TDD and FDD: baseline large-cell deployment	St. Louis, MO: GOES-East and -West	GOES-East: 27 km (FDD and TDD) GOES-West: 27 km (FDD and TDD) Aggregate RFI is slightly higher than when pointing to GOES-West, but the exclusion distance remains consistent at approximately 27 km.	GOES-East: Small difference between FDD and TDD results GOES-West: Small difference between FDD and TDD results
	King of Prussia, PA: GOES-East and -West (manufacture and test facility for Air Force Mark-IVB systems)	GOES-East: 150 km (FDD and TDD) GOES-West: ~60 km (FDD and TDD) When pointing to GOES-East, as the exclusion distance is increased, the aggregate RFI at each increment is greater than the instance in which the earth station is pointing to GOES-West. The required exclusion distance is vastly different.	GOES-East: Minimal difference between FDD and TDD results GOES-West: Minimal difference between FDD and TDD results
	Boulder, CO: GOES-East and -West	GOES-East: 123 km (FDD and TDD) GOES-West: 123 km (FDD and TDD)	GOES-East: Nearly identical FDD and TDD results GOES-West: Nearly identical FDD and TDD results
	Fairmont, WV: GOES-East and -West	GOES-East: 5 km (FDD and TDD) GOES-West: 5 km (FDD and TDD)	GOES-East: Nearly identical FDD and TDD results GOES-West: Nearly identical FDD and TDD results
	Miami, FL: GOES-East and -West	GOES-East: 55 km (FDD and TDD) GOES-West: 50 km (FDD and TDD)	GOES-East: Nearly identical FDD and TDD results GOES-West: Nearly identical FDD and TDD results
	Norman, OK: GOES-East and -West	GOES-East: 50 km (FDD and TDD) GOES-West: 51 km (FDD and TDD)	GOES-East: Nearly identical FDD and TDD results GOES-West: Nearly identical FDD and TDD results
	Wallops Island, VA: GOES-East and -West	GOES-East: 175 km (FDD and TDD) GOES-West: 90 km (FDD), 50 km (TDD)	GOES-East: Nearly identical FDD and TDD results GOES-West: Highly different FDD and TDD results

Table 4.11-7. cont.

Table 4.11-7. Summary of exclusion distance for GOES-East and GOES-West.

Scenario	Earth station	Exclusion distance for GOES-East and GOES-West	Exclusion distance for FDD and TDD deployments
IoT LTE-M deployment	Boulder, CO: GOES-West	123 km (FDD and TDD)	Nearly identical FDD and TDD results
	Fairmont, WV: GOES-West	5 km (FDD and TDD)	Nearly identical FDD and TDD results
	Miami, FL: GOES-West	55 km (FDD and TDD)	Nearly identical FDD and TDD results
	Norman, OK: GOES-West	60 km (FDD and TDD)	Nearly identical FDD and TDD results
	Wallops Island, VA: GOES-West	175 km (FDD and TDD)	Nearly identical FDD and TDD results

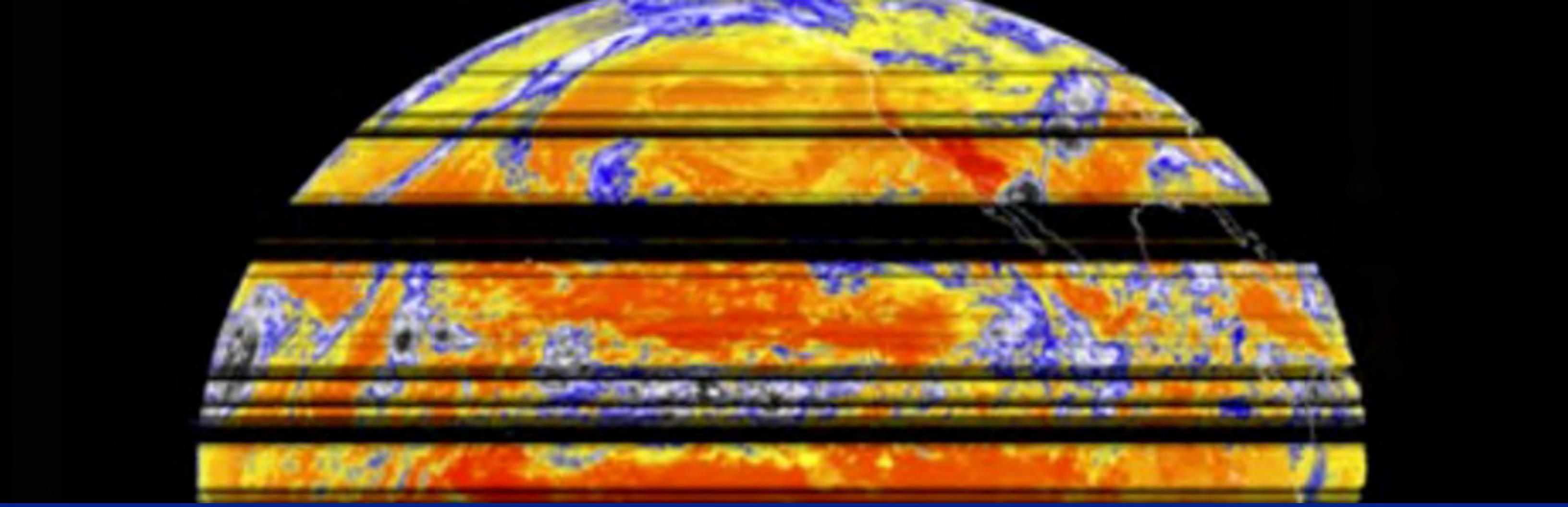
4.11.7 Recommendations and areas for further study

Additional analyses could address scenarios and modeling limitations that are beyond the scope of this project.

1. This study addressed existing and near-term LTE standards. A more comprehensive examination of additional scenarios was deemed out of scope for SPRES. For a future study, additional LTE standards could be evaluated that address the evolving 5G technologies that might be deployed in the 1675–1680 MHz band.

2. This study addressed mitigations applied to the LTE systems and deployments. RFI mitigation methods applied to GOES earth stations such as GOES antenna sidelobe reductions could also have an impact on RFI risks and should be assessed.

3. Ground clutter has a significant impact on propagation loss and the results of RFI analyses. A range of models exist with widely varying differences among them because clutter loss is difficult to model in a general way. This project selected a model incorporating land cover data obtained from USGS and applied losses based on industrial standards, but future analyses should incorporate clutter-loss uncertainty in assessing RFI risks.



5 Conclusion

The 11 SPRES projects revealed a wealth of information concerning the users of GOES satellite data, their applications and requirements, the RFI modalities and impacts that can be predicted to occur in a shared environment, and the overall feasibility of sharing the 1675–1680 MHz band with wireless broadband operations while protecting incumbent operations using one or more mitigation strategies. A close examination of each of the study's objectives has led to the following summarized conclusions. These conclusions are followed by the specific findings and recommendations of the study.

5.1 Summary of Study Objectives

5.1.1 GOES data use

Currently, there are 66 sites/users that operate GRB earth stations, with 15 more planned, and 34 sites/users that operate 44 DRGS direct downlink DCS earth stations. Each of these GOES-R systems has many additional users who retrieve data from an earth station operator.

Users of the DCS broadcast (i.e., operators of DRGS ground stations in the continental United States, as well as others in the Western Hemisphere) rely on DCS capabilities for their mission-critical operations, which are highly sensitive to latency and which must be resilient during natural disasters to reduce loss of life and property. The resiliency requirement rules out use of terrestrial dissemination systems as a broadcast replacement for these entities to retrieve their data, and existing alternate broadcast services (such as HRIT) will not meet latency requirements. It is important to point out that DCS is a relay of original data direct from sources, and that it is not a rebroadcast of information that may have already been sent to earth in another format. DCS is used in many essential applications, including aiding fire prediction and management, determining road closures during weather events, and providing information for a vast array of hydrological applications such as flood warnings, river and reservoir levels, irrigation management, and tsunami warnings.

The study further found that some GRB meteorological products, such as GLM and space weather data and imagery, are very perishable and lose value after only small delays. Although only a small number of users rely on these products today, the significance and extent of their applications make the case that nationwide reception of the existing DCPR and GRB broadcasts should be continued.

GLM data combined with other GOES products can serve as a replacement for weather radars during times when they are not functional or in places where they are nonexistent, such as over oceans. When the weather radar was destroyed by a hurricane in Puerto Rico, leaving the U.S. territory without radar coverage, a combination of GLM data and GOES ABI imagery was used to provide radar-like coverage. This is just one of many examples of how the availability and low latency of GRB play an important role.

GRB imagery products are critical to the production of aviation warnings, and they also contribute to the forecasting of hurricane parameters and severe storms, the reporting of volcanic eruptions and ash events, and the situational awareness of human forecasters. Some specialized NOAA centers, such as the Aviation Weather Center in Kansas City, absolutely must obtain their products in the Level 1b format from GRB with high availability and low latency in support of aviation operations.

Future NOAA L-band spectrum plans are being studied for next-generation development (after GOES-R); however, the high reliability and accessibility of satellite broadcast dissemination during all weather conditions suggests that it is likely to continue to be used for many years.

5.1.2 RFI modalities and risks

The SPRES study looked in depth at 32 Federal sites, but the conclusions drawn are generally applicable as well to other users, including state, local, and non-governmental entities.

The study found that the GOES-R DCS and GRB broadcast signals would be at high risk of harmful interference in a shared environment. This was primarily due to the high (LTE) radiated power levels and to the overlap or close proximity of simultaneous spectrum use. RFI risk resulted from the large amount of direct line-of-site energy from both individual and aggregate sources. In addition, many sites have high potential for anomalous propagation, which can exacerbate RFI by guiding LTE signals over longer distances.

The study also found that, for some applications and users, the real-time broadcast of DCS and GRB data is essential and could not be replaced by terrestrial dissemination techniques due to stringent latency and reliability requirements.

There are 100 sites that currently receive the GRB or DCS service, and 15 more GRB sites are planned or in process. These numbers include both Federal and non-Federal sites. All face an unacceptable level of risk for RFI based upon the LTE downlink sharing scenario, which can be mitigated only by extensive power limitations and geographic separation. Many sites also require protection in the LTE *uplink* sharing scenario. Receiver protection is especially critical at Federal

DCS primary ground stations that are data ingest sites for ground dissemination systems. Many non-Federal users who have installed DRGS stations have done so to protect critical services.

5.1.3 Mitigation options and feasibilities

Earth station operators and users of two GOES L-band satellite broadcast services, the DCS and the GRB services, would be strongly impacted by harmful RFI caused by sharing with LTE carriers. The study found that if the band is used by the mobile broadband service as a downlink band, with the accompanying radiated power levels of current LTE deployments, large exclusion zones would be required, ranging from 18 to 300 km, because of the high EIRP of mobile wireless downlinks and, at some locations, also because of susceptibility to interfering energy transported from distant sources via atmospheric ducting. Mitigating RF interference to such sites is extremely challenging and would entail loss of use of the spectrum by a commercial licensee over wide areas during ducting events to protect incumbent operations. Therefore, sharing in these downlink cases would be impractical. Conversely, allowing unfettered use of LTE services in this band would require costly network redesign, beginning with expenditures totaling $1 billion to modify or replace 40,000 DCS platforms (see Section 3.2.4). Additional, and costly, satellite and ground architecture changes would also be needed.

If the band is shared with LTE uplinks, protection requirements would be reduced significantly, leading to smaller exclusion zones of less than 60 km in size. Exclusion zone requirements are especially reduced in areas prone to atmospheric ducting. Some or all of the RFI risk could be mitigated through application of one or more techniques, further reducing protection distances at most sites.

The study considered a number of such mitigations that might reduce ground-site exclusion zone sizes or obviate the need for the L-band broadcasts. Risks to some sites susceptible to RFI can be mitigated only by moving operations to another location, which was only partially explored in this study. Terrestrial dissemination options exist or could be implemented, but these do not yet meet the needs of many users who require very low latency and very high reliability.

5.2 Findings

Over the course of the two-year study, the data gathered, the ensuing analyses, and the resultant findings have led to the following findings:

Finding 1: Anomalous propagation is a significant contributor to RFI risk in this band, particularly in the downlink sharing scenario.
Atmospheric ducts create conditions conducive to anomalous propagation, and occur frequently at certain sites to become a significant contributor to RFI risk in this band. The height and pointing angle of cell towers, combined with the level of radiated power, result in effective transport of energy from towers over many hundreds of kilometers during ducting events. The risk of interference from anomalous propagation was found to be most significant at sites where (1) there are high probabilities of duct formation, particularly along the Atlantic and Gulf coastlines where humidity is high, including at the NOAA Wallops Island, Virginia, site; and (2) there are nearby population centers where high LTE network deployment density is likely.

Finding 2: Spectrum sharing in the 1675–1680 MHz band with commercial wireless carriers operating in the ***downlink*** mode is ***not*** viable.

The SPRES study found that the GOES-R DCS and GRB receive sites would require large physical separation distances from LTE downlink stations—as much as 300 km at some locations—in order to provide 95% protection (see Table 5.2-1); 100% protection would require distances as great as 650 km. This is primarily due to the high (LTE) radiated power levels: at the GOES receivers, downlinks from a cell tower at a distance of 5 km will exceed the power of the received GOES satellite signals by more than 30 dB, or 1,000 times. No mitigations were found that were able to significantly reduce the required separation distances or remove the need for the GOES downlink sites.

Table 5.2-1. Exclusion zone sizes for 1675–1680 MHz downlink scenario.

GOES receiver	RFI scenario	Maximum separation distance (km)*
DCS	LTE downlink	286
GRB	LTE downlink	203
HRIT	LTE downlink	<5
*Contours assume protection against 95% of RFI events.		

The most effective mitigation solutions were those that reduce the transmitted LTE power levels or reduce the spectrum overlap. This places an imposition on the carrier to operate at levels that are significantly less than what would be expected if NOAA's incumbent operators were not present. On the other hand, not employing these stringent mitigation solutions would put many of the important meteorological missions at undue risk.

Finding 3: Spectrum sharing in the 1675–1680 MHz band with commercial wireless carriers operating in the ***uplink*** mode is ***potentially*** feasible.

There are some mitigation solutions that must be applied. The risks of RFI to the GOES receive stations are reduced, typically by 40 dB or more, relative to LTE downlink signals. The SPRES report recommends specific mitigation techniques that can reduce separation distances and RFI risk, but these require testing and verification and may not eliminate all RFI risk or the need for physical separation. Even if the following conditions are applied, at least one known consequence is anticipated.

- Condition 1: Carriers must maintain transmission power below protection levels at the GOES antenna.
- Condition 2: Carriers must agree to accommodate future earth stations that may be required by NOAA and other Federal incumbents (e.g. DoD) to carry out their assigned missions in operational meteorology.
- Condition 3: Sharing would assume that U.S. meteorological satellites maintain seniority over any new fixed and mobile allocation.
- Condition 4: Sharing with LTE services in uplink mode must be done in accordance with the exclusion zone sizes summarized in Table 5.2-2, and for the specific sites identified in Table 3.3-3.
- Consequence: Such sharing would mean that NOAA is permanently limited to the existing spectrum use. There is a potential for higher-resolution images in the future GEO-XO architecture, and sharing the 1675–1680 MHz band would preclude expansion of the GRB or successor signal needed to support that higher capability.

Finding 4: Some mitigations may be effective, but only in the ***uplink*** sharing scenario.

Over two dozen possible mitigation techniques were studied in both the LTE downlink and uplink scenarios. These included GOES receive antenna and site hardening, GOES receiver improvements, active RFI cancellation techniques, RFI monitoring, dynamic exclusion zones, carrier use of small-cell equipment, and the use of terrestrial rather than satellite dissemination. Most of these proposed mitigations were found to be either incapable of reducing RFI to acceptable levels, excessively expensive to implement, impractical for cellular carriers, or inadequate in meeting the needs of GOES-R product users. The most effective mitigations were those that (1) reduced unwanted energy reaching the GOES receiver through a combination of antenna and site hardening techniques, (2) provided (additional) separation from the GOES signals by moving or truncating the LTE signal below the upper end of the 1675–1680 MHz band, or (3) optimized the GOES receiver performance. The study found that the mitigations would be effective only for the LTE uplink sharing scenario, and not for the downlink scenario.

Table 5.2-2. Exclusion zone sizes for 1675–1680 MHz uplink scenario.

GOES receiver	RFI scenario	Maximum separation distance (km)*
DCS	LTE uplink	60
GRB	LTE uplink	20
HRIT	LTE uplink	<5
*Contours assume protection against 95% of RFI events.		

Finding 5: The GOES-R direct broadcast signals are essential and must be protected.

The study found that meteorological data collected and disseminated by the GOES satellites and ground system makes significant contributions to public safety and our national water resource management system. GOES-distributed data underpins our national weather infrastructure, including the advance weather warning and forecasting system relied upon by industries including aviation, satellite operations, and maritime shipping, by emergency managers responsible for safeguarding life and property, and by the general public.

Among the 100 DCS and GRB sites, the study found a combination of Federal and non-Federal users, all with compelling missions and business cases. Many of the GRB and DCS earth stations also support other users by distributing downlinked data in near-real time.

GRB is the primary way that NOAA provides weather and environmental data and products to many of its users. For some extremely time-sensitive applications, such as space weather and lighting maps, distribution via GRB is the only method that can be used because of the inherent latencies found with other dissemination methods. Overall, L-band direct broadcast provides an efficient means for disseminating large volumes of critical weather data to users in many different locations under most conditions, including severe weather events.

The study further found that DCS is critical infrastructure for NOAA (including the National Weather Service and National Ocean Service), the U.S. Geological Survey, the Department of Defense, the National Interagency Fire Center, the Bureau of Land Management, the U.S. Army Corps of Engineers, the USDA's U.S. Forest Service, and international hydrometeorological agencies in Canada, Mexico, Central America, South America, the Pacific, and the Caribbean.

Looking beyond the current GOES-R architecture, any possible sharing scenario may limit existing spectrum use and impact NOAA's ability to design and develop a future satellite communications architecture. Repurposing the 1675–1680 MHz band would restrict the available bandwidth to support next-generation broadcast capabilities.

5.3 Recommendations and Future Work

While the study itself is complete in addressing the primary objectives and providing the recommendations originally sought, this section recommends additional work that could enhance the process of addressing future questions about the feasibility of spectrum sharing.

Recommendation 1: Direct broadcast services are vital for the weather enterprise.
As discussed in the Findings (Section 5.2), emergency managers, the general public, and many industry segments including aviation, satellite operations, and maritime shipping rely upon meteorological data collected and disseminated by the GOES satellites and ground systems to accomplish their various missions, including safeguarding life and property. The next generation of architectures, including the GEO-XO satellites, should retain the spectrum for the L-band services identified in the current filing for 1675–1695 MHz. These services can serve as a benchmark capability as NESDIS considers a broad range of options for sensor acquisition, data processing, and dissemination of data products.

Recommendation 2: Perform testing and verification of mitigations for uplink interference.
The risk of radio frequency interference to the satellite receiver stations is reduced in the LTE uplink scenario, as compared to the more powerful LTE downlink signals. Separation distance is still required for DCS and GRB ground stations (Table 5.2-2). The study recommends specific mitigations that can reduce separation distances and RFI risk. Among those identified, first considerations should be given to (1) reducing amplifier gain in the receive path to lower the energy in intermodulation and third-order products, (2) enhanced/redesigned filtering in both the low-noise block (antenna L-band electronics) and the DCS receiver (IF chain) to improve rejection of signals below the DCS band (1679.7–1680.1 MHz), and (3) installation of an RF barrier, such as a wall or fence, where technically feasible to surround the ground station antenna to attenuate RFI signals arriving from the horizon. These mitigations, however, require further testing and verification to assess their full benefits, and they may not eliminate all RFI risk or the need for separation.

Recommendation 3: Conduct analysis of techniques to establish appropriate frequency separation.
The 1675–1680 MHz band proposed for LTE sharing partially overlaps with critical DCS services. The viability of LTE uplink sharing could be improved through frequency separation from the DCS signal. Removing the upper resource block(s) can reduce issues related to signal overlap and improve the conditions for uplink sharing, but it is unclear precisely what degree of separation is required to sufficiently mitigate RFI risks. While frequency separation has potential for implementation in this case, further analysis is needed to assess its feasibility for the various mobile broadband applications that may be implemented. Therefore, the optimal separation between the shared spectrum band and the lower edge of the DCS signal requires further investigation. If the removal of the upper resource block(s) proves to be technically feasible and commercially viable, it should be mandated by regulation.

Recommendation 4: Conduct higher-fidelity atmospheric ducting characterization analysis. Further study for characterization of duct size, duration, and variability should be conducted. As the SPRES study has uncovered, ducting is a significant factor in the risks of sharing, particularly with mobile wireless downlinks. The fact that ducting occurs is problematic regardless of the exact characteristics of the duct. Ducting has not been well characterized in past scientific studies, yet even with limited data this study estimated duct size based on statistical correlations of adjacent radiosonde readings. While this approach provided a general approximation of duct sizes, higher-fidelity characterizations would be useful for future sharing scenarios because duct size and shape critically impact interference levels. One possible way to accomplish this is to use a network of ground-based beacons to measure duct characteristics with higher resolution.

5.4 Summary

Environmental and weather information collected by satellites is crucial to the national security, economic health, and public safety of the United States. This data has a significant impact on the U.S. economy. Economic studies estimate that the benefits and savings attributable to satellite data for aviation, irrigated agriculture, electricity, and natural gas are more than $740 million annually. Satellites perform a number of vital functions, including remote sensing, radio navigation, and communications. These functions involve use of radio frequency spectrum, which is divided into radio frequency bands that are allocated for specific uses. These allocations are designed into the current satellites. Once a satellite is launched into orbit, these radio frequencies cannot be changed. Because radio spectrum is shared by many different users and applications—Federal and non-Federal, television and radio broadcasting, radio astronomy, satellites, GPS equipment, mobile phones, radar, Wi-Fi networks, and dozens more—it is governed by an intricate, apportioned regulatory framework.

Given the AWS-3 auction of the 1695–1710 MHz band and the 2003 auction of the 1670–1675 MHz band, NOAA has already made available half of the original 1670–1710 MHz Met-Sat allocation (20 MHz of the original 40 MHz) for wireless broadband. An additional portion of the remaining essential Met-Sat spectrum (1675–1680 MHz) is being proposed for sharing with LTE wireless broadband. This study examined the feasibility of such sharing, and the results indicate that sharing of the 1675–1680 MHz band without explicit protections for incumbent meteorological satellite services (space-to-earth) in the Federal regulations and implementation of mitigations to reduce RFI risks would subject both Federal and non-Federal users to harmful RFI and loss of data.

A range of mitigations was considered, including alternatives to the GRB and DCS broadcasts. However, there were no terrestrial distribution solutions that met the requirements, functionality, and performance of existing systems. Beyond geographic separation, other mitigations considered require additional assessment and testing.

Spectrum sharing with the commercial wireless carriers operating in the uplink mode is potentially feasible. In this uplink scenario, the risk of radio frequency interference to the satellite receiver stations is reduced, given the far lower transmitter power and height above ground level.

The volume of weather data is expected to increase in the future as improved instruments are fielded to meet the need for better accuracy and increased warning time. L-band has the distinct advantage of resilience in severe weather conditions, even during hurricanes, thunderstorms, and other similar circumstances, when higher-frequency bands perform poorly and terrestrial communication is unreliable. It is in these conditions that direct broadcast transmission would be needed the most.

It is imperative that any proposed changes to the current spectrum allocations carefully consider the findings and recommendations of this study, and the measures that must be taken to protect the important incumbent missions from the harmful effects of interference.

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Appendix B. Acronyms and Terminology

Table B-1. Acronyms.

AAWU	Alaska Aviation Weather Unit
ABI	Advanced Baseline Imager
ACI	adjacent-channel interference
ACM	adaptive code modulation
AFB	Air Force Base
AoA	angle of arrival
AP	anomalous propagation
API	application programming interface
APM	Advanced Propagation Model
APT	antenna pattern tool
AR	Alaska region
ARTCC	Air Route Traffic Control Centers
ATO	authorization to operate
AWC	Aviation Weather Center
AWGN	additive white Gaussian noise
AWIPS	Advanced Weather Interactive Processing Systems
AWS	Advanced Wireless Services
BCH	Bose-Chaudhuri-Hocquenghem
BDP	Big Data Project
BEA	business economic area
BER	bit error rate
BLM	Bureau of Land Management
BOM	bill of materials
BOR	Bureau of Reclamation
BW	bandwidth
CBRS	Citizens Broadband Radio Service
CBU	Consolidated Backup Unit
CCB	configuration control board
CDA	command and data acquisition
CDAS	command and data acquisition station
CDF	cumulative distribution function
CDMA	code division multiple access
CID	carrier identification
CIFAR	Cooperative Institute for Alaska Research
CIM	common infrastructure management
CIMMS	Cooperative Institute for Mesoscale Meteorological Studies
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CIO	chief information officer
CIRA	Cooperative Institute for Research in the Atmosphere
CIRES	Cooperative Institute for Research in Environmental Sciences
CISESS	Cooperative Institute for Satellite Earth System Studies
CJSMPT	Coalition Joint Spectrum Management Planning Tool
CLASS	Comprehensive Large Array-data Stewardship System

CMA	cellular market area
CMF	Canadian Master File
CMMI	Capability Maturity Model Integration
CNMOC	Naval Meteorology and Oceanography Command
CONUS	continental United States
COOP	continuity of operations
COR	contracting office representative
COTS	commercial off-the-shelf
CPC	Climate Prediction Center
CPHC	Central Pacific Hurricane Center
CSMAC	Commerce Spectrum Management Advisory Committee
CSP	cloud service provider
CSU	Colorado State University
CW	continuous wave
CWA	Center Weather Advisories
CWSU	Center Weather Service Unit
DADDS	DCS Administration and Data Distribution System
DAMS-NT	data acquisition and monitoring systems–new technology
DAQ	data acquisition
DAR	decision analysis and resolution
dB	decibel
dBm	decibel-milliwatts
DCI	downlink control information
DCP	Data Collection Platform
DCPI	Data Collection Platform interrogation
DCPR	Data Collection Platform Report
DCPRCS	Data Collection Platform Radio Certification Standard
DCPRS	Data Collection Platform Radio Set
DCS	Data Collection System
DDA	data distribution and access
DDS	DCP Data Service
DISA	Defense Information Systems Agency
DMS	document management system
DMSP	Defense Meteorological Satellite Program
DOC	Department of Commerce
DoD	Department of Defense
DOE	Department of Energy
DOI	Department of Interior
DOS	Department of State
DOT	Department of Transportation
DPCM	Dual Pilot Control Module
DRGS	Direct Readout Ground Station
DRS	discovery reference signal
DVB-H	digital video broadcast–horizontally polarized
DVB-S2	digital video broadcast satellite–2nd generation
E2ESS	End-to-End Spectrum Supportability
ECCC	Environment and Climate Change Canada
EDDN	Emergency Data Distribution Network
EDT	Eastern Daylight Time
EEP	Early Entry Portal
EESS	Earth exploration satellite service
EIA	Energy Information Administration
EIRP	effective isotropic radiated power
EMWIN	Emergency Managers Weather Information Network
eNB	Evolved NodeB
EROS	Earth Resource Observation and Science Center
ERTDS	Eastern Range Timing Distribution System
ESPC	Environmental Satellite Processing Center
ESPDS	Environmental Satellite Processing and Distribution System
ESRL	Earth System Research Laboratory
ESRP	Environmental Satellite Receiver/Processor
EUV	Extreme Ultraviolet
EXIS	Extreme Ultraviolet and X-ray Irradiance Sensor Instrument
FAA	Federal Aviation Administration
FCC	Federal Communications Commission

FCDAS	Fairbanks Command and Data Acquisition Station
FDD	frequency division duplex
FDOT	Florida Department of Transportation
FDR	frequency-dependent rejection
FEC	forward error correction
FEP	front-end processor
FER	frame error rate
FFRDC	Federally funded research and development center
FFT	fast Fourier transform
FHWA	Federal Highway Administration
FISMA	Federal Information Security Management Act
FNMOC	Fleet Numerical Meteorology and Oceanography Center
FRRS	Frequency Resources Records System
FSS	fixed-satellite service
FTP	file transfer protocol
FTPS	file transfer protocol secure
FWC	Fleet Weather Center
GCP	Google Cloud Platform
GDP	gross domestic product
GEMSIS	Global Electromagnetic Spectrum Information System
GEO-XO	Geostationary and Extended Orbits
GHz	gigahertz
GLM	Geostationary Lightning Mapper
GMF	FCC Government Master File
GNC-A	GEONETCast
GOES	Geostationary Operational Environmental Satellites
GOES-14	GOES on-orbit spare
GOES-15	GOES on-orbit spare
GOES-16	alternate name for GOES-East
GOES-17	alternate name for GOES-West
GOES-East	GOES satellite at longitude 75.2° west
GOES-NEXT	planned future generation of GOES
GOES-NOP	legacy generation of GOES
GOES-R	Current generation of GOES
GOES-RSTU	The four GOES-R class satellites
GOES-West	GOES satellite at longitude 137.2° west
GPS	Global Positioning System
GRB	GOES Rebroadcast
GSO	geostationary orbit
GVAR	GOES Variable
HADS	Hydrometeorological Automated Data System
HARQ	hybrid automatic repeat request
HRIT	High Rate Information Transmission
HRIT/EMWIN	High Rate Information Transmission/ Emergency Managers Weather Information Network
HSU	Hurricane Specialist Unit
I&Q	in-phase and quadrature
IBWC	International Boundary and Water Commission
ICAO	International Civil Aviation Organization
IDIQ	indefinite delivery/indefinite quantity
IDP	Integrated Dissemination Program
IF	intermediate frequency
IFL	interfacility link
INR	interference-to-noise ratio
IO	instrument of opportunity
IoT	internet of things
IRC	Inouye Regional Center
ISD	Integrated Spectrum Desktop
ITM	Irregular Terrain Model
ITU	International Telecommunication Union
JETS	JSC Equipment Tactical & Space
JPSS	Joint Polar Satellite System
JSC	Joint Spectrum Center
JSDR	Joint Spectrum Data Repository
JTWC	Joint Typhoon Warning Center
LAN	local area network
LDM	local data management

LDPC	low-density parity-check
LEO	low Earth orbit
LHCP	left-hand circular polarization
LMR	land mobile radio
LNA	low-noise amplifier
LNB	low-noise block
LOE	level of effort
LRGS	Local Readout Ground Station
LRIT	Low Rate Information Transmission
LTE	Long-Term Evolution
LTE-M	LTE for Machines
MADIS	Meteorological Assimilation Data Ingest System
MAG	Magnetometer
MDL	Multi-use Data Link
Met-Sat	meteorological satellite
MHz	megahertz
MIB	master information block
MIDDS	Meteorological Information Data Display System
MIMO	multiple-input and multiple-output
MIS	Meteorological Impact Statement
MRS&S	MDL receive system and server
MSAM	Microcomputer Spectrum Analysis Models
MSC	Meteorological Service of Canada
MU-MIMO	multi-user multiple-input and multiple-output
MUD	multi-user detection
MWO	meteorological watch office
NAICS	North American Industry Classification System
NAS	network-attached storage
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NAVO	Naval Oceanographic Office
NAVWAR	Naval Information Warfare Systems Command
NB-IoT	narrowband internet of things
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCICS	North Carolina Institute for Climate Studies
NCWCP	National Center for Weather and Climate Prediction
NDE	NOAA Data Exploitation
NESDIS	National Environmental Satellite, Data, and Information Service
NEXRAD	Next-Generation Radar
NFS	network file system
NHC	National Hurricane Center
NIFC	National Interagency Fire Center
NIx	NOAA-initiated transfer
NMOC	U.S. Navy Meteorology and Oceanography Command
NMOC	Numerical Meteorological and Oceanographic Command
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NPG	NDE Proving Ground
NPRM	notice of proposed rulemaking
NPSS	Next Phase Solutions and Services Inc.
NRE	nonrecurring engineering
NRL	Naval Research Lab
NSA	National Security Agency
NSF	National Science Foundation
NSOF	NOAA Satellite Operations Facility
NSOSA	NOAA Satellite Observing System Architecture
NTIA	National Telecommunications and Information Administration
NWIS	National Water Information System
NWLON	National Water Level Observation Network
NWP	numerical weather prediction
NWS	National Weather Service
NWSTG	National Weather Service Telecommunication Gateway
OAR	Office of Oceanic and Atmospheric Research

O&M	operations and maintenance
ODAPS	OGE Data Acquisition and Patching Subsystem
OFDM	orthogonal frequency division multiplexing
OFR	off-frequency rejection
OGE	Operations Ground Equipment
OOB	out-of-band
OOBE	out-of-band emissions
OPC	Ocean Prediction Center
OPC	Offshore Precipitation Capability
OSPO	Office of Satellite and Product Operations
OSSO	orthogonal signal spectrum overlay
OTR	on-tune rejection
PCFICH	physical control format indicator channel
PCI	peripheral component interconnect
PCM	pulse-code modulation
PDA	Product Distribution and Access
PDCCH	physical downlink control channel
PDF	probability density function
PDSCH	physical downlink shared channel
PE	parabolic equation
PG	product generation
PLMN	public land mobile networks
PLT	post-launch test
PM	program manager
POES	Polar Operational Environmental Satellites
PORTS	Physical Oceanographic Real-Time System
PPZ	product production zone
PRB	physical resource block
PSS	primary synchronization signal
PTWC	Pacific Tsunami Warning Center
QAM	quadrature amplitude modulation
QPSK	quadrature phase-shift keying
RAWS	Remote Automated Weather Stations
RB	resource block
RDS	Relational Database Services
Ref BW	reference bandwidth
RFC	River Forecast Centers
RFI	radio frequency interference
RFIMS	RFI monitoring system
RFP	request for proposal
RFPT	Radio Frequency Processing Tool
RHCP	righ-hand circular polarization
RMS	remote monitoring site
ROM	rough order of magnitude
RS	Reed–Solomon
RSSI	received signal strength indicator
RT-STPS	Real-time Software Telemetry Processing System
SARD	System Architecture and Requirements Division
SATCOM	satellite communication
SAW	surface acoustic wave
SBA	Small Business Administration
SBN	Satellite Broadcast Network
SCS	Spectrum Certification System
SD	Sensor Data
SDIFMS	Satellite Downlink Interference Filtering and Monitoring System
SDR	software-defined radio
SDS	Satellite Data Services
SEISS	Space Environment In-Situ Suite
SFTP	secure file transfer protocol
SIB	system information block
SIEM	security information and event management
SIGMET	significant meteorological event
SINR	signal-to-interference-plus-noise ratio
SME	subject-matter expert/expertise
SMG	Spaceflight Meteorology Group
SNPP	Suomi National Polar-orbiting Partnership
SNR	signal-to-noise ratio
SNS	simple notification service
SOC	standard occupational classification

SOC	Security Operations Center
SOCC	Satellite Operations and Control Center
SOH	state of health
SOSC	Spectrum Operations Support Center
SOZ	satellite operations zone
SPC	Storm Prediction Center
SPoRT	Short-term Prediction Research and Transition Center
SPRES	Spectrum Pipeline Reallocation Engineering Study
SPRWG	Space Platform Requirements Working Group
SPS	Sensor Processing System
SRTM	Shuttle Radar Topography Mission
SSC	Shared Spectrum Company
SSEC	Space Science and Engineering Center
SSS	secondary synchronization signal
SU-MIMO	single-user multiple-input and multiple-output
SUVI	Solar UltraViolet Imager
SWPC	Space Weather Prediction Center
SXI	Solar X-ray Imager
SXXI	Spectrum XXI
TDD	time division duplex
TDOA	time difference of arrival
TIREM	Terrain Integrated Rough Earth Model
TPIO	Technology, Planning, and Integration for Observation
TPS	transmission parameter signaling
TVA	Tennessee Valley Authority
Tx	transmitter
UCAR	University Center for Atmospheric Research
UE	user equipment
UHF	ultra high frequency
UIx	user-initiated transfer
US&P	United States and its possessions
USACE	United States Army Corps of Engineers
USAF	United States Air Force
USB	universal serial bus
USBR	United States Bureau of Reclamation
USD	United States dollars
USDA	United States Department of Agriculture
USFS	United States Forest Service
USG	United States Government
USGS	United States Geological Survey
USMC	United States Marine Corps
USN	United States Navy
V&V	verification and validation
VAAC	Volcanic Ash Advisory Centers
VAGL	Vendor-Allocated Ground Latency
VHF	very high frequency
VM	virtual machine
VPC	virtual private cloud
VRAMS	Versatile RF Automated Monitoring System
VSG	vector signal generator
WAN	wide area network
WBS	work breakdown structure
WCDAS	Wallops Command and Data Acquisition Station
WFO	Weather Forecast Office
WMO	World Meteorological Organization
WPC	Weather Prediction Center

Table B-2. Technical terms.

Advanced Wireless Services (AWS)	FCC term for spectrum bands allocated for radiocommunication services. AWS-1, defined in 2002, covers 1710–1755 and 2110–2155 MHz. AWS-2, defined in 2012, covers 1915–1920 and 1995–2000 MHz. AWS-3, defined in 2013, covers 1695–1710, 1755–1780, and 2155–2180 MHz.
decibel-milliwatts (dBm)	Unit used to define the strength of a transmission signal.
downlink, uplink	In cellular communications, uplinks are transmissions from handheld equipment to the cell tower, while downlinks are tower-to-device communications. Downlinks produce much more powerful signals.
downtilt	Temporary adjustment of the angle of a cellular antenna more toward the ground in order to reduce RFI.
effective isotropic radiated power (EIRP)	The measured radiated power of an antenna in a specific direction.
frequency division duplex (FDD), time division duplex (TDD)	Implementations of LTE wireless services. In FDD, the LTE transmitter and receiver operate at different carrier frequencies. In TDD, the sender and receiver use the same channel but sending is separated from receiving by the allocation of different time slots.
terrestrial networks	Non-satellite, earth-based communications networks, which may include the internet and mobile networks.
anomalous propagation due to atmospheric ducting	A phenomenon resulting from strong temperature and humidity gradients in the troposphere. Rather than dissipating with distance, a radio signal becomes trapped between the layers and propagates within this “duct,” traveling farther, and at a higher power level, than would normally occur. This phenomenon increases the chances that the signal will interfere with other signals in or near the duct.
clutter	Structures, vegetation, or other objects that can attenuate RFI.
internet of things	Services that rely on lower data rates and low-power signals to connect devices related to remote infrastructure monitoring, home automation, healthcare monitoring, and other applications.
L-band, X-band	L-band is the range of radio frequencies from 1–2 GHz. X-band is the range from 8–12 GHz.
latency	Delay in the transmission of data from one point to another.
left- or right-hand circular polarization (LHCP/RHCP)	A type of radio transmitter that produces an electric field that rotates in either a right-hand (RHCP) or left-hand (LHCP) sense with respect to the direction of propagation.
LTE, 5G	LTE (Long-Term Evolution) and 5G (fifth generation) are standards for wireless broadband communication. 5G is the more recent standard and promises faster data rates.
exclusion zone, coordination zone	Geographical areas where cellular deployments are prohibited or controlled (by coordination between the incumbent and the wireless provider) in order to limit RFI.
radiosonde	Instruments carried into the atmosphere, usually by weather balloons, to collect meteorological information.
radio frequency interference (RFI)	Unwanted radio signals that cause disruptions in the reception of desired signals.
radio propagation models	Mathematical formulations used to characterize the propagation of radio waves as a function of frequency, distance, and other conditions. The U.S. Navy’s Advanced Propagation Model (APM) is especially effective at characterizing anomalous propagation. The Longley-Rice Irregular Terrain Model (ITM) is especially effective at characterizing line-of-sight interference from RF sources and attenuation effects from buildings and other clutter sources.
sidelobe, shroud	In a receiving antenna, a **sidelobe** is a radio signal received from a direction other than the one desired, which can cause RFI. Sidelobe levels can be reduced by the addition of a **shroud**, a device that shields the antenna from radiation arriving from angles other than the one desired.
small cell, large cell	In a mobile network, a large cell is higher-powered equipment that provides radio coverage over a larger area, whereas a small cell transmits at lower power over a smaller area, posing less risk of RFI.

Table B-3. GOES systems and products.

GOES satellites	NOAA's current generation of geostationary weather satellites, known as the **GOES-R** series, operates from two primary locations: **GOES-East** (also known as **GOES-16**) at 75.2° west longitude and **GOES-West** (also known as **GOES-17**) at 137.2° west longitude. NOAA also maintains at least one on-orbit spare to serve as backup in the event of problems with a primary satellite. Currently that spare is an older generation of GOES, known as the **GOES-NOP** series. **GOES-NEXT** is the planned future generation of GOES.
GOES-R satellite instruments	The Advanced Baseline Imager (ABI) is the primary instrument on the GOES-R series for imaging earth's weather, oceans, and environment. The Geostationary Lightning Mapper (GLM) detects lightning activity continuously, allowing forecasters to identify developing storms and issue warnings. Four remaining GOES-R sensors are collectively known as space weather sensors: Space Environment In-Situ Suite (SEISS), Magnetometer (MAG), Extreme Ultraviolet and X-ray Irradiance Sensors (EXIS), and Solar Ultraviolet Imager (SUVI) monitor solar flares and other phenomena that could pose dangers to astronauts, spacecraft, and satellites, as well as to power grids and communications and navigation systems on earth.
GOES-R ground system	The GOES-R ground system receives data from the satellites and prepares it for distribution. The core of the ground system is located at three sites: the two primary locations are NOAA Satellite Operations Facility (NSOF) in Suitland, Maryland, and Wallops Command and Data Acquisition Station (WCDAS) in Wallops Island, Virginia; a third site is the Consolidated Backup Facility (CBU) in Fairmont, West Virginia. The primary sites normally receive and process the raw data, but the backup site can perform nearly all critical functions in the event of a primary site failure.
GOES-R data levels	The NSOF and WCDAS ground stations receive the GOES-R satellite data in its raw format, called Level 0 data, and process it into usable products. Level 1b data products are produced when the ground system translates the raw data into information that computer modeling systems can utilize. Further processing adds color corrections and highlights certain conditions of interest—including cloud and moisture imagery, hurricane intensity estimation, and lightning detection—to create Level 2+ products that are even more useful to meteorologists.
GOES-R user systems: GRB, ESPDS, PDA	After the ground stations process the raw GOES data into usable products, all results are transmitted in full resolution and in near-real time back to the GOES-R satellites for broadcast to users. This broadcast of processed satellite meteorological information is known as the **GOES Rebroadcast (GRB)**, a continuous stream of weather and meteorological images and products. (GRB replaced the **GOES Variable [GVAR]** service provided by the GOES-NOP series.) In parallel with GRB, the Environmental Satellite Processing and Distribution System (ESPDS) processes and distributes meteorological data and products from NOAA and international sources. The **Product Distribution and Access (PDA)** service provides real-time distribution of ESPDS.
GOES-R user systems: DCS	The Data Collection System (DCS) is a relay system used to collect information from a large number of widely distributed earth-based platforms, known as Data Collection Platforms (DCPs), which are located primarily in remote areas. DCPs use sensors to acquire data and transmit it to the GOES-East or GOES-West satellite via a UHF directional antenna. The GOES-R satellite transponder receives the UHF signal and retransmits the data, now known as a Data Collection Platform Report (DCPR), in L-band. The data user acquires the DCPR signal using a Direct Readout Ground Station (DRGS). Major DRGS sites include NOAA's WCDAS and NSOF, as well as the U.S. Geological Survey (USGS) Emergency Data Distribution Network (EDDN) in Sioux Falls, South Dakota. The DCPR data is processed using ground equipment collectively called the DCS Access and Data Distribution System (DADDS). EDDN adds an independent GOES DCS reception and distribution system to complement DADDS.
GOES-R user systems: HRIT/EMWIN	The Emergency Managers Weather Information Network/High Rate Information Transmission **(HRIT/EMWIN)** transmits weather forecasts and warnings via satellite in a form well suited for emergency managers and other decision-makers who may be functioning in an environment where the power grid, wireless services, and the internet are not in service. The signal incorporates weather event warnings, low-resolution GOES satellite imagery data, DCP messages, and other selected products.

Appendix C. Program Organization and Acknowledgments

C1 Program Organization

The organizational structure and staffing approach for SPRES, outlined in Figure C-1, provided appropriate skillsets, experience, and staff resources to execute the independent and objective government acquisition and oversight activities required. SPRES was led by government officers in the Branch Chief, Contracting Office Representative (COR), and Program Manager (PM) positions. The SPRES COR defended the budget, monitored spending, and was the focal point and primary interface for the program to internal NOAA/NESDIS/CIO components and external organizations including Congress, oversight agencies, and mission partners. The SPRES PM had authority and responsibility for managing the overall performance and operation of the program. The PM was accountable to the Branch Chief and NOAA/NESDIS/CIO management for all aspects of the program, including financial, technical, information security, programmatic, and operational performance.

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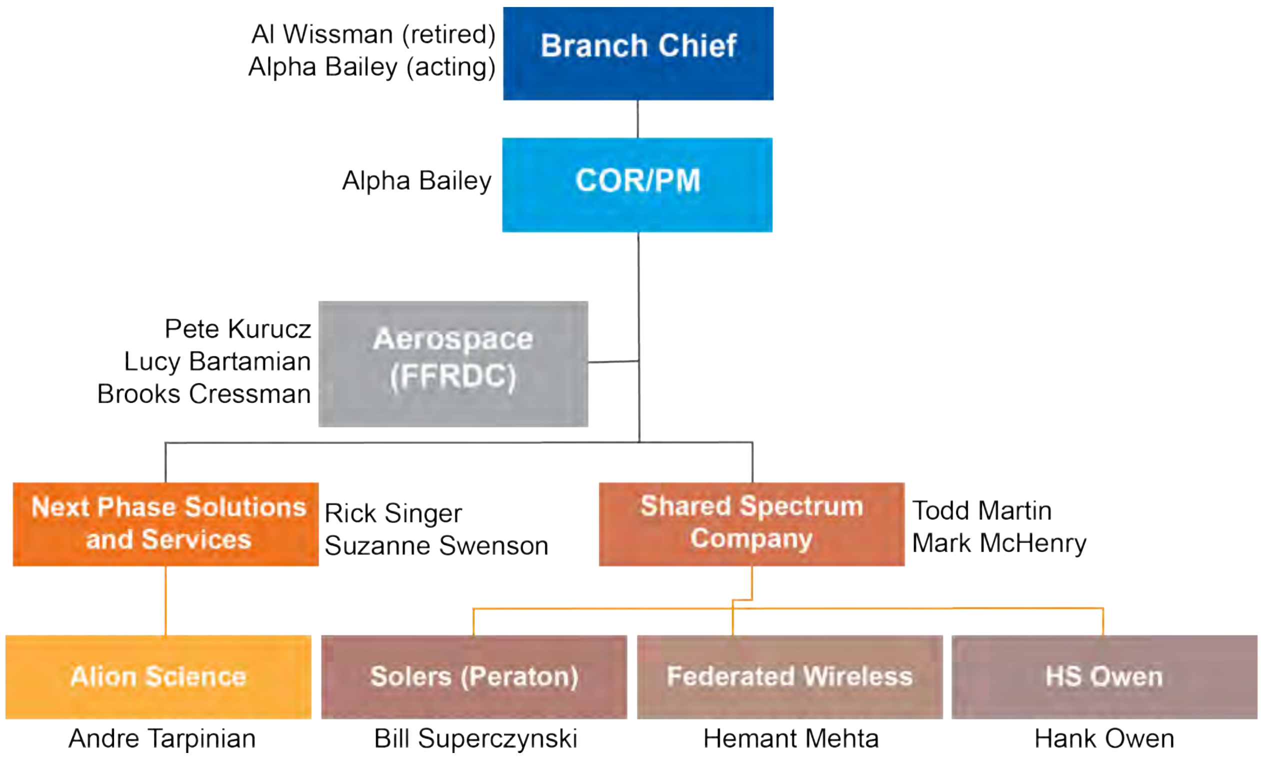

Figure C-1. SPRES organizational structure and leadership.

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Jessicca Griffin, Graphics Production, Cooperative Institute for Satellite Earth System Studies, North Carolina State University, Asheville, NC

Gregory Hammer, Content Team Lead, Communications and Outreach, NOAA/NESDIS National Centers for Environmental Information, Asheville, NC

S. Elizabeth Love-Brotak, Graphics Production, NOAA/NESDIS National Centers for Environmental Information, Asheville, NC

Deborah Misch, Graphics Production, Innovative Consulting and Management Services, NOAA/NESDIS National Centers for Environmental Information, Asheville, NC

Deborah Riddle, Graphics Production, NOAA/NESDIS National Centers for Environmental Information, Asheville, NC

Mary Slagle, Graphics Support/Printing, Innovative Consulting and Management Services, NOAA/NESDIS National Centers for Environmental Information, Asheville, NC

Sara Veasey, Visual Communications Team Lead, Communications and Outreach, NOAA/NESDIS National Centers for Environmental Information, Asheville, NC

Jewel H. Ward, Librarian, LAC Group, NOAA/NESDIS National Centers for Environmental Information, Asheville, NC

Appendix D. GOES Downlink Stations

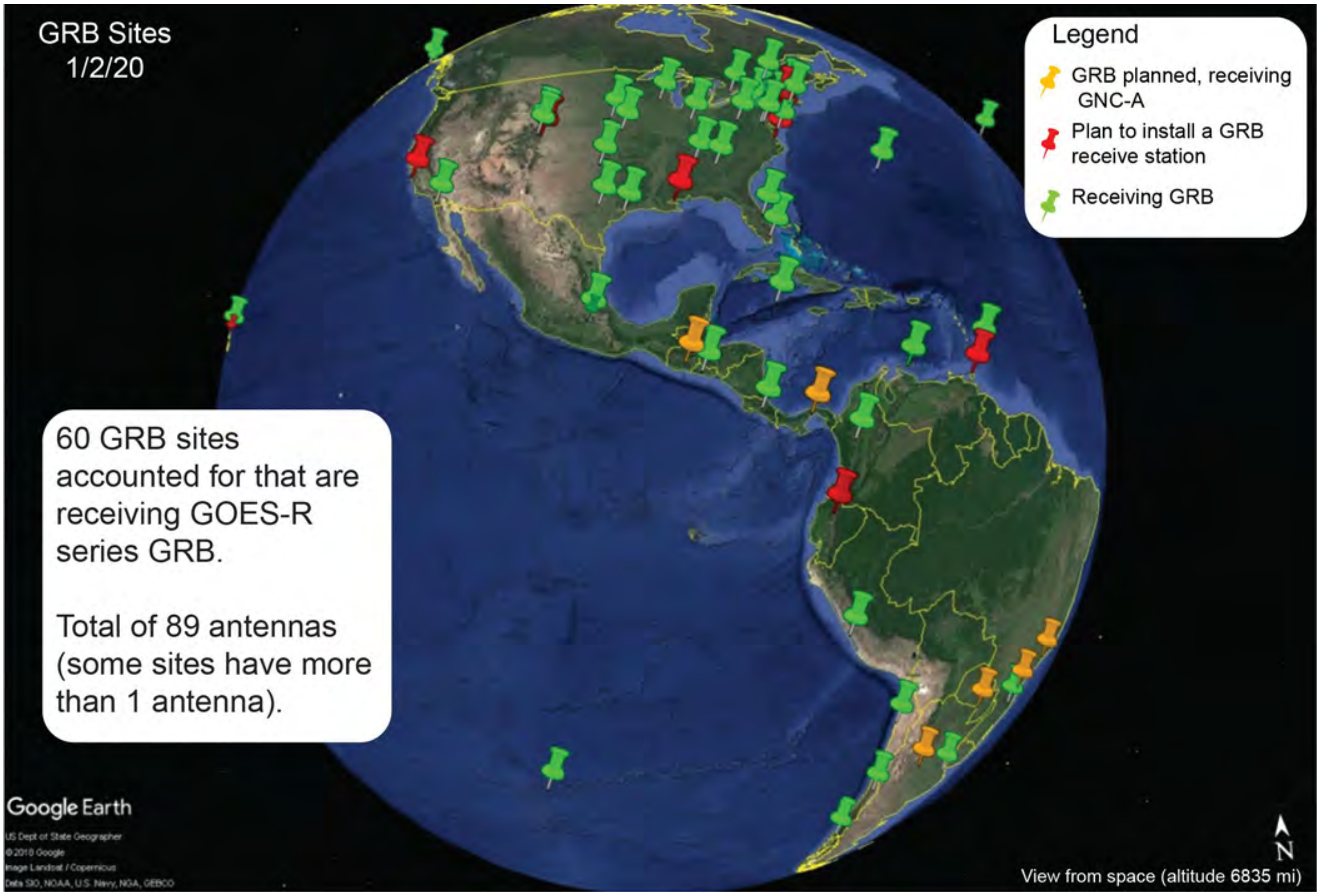

Figure D-1. GRB receive stations (as of January 2, 2020).

Figure D-2. DCP transmitter locations (as of July 3, 2018).

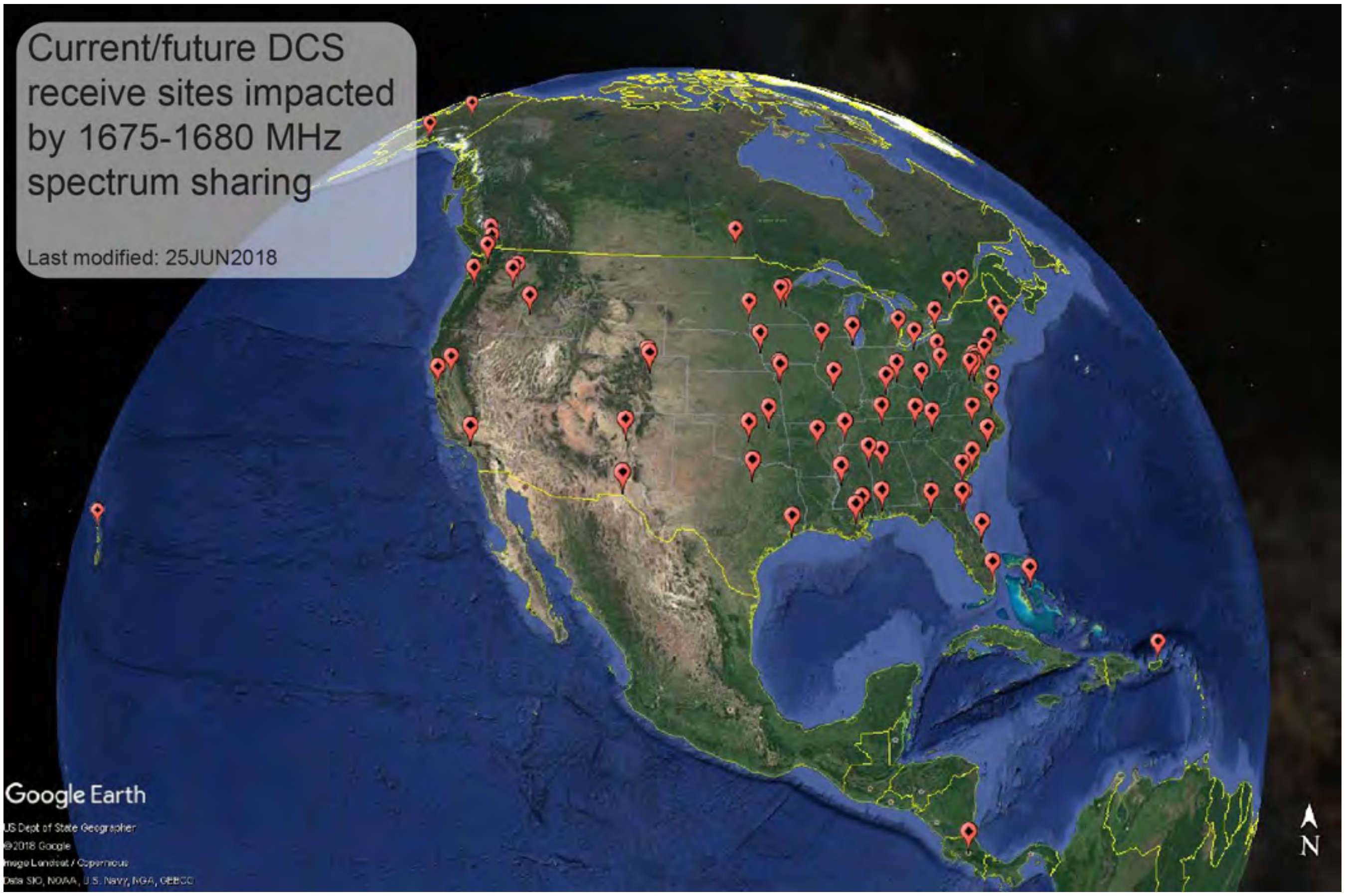

Figure D-3. DCS direct broadcast user receive sites (as of July 3, 2018).

Appendix E. Overview of Federal Use Cases

Table E-1 is a list of Federal and affiliated agencies that have use of GOES direct broadcast services.

Table E-1. Federal agencies and use cases.

Agency	Services and use cases
NOAA/NWS	
NOAA	Hurricane tracking and landfall predictions, volcanic ash cloud detection and tracking, aviation hazards, severe storm prediction and warnings, cloud-to-ground lightning, ocean and precipitation product generation for marine charts and text forecasts. Communications relay via space of coastal, river, and stream water gages; drought monitoring in reservoirs; wildfire weather sensors; and selected buoys.
Alaska Aviation Weather Unit	The Alaska Aviation Weather Unit is the only International Civil Aviation Organization (ICAO) meteorological office in the world that is both a Volcanic Ash Advisory Center and a Meteorological Watch Office (MWO). This unit is responsible for issuing Volcanic Ash Significant Meteorological Information Statements (SIGMET), which is the primary warning product to the aviation community of the hazard of volcanic ash.
Pacific Region (Honolulu, HI: headquarters)	Pacific Region offices provide products for aviation, maritime, flooding/hydrology, and public forecast services. The Central Pacific Hurricane Center (CPHC) issues tropical cyclone watches, warnings, advisories, discussions, and statements for all tropical cyclones in the Central Pacific.
Pacific Tsunami Warning Center (NWS)	Tsunami warning and hurricane-related storm-surge warnings for coastlines and islands within the U.S. and Possessions.
Aviation Weather Center (AWC)	Aviation Weather Center provides aviation warnings and forecasts of hazardous flight conditions at all levels within domestic and international air space.
National Hurricane Center (NHC)	National Hurricane Center provides forecasts of the movement and strength of tropical weather systems and issues watches and warnings for the U.S. and surrounding areas.
Weather Prediction Center (WPC)	Weather Prediction Center provides nationwide analysis and forecast guidance products out through seven days.
Climate Prediction Center (CPC)	Climate Prediction Center monitors and forecasts short-term climate fluctuations and provides information on the effects climate patterns can have on the nation.
Space Weather Prediction Center (SWPC)	Near-earth space environments, impacts to orbiting satellites, protection of aircraft crew and passengers from excessive natural radiation, space weather warnings to electrical power distribution operators, and protection of GPS and HF communications.
Ocean Prediction Center (OPC)	Marine charts and text forecasts, lightning strike density, unified surface analysis, product loops, volcanic ash information.

Table E-1. cont.

Table E-1. Federal agencies and use cases.

Agency	Services and use cases
Storm Prediction Center (SPC)	National hazardous weather forecast responsibility across the continental United States for severe storms producing tornadoes, damaging wind gusts, and large hail; hazardous winter weather; and wildfires.
Physical Oceanographic Real-Time System (PORTS) National Ocean Service (NOS)	Real-time tide and current data to promote navigation safety for maritime navigation. Located at major ports in U.S. and Canada, in support of commercial cargo and passenger shipping for navigation safety.
DoD	
U.S. Army Corps of Engineers (USACE)	Flood forecasting, water management for hydroelectric power generation and reservoir operation, and water data, all of which allow for timely warnings that save lives and decrease property damage. Stream and precipitation gages aboard GOES data collection platforms provide data for river models that enables shipment of commodities via the nation's inland waterways. These forecast models are also used at NWS offices to issue river forecasts and flood warnings for the safety of life and property.
U.S. Air Force	Severe storm prediction and warnings. Meteorological products used by all military departments. Mark-IVB receive stations capture GRB data at these locations: • Offutt AFB, NE • Lajes Field, Azores, Portugal • Joint Base Pearl Harbor–Hickam, HI • Lockheed Martin Depot, King of Prussia, PA • Joint Base Elmendorf–Richardson, AK
U.S. Navy	The Naval Meteorology and Oceanography Command (COMNAVMETOCCOM), or CNMOC, utilizes four operational meteorological sites planned to capture GOES GRB data. CNMOC is focused on providing critical environmental knowledge to the warfighting disciplines of antisubmarine warfare; naval special warfare; mine warfare; intelligence, surveillance, and reconnaissance; and fleet operations (strike and expeditionary), as well as to the support areas of maritime operations, aviation operations, navigation, precise time, and astrometry. The Navy is testing the new GRB-capable FMQ-26 system at the Indianapolis Depot (managed by Raytheon), which is receiving GRB from GOES-16. GRB receive station installations are planned for the following sites: • Fleet Weather Center (FWC), Norfolk, VA • Naval Oceanographic Office (NAVO), Stennis Space Center, MS • Numerical Meteorological and Oceanographic Command (NMOC), Monterey, CA • Joint Typhoon Warning Center (JTWC), Joint Base Pearl Harbor–Hickam, HI
FAA	
Air Route Traffic Control Centers (ARTCC)	Twenty-one locations that house Center Weather Service Units (CWSU) that are staffed by the NWS. Each CWSU provides weather information by computer products and standup briefings to air traffic control area managers.
International Civil Aviation Organization (ICAO)	Has created nine Volcanic Ash Advisory Centers (VAAC) worldwide to support aviation operations and safety. Two of these VAAC locations operate in the United States and generate products used by AWC and NOAA to provide warnings of volcanic ash events. Meteorological Watch Offices (WMO), operated by NWS, are responsible for providing en-route domestic and international weather information and services to the FAA. WMOs create customized aviation product mosaic forecasts of GOES GVAR and GRB data sources.
Offshore Precipitation Capability (OPC)	Combined products using GOES-R imagery and GLM data were developed from work for the FAA by MIT/Lincoln Labs for the OPC. OPC is a system that helps compensate for the fact that there are no land-based radars over the ocean. This is a new capability. Air traffic controllers work to keep aircraftaway from severe storms and conditions that are hazardous to air transportation.

Table E-1. cont.

Table E-1. Federal agencies and use cases.

Agency	Services and use cases
DOI	
U.S. Geological Survey (USGS)	Water data for the nation, program for disseminating water data within USGS, to USGS cooperators, and to the general public. Tsunami warning and hurricane-related storm surge warnings for coastlines and islands within the U.S. and Possessions.
BLM	
National Interagency Fire Center (NIFC)	The Remote Automated Weather Stations (RAWS) DCPs are deployed in about 4,000 strategic locations throughout the United States and are packaged for rapid deployment in areas where data needs to be collected to monitor changing wildfire weather conditions. These remote weather sensors are primarily owned by wildland fire agencies, monitoring fire danger by collecting, storing, and forwarding precipitation, relative humidity, wind, solar radiation, and other data.
NASA	
Spaceflight Meteorology Group (SMG)	SMG provides unique world-class weather support to the U.S. Human Spaceflight effort by: (1) providing weather forecasts and briefings to NASA personnel; (2) providing pre- and post-spaceflight weather analyses and documentation; (3) advising the JSC community of adverse weather impacting the JSC complex; (4) serving as meteorological consultants to the JSC community for current and future spaceflight endeavors; (5) developing tools and techniques to enhance SMG's weather support and to improve the science of meteorology.
Short-Term Prediction Research and Transition Center (SPoRT)	SPoRT project at NASA's Marshall Space Flight Center in Huntsville, AL, is a NASA- and NOAA-funded activity to transition experimental/quasi-operational satellite observations and research capabilities to the operational weather community to improve short-term weather forecasts on a regional and local scale.
Direct Readout Laboratory	The Direct Readout Lab at Goddard Spaceflight Center in Greenbelt, MD, monitors the GOES-16 GRB. It acts as an intermediary between missions and the direct broadcast community members that are not directly involved in the missions.
NSF	
National Center for Atmospheric Research (NCAR)	NCAR is operated by the University Center for Atmospheric Research (UCAR). It is a Federally funded research and development center (FFRDC) that provides the atmospheric and related earth system science community with state-of-the-art resources, including supercomputers, research aircraft, sophisticated computer models, and extensive data sets.
NOAA-affiliated other agencies	
Cooperative Institute for Research in the Atmosphere (CIRA)	CIRA is a scientific research institution at Colorado State University (CSU) that operates under a cooperative agreement with NOAA-OAR and NESDIS. CIRA focuses on augmenting operational meteorology with advanced techniques in satellite observations and retrievals; numerical modeling and computational techniques; and data analysis, visualization, and storage.
Cooperative Institute for Mesoscale Meteorological Studies (CIMMS)	CIMMS is a research organization that promotes collaborative research between NOAA and Oklahoma University (OU) scientists on problems of mutual interest to improve basic understanding of mesoscale meteorological phenomena, weather radar, and regional climate to help produce better forecasts and warnings that save lives and property. CIMMS research contributes to the NOAA mission through improvement of the observation, analysis, understanding, and prediction of weather elements and systems and climate anomalies ranging in size from cloud nuclei to systems affecting multistate areas.
Tennessee Valley Authority (TVA)	TVA is a Federally owned corporation that provides navigation, flood control, electricity generation, fertilizer manufacturing, and economic development to the Tennessee Valley.

Table E-1. cont.

Table E-1. Federal agencies and use cases.

Agency	Services and use cases
Cooperative Institute for Meteorological Satellite Studies (CIMSS)	CIMSS is a Cooperative Institute formed through a memorandum of understanding among the University of Wisconsin–Madison, NOAA, and NASA. CIMSS scientists conduct research using remote-sensing systems for meteorological and surface-based applications. CIMSS research investigations increase understanding of remote sensing of the earth and its application to weather and now-casting, clouds and radiation, the global hydrological cycle, environmental trends, and climate. Using observations from operational and research satellites and data collected from ground- based and aircraft platforms through participation in a variety of field programs, CIMSS scientists are engaged in a broad array of research activities ranging from using real-time GOES observations to derive atmospheric stability indices in support of severe weather forecasting to designing the next generation of satellite instruments.
Cooperative Institute for Research In Environmental Sciences (CIRES)	CIRES is a partnership of NOAA and the University of Colorado–Boulder. Areas of expertise include weather and climate, changes at earth's poles, air quality and atmospheric chemistry, water resources, and solid-earth sciences. CIRES helps strengthen the scientific foundation upon which NOAA's environmental intelligence services depend. This partnership fosters fundamental and applied research in disciplines including the atmosphere, biosphere, geosphere, oceans, hydrosphere, and cryosphere. It provides NOAA with access to university intellectual depth and resources while giving students direct experience in operational and mission-focused research.
Cooperative Institute for Satellite Earth System Studies (CISESS)	CISESS is a national consortium of academic and nonprofit institutions, with leadership from the University of Maryland–College Park and North Carolina State University. CISESS (1) supports the NOAA NESDIS mission of providing "secure and timely access to global environmental data and information from satellites and other sources to both promote and protect the Nation's environment, security, economy, and quality of life"; (2) promotes and augments the research capabilities of NOAA's mission "to understand and predict changes in climate, weather, oceans, and coasts, to share that knowledge and information with others, and to conserve and manage coastal and marine ecosystems and resources"; and (3) delivers innovative research products, education, training, and outreach aligned with these missions. CISESS engages in collaborative and transformative research activities with NOAA scientists to enhance NOAA's ability to generate and use satellite and in situ observations and earth system models to meet that challenge, advance NOAA's science mission, and identify emerging science needs that will effectively contribute to meeting NOAA's mission in the future.
Cooperative Institute for Alaska Research (CIFAR)	CIFAR conducts ecosystem and environmental research related to Alaska and its associated Arctic regions, including the Gulf of Alaska, Bering Sea, Chukchi/Beaufort Seas, and Arctic Ocean. CIFAR's research activities assist NOAA in four of its mission goals: (1) protect, restore, and manage the use of coastal and ocean resources through an ecosystem approach to management; (2) understand climate variability and change to enhance society's ability to plan and respond; (3) serve society's needs for weather and water information; and (4) support the nation's commerce with information for safe, efficient, and environmentally sound transportation.
DOS	
International Boundary and Water Commission (IBWC)	The IBWC measures the spring inflows to the Rio Grande along the border between the U.S. and Mexico for treaty compliance. The U.S. gages, operated by DOS, use the DCS system. The U.S. operates 39 gages, including 14 on the main channel of the Rio Grande, 12 on U.S. tributaries, and 13 that assist in flood warnings and the operation of the flood regulation storage in the International Amistad and Falcon reservoirs. The gage data, and similar data collected by Mexico, forms the basis for joint accounting of the waters belonging to each country. The national ownership of waters has been determined since 1953. The IBWC also oversees the operation of ten gaging stations on the Lower Colorado River in association with deliveries of water to Mexico pursuant to the 1944 Water Treaty.

Appendix F. Earth Station Hardware Test Results (Project 6)

Table F-1 shows the Project 6 margin results by site. The table also shows the receiver type, antenna size, feed polarization, satellite used by the system, and the received signal types at each site.

Table F-1. Margin test results by site.

Location	Site name	NOAA signal	Receiver model	Antenna size (m)	Polarization	Satellite	Margin (dB)
EROS_Sioux_Falls_3.8m	USGS_EROS_SiouxFalls_DCS_WEST_3.8	DCS	Microcom Dual Pilot Control Module	3.8	linear	GOES-West	32.9
EROS_Sioux_Falls_3.8m	USGS_EROS_SiouxFalls_DCS_WEST_3.8	DCS	Microcom Dual Pilot Control Module	3.8	linear	GOES-West	32.1
ACE_Cincinnati_5m	ACE_Cincinnati_DCS_EAST_5	DCS	Signal Engineering, GOES DirectLink 16 Receiver	5	linear	GOES-East	28.1
ACE_Rock_Island_5m	ACE_Rock_Island_DCS_EAST_5	DCS	Microcom Dual Pilot Control Module	5	linear	GOES-East	31.2
ACE_Rock_Island_5m	ACE_Rock_Island_DCS_EAST_5	DCS	Microcom Dual Pilot Control Module	5	linear	GOES-East	30.6
ACE_ST_Louis_5m	ACE_St_Louis_DCS_EAST_5	DCS	Signal Engineering, GOES DirectLink 16 Receiver	5	linear	GOES-East	26.1
ACE_ST_Louis_5m	ACE_St_Louis_DCS_EAST_5	DCS	Signal Engineering, GOES DirectLink 16 Receiver	5	linear	GOES-East	28.3
NIFC_Boise_5m	NIFC_Boise_DCS_WEST_5	DCS	Microcom Dual Pilot Control Module	5	linear	GOES-West	32.3
NIFC_Boise_5m	NIFC_Boise_DCS_WEST_5	DCS	Microcom Dual Pilot Control Module	5	linear	GOES-West	32.2

Table F-1. cont.

Table F-1. Margin test results by site.

Location	Site name	NOAA signal	Receiver model	Antenna size (m)	Polarization	Satellite	Margin (dB)
ACE_Rock_ Island_7m	ACE_Rock_ Island_DCS_ WEST_7	DCS	Microcom Dual Pilot Control Module	7	linear	GOES-West	35.1
ACE_Rock_ Island_7m	ACE_Rock_ Island_DCS_ WEST_7	DCS	Microcom Dual Pilot Control Module	7	linear	GOES-West	35.0
BOR_Boise_7m	BOR_Boise_ DCS_WEST_7	DCS	Microcom Dual Pilot Control Module	7	linear	GOES-West	24.4
BOR_Boise_7m	BOR_Boise_ DCS_WEST_7	DCS	Microcom Dual Pilot Control Module	7	linear	GOES-West	25.2
EROS_Sioux_ Falls_7.5m	USGS_EROS_ SiouxFalls_DCS_ WEST_7.5	DCS	Microcom Dual Pilot Control Module	7.5	linear	GOES-West	33.8
EROS_Sioux_ Falls_7.5m	USGS_EROS_ SiouxFalls_DCS_ WEST_7.5	DCS	Microcom Dual Pilot Control Module	7.5	linear	GOES-West	33.4
EROS_Sioux_ Falls_8.1m	USGS_EROS_ SiouxFalls_DCS_ EAST_8.1	DCS	Microcom Dual Pilot Control Module	8.1	linear	GOES-East	32.6
EROS_Sioux_ Falls_8.1m	USGS_EROS_ SiouxFalls_DCS_ EAST_8.1	DCS	Microcom Dual Pilot Control Module	8.1	linear	GOES-East	34.8
NWS_PRHQ_ Honolulu_3.7m	NWS_PRHQ_ Honolulu_GRB_ WEST_3.7	GRB	GRB-200	3.7	LHCP	GOES-West	14.0
NWS_PRHQ_ Honolulu_3.7m	NWS_PRHQ_ Honolulu_GRB_ WEST_3.7	GRB	GRB-200	3.7	RHCP	GOES-West	14.6
JSC_ Houston_4.5m	NASA_JSC_ Houston_GRB_ WEST_4.5	GRB	GRB-200	4.5	LHCP	GOES-West	21.2
JSC_ Houston_4.5m	NASA_JSC_ Houston_GRB_ WEST_4.5	GRB	GRB-200	4.5	RHCP	GOES-West	19.6
NRL_ Monterey_4.5m	USN_NRL_ Monterey_GRB_ WEST_4.5	GRB	GRB-200	4.5	LHCP	GOES-West	14.7
NRL_ Monterey_4.5m	USN_NRL_ Monterey_GRB_ WEST_4.5	GRB	GRB-200	4.5	RHCP	GOES-West	14.7
LM_AF_ MK4B_5.2m	AF_LMKOP_ Mark_4B_GRB_ EAST_17ft	GRB	GRB-200	5.18	LHCP	GOES-East	13.7

Table F-1. cont.

Table F-1. Margin test results by site.

Location	Site name	NOAA signal	Receiver model	Antenna size (m)	Polarization	Satellite	Margin (dB)
LM_AF_ MK4B_5.2m	AF_LMKOP_ Mark_4B_GRB_ EAST_17ft	GRB	GRB-200	5.18	RHCP	GOES-East	15.7
AWS_ KansasCity_6.5m	NWS_AWS_ Kansas_City_ GRB_SPARE_6.5	GRB	GRB-200	6.5	LHCP	GOES-East	20.0
AWS_ KansasCity_6.5m	NWS_AWS_ Kansas_City_ GRB_SPARE_6.5	GRB	GRB-200	6.5	RHCP	GOES-East	18.5
NASA_ Huntsville_6.5m	NASA_SPoRT_ Huntsville_GRB_ WEST_6.5	GRB	GRB-200	6.5	LHCP	GOES-West	16.9
NASA_ Huntsville_6.5m	NASA_SPoRT_ Huntsville_GRB_ WEST_6.5	GRB	GRB-200	6.5	RHCP	GOES-West	18.1
NASA_ Huntsville_6.5m	NASA_SPoRT_ Huntsville_GRB_ WEST_6.5	GRB	GRB-200	6.5	RHCP	GOES-West	17.1
NCWCP_College_ Park_6.5m	NOAA_ CollegePark_ GRB_SPARE_6.5	GRB	GRB-200	6.5	LHCP	GOES-East	19.2
NCWCP_College_ Park_6.5m	NOAA_ CollegePark_ GRB_SPARE_6.5	GRB	GRB-200	6.5	RHCP	GOES-East	19.5
NCWCP_College_ Park_6.5m	NOAA_ CollegePark_ GRB_SPARE_6.5	GRB	GRB-200	6.5	LHCP	GOES-West	17.6
NCWCP_College_ Park_6.5m	NOAA_ CollegePark_ GRB_SPARE_6.5	GRB	GRB-200	6.5	LHCP	GOES-West	17.4
NCWCP_College_ Park_6.5m	NOAA_ CollegePark_ GRB_SPARE_6.5	GRB	GRB-200	6.5	RHCP	GOES-West	17.0
NCWCP_College_ Park_6.5m	NOAA_ CollegePark_ GRB_SPARE_6.5	GRB	GRB-200	6.5	RHCP	GOES-West	17.6
NCWCP_College_ Park_6.5m	NOAA_ CollegePark_ GRB_SPARE_6.5	GRB	GRB-200	6.5	RHCP	GOES-West	16.8
NCWCP_College_ Park_6.5m	NOAA_ CollegePark_ GRB_SPARE_6.5	GRB	GRB-200	6.5	RHCP	GOES-West	18.6

Table F-1. cont.

Table F-1. Margin test results by site.

Location	Site name	NOAA signal	Receiver model	Antenna size (m)	Polarization	Satellite	Margin (dB)
NCWCP_College_ Park_6.5m	NOAA_ CollegePark_ GRB_SPARE_6.5	GRB	GRB-200	6.5	RHCP	GOES-West	15.5
NCWCP_College_ Park_6.5m	NOAA_ CollegePark_ GRB_SPARE_6.5	GRB	GRB-200	6.5	RHCP	GOES-West	17.6
NHC_Miami_6.5m	NWS_NHC_ Miami_GRB_ EAST_6.5	GRB	GRB-200	6.5	LHCP	GOES-East	18.5
NHC_Miami_6.5m	NWS_NHC_ Miami_GRB_ EAST_6.5	GRB	GRB-200	6.5	RHCP	GOES-East	19.7
NRL_ Monterey_6.5m	USN_NRL_ Monterey_GRB_ EAST_6.5	GRB	GRB-200	6.5	LHCP	GOES-East	20.7
NRL_ Monterey_6.5m	USN_NRL_ Monterey_GRB_ EAST_6.5	GRB	GRB-200	6.5	RHCP	GOES-East	19.5
SPC_ Norman_6.5m	NWS_SPC_ Norman_GRB_ EAST_6.5	GRB	GRB-200	6.5	LHCP	GOES-East	17.6
SPC_ Norman_6.5m	NWS_SPC_ Norman_GRB_ EAST_6.5	GRB	GRB-200	6.5	RHCP	GOES-East	18.8
NSOF_ Suitland_9.1m	NOAA_NSOF_2_ Suitland	GRB	RT Logic T400	9.1	LHCP	GOES-West	9.2
NSOF_ Suitland_9.1m	NOAA_NSOF_2_ Suitland	GRB	RT Logic T400	9.1	LHCP	GOES-West	9.5
WCDAS_Wallops_ HR6_16.4m	NOAA_Wallops_ HR6	GRB	RT Logic T400	16.4	RHCP	GOES-West	21.6
WCDAS_Wallops_ HR6_16.4m	NOAA_Wallops_ HR6	GRB	RT Logic T400	16.4	RHCP	GOES-West	22.1
WCDAS_Wallops_ HR6_16.4m	NOAA_Wallops_ HR6	GRB	RT Logic T400	16.4	LHCP	GOES-West	19.5
WCDAS_Wallops_ HR6_16.4m	NOAA_Wallops_ HR6	GRB	RT Logic T400	16.4	LHCP	GOES-West	20.0
FCDAS_ Fairbanks_21m	NOAA_FCDAS_ Fairbanks_GVAR_ WEST_21	GVAR	SRI Summation Research Inc.	6.5	linear	GOES-15	24.8

Table F-1. cont.

Table F-1. Margin test results by site.

Location	Site name	NOAA signal	Receiver model	Antenna size (m)	Polarization	Satellite	Margin (dB)
USMC_San_ Diego_1.2m	USN_USMC_ SanDiego_LRIT_ HRIT_WEST_1.2	HRIT	LRD-100	1.2	linear	GOES-East	5.1
USMC_San_ Diego_1.2m	USN_USMC_ SanDiego_LRIT_ HRIT_WEST_1.2	HRIT	LRD-100	1.2	linear	GOES-East	5.8
USMC_San_ Diego_1.2m	USN_USMC_ SanDiego_LRIT_ HRIT_WEST_1.2	HRIT	LRD-100	1.2	linear	GOES-West	5.1
USMC_San_ Diego_1.2m	USN_USMC_ SanDiego_LRIT_ HRIT_WEST_1.2	HRIT	LRD-100	1.2	linear	GOES-West	7.5
TVA_ Knoxville_1.8m	TVA_Knoxville_ HRIT_EAST_1.8	HRIT	Dartcom USB-LRITRX-02/SYN receiver	1.8	linear	GOES-East	9.1

Table F-2 shows the measured FDR results by site. The table also shows the receiver type, antenna size, feed polarization, satellite used by the system, and the received signal types at each site.

Table F-2. Measured FDR results by site.

Location	NOAA signal	Receiver model	Antenna size (m)	Polarization	Satellite location	FDR (dB)
EROS_Sioux_Falls	DCS	Microcom Dual Pilot Control Module	3.8	linear	GOES-West	−3.0
EROS_Sioux_Falls	DCS	Microcom Dual Pilot Control Module	3.8	linear	GOES-West	−2.7
ACE_Cincinnati	DCS	Signal Engineering, GOES DirectLink 16 Receiver	5	linear	GOES-East	−7.2
ACE_Rock_Island	DCS	Microcom Dual Pilot Control Module	5	linear	GOES-East	−4.3
ACE_Rock_Island	DCS	Microcom Dual Pilot Control Module	5	linear	GOES-East	−2.1
ACE_ST_Louis	DCS	Signal Engineering, GOES DirectLink 16 Receiver	5	linear	GOES-East	−3.4
ACE_ST_Louis	DCS	Signal Engineering, GOES DirectLink 16 Receiver	5	linear	GOES-East	−2.8
NIFC_Boise	DCS	Microcom Dual Pilot Control Module	5	linear	GOES-West	−3.6
NIFC_Boise	DCS	Microcom Dual Pilot Control Module	5	linear	GOES-West	−5.4

Table F-2. cont.

Table F-2. Measured FDR results by site.

Location	NOAA signal	Receiver model	Antenna size (m)	Polarization	Satellite location	FDR (dB)
ACE_Rock_Island	DCS	Microcom Dual Pilot Control Module	7	linear	GOES-West	−1.7
ACE_Rock_Island	DCS	Microcom Dual Pilot Control Module	7	linear	GOES-West	−1.5
BOR_Boise	DCS	Microcom Dual Pilot Control Module	7	linear	GOES-West	−10.1
BOR_Boise	DCS	Microcom Dual Pilot Control Module	7	linear	GOES-West	−10.4
EROS_Sioux_Falls	DCS	Microcom Dual Pilot Control Module	7.5	linear	GOES-West	−6.4
EROS_Sioux_Falls	DCS	Microcom Dual Pilot Control Module	7.5	linear	GOES-West	−8.0
EROS_Sioux_Falls	DCS	Microcom Dual Pilot Control Module	8.1	linear	GOES-East	−4.4
EROS_Sioux_Falls	DCS	Microcom Dual Pilot Control Module	8.1	linear	GOES-East	−3.5
NWS_PRHQ_ Honolulu	GRB	GRB-200	3.7	LHCP	GOES-West	−27.9
NWS_PRHQ_ Honolulu	GRB	GRB-200	3.7	RHCP	GOES-West	−23.4
JSC_Houston	GRB	GRB-200	4.5	LHCP	GOES-West	−16.6
JSC_Houston	GRB	GRB-200	4.5	RHCP	GOES-West	−18.8
NRL_Monterey	GRB	GRB-200	4.5	LHCP	GOES-West	−26.2
NRL_Monterey	GRB	GRB-200	4.5	RHCP	GOES-West	−28.2
LM_AF_MK4B	GRB	GRB-200	5.18	LHCP	GOES-East	−26.8
LM_AF_MK4B	GRB	GRB-200	5.18	RHCP	GOES-East	−26.2
AWS_KansasCity	GRB	GRB-200	6.5	LHCP	GOES-East	−23.7
AWS_KansasCity	GRB	GRB-200	6.5	RHCP	GOES-East	−26.2
NASA_Huntsville	GRB	GRB-200	6.5	LHCP	GOES-West	−29.2
NASA_Huntsville	GRB	GRB-200	6.5	RHCP	GOES-West	−30.2
NASA_Huntsville	GRB	GRB-200	6.5	RHCP	GOES-West	−29.3
NCWCP_College_ Park	GRB	GRB-200	6.5	LHCP	GOES-East	−29.7
NCWCP_College_ Park	GRB	GRB-200	6.5	RHCP	GOES-East	−31.0
NCWCP_College_ Park	GRB	GRB-200	6.5	LHCP	GOES-West	−30.3
NCWCP_College_ Park	GRB	GRB-200	6.5	LHCP	GOES-West	−28.7
NCWCP_College_ Park	GRB	GRB-200	6.5	RHCP	GOES-West	−29.9
NCWCP_College_ Park	GRB	GRB-200	6.5	RHCP	GOES-West	−29.3

Table F-2. cont.

Table F-2. Measured FDR results by site.

Location	NOAA signal	Receiver model	Antenna size (m)	Polarization	Satellite location	FDR (dB)
NCWCP_College_ Park	GRB	GRB-200	6.5	RHCP	GOES-West	−29.8
NCWCP_College_ Park	GRB	GRB-200	6.5	RHCP	GOES-West	−29.6
NCWCP_College_ Park	GRB	GRB-200	6.5	RHCP	GOES-West	−30.7
NCWCP_College_ Park	GRB	GRB-200	6.5	RHCP	GOES-West	−29.9
NHC_Miami	GRB	GRB-200	6.5	LHCP	GOES-East	−30.4
NHC_Miami	GRB	GRB-200	6.5	RHCP	GOES-East	−27.3
NRL_Monterey	GRB	GRB-200	6.5	LHCP	GOES-East	−25.7
NRL_Monterey	GRB	GRB-200	6.5	RHCP	GOES-East	−25.5
SPC_Norman	GRB	GRB-200	6.5	LHCP	GOES-East	−27.9
SPC_Norman	GRB	GRB-200	6.5	RHCP	GOES-East	−25.2
NSOF_Suitland	GRB	RT Logic T400	9.1	LHCP	GOES-West	−26.2
NSOF_Suitland	GRB	RT Logic T400	9.1	LHCP	GOES-West	−29.3
WCDAS_Wallops	GRB	RT Logic T400	16.4	RHCP	GOES-West	−11.1
WCDAS_Wallops	GRB	RT Logic T400	16.4	RHCP	GOES-West	−9.0
WCDAS_Wallops	GRB	RT Logic T400	16.4	LHCP	GOES-West	−11.6
WCDAS_Wallops	GRB	RT Logic T400	16.4	LHCP	GOES-West	−11.6
FCDAS_Fairbanks	GVAR	SRI Summation Research Inc.	6.5	linear	G-15	−25.1
USMC_San_ Diego	HRIT	LRD-100	1.2	linear	GOES-East	n/a
USMC_San_ Diego	HRIT	LRD-100	1.2	linear	GOES-East	n/a
USMC_San_ Diego	HRIT	LRD-100	1.2	linear	GOES-West	n/a
USMC_San_	HRIT	LRD-100	1.2	linear	GOES-West	n/a
TVA_Knoxville	HRIT	Dartcom USB-LRITRX-02/SYN receiver	1.8	linear	GOES-East	n/a

Appendix G. Project 11 Simulation Results

This section describes the results obtained during the project for large-cell and IoT deployments. Section G.1 describes the use case of an exclusion zone, in addition to differences in results when the earth station is pointing to GOES-East or GOES-West. Section G.1 also presents the results for the LTE large-cell deployment. Section G.2 describes the results obtained from the IoT analysis.

G.1 LTE TDD and FDD: Baseline Large-Cell Deployment

This section quantifies the amount of RFI that the baseline large-cell deployment could potentially create at all Federal satellite receiver ground sites. The deployment will be used to identify LTE TDD and FDD RFI risk. In addition, the results will be compared with the results obtained from the mitigation analysis to determine the most effective mitigation techniques.

G.1.1 LTE downlink large-cell use case

All assumptions were made for the downlink use of the 1675–1680 MHz band in a typical three-sector large-cell configuration. The sectors consist of antennas with identical transmit EIRPs, antenna patterns, and configured downtilts. Each antenna assumed a channel bandwidth of 4.5 MHz. An EIRP of 63 dBm was assumed, in addition to a 2° downtilt. All sectors were assigned antenna azimuths with a 120° offset. The three sectors consist of three antennas with azimuths of 0°, 120°, and 240°. The antenna pattern is displayed in Figure G-1. The horizontal plane of Figure G-1 is configured for an antenna with an azimuth of 0° and was configured for antennas of other azimuths such that the peak gain is along the assigned antenna orientation.

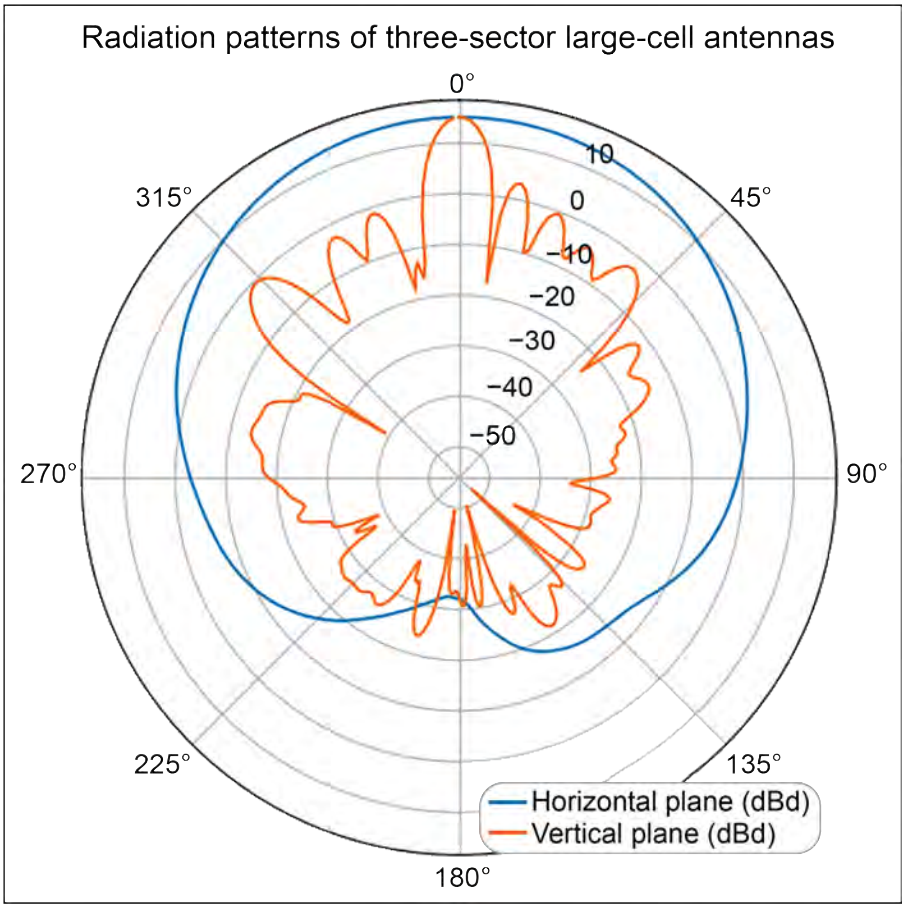

Figure G-1. Radiation patterns of antenna with a 0° azimuth and a downtilt of 0°.

G.1.2 LTE uplink large-cell use case

All assumptions were made for the uplink use of the 1675–1680 MHz band in a typical three-sector, large-cell configuration. Each sector will consist of three UEs with eight resource blocks allocated to each UE. The EIRP is randomized from the curve, as displayed in Figure G-1, and an omnidirectional antenna with a 2.15 dBi gain was assumed.

G.1.3 Exclusion distance comparisons: GOES-East versus GOES-West

Results determined from the analysis of LTE TDD and FDD deployments and different mitigations will mostly remain consistent for results produced in which the GOES ground station is pointing to either GOES-East or GOES-West. However, the exclusion distance determined will change on this condition. Figures G-2 through G-5 show the potential similarities and differences in exclusion distance outcomes. Figures G-2 and G-3 represent the baseline large-cell results for the GOES earth station in St. Louis, Missouri, for instances in which the earth station is directed toward GOES-East or GOES-West. When pointing to GOES-East, the aggregate RFI is initially slightly higher than when pointing to GOES-West; however, the exclusion distance remains consistent at approximately 27 km. There also remains a small difference in the required exclusion distance for FDD and TDD deployments.

Note that in several of these figures, the individual co-channel and adjacent channel plots are extremely close together and appear to be single curves.

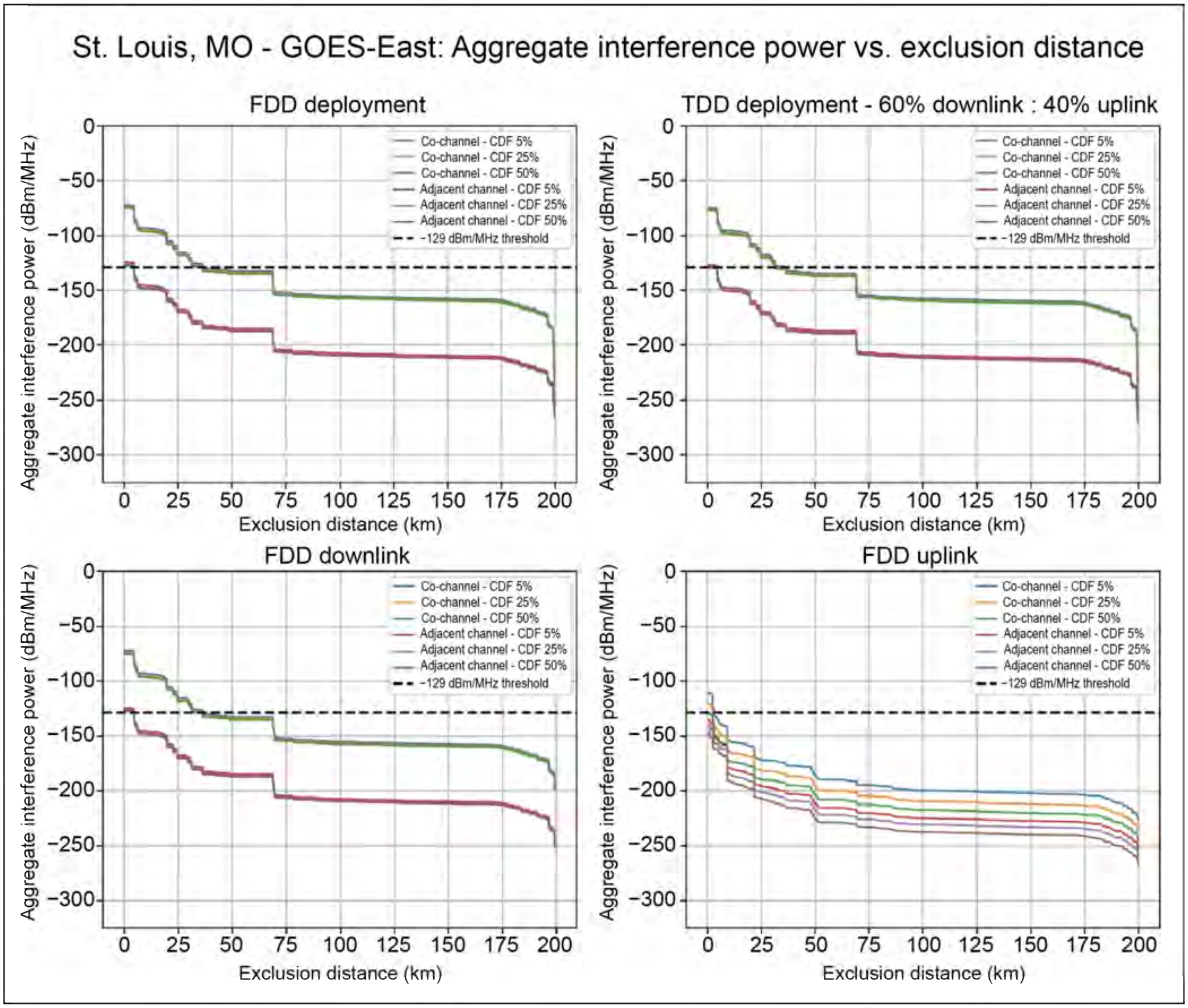

Figure G-2. Baseline large-cell deployment for the earth station in St. Louis, Missouri: GOES-East.

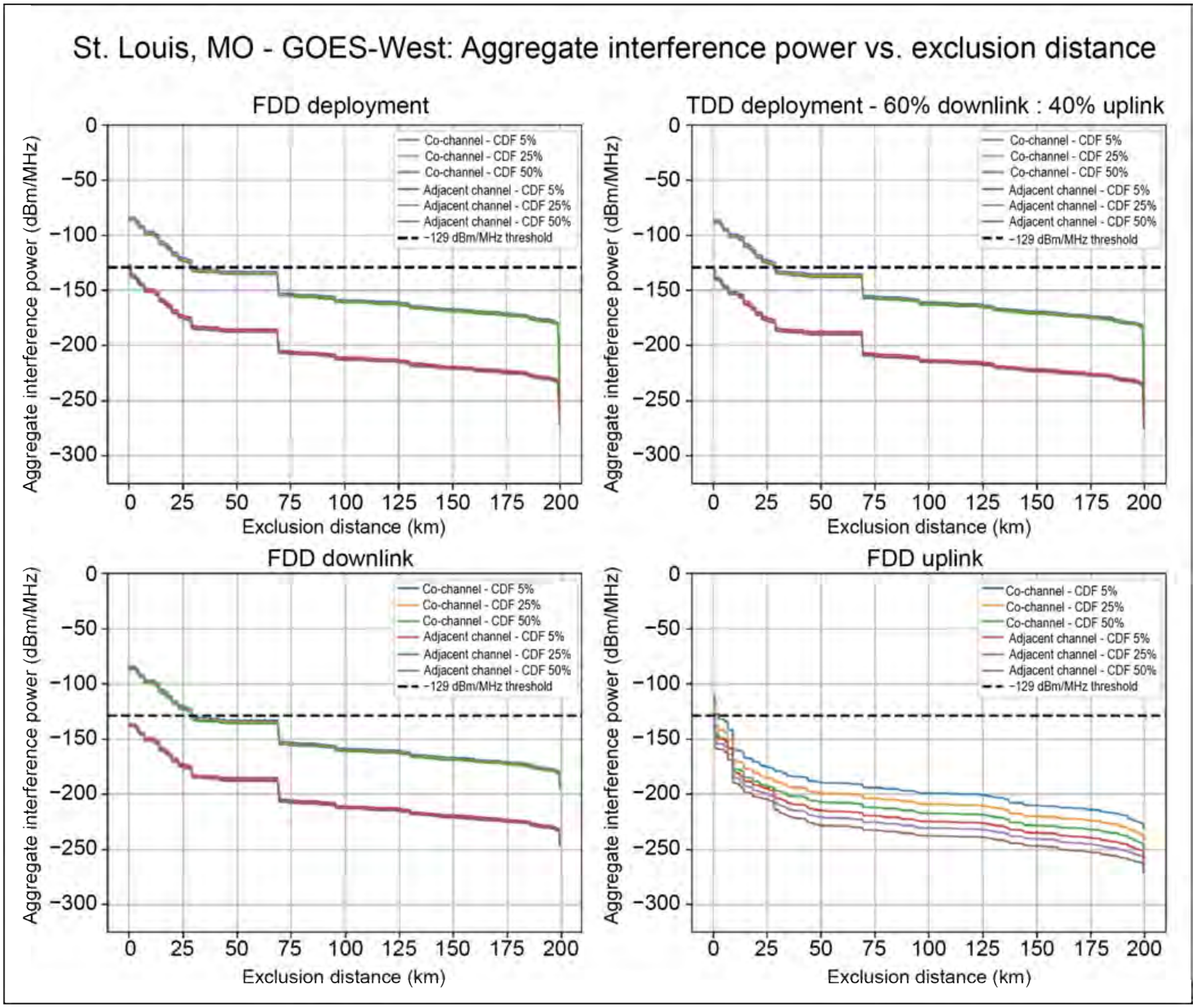

Figure G-3. Baseline large-cell deployment for the earth station in St. Louis, Missouri: GOES-West.

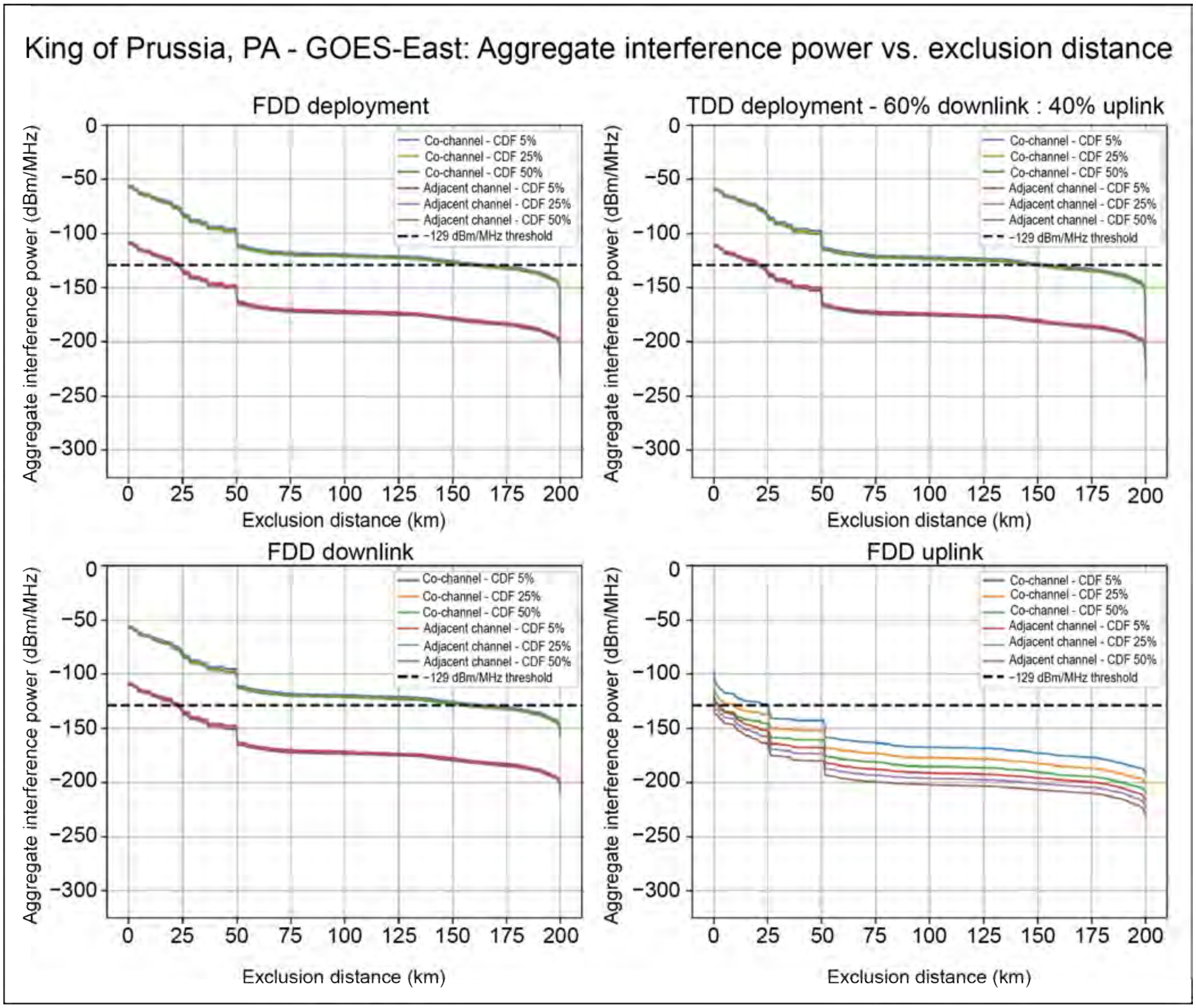

Figure G-4. Baseline large-cell deployment for the earth station in King of Prussia, Pennsylvania: GOES-East.

Figures G-4 and G-5 represent the baseline large-cell results for the GOES earth station in King of Prussia, Pennsylvania. When pointing to GOES-East, as the exclusion distance is increased, the aggregate RFI at each increment is greater than the instance in which the earth station is pointing to GOES-West. The required exclusion distance is vastly different between the two scenarios. However, there continues to be a minimal difference between the LTE TDD and FDD deployments as indicated between both scenarios. Additionally, the mitigation impacts will remain consistent between the two different configurations.

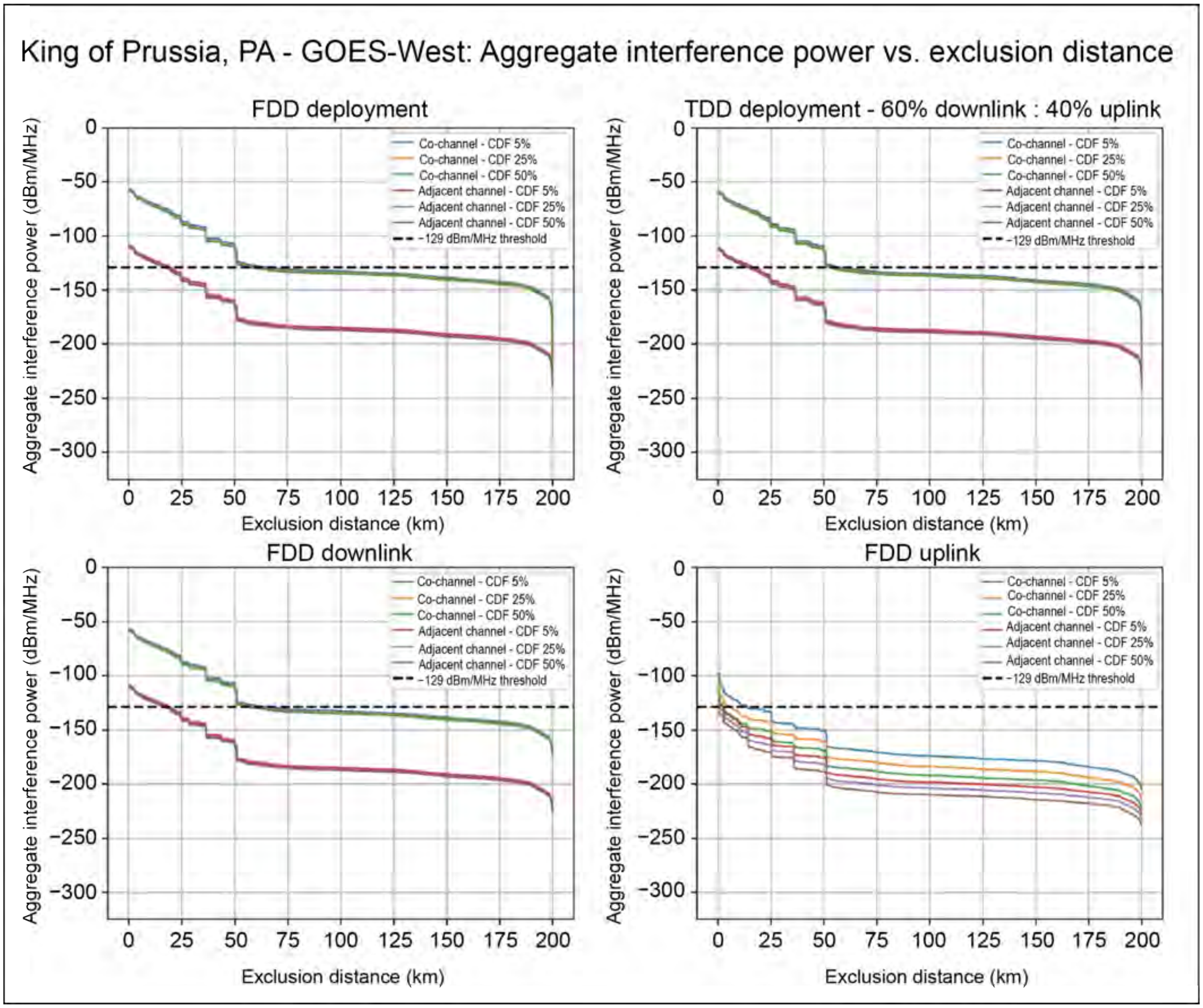

Figure G-5. Baseline large-cell deployment for the earth station in King of Prussia, Pennsylvania: GOES-West.

G.1.4 Aggregate RFI versus exclusion distance

Figures G-6 through G-15 consist of four aggregate RFI versus exclusion distance subplots representing LTE TDD and FDD deployments for co-channel and adjacent-channel scenarios. The subplots represent the LTE FDD deployment (top left), a 60% downlink–40% uplink LTE TDD deployment (top right), the FDD downlink (bottom left), and the FDD uplink (bottom right).

A TDD analysis is performed by combining FDD downlink and FDD uplink analysis results. This is done by considering a downlink-to-uplink timing ratio. RFI levels above −129 dBm/MHz are expected to result in a degradation of the GOES receiver performance. Furthermore, the exclusion zone is increased in 100 m steps. Any significant drop indicates the removal of a significant tower or group of towers within that particular step. Plots with a greater number of drops are the result of a lower density of towers and/or the impact of terrain at that particular exclusion distance. Plots indicating a gradual decline between the 100 m steps represent an area with a higher density of towers with flat terrain. The separation of curves as seen in Figures G-6 through G-15 depends on the number of randomized parameters within the Monte Carlo trials. In the FDD downlink, since the only randomized parameter is the ITM confidence, the spacing between the 5th, 25th, and 50th percentiles for both the co-channel and adjacent-channel results are going to be more compact compared to the FDD uplink. The ITM confidence levels were selected through a probability distribution; thus, the 50% ITM confidence is most likely to occur compared to the other confidence levels—hence, the minimal separation of the curves produced from the Monte Carlo trials.

Figure G-6 shows the received interference power at the Boulder, Colorado, site versus exclusion distance when the earth station is pointing to GOES-East. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 123 km circular exclusion radius. LTE FDD and TDD similarities arise from the significance of the downlink compared to the uplink. This can be observed through the FDD downlink and FDD uplink subplots. The aggregate RFI originating

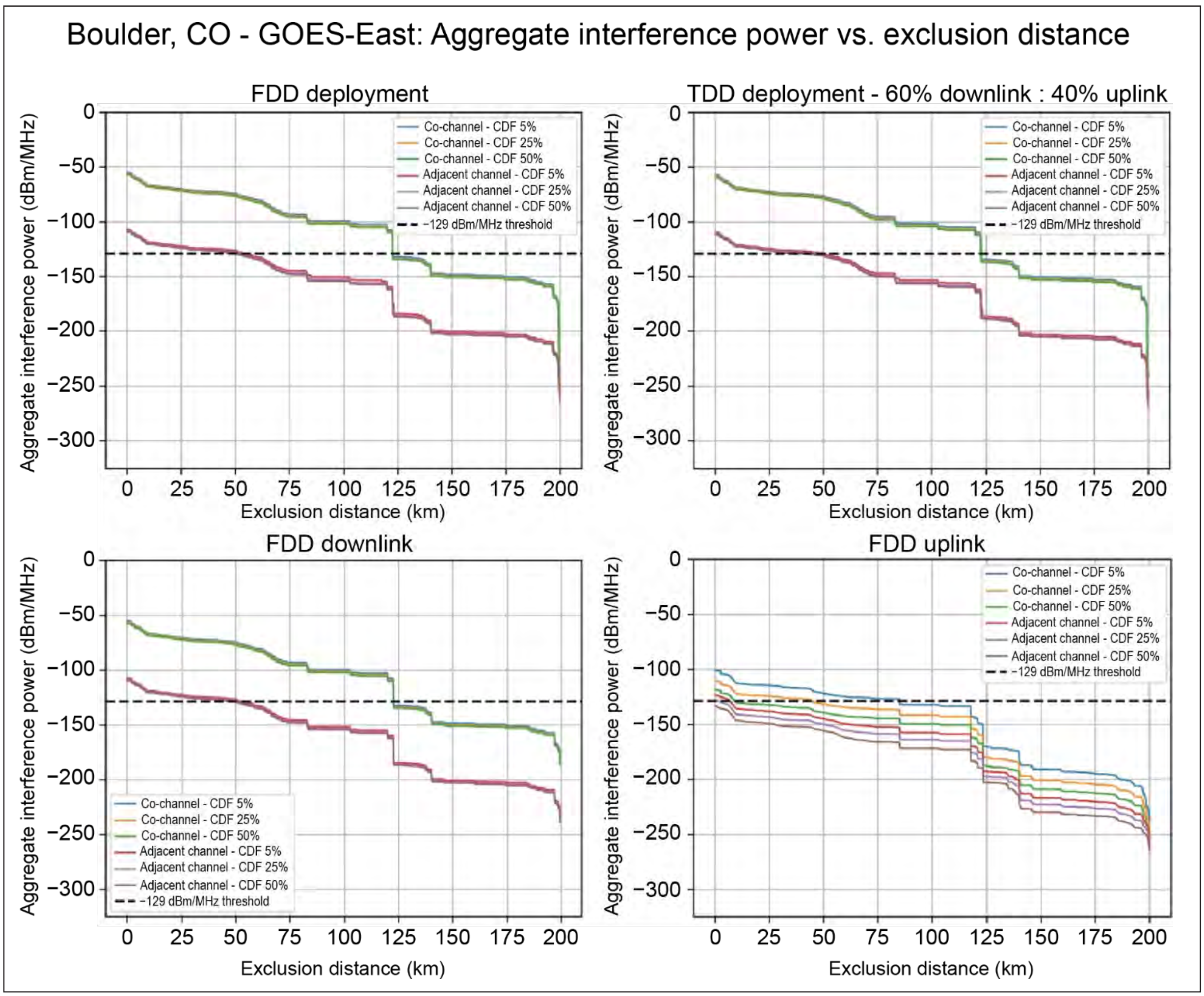

Figure G-6. Baseline large-cell deployment for the earth station in Boulder, Colorado: GOES-East.

from the FDD downlink is several orders of magnitude higher compared to the FDD uplink, primarily due to the large differences in transmit power, peak gain, and propagation losses.

Figure G-7 shows the received interference power at the Boulder, Colorado, site versus exclusion distance when the earth station is pointing to GOES-West. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 123 km circular exclusion radius.

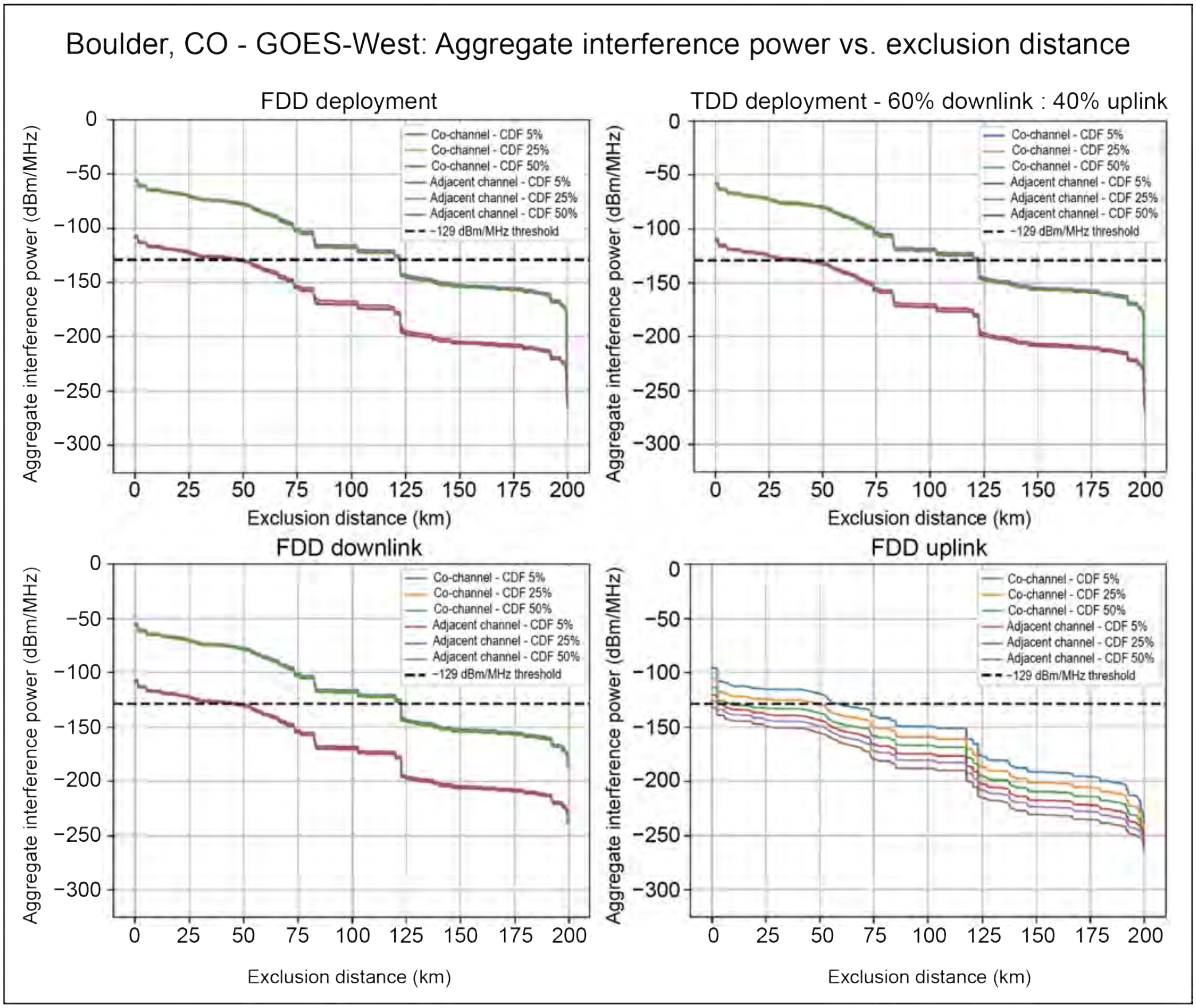

Figure G-7. Baseline large-cell deployment for the earth station in Boulder, Colorado: GOES-West.

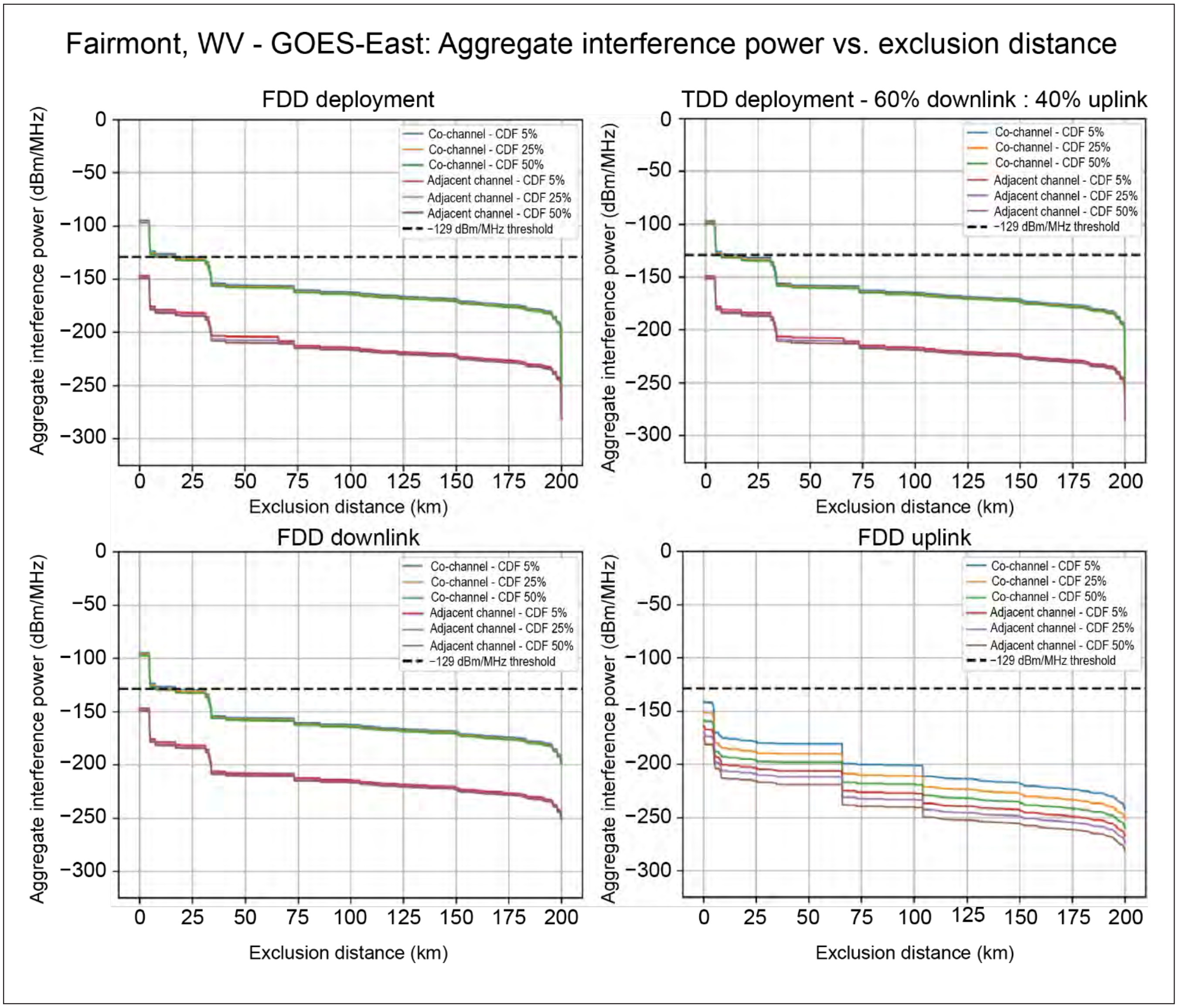

Figure G-8. Baseline large-cell deployment for the earth station in Fairmont, West Virginia: GOES-East.

Figure G-8 shows the received interference power at the Fairmont, West Virginia, site versus exclusion distance when the earth station is pointing to GOES-East. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 5 km circular exclusion radius.

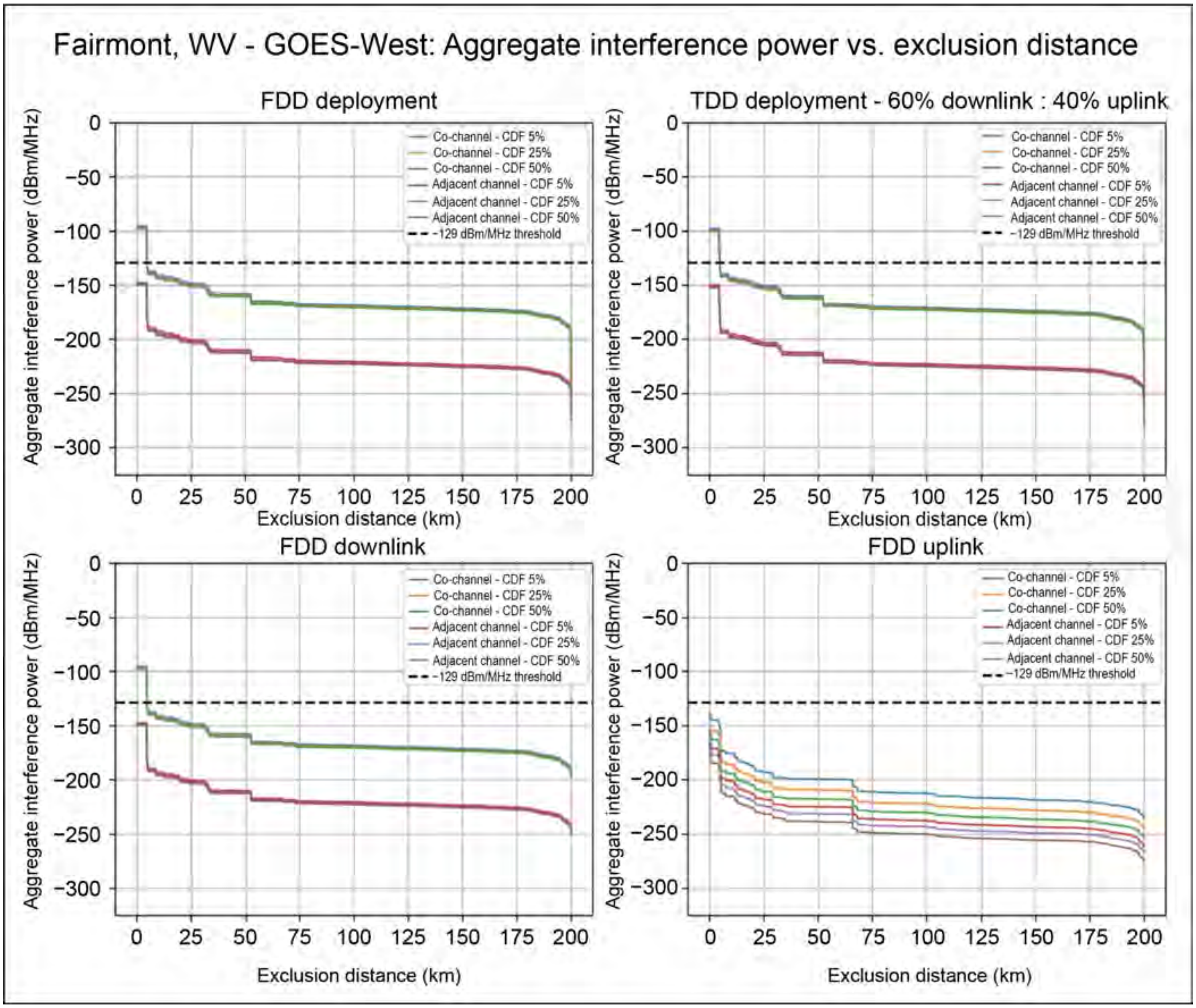

Figure G-9. Baseline large-cell deployment for the earth station in Fairmont, West Virginia: GOES-West.

Figure G-9 shows the received interference power at the Fairmont, West Virginia, site versus exclusion distance when the earth station is pointing to GOES-West. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 5 km circular exclusion radius.

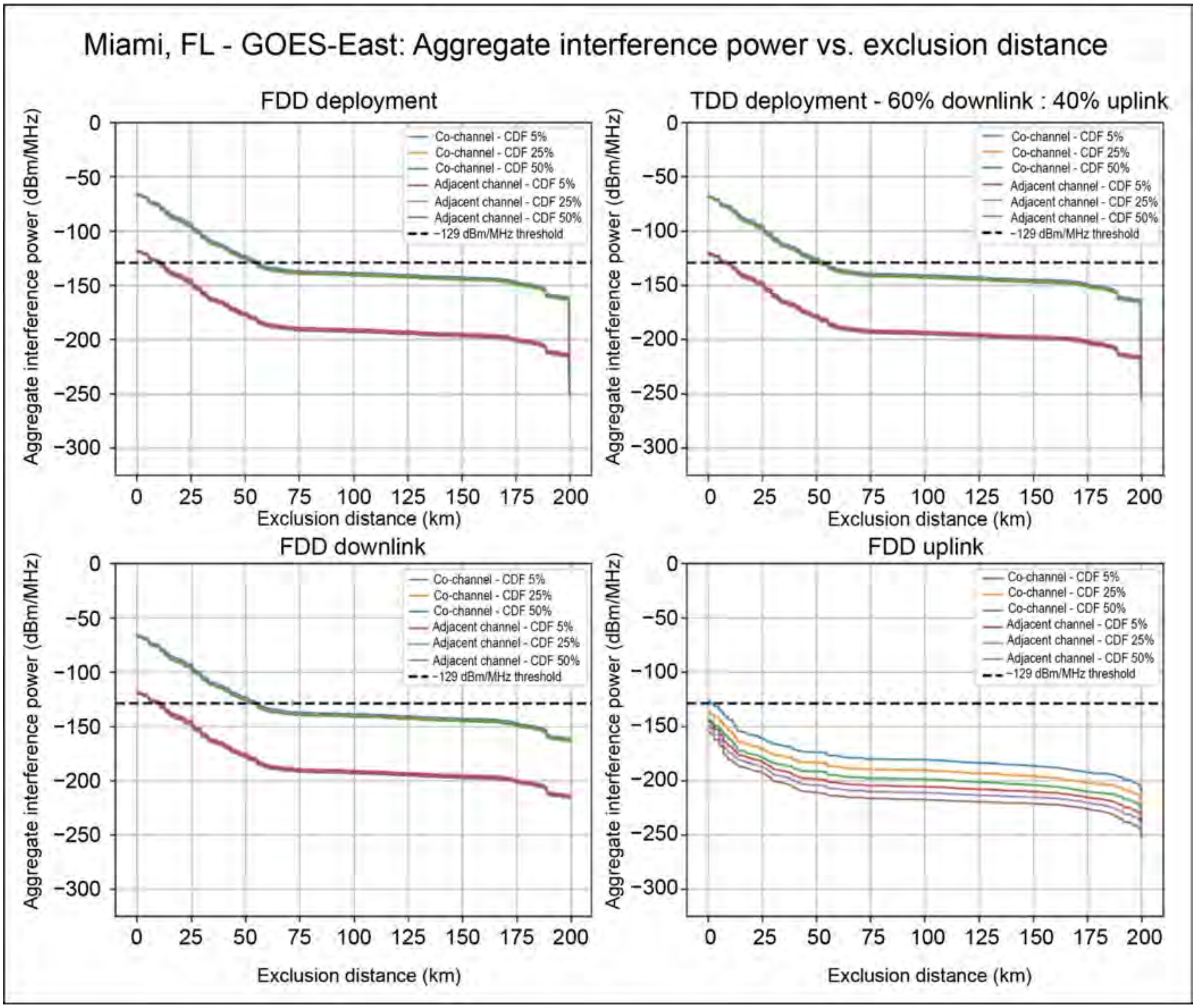

Figure G-10. Baseline large-cell deployment for the earth station in Miami, Florida: GOES-East.

Figure G-10 shows the received interference power at the Miami, Florida, site versus exclusion distance when the earth station is pointing to GOES-East. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 55 km circular exclusion radius.

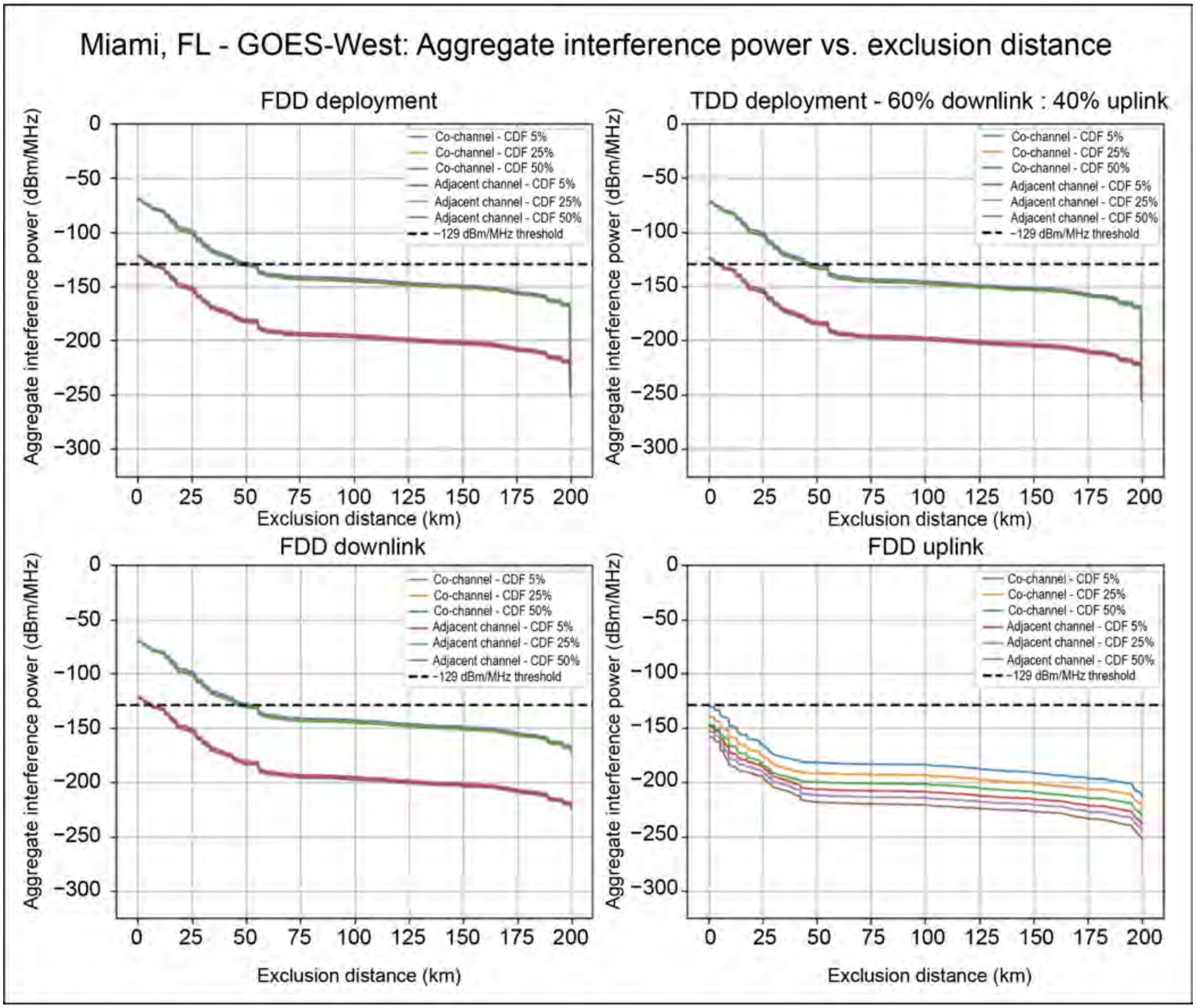

Figure G-11. Baseline large-cell deployment for the earth station in Miami, Florida: GOES-West.

Figure G-11 shows the received interference power at the Miami, Florida, site versus exclusion distance when the earth station is pointing to GOES-West. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 50 km circular exclusion radius.

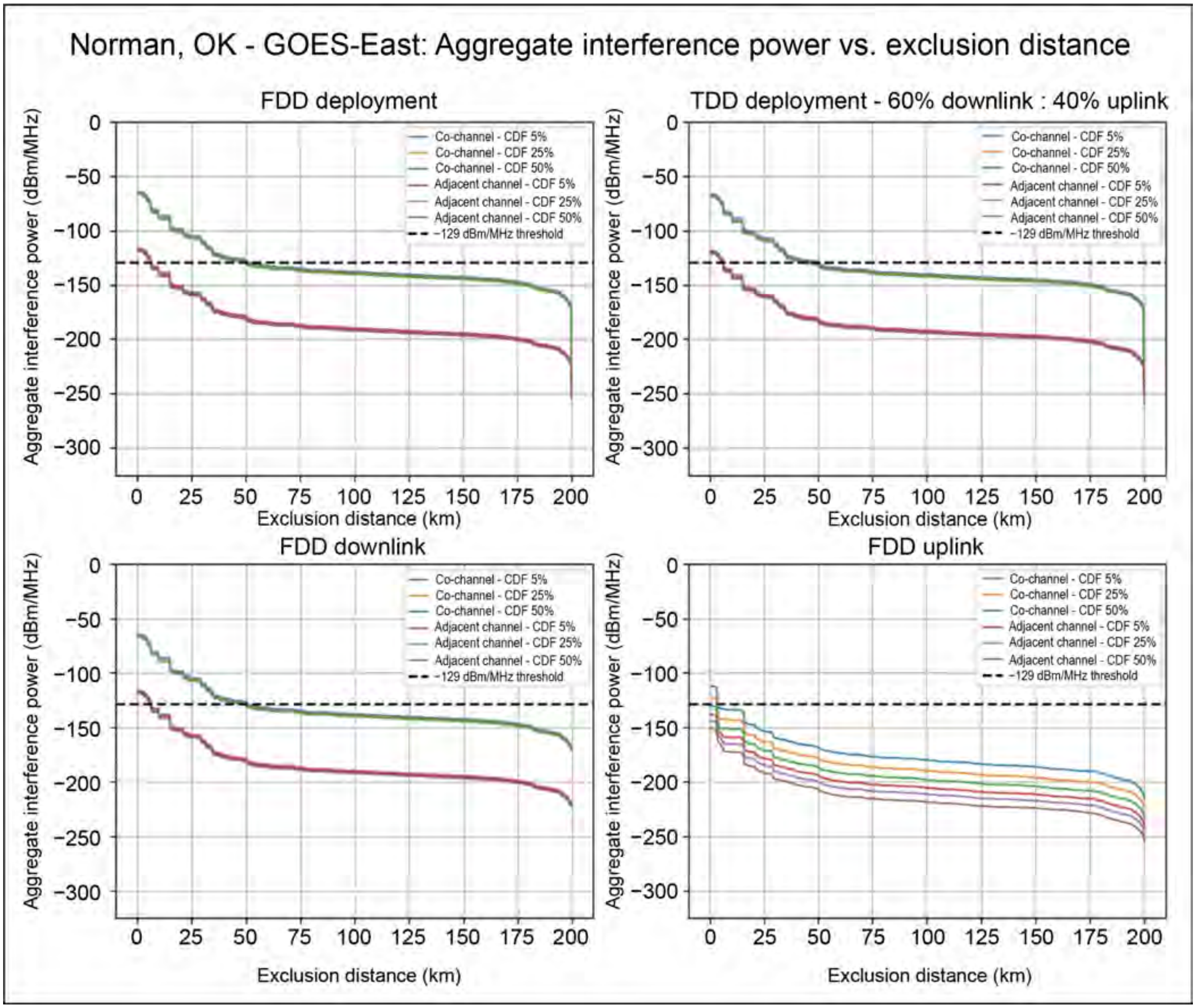

Figure G-12. Baseline large-cell deployment for the earth station in Norman, Oklahoma: GOES-East.

Figure G-12 shows the received interference power at the Norman, Oklahoma, site versus exclusion distance when the earth station is pointing to GOES-East. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 50 km circular exclusion radius.

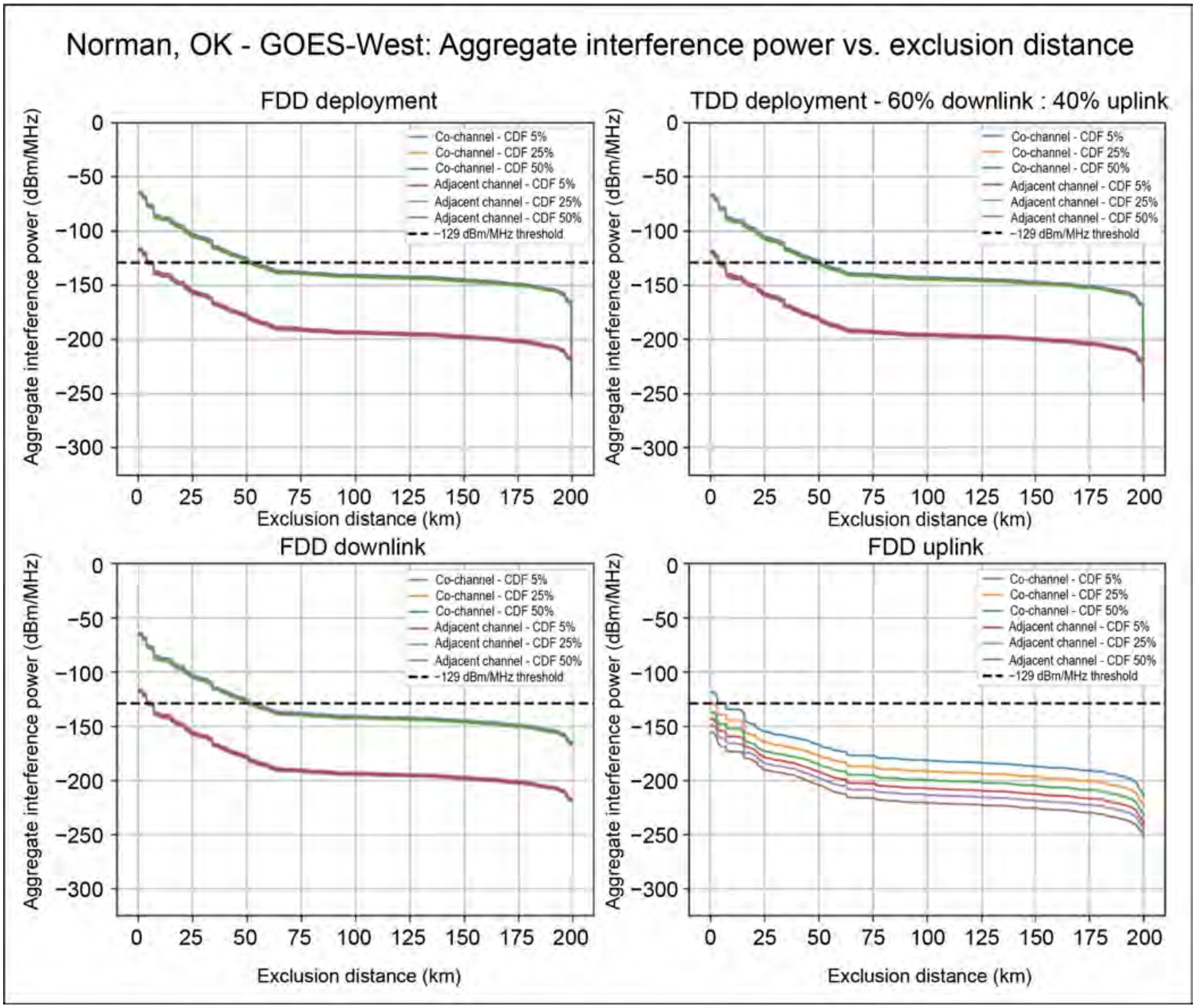

Figure G-13. Baseline large-cell deployment for the earth station in Norman, Oklahoma: GOES-West.

Figure G-13 shows the received interference power at the Norman, Oklahoma, site versus exclusion distance when the earth station is pointing to GOES-West. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 51 km circular exclusion radius.

There are similarities between Figures G-12 and G-13 due to the even distribution of interferers about the sidelobes of the earth station.

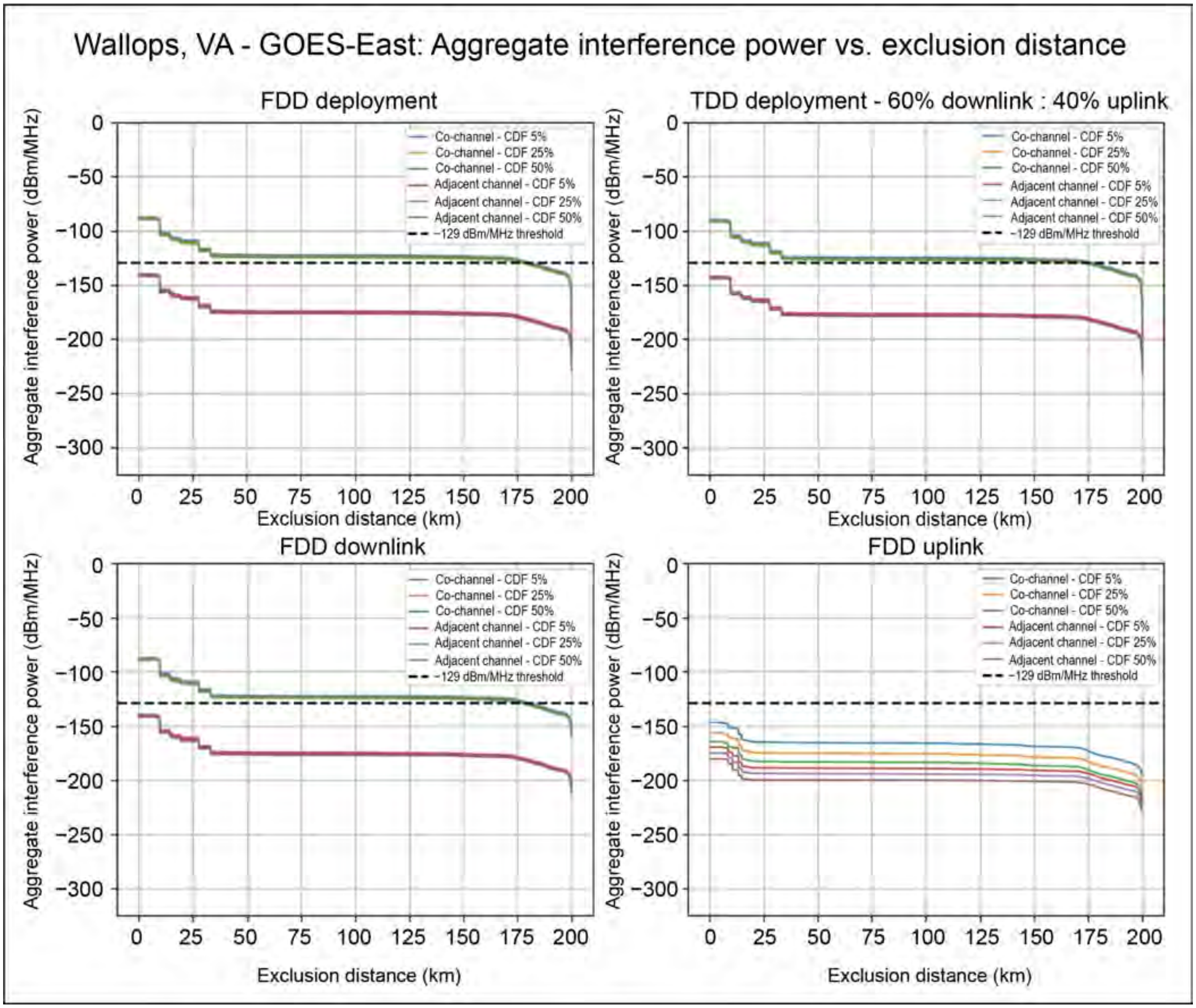

Figure G-14. Baseline large-cell deployment for the earth station in Wallops Island, Virginia: GOES-East.

Figure G-14 shows the received interference power at the Wallops Island, Virginia, site versus exclusion distance when the earth station is pointing to GOES-East. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 175 km circular exclusion radius.

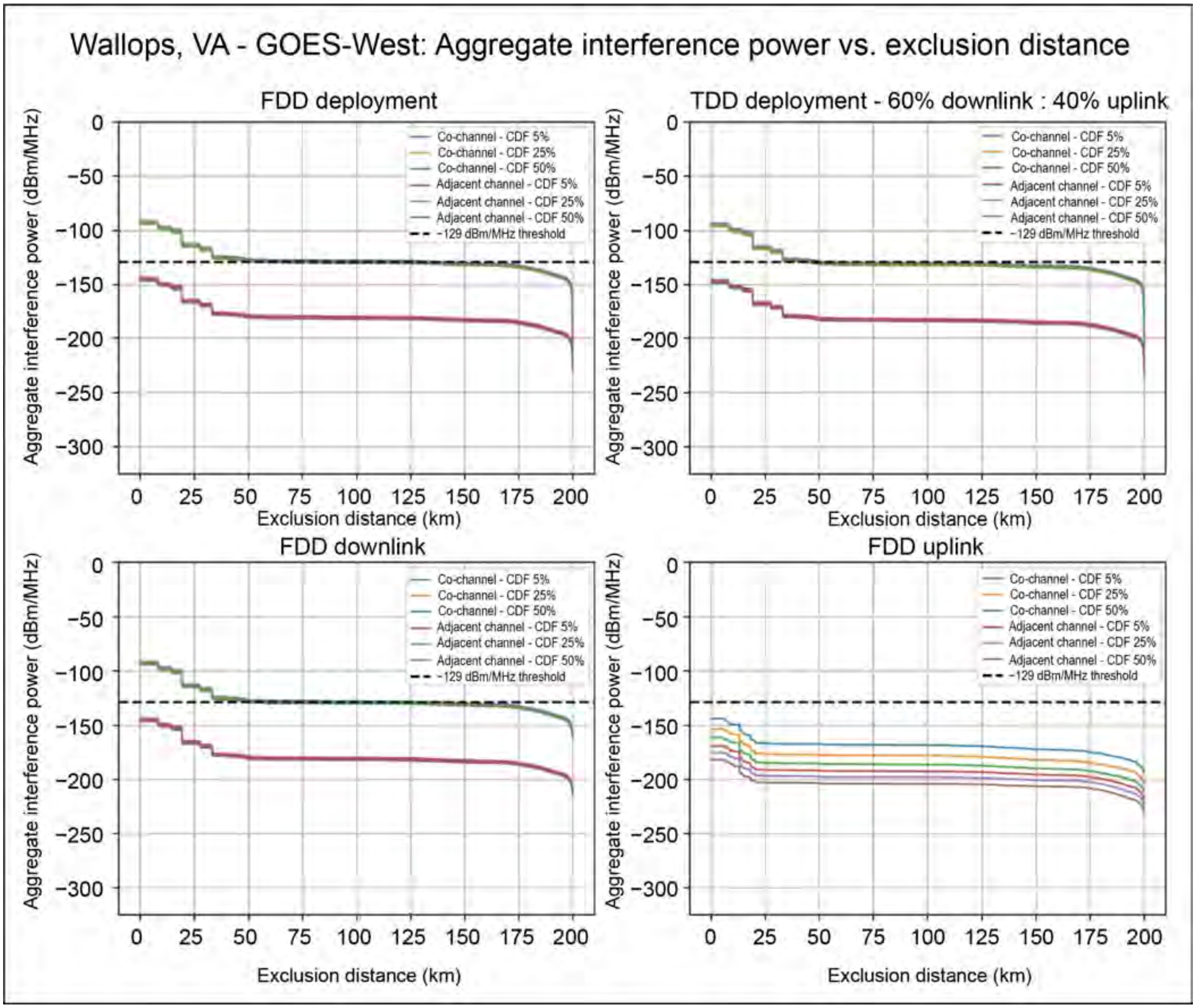

Figure G-15. Baseline large-cell deployment for the earth station in Wallops Island, Virginia: GOES-West.

Figure G-15 shows the received interference power at the Wallops Island, Virginia, site versus exclusion distance when the earth station is pointing to GOES-West. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield highly different exclusion distances. As indicated by the top subplots, the aggregate RFI is driven mainly along the interference threshold set. The LTE FDD deployment requires approximately a 90 km exclusion distance, whereas the LTE TDD deployment requires approximately a 50 km exclusion distance.

G.2 Internet of Things

This section quantifies the amount of RFI that IoT deployments could potentially create at all the Federal satellite receiver ground sites. The deployment will be used to identify LTE TDD and FDD RFI risks. Analysis was done on LTE-M, IoT in-band, IoT guard-band, and IoT stand-alone scenarios. Narrowband IoT (NB-IoT) services and existing LTE networks must coexist in harmony. LTE-M is a low-powered, wide-area network that supports IoT through the reuse of LTE bases. IoT devices are directly connected to an LTE network through LTE-M. NB-IoT in-band allows for a narrowband signal (180 kHz bandwidth, or one resource block) within the LTE broadband carrier. NB-IoT guard-band is the deployment of NB-IoT in a guard band. The focus is to operate in the guard bands of LTE without causing interference. Lastly, NB-IoT stand-alone is deployed where LTE services are not present, which allows for a narrowband spectrum available.

The capacity of a single NB-IoT carrier is significant within a cell. An Ericsson analysis[1] determined that a standard deployment can support a density of 200,000 NB-IoT devices within a cell (for activity levels that are in line to common use cases). Therefore, for the IoT deployments coexisting with LTE networks, this study used a single NB-IoT carrier for analysis.

G.2.1 LTE-M downlink use case

The LTE-M results produced assumed a single LTE-M RF carrier in the 5 MHz channel. Thus, each antenna will assume a channel bandwidth of 1.08 MHz. A standard three-sector configuration as used in the downlink large-cell deployment will be replicated. The sectors consist of antennas with identical transmit EIRPs, antenna patterns, and configured downtilts. An EIRP of 63 dBm was assumed in addition to a 2° downtilt. All sectors were assigned antenna azimuths with a 120° offset. The three sectors consist of three antennas with azimuths of 0°, 120°, and 240°. The antenna pattern is displayed in Figure G-1. The horizontal plane of Figure G-1 was configured for an antenna with an azimuth of 0°, and was configured for antennas of other azimuths such that the peak gain is along the assigned azimuth.

G.2.2 LTE-M uplink use case

Each LTE-M carrier will support one to six UEs in the uplink. However, the results produced assumed the worst case of six UEs per sector in which each UE assumed a 180 kHz channel bandwidth (one resource block). The EIRP is randomized from the curve as displayed in Figure G-1, and an omnidirectional antenna with a 2.15 dBi gain was assumed.

[1] Sara Landström, Joakim Bergström, Erik Westerberg, and David Hammarwall, "NB-IoT: A Sustainable Technology for Connecting Billions of Devices," *Ericsson Technology Review 4* (2016): 2-11, https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/nb-iot-a-sustainable-technology-for-connecting-billions-of-devices.

G.2.3 LTE-M deployment: Aggregate RFI versus exclusion distance

The differences in LTE FDD and TDD risks associated with a LTE-M deployment will remain consistent with the differences described in Section G.2.4. Figures G-16 through G-20 consist of four aggregate RFI versus exclusion distance subplots representing LTE FDD and TDD LTE-M deployments for co-channel and adjacent-channel scenarios. RFI levels above −129 dBm/MHz are expected to result in a degradation of the GOES receiver performance.

Figure G-16 shows the received interference power at the Boulder, Colorado, site versus exclusion distance when the earth station is pointing to GOES-West in an LTE-M deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 123 km circular exclusion radius.

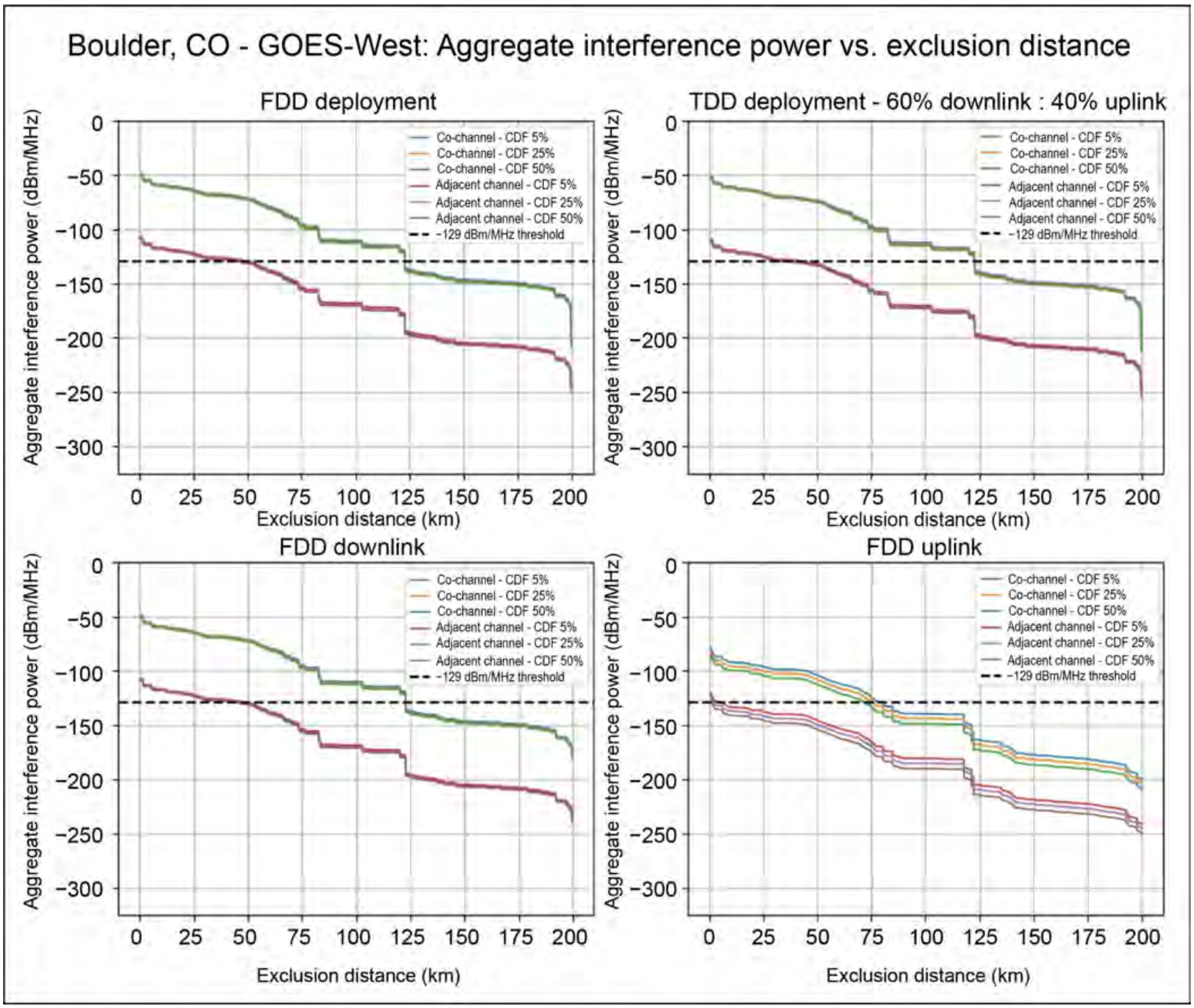

Figure G-16. LTE-M deployment for the earth station in Boulder, Colorado: GOES-West.

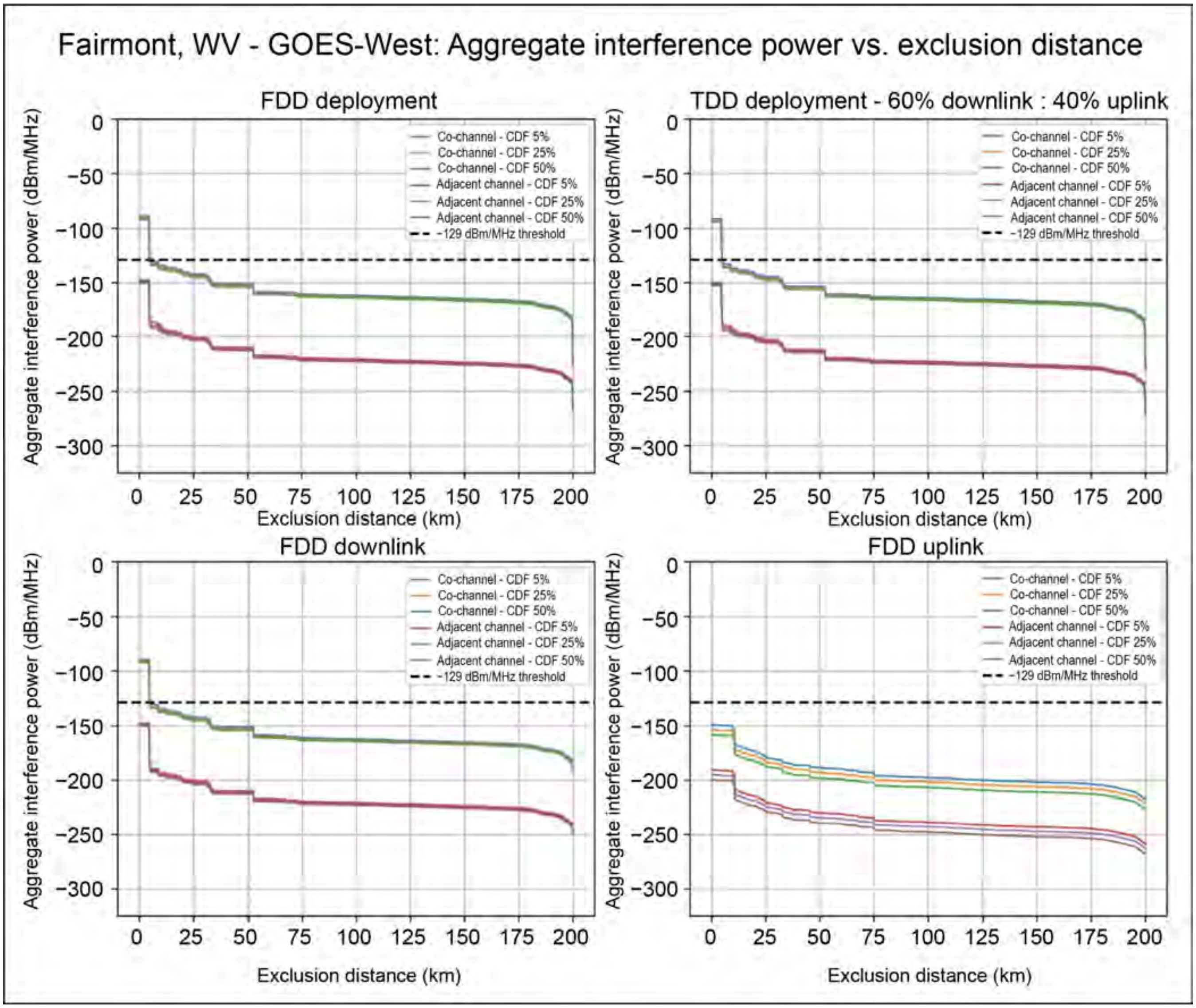

Figure G-17. LTE-M deployment for the earth station in Fairmont, West Virginia: GOES-West.

Figure G-17 shows the received interference power at the Fairmont, West Virginia, site versus exclusion distance when the earth station is pointing to GOES-West in an LTE-M deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 5 km circular exclusion radius.

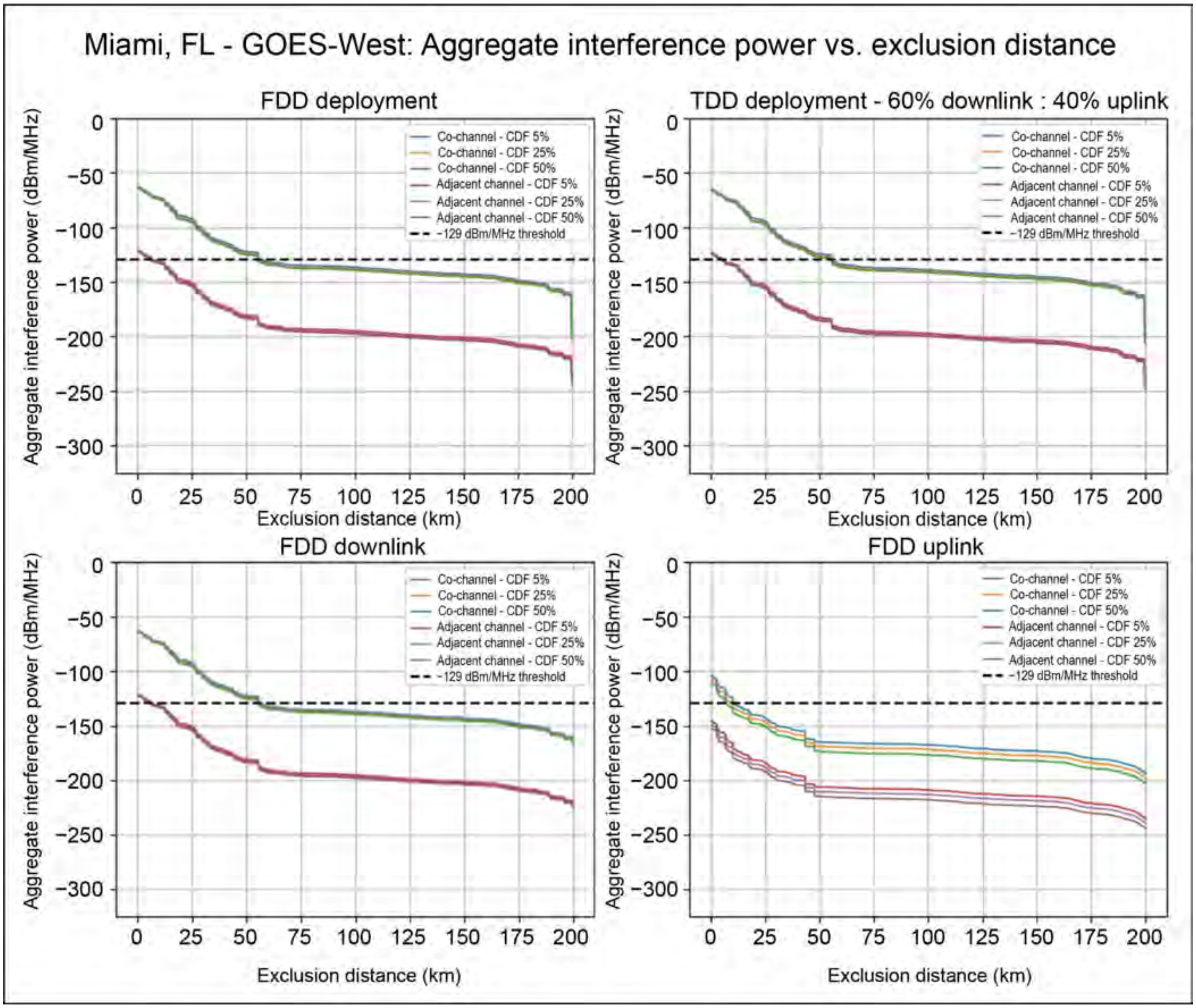

Figure G-18. LTE-M deployment for the earth station in Miami, Florida: GOES-West.

Figure G-18 shows the received interference power at the Miami, Florida, site versus exclusion distance when the earth station is pointing to GOES-West in an LTE-M deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 55 km circular exclusion radius.

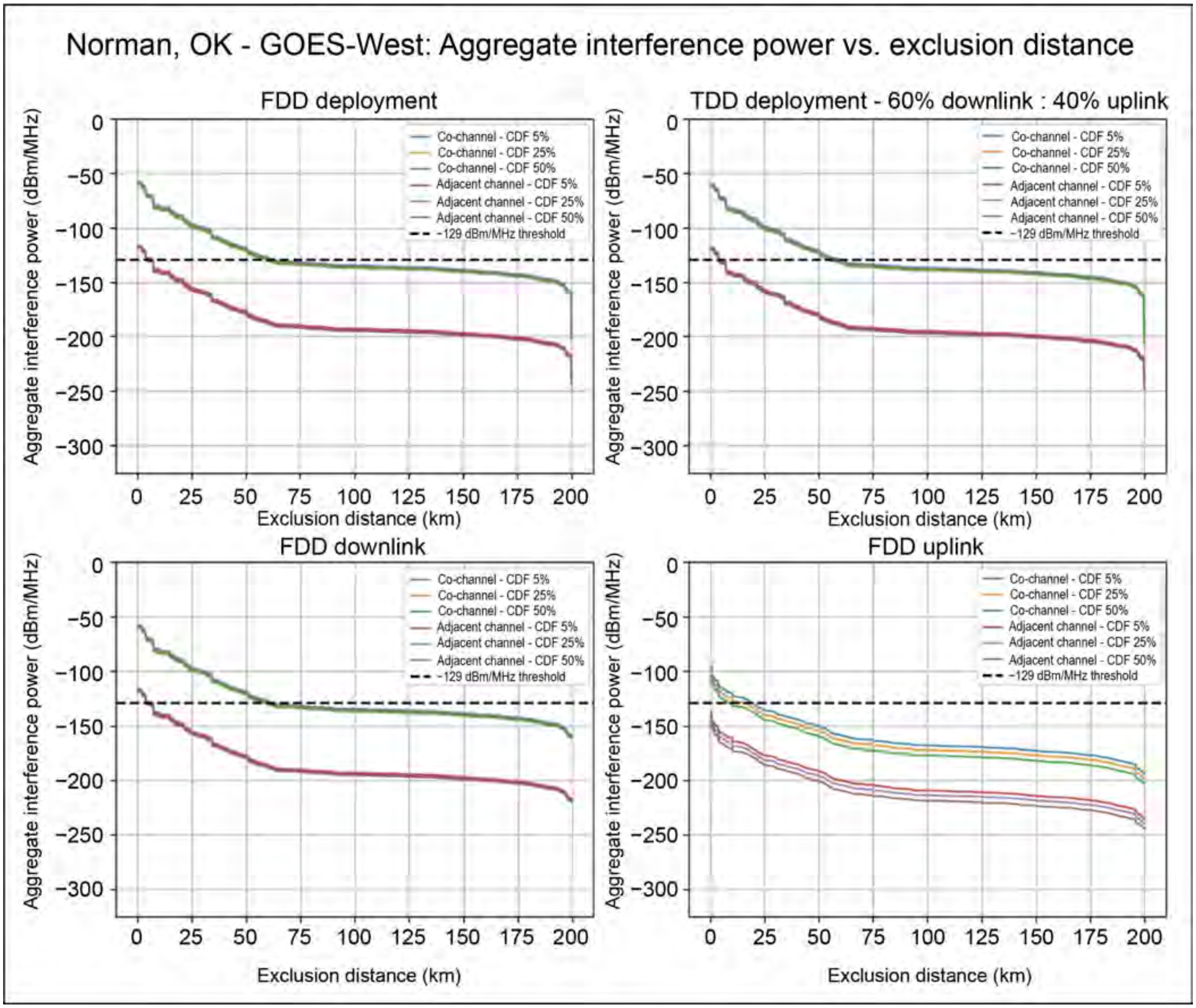

Figure G-19. LTE-M deployment for the earth station in Norman, Oklahoma: GOES-West.

Figure G-19 shows the received interference power at the Norman, Oklahoma, site versus exclusion distance when the earth station is pointing to GOES-West in an LTE-M deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 60 km circular exclusion radius.

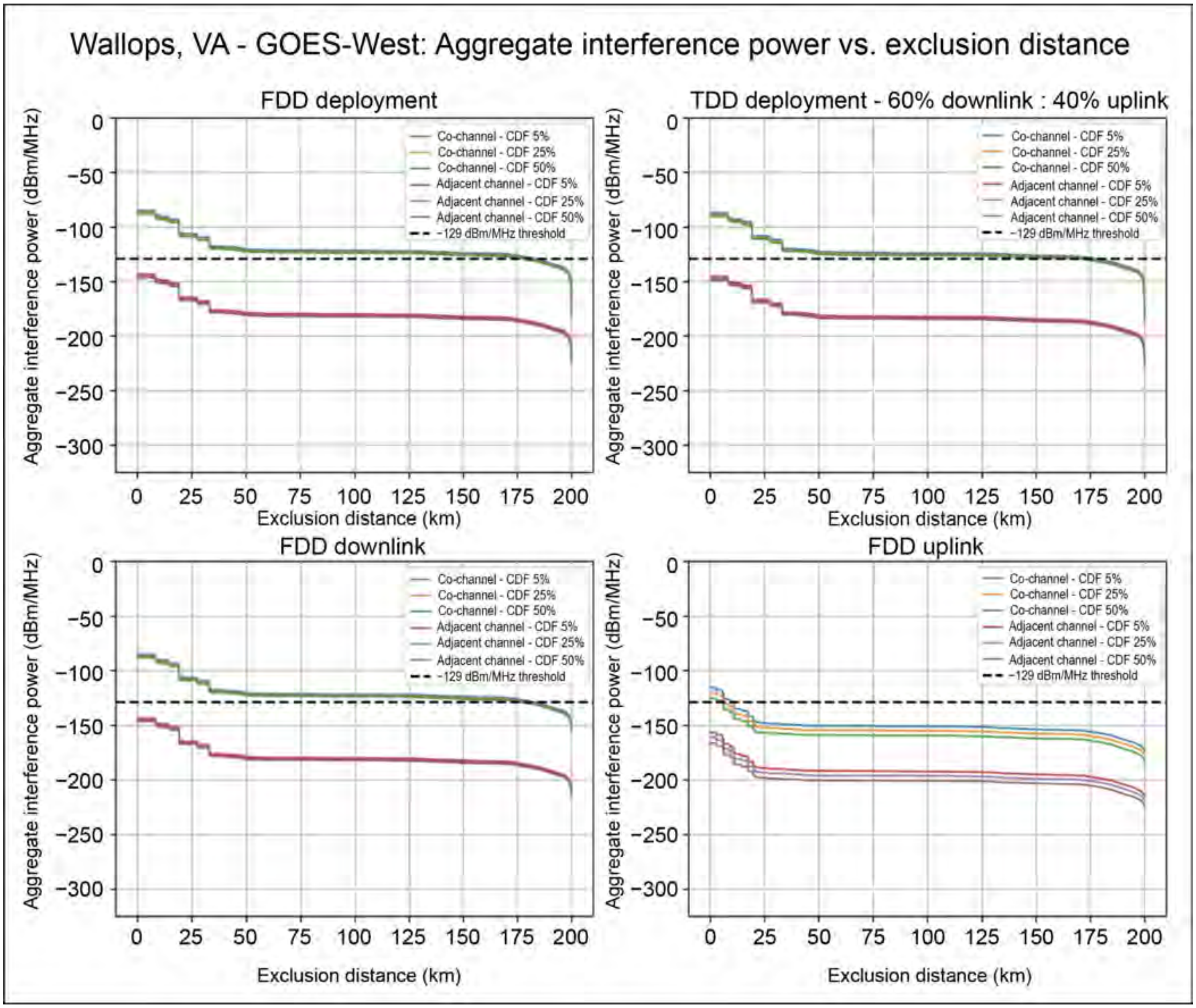

Figure G-20. LTE-M deployment for the earth station in Wallops Island, Virginia: GOES-West.

Figure G-20 shows the received interference power at the Wallops Island, Virginia, site versus exclusion distance when the earth station is pointing to GOES-West in an LTE-M deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 175 km circular exclusion radius.

G.2.4 IoT in-band downlink use case

The IoT in-band results produced assumed a single NB-IoT carrier in the 5 MHz channel. One or more of the 25 RBs in the 5 MHz channel may be configured as NB-IoT channels. Thus, each antenna will assume a channel bandwidth of 4.5 MHz. A standard three-sector configuration as used in the downlink large-cell deployment will be replicated. Identical eNB sites will be used since this configuration also supports the LTE use case. The sectors consist of antennas with identical transmit EIRPs, antenna patterns, and configured downtilts. An EIRP of 63 dBm was assumed in addition to a 2° downtilt. All sectors were assigned antenna azimuths with a 120° offset. The three sectors consist of three antennas with azimuths of 0°, 120°, and 240°. The antenna pattern is displayed in Figure G-1. The horizontal plane of Figure G-1 is configured for an antenna with an azimuth of 0°, and was configured for antennas of other azimuths such that the peak gain is along the assigned azimuth.

G.2.5 IoT in-band uplink use case

Each NB-IoT carrier can support one to four UEs in the uplink per sector depending on the number of tones (multitone configurations currently support a carrier spacing of 15 kHz, whereas a single tone supports a carrier spacing of 15 kHz or 3.75 kHz), assuming a tone size of 15 kHz. A multitone (three tones) assumption was made. The results produced assumed the worst case of four UEs per sector, in which each UE assumed a 45 kHz channel bandwidth. Additionally, three non-IoT LTE UEs are assumed per sector, each assuming a channel bandwidth of 1.44 MHz. The EIRP is randomized from the curve as displayed in Figure G-1 and an omnidirectional antenna with a 2.15 dBi gain was assumed.

G.2.6 IoT in-band deployment: Aggregate RFI versus exclusion distance

The LTE FDD and TDD risks associated with an IoT in-band deployment will be identical with the results described in Section 3.3.4. Despite the significant increase in UEs, the RFI produced from the downlink is much more significant than in the uplink. Since the downlink is identical to the baseline large-cell deployment, the results will remain consistent, as seen in Figures G-6 through G-15. However, there will be an increase in RFI produced by the uplink due to the larger density of UEs. Figures G-21 through G-25 consist of four aggregate RFI versus exclusion distance subplots representing LTE FDD and TDD deployments for IoT in-band co-channel and adjacent-channel scenarios. RFI levels above −129 dBm/MHz are expected to result in a degradation of the GOES receiver performance.

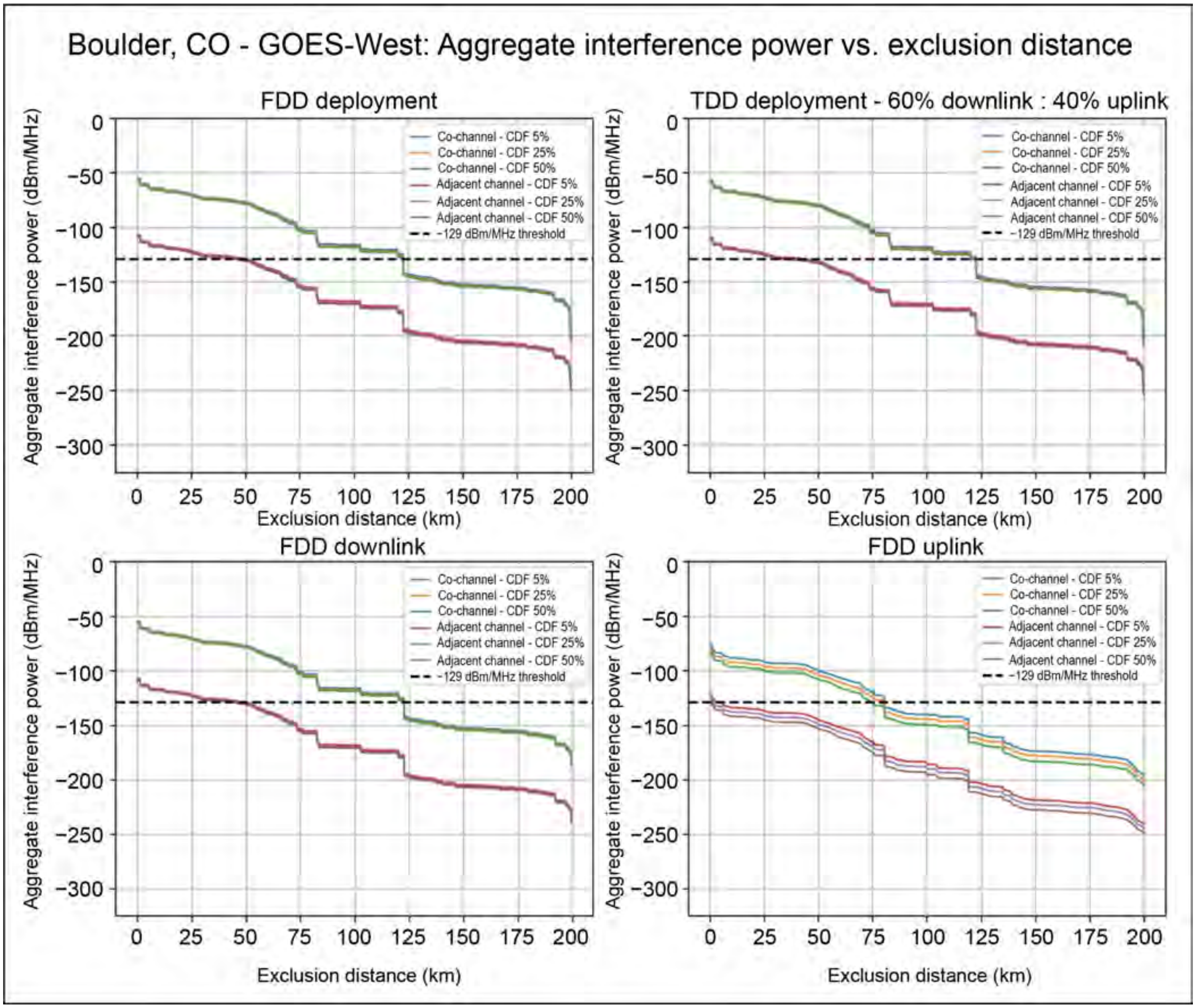

Figure G-21. IoT in-band deployment for the earth station in Boulder, Colorado: GOES-West.

Figure G-21 shows the received interference power at the Boulder, Colorado, site versus exclusion distance when the earth station is pointing to GOES-West in an IoT in-band deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 123 km circular exclusion radius.

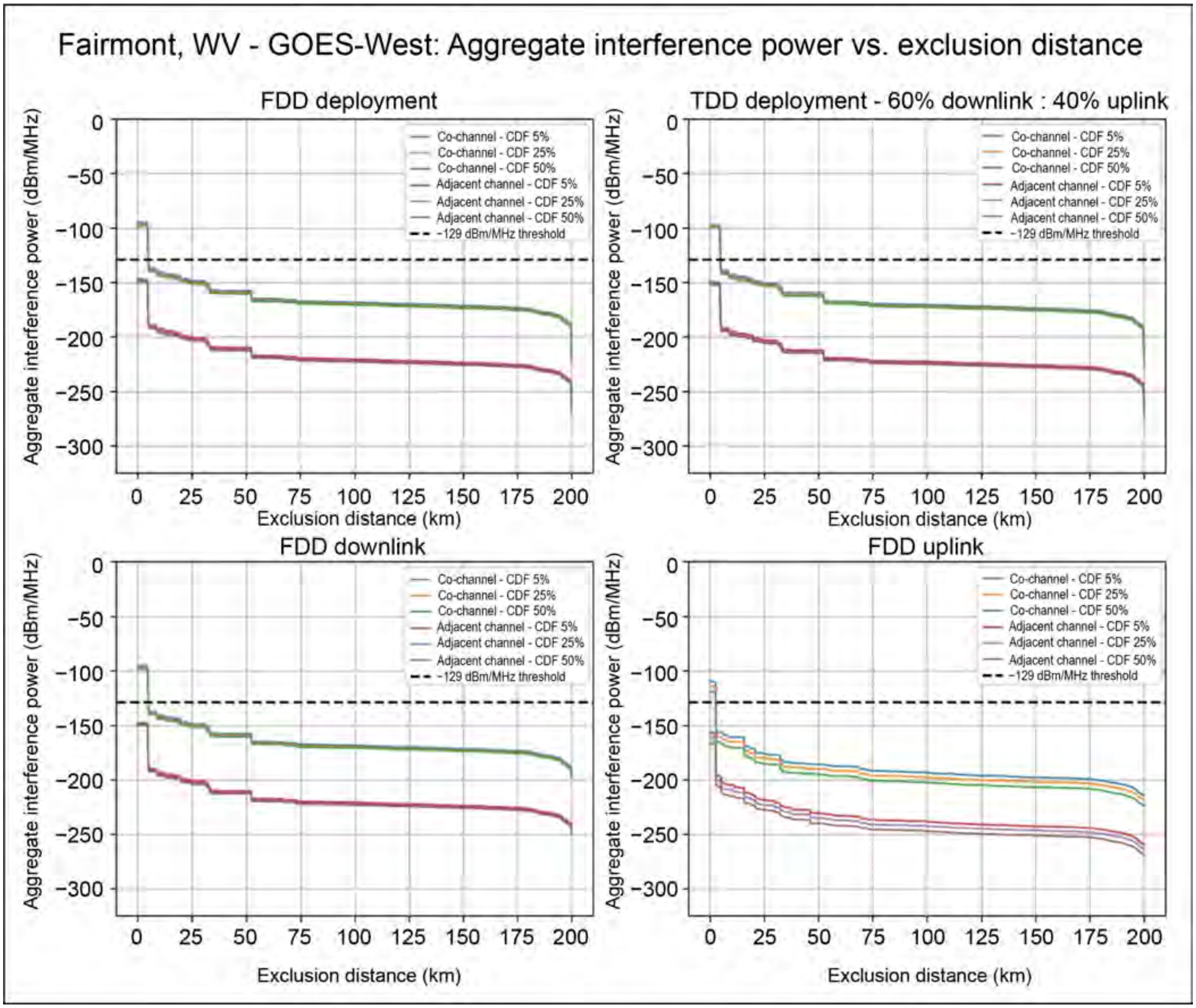

Figure G-22. IoT in-band deployment for the earth station in Fairmont, West Virginia: GOES-West.

Figure G-22 shows the received interference power at the Fairmont, West Virginia, site versus exclusion distance when the earth station is pointing to GOES-West in an IoT in-band deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 5 km circular exclusion radius.

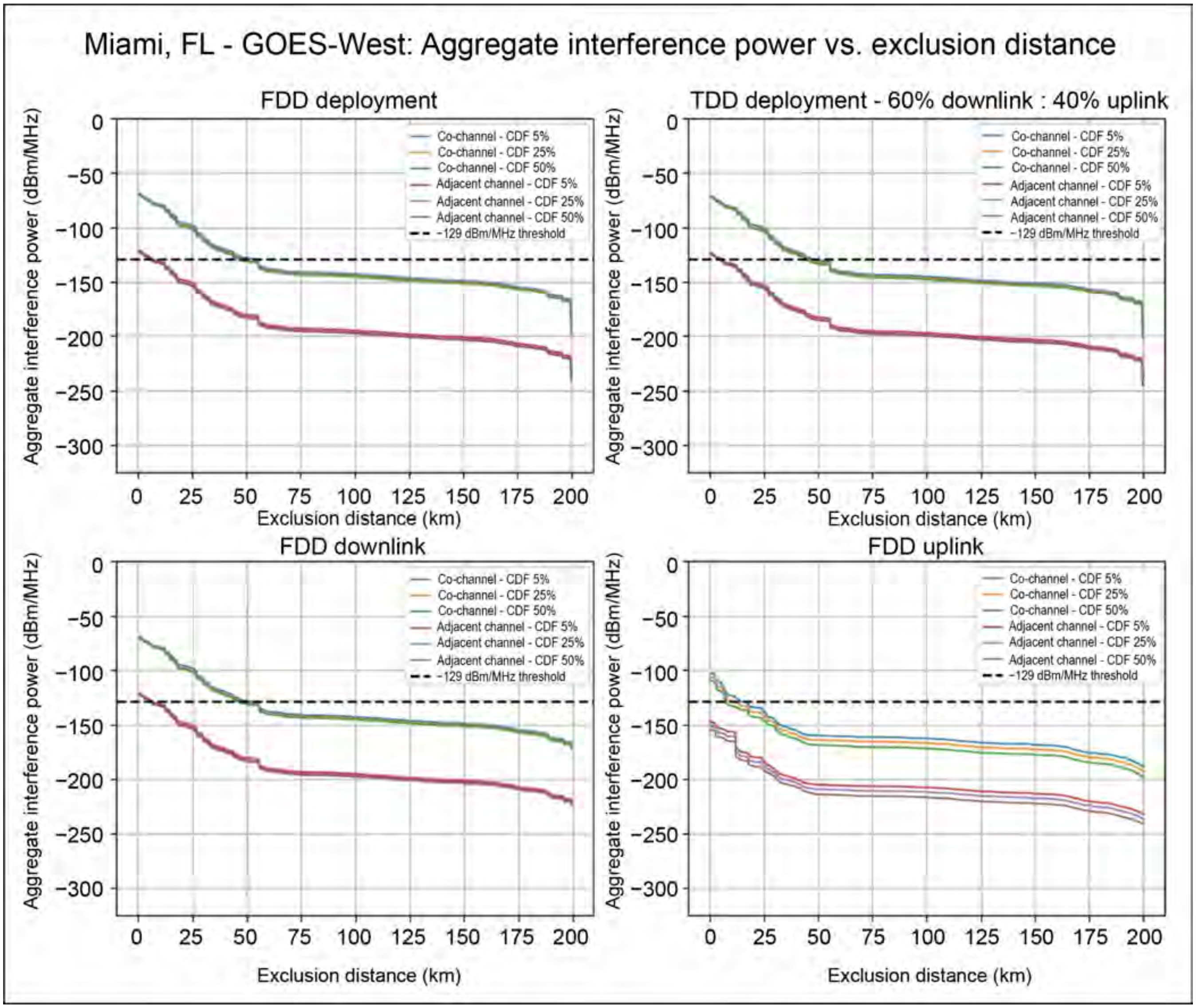

Figure G-23. IoT in-band deployment for the earth station in Miami, Florida: GOES-West.

Figure G-23 shows the received interference power at the Miami, Florida, site versus exclusion distance when the earth station is pointing to GOES-West in an IoT in-band deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 50 km circular exclusion radius, due to the large differences in transmit power, peak gain, and propagation losses.

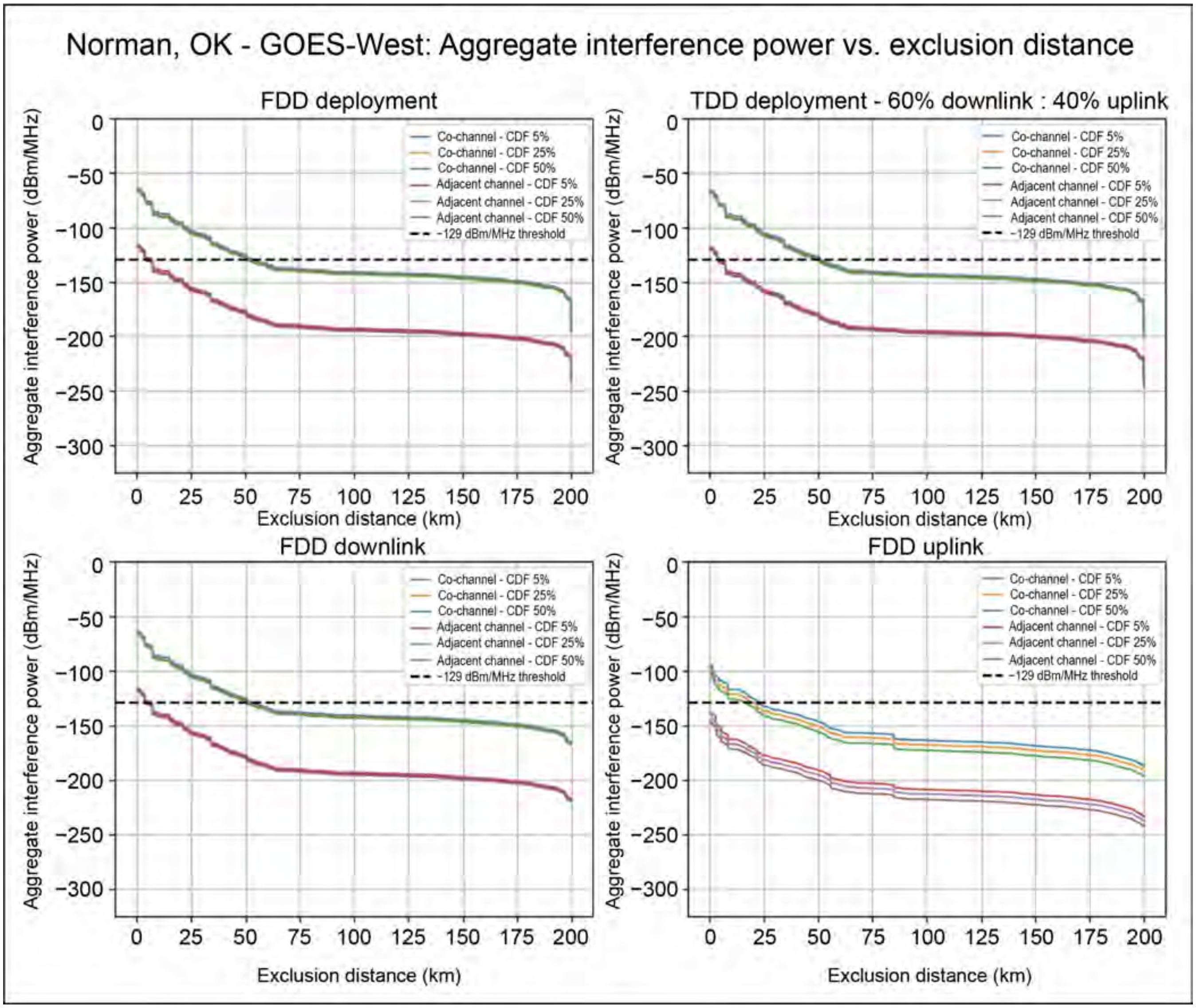

Figure G-24. IoT in-band deployment for the earth station in Norman, Oklahoma: GOES-West.

Figure G-24 shows the received interference power at the Norman, Oklahoma, site versus exclusion distance when the earth station is pointing to GOES-West in an IoT in-band deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 50 km circular exclusion radius.

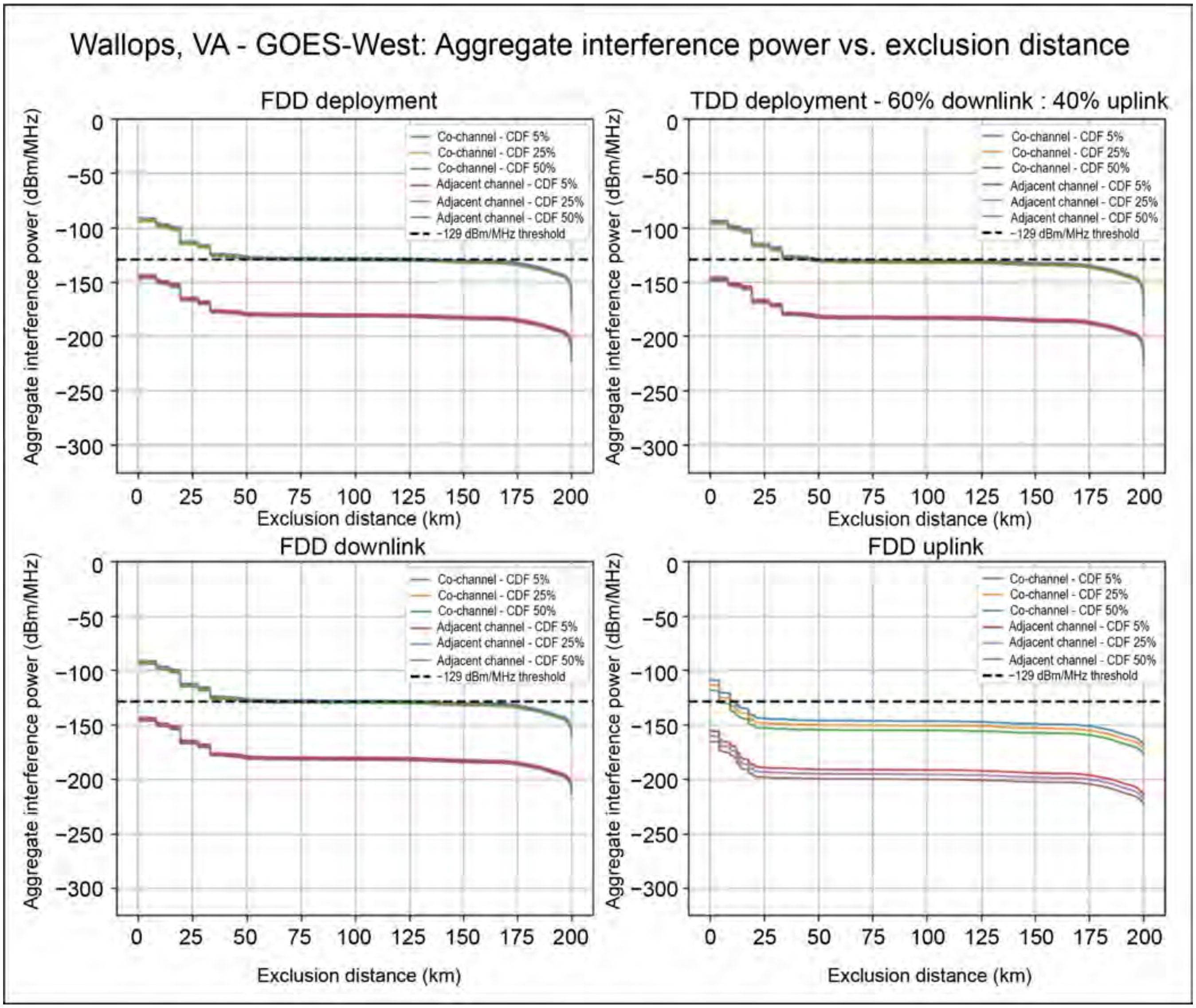

Figure G-25. IoT in-band deployment for the earth station in Wallops Island, Virginia: GOES-West.

Figure G-25 shows the received interference power at the Wallops Island, Virginia, site versus exclusion distance when the earth station is pointing to GOES-West in an IoT in-band deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield highly different exclusion distances. As indicated by the top subplots, the aggregate RFI is driven mainly along the threshold set. The LTE FDD deployment requires approximately a 90 km exclusion distance, whereas the LTE TDD deployment requires approximately a 50 km exclusion distance.

G.2.7 IoT guard-band downlink use case

IoT guard-band results produced assumed a single NB-IoT carrier in the 5 MHz channel. A single guard band was assumed in the analysis. This guard band is placed at either end of the LTE-occupied bandwidth. Therefore, the occupied bandwidth of the configuration increases to 4.68 MHz. A standard three-sector configuration as used in the downlink large-cell deployment will be replicated. Identical eNB sites will be used since this configuration also supports the LTE use case. The sectors consist of antennas with identical transmit EIRPs, antenna patterns, and configured downtilts. An EIRP of 63 dBm was assumed in addition to a 2° downtilt. All sectors were assigned antenna azimuths with a 120° offset. The three sectors consist of three antennas with azimuths of 0°, 120°, and 240°. The antenna pattern is displayed in Figure G-1. The horizontal plane of Figure G-1 is configured for an antenna with an azimuth of 0°, and was configured for antennas of other azimuths such that the peak gain is along the assigned azimuth.

G.2.8 IoT guard-band uplink use case

Each NB-IoT carrier can support one to four UEs in the uplink per sector depending on the number of tones, assuming a tone size of 15 kHz. A multitone (three tones) assumption was made. The results produced assumed the worst case of four UEs per sector in which each UE assumed a 45 kHz channel bandwidth. Additionally, three non-IoT LTE UEs are assumed per sector, each assuming a channel bandwidth of 1.44 MHz. The EIRP is randomized from the curve as displayed in Figure G-1, and an omnidirectional antenna with a 2.15 dBi gain was assumed. The uplink will be identical to the uplink within the IoT in-band deployment.

G.2.9 IoT guard-band deployment: Aggregate RFI versus exclusion distance

The LTE FDD and TDD risks associated with an IoT in-band deployment will be identical with the results described in Section G.2.4. Despite the significant increase in UEs, the RFI produced from the downlink is much more significant than in the uplink. The results were exact to what was observed in the IoT in-band scenario. Moreover, the downlink and uplink assumptions between the IoT guard-band and IoT in-band scenarios are alike, the only difference being the change in occupied bandwidths. To compare the two deployments, consider the normalization of the EIRP to a per-MHz basis. Following the normalization, the downlink EIRP per antenna considered for the IoT guard-band deployment would be 56.3 dBm/MHz compared to the EIRP of 56.5 dBm/MHz in the IoT in-band deployment. Because of the similarities, the results as observed in Figures G-21 through G-25 are applicable to the IoT guard-band deployment.

G.2.10 IoT stand-alone downlink use cases

The IoT stand-alone results produced assumed six NB-IoT carriers in the 5 MHz channel. Since one or more NB-IoT channels can be configured to operate without any other LTE carrier in the bandwidth, each antenna will assume a channel bandwidth of 1.08 MHz because of the use of six channels. A standard three-sector configuration as used in the downlink large-cell deployment will be replicated. The sectors consist of antennas with identical transmit EIRPs, antenna patterns, and configured downtilts. An EIRP of 63 dBm was assumed in addition to a 2° downtilt. All sectors were assigned antenna azimuths with a 120° offset. The three sectors consist of three antennas with azimuths of 0°, 120°, and 240°. The antenna pattern is displayed in Figure G-1. The horizontal plane of Figure G-1 is configured for an antenna with an azimuth of 0°, and was configured for antennas of other azimuths such that the peak gain is along the assigned azimuth.

G.2.11 IoT stand-alone uplink use cases

Each NB-IoT carrier can support one to four UEs in the uplink per sector depending on the number of tones, assuming a tone size of 15 kHz. A multitone (three tones) assumption was made. The results produced assumed the worst case of four UEs per sector in which each UE assumed a 45 kHz channel bandwidth. Thus, 24 UEs were configured per sector for six NB-IoT carriers. The EIRP is randomized from the curve as displayed in Figure G-1 and an omnidirectional antenna with a 2.15 dBi gain was assumed. The uplink will be identical to the uplink within the IoT in-band deployment.

G.2.12 IoT stand-alone deployment: Aggregate RFI versus exclusion distance

The LTE FDD and TDD risks associated with an IoT stand-alone deployment will be identical with the results described in Section G.2.4. Despite the significant increase in UEs, the RFI produced from the downlink is much more significant than in the uplink. Since the downlink is almost identical to the baseline large-cell deployment, the results will remain mostly consistent, as seen in Figures G-6 through G-15. However, because of the larger density of UEs, there will be a significant increase in RFI produced by the uplink. Figures G-26 through G-30 consist of four aggregate RFI versus exclusion distance subplots representing LTE FDD and TDD deployments for IoT stand-alone co-channel and adjacent-channel scenarios. RFI levels above −129 dBm/MHz are expected to result in a degradation of the GOES receiver performance.

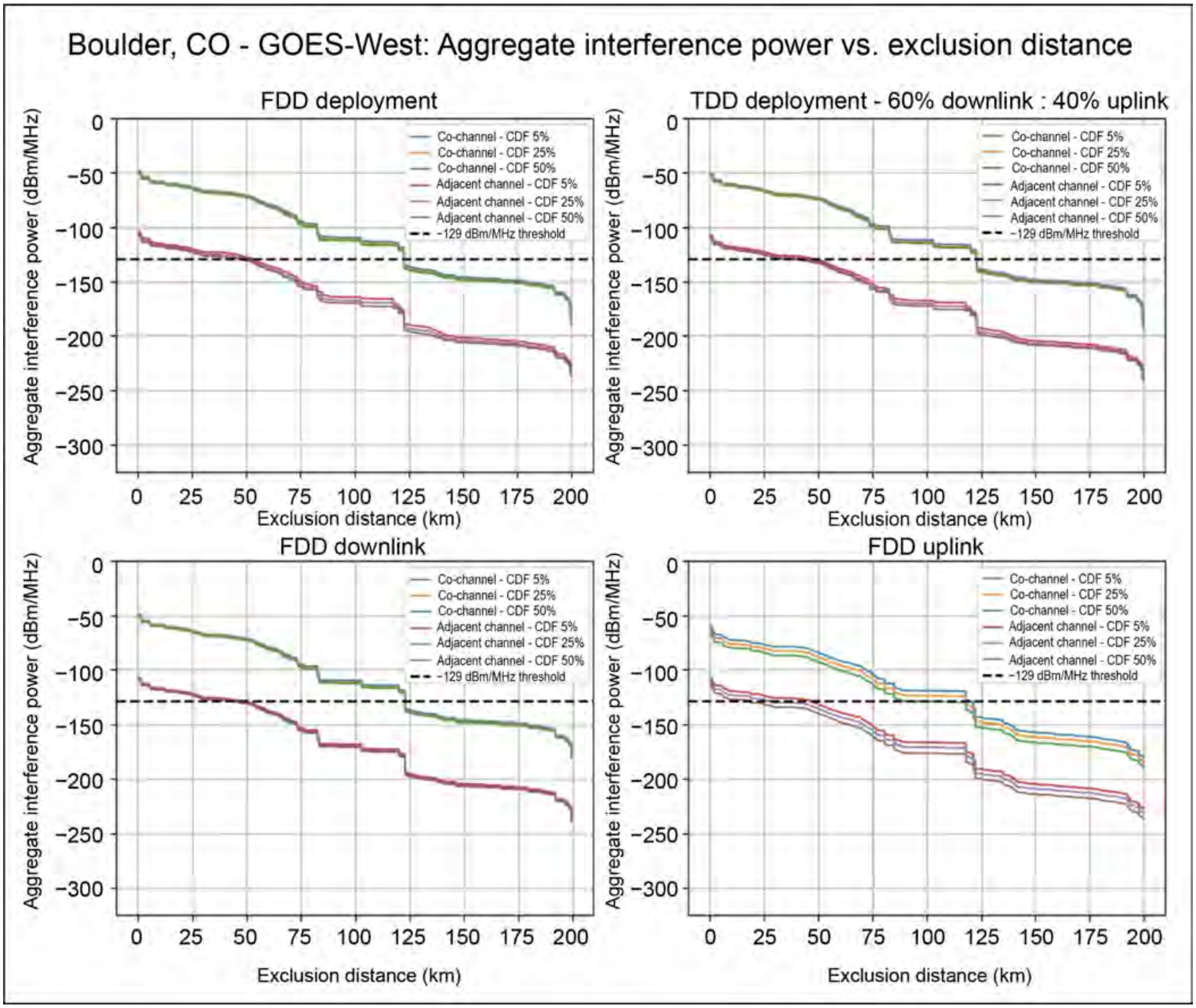

Figure G-26. IoT stand-alone deployment for the earth station in Boulder, Colorado: GOES-West.

Figure G-26 shows the received interference power at the Boulder, Colorado, site versus exclusion distance when the earth station is pointing to GOES-West in an IoT stand-alone deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 123 km circular exclusion radius.

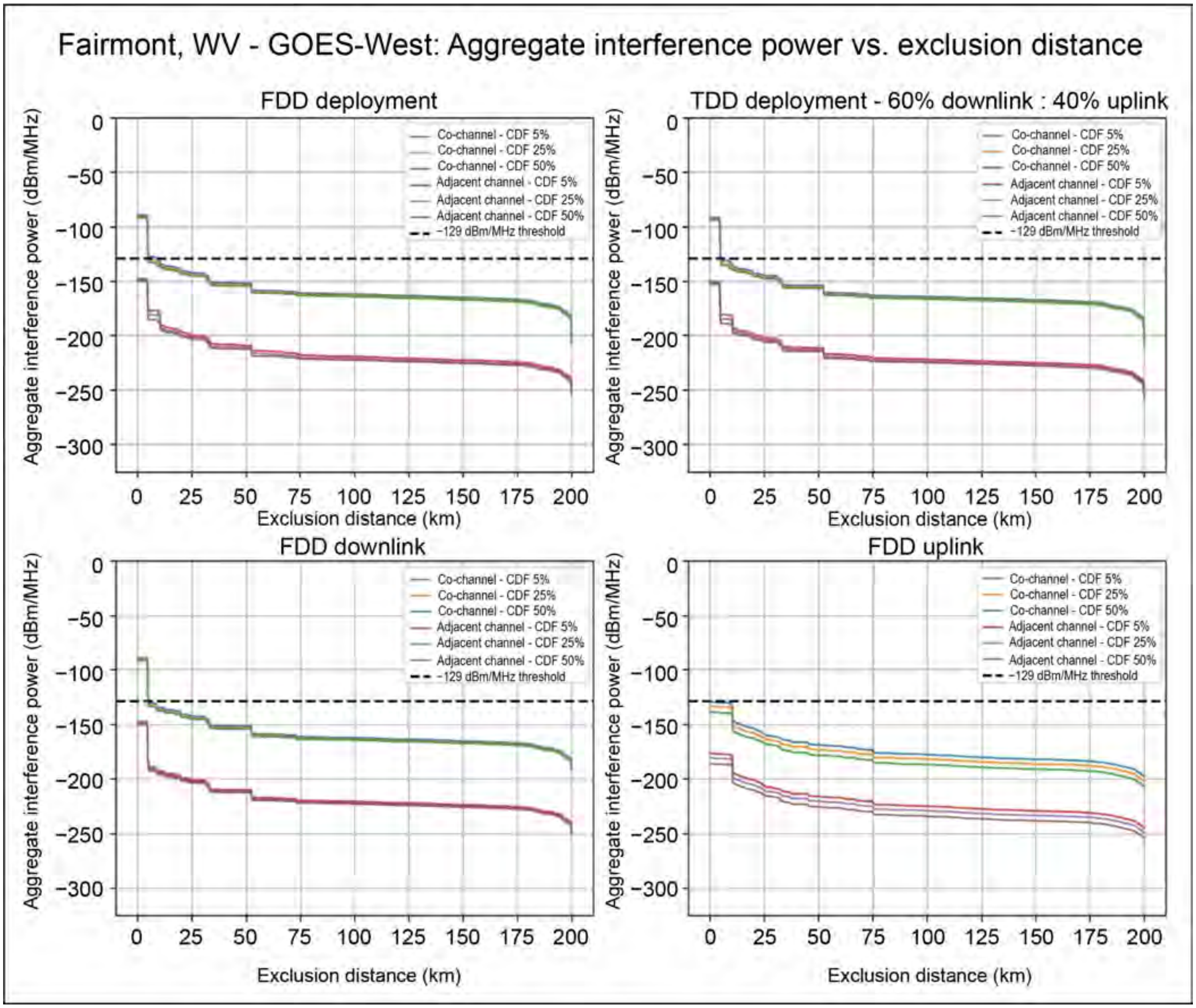

Figure G-27. IoT stand-alone deployment for the earth station in Fairmont, West Virginia: GOES-West.

Figure G-27 shows the received interference power at the Fairmont, West Virginia, site versus exclusion distance when the earth station is pointing to GOES-West in an IoT stand-alone deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 5 km circular exclusion radius.

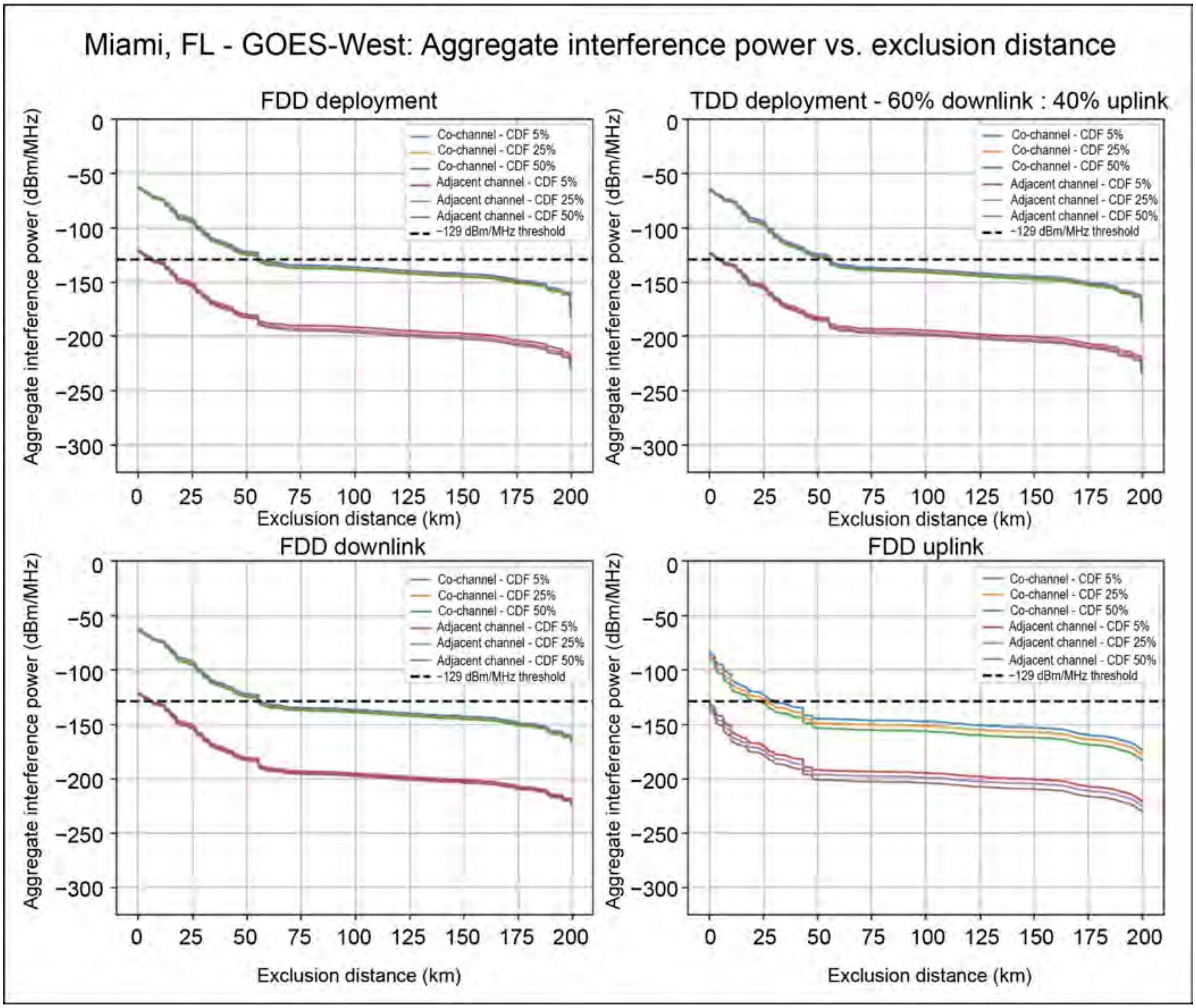

Figure G-28. IoT stand-alone deployment for the earth station in Miami, Florida: GOES-West.

Figure G-28 shows the received interference power at the Miami, Florida, site versus exclusion distance when the earth station is pointing to GOES-West in an IoT stand-alone deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 55 km circular exclusion radius.

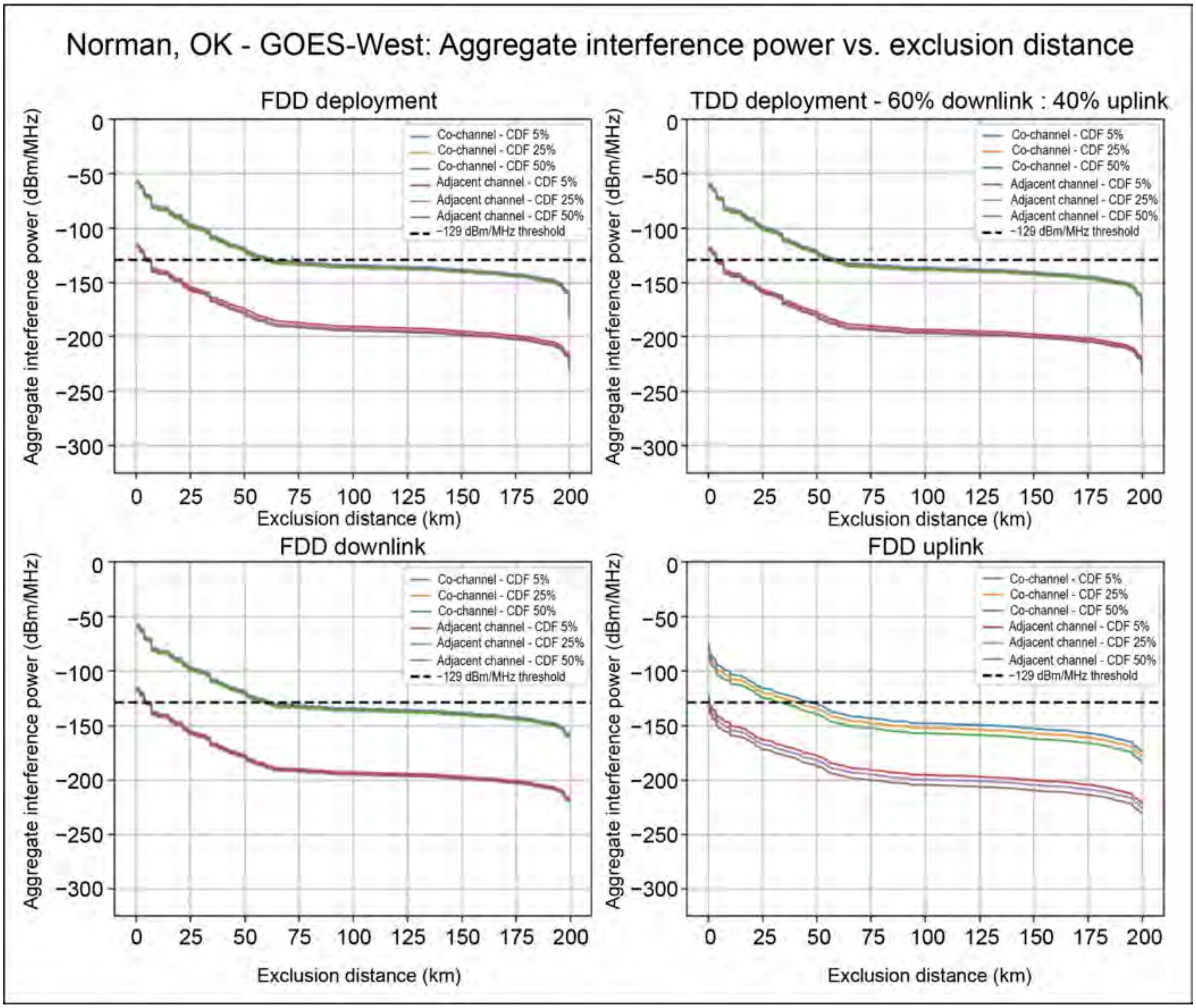

Figure G-29. IoT stand-alone deployment for the earth station in Norman, Oklahoma: GOES-West.

Figure G-29 shows the received interference power at the Norman, Oklahoma, site versus exclusion distance when the earth station is pointing to GOES-West in an IoT stand-alone deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 58 km circular exclusion radius.

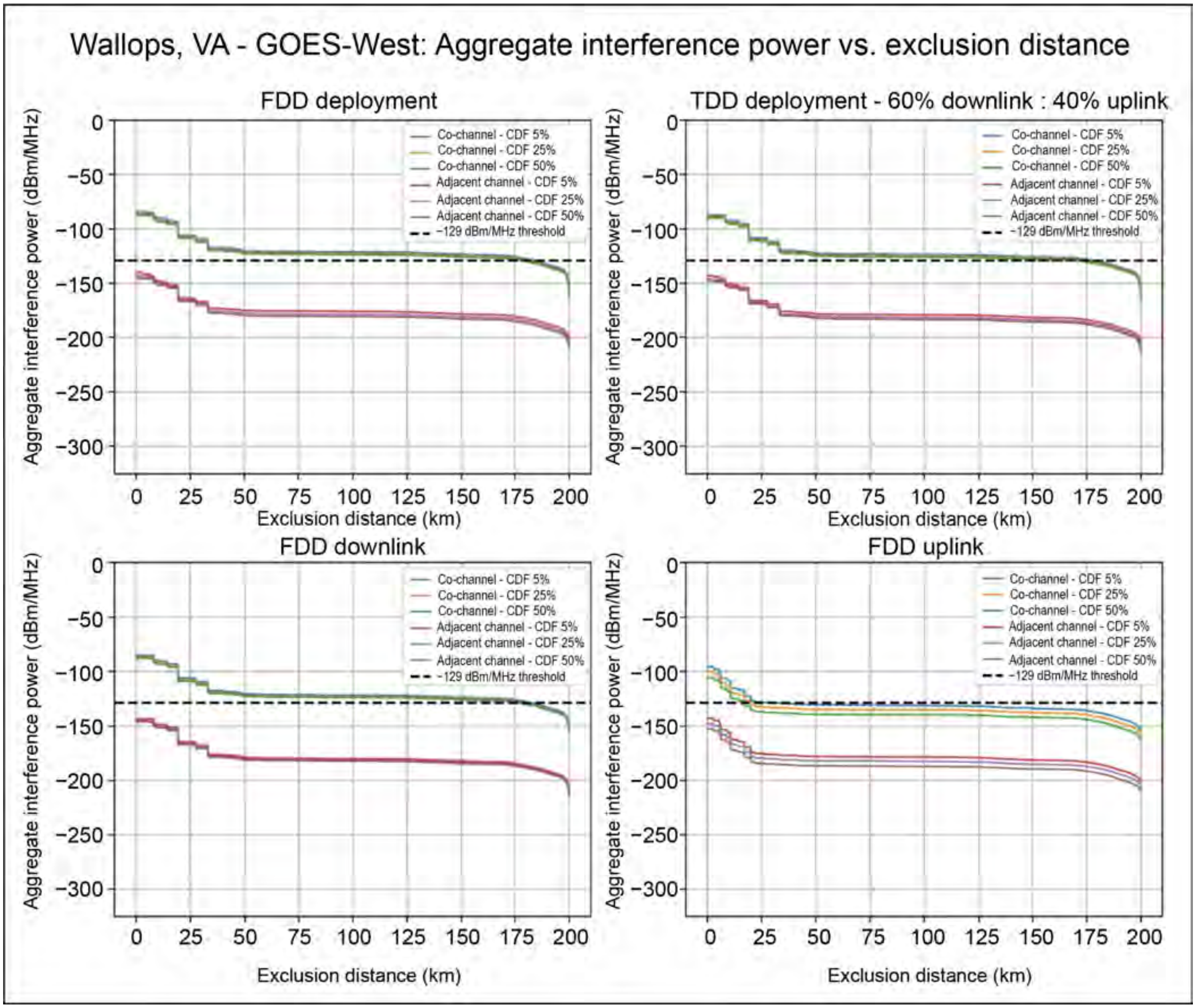

Figure G-30. IoT stand-alone deployment for the earth station in Wallops Island, Virginia: GOES-West.

Figure G-30 shows the received interference power at the Wallops Island, Virginia, site versus exclusion distance when the earth station is pointing to GOES-West in an IoT stand-alone deployment. The allowable interference to the Federal ground station is −129 dBm/MHz. LTE FDD and TDD yield nearly identical exclusion distances. Both deployments require approximately a 180 km circular exclusion radius.

Appendix H. Methods of Carrier ID Analysis and Assumptions (Project 10)

H.1 Carrier ID Specifications

The 4G LTE downlink frame structure consists of a time/frequency map where different signaling, data, and synchronization signals are transmitted.[1]

Public land mobile networks (PLMNs) transmit a carrier ID as part of the System Information Block–1 (SIB1). A receiver can extract the PLMN ID by decoding the SIB1. Decoding the SIB1 has two primary aspects:

1. The receiver must time-align itself with LTE signal to capture and decode the message(s).
2. The signal must have enough signal strength relative to noise and other signals on the channel to be decoded.

The 3rd Generation Partnership Project (3GPP) specifications define the SIB1 message and its transmission. An SIB1 message is dynamically scheduled in the physical downlink shared channel (PDSCH), and its allocation to resource blocks (RB) varies on a cell-by-cell basis. A typical single SIB1 message occupies two RBs and a cell broadcasts an SIB1 message once every 20 milliseconds in subframe 5. While transmission of the SIB1 is periodic for each tower, the transmission time varies from tower to tower. 3GPP specifications recommend synchronization in some cases but do not specify a synchronization method.[2] Further, towers generally do not coordinate their SIB1 transmissions, which results in overlapping SIB1s if multiple towers are within reception distance.

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[1] The composition of the LTE signal and relative power levels of its components is described in Reiner Stuhlfauth, "LTE Measurements—From RF to Application Testing," slide 37, Slideshare, accessed August 17, 2020, https://www.slideshare.net/RohdeSchwarzNA/lte-eutran-rsanov2012day2?qid=2f396b72-54dd-4565-a19b-d3214fecb005&v=&b=&from_search=1.

[2] "Downlink Power Allocation in LTE," Huawei Enterprise Support Community, created July 6, 2018, https://forum.huawei.com/enterprise/en/downlink-power-allocation-in-lte/thread/457683-100305.

H.2 Determining SIB1 SINR

The SINR for a given signal containing an SIB1 depends on the number of overlapping messages and their relative signal strength at the receiver. A statistical characterization of SIB1 SINR can be established using one of two methods: measuring SINR from current LTE deployments or establishing a statistical model from simulation.

The study evaluated the feasibility of conducting field measurements using COTS equipment. For this to work, the equipment must provide sufficient performance to decode low SINR signals. Tests revealed that the demodulation SINR (or SNR) must be greater than −3 dB, based on 3GPP specifications[3] and analyses performed in various studies.[4] Receiver sensitivity levels for various frequency bands are shown in Table H-1. The table shows that COTS device carrier ID levels (approximately −100 dBm) are not low enough to support NOAA low-noise requirements.

[3] European Telecommunications Standards Institute, “LTE: Evolved Universal Terrestrial Radio Access (E-UTRA),” 3GPP TS 36.101, version 13.3.0, release 13 (Sophia Antipolis, France, 2016), test 1, table 8.2.1.1.1-2.
[4] “Analyze Throughput for PDSCH Demodulation Performance,” Mathworks, accessed May 12, 2020, https://www.mathworks.com/help/lte/ug/analyze-throughput-for-pdsch-demodulation-performance-test.html.

Table H-1. Receiver sensitivity levels required for decoding carrier IDs.

	Channel bandwidth						
E-UTRA band	1.4 MHz (dBm)	3 MHz (dBm)	5 MHz (dBm)	10 MHz (dBm)	15 MHz (dBm)	20 MHz (dBm)	Duplex mode
1	—	—	−100	−97	−95.2	−94	FDD
2	−102.7	−99.7	−98	−95	−93.2	−92	FDD
3	−101.7	−98.7	−98	−94	−92.2	−91	FDD
4	−104.7	−101.7	−100	−97	−95.2	−94	FDD
5	−103.2	−100.2	−98	−95	—	—	FDD
6	—	—	−100	−97	—	—	FDD
7	—	—	−98	−95	−93.2	−92	FDD
8	−102.2	−99.2	−97	−94	—	—	FDD
9	—	—	−99	−96	−94.2	−93	FDD
10	—	—	−100	−97	−95.2	−94	FDD
11	—	—	−100	−97	—	—	FDD
12	−101.7	−98.7	−97	−94	—	—	FDD
13	—	—	−97	−94	—	—	FDD
14	—	—	−97	−94	—	—	FDD
—	—	—	—	—	—	—	—
17	—	—	−97	−94	—	—	FDD
18	—	—	−1007	−977	−95.27	—	FDD
19	—	—	−100	−97	−95.2	—	FDD
20	—	—	−97	−94	−91.2	−90	FDD

Table H-1. cont.

Table H-1. Receiver sensitivity levels required for decoding carrier IDs.

	Channel bandwidth						
E-UTRA band	1.4 MHz (dBm)	3 MHz (dBm)	5 MHz (dBm)	10 MHz (dBm)	15 MHz (dBm)	20 MHz (dBm)	Duplex mode
21	—	—	−100	−97	−95.2	—	FDD
22	—	—	−97	−94	−92.2	−91	FDD
23	−104.7	−101.7	−100	−97	−95.2	−94	FDD
24	—	—	−100	−97	—	—	FDD
25	−101.2	−98.2	−96.5	−93.5	−91.7	−90.5	FDD
26	−102.7	−99.7	−97.56	−94.56	−92.76	—	FDD
27	−103.2	−100.2	−98	−95	—	—	FDD
28	—	−100.2	−98.5	−95.5	−93.7	−91	FDD
30	—	—	−99	−96	—	—	FDD
31	−99	−95.7	−93.5	—	—	—	FDD
33	—	—	−100	−97	−95.2	−94	TDD
34	—	—	−100	—	−95.2	−94	TDD
35	−106.2	−102.2	−100	−97	−95.2	−94	TDD
36	−106.2	−102.2	−100	−97	−95.2	−94	TDD
37	—	—	−100	−97	−95.2	−94	TDD
38	—	—	−100	−97	−95.2	−94	TDD
39	—	—	−100	−97	−95.2	−94	TDD
40	—	—	−100	−97	−95.2	−94	TDD
41	—	—	−98	−95	−93.2	−92	TDD
42	—	—	−99	−96	−94.2	−93	TDD
43	—	—	−99	−96	−94.2	−93	TDD
44	—	[−100.2]	[−98]	[−95]	[−93.2]	[−92]	TDD
45	—	—	−100	−97	−95.2	−94	TDD
48	—	—	−99	−96	−94.2	−93	TDD
50	—	−102.2	−100	−97	−95.2	−94	TDD
51	—	−102.2	−100	—	—	—	TDD
52	—	—	−99	−96	−94.2	−93	TDD
53	−106.2	−102.2	−100	−97	—	—	TDD
—	—	—	—	—	—	—	—
65	−104.2	−101.2	−99.5	−96.5	−94.7	−93.5	FDD
66	−104.2	−101.2	−99.5	−96.5	−94.7	−93.5	FDD
68	—	—	−98.5	−96.5	−93.7	—	FDD

Table H-1. cont.

Table H-1. Receiver sensitivity levels required for decoding carrier IDs.

Channel bandwidth							
E-UTRA band	1.4 MHz (dBm)	3 MHz (dBm)	5 MHz (dBm)	10 MHz (dBm)	15 MHz (dBm)	20 MHz (dBm)	Duplex mode
—	—	—	—	—	—	—	
70	—	—	−100	−97	−95.2	−94	FDD
71	—	—	−97.2	−94.2	−92	−87.5	FDD
72	−99	−95.7	−93.5	—	—	—	FDD
73	−99	−95.7	−93.5	—	—	—	FDD
74	−104.78	−101.78	−99.58	−96.58	−94.78	−93.58	FDD
85	—	—	−97	−94	—	—	FDD

A statistical model was then developed based on Project 8 RFI signal level results. The following subsections establish how the statistical model regarding SIB1 SINRs and our process for model- ing the probability of decoding the carrier ID were defined.

Consider the packet collision depicted in Figure H-1 as a reference for developing a probabil- ity model. The graphic shows packets from two transmitters (labeled Tx1 and Tx2) arriving at a receiver on the same channel. Packet collisions occur if the packets arrive such that they overlap in time. The packets may not be decodable if the resulting SINR is too low. The picture depicts a situation where one packet from Tx1 interferes with two packets from Tx2.

Figure H-1. A depiction of packet collisions from two transmitters (Tx1 and Tx2) showing that a single packet from one transmitter can interfere with two packets from another transmitter.

The model describing the packet collision probability is a Poisson distribution, which is commonly used to model arrival probability. It is defined as:

$$p(k) = \frac{\lambda^{k} e^{-\lambda}}{k!},$$

where:

λ is the expected (mean) arrival rate;

k is the number of arrivals within a given time window (i.e., the arrival rate).

Thus p(k) is the probability that k arrivals occur in the time window given that the average arrival rate is λ.

For the SIB1 problem, λ is defined by the expected arrival rate of SIB1 messages from all the towers. This is determined by:

$$\lambda\lambda = \frac{NNTT}{CC},$$

where:

N is the number of LTE towers in the scenario;

T is the number of resource blocks per message;

C is the number of resource blocks per frame and T ≤ C.

This formulation then defines the probability of k overlapping SIB1 messages given N towers, T resource blocks per message, and C resource blocks per frame.

Figures H-2 and H-3 provide examples of the resulting probability distributions. Figure H-2 shows the probability distribution functions (PDF) for N = 50/75/100 and a 45% utilization factor (T/C = 45%).[5]

Figure H-3 shows the PDF and cumulative distribution functions (CDF) for a 60% utilization factor.

[5]Loading can vary from frame to frame. For simplifying the calculations, constant loading is assumed.

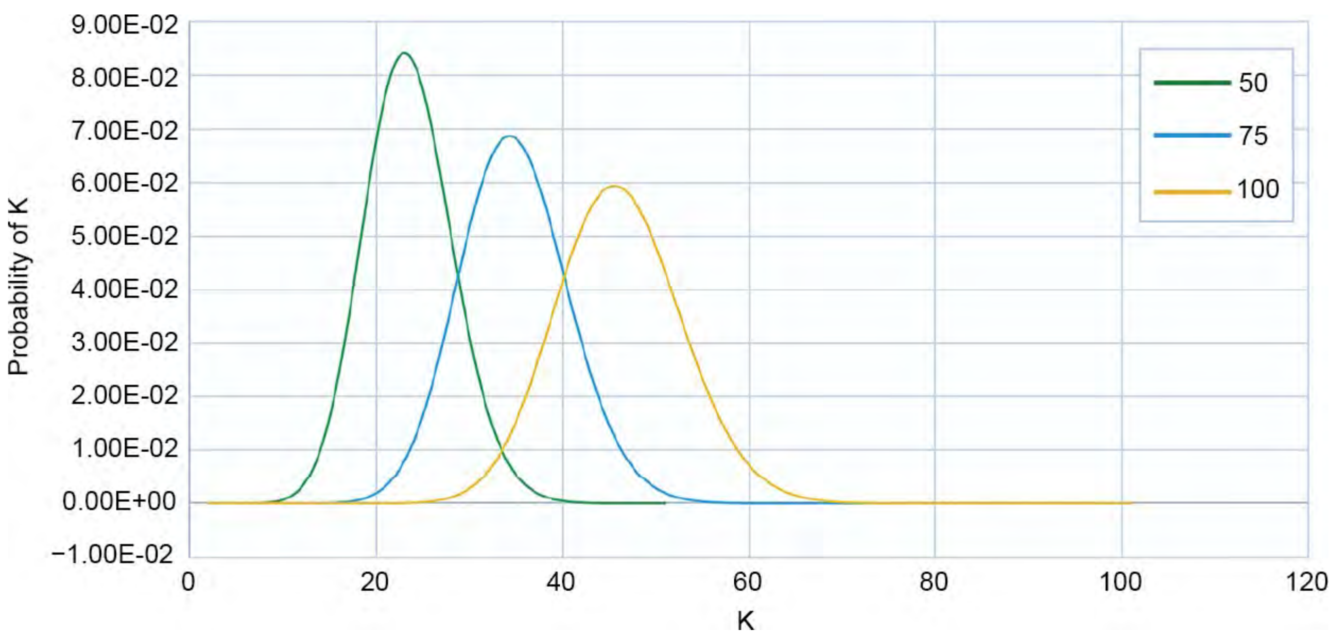

Figure H-2. Probability of overlapping messages at 45% loading.

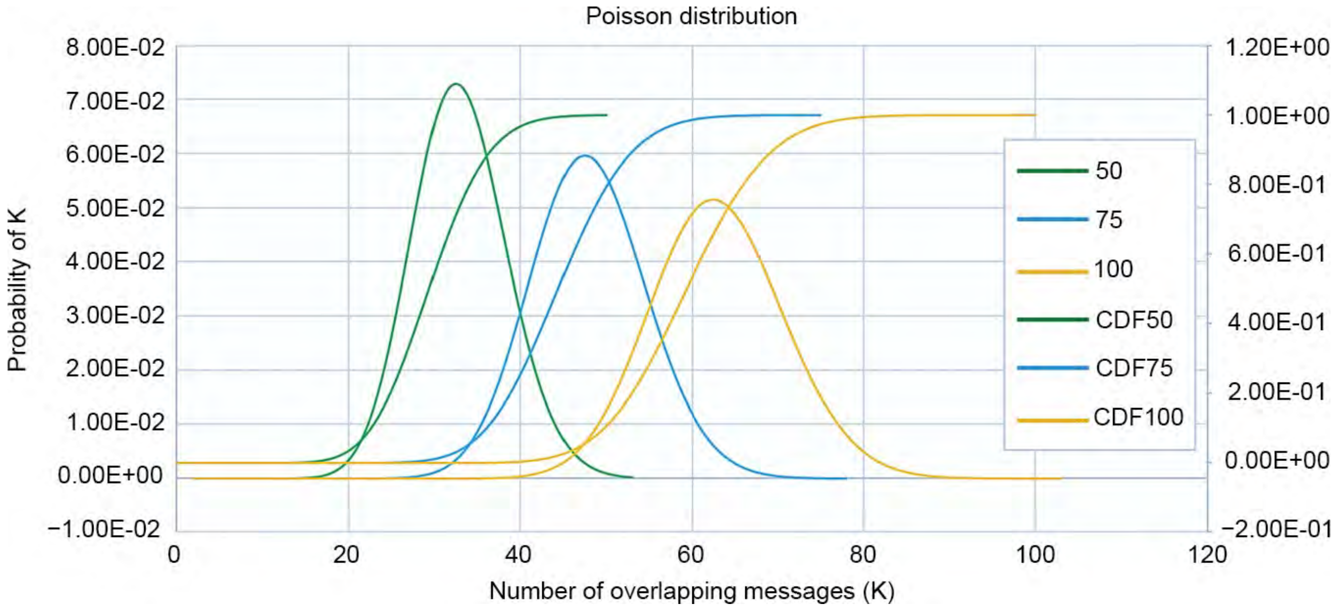

Figure H-3. Overlapping message PDF and CDF at 60% loading.

The SINR for each signal can be derived by selecting signals from the Project 8 analysis and determining if they could be decoded given k−1 other signals are received at the same time. Those k−1 signals are drawn at random, and their resulting aggregate power becomes the interference power in the SINR. A Monte Carlo process is implemented to randomly select different interfering signals to define the SINR probability distribution given k signals (the desired signal and k−1 interfering signals), given as p(SINR|k). This distribution can then be combined with the probability of k overlapping signals, p(k), to give the SINR probability:

$$p(SINR) = p(k) \,\square\, p(k).$$

H.3 Decoding the SIB1

Decoding an SIB1 requires several steps at the receiver, which are detailed in Table H-2. The table shows the assumptions used for the simulation parameters based on values found in literature. Step 8 is the most susceptible to interference,[6] allowing the analysis to only consider the expected receiver performance of an LTE receiver for the PDSCH in the presence of interference.

Figure H-4 shows the simulation results for the likelihood of decoding the various messages using RFI sample data from Project 8. Per the discussion above, PSS is established first, followed by SSS recovery. PSS recovery does not guarantee SSS recovery. PDCCH (for DCI extraction) has a lower recovery threshold than PDSCH, so extracting DCI from PDCCH almost always enables extraction of SIB1 from PDSCH. Note that successful demodulation of the SIB1 (in the PDSCH) is approximately 0.05% across the different cases evaluated, including standard atmosphere (non-ducting) conditions.

[6] For instance, the cross-correlation between Zadoff-Chu sequences used between cells is normally very low.

Table H-2. SIB1 decoding steps.

Step	Description	Simulation parameters
1. Frequency acquisition	—	Assume frequency is known
2. Primary synchronization signal (PSS) acquisition	Establishes frame synchronization using three correlators.	3 messages encoded using 124 bits. ~ 25.7 dB
3. Secondary synchronization signal (SSS) acquisition	Establishes cell ID calculation and reference signal location.	I/S = 15 dB*
4. Reference signal recovery	Not needed, but typically done for standard LTE modems.	Not relevant
5. Master information block (MIB) recovery	Provides signal bandwidth information. Can also recover PCFICH (step 6) timing.	I/S = 0 dB*
6. Physical control format indicator channel (PCFICH) recovery	Determines the number of orthogonal frequency division multiplex (OFDM) symbols used for control-channel information. Provides information needed for DCI (step 7).	I/S = 0 dB*
7. Decode downlink control information (DCI) from physical downlink control channel (PDCCH)	Provides the uplink and downlink resource assignment information (e.g., modulation and coding, power control, block assignments).	I/S = -5 dB*
8. Decode SIB1	Decoded from PDSCH using information extracted from DCI.	I/S = 0 dB*

*I/S = ratio of interference power to signal power. See Mark Lichtman et al., "LTE/LTE-A Jamming, Spoofing, and Sniffing: Threat Assessment and Mitigation," IEEE Communications Magazine 54, no. 4 (2016): 54-61, http://rogerpiquerasjover.net/LTE_Jamming_Magazine_Paper_final.pdf.

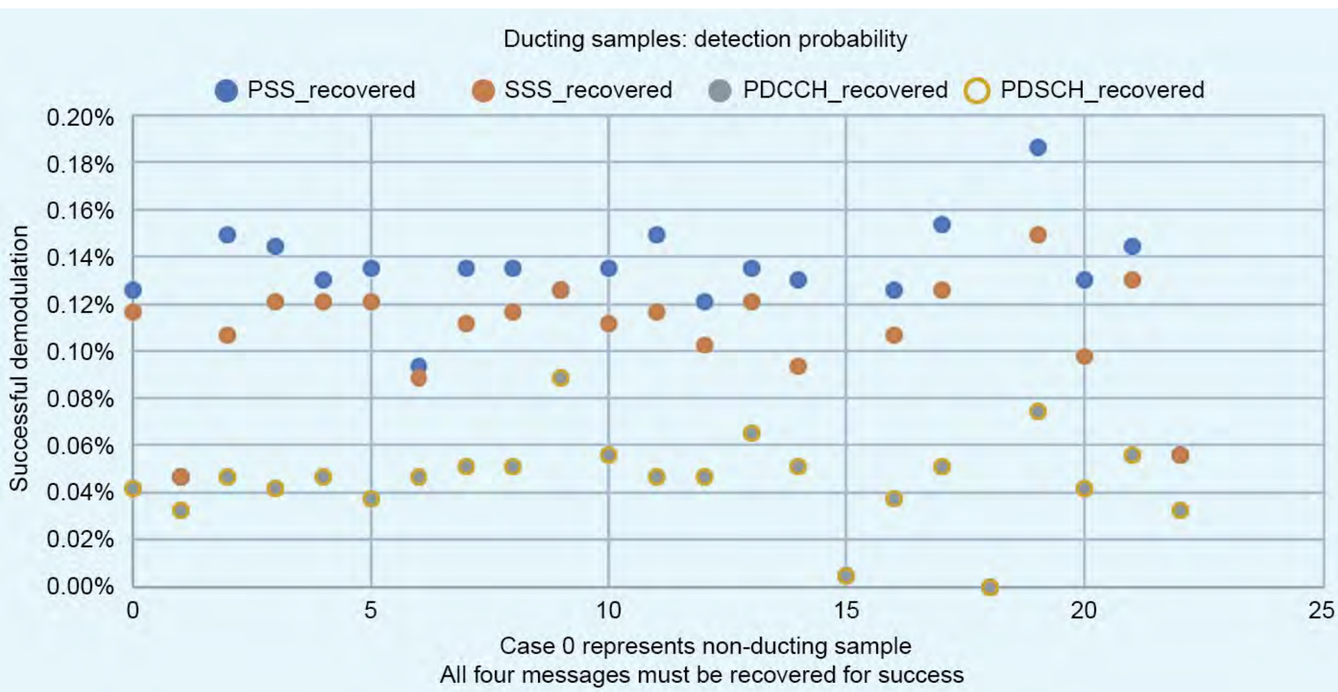

Figure H-4. Successful demodulation probabilities for LTE messages required for extracting the carrier ID.

H.4 Analysis Assumptions and Clarifying Points

The preceding analysis made the following simplifying assumptions:

- SNR as a stand-in for SINR. The effect of correlated interference on signal recovery is not generally the same as the effect of uncorrelated noise, so slightly worse receiver performance could be assumed for −3 dB SINR than for −3.0 dB SNR.

- Uniform receive power at the observer. In practice, the observer can expect to measure greatly differing receive powers from the visible towers due to the different path losses from tower to receiver. Thus, stronger power signals will be easier to recover even in the presence of interference, while weaker signals will require that no interfering signals be present (though still recoverable 3 dB below the noise floor), which is a lower probability event.

- Irrelevance of interference to completion of steps 1–7. While the steps prior to SIB1 recovery can be performed under worse conditions, the probability of those steps failing is not zero. PDCCH recovery, in particular, has a very similar performance profile to SIB1 recovery from the PDSCH[7] and system synchronization would further degrade PDCCH recovery due to the smaller transmission window.

- Standard LTE UE receiver model. While convenient for use as a reference for analysis, a special-purpose observer built to recover SIB1 information in a practical setting would likely adopt various techniques to improve performance for this specific task, including:

    - Use of multi-user techniques, particularly successive interference cancellation, to increase the number of interfering signals that can be present during SIB1 recovery.
    - Higher-quality receivers than possible for mass-marketed UEs to achieve higher dynamic range (e.g., to aid in multi-user detection [MUD]) or to lower effective noise floors.
    - The use of SIB1 specific recovery techniques that could combine information across multiple copies of SIB1 messages from a single cell to improve receiver performance.
    - Longer times for detection, which, in addition to aiding SIB1 specific recovery techniques, would also increase the number of opportunities to receive an interference-free copy of an SIB1 message.
    - Greater spatial selectivity. While technically irrelevant to this analysis, as it starts from a premise of a given number of visible towers, such a capability should be expected for a dedicated SIB1 recovery sensor and would be expected to significantly impact the distribution of receive signal powers.
    - Connection to tower. A standard UE is connected to an eNodeB and thus has techniques available at its disposal that an independent observer may not, e.g., hybrid automatic repeat request (HARQ).

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[7]Fujitsu Network Communications, *Enhancing LTE Cell-Edge Performance via PDCCH ICIC* (Richardson, Texas: 2011), http://www.fujitsu.com/downloads/TEL/fnc/whitepapers/Enhancing-LTE-Cell-Edge.pdf.

Appendix I. Cost Estimating Methods for Alternative Terrestrial Architectures (Project 4)

I.1 DCS Alternative Architecture ROM Cost

I.1.1 DCS/ESPDS alternative ROM cost

I.1.1.1 Implementation cost

Implementation cost estimates were developed based on the required high-level tasks and material cost estimates from Section 2.3. The high-level tasks to implement this alternative architecture were used to estimate labor hours. Once the labor estimates were made, the labor costs for implementation were developed. The timeline to implement the alternative was developed while making labor estimates. Table I-1 shows the labor estimates to implement this alternative. There were three estimators, and the final estimate is the average of the three. Multiplying these labor hours using a flat rate of $130/hour gives the total labor cost. The material costs were fixed based on model estimates and previously generated bills of materials (BOMs). The variance of the implementation cost estimates was a maximum of 22%.

Table I-1. Implementation cost for DCS/ESPDS alternative architecture.

Goal	Estimate time to implement DCS/ESPDS alternative architecture as described in scope sheet				
Unit	Hours				
WBS or task	Task name	Estimate 1	Estimate 2	Estimate 3	Final estimate
	Program management	**200**	**160**	**48**	**136**
1.1, 1.2	Provide PDA PM support to integrate existing DRGS users into PDA to receive DCS data.	200	160	48	136
	System engineering/development/I&T	**472**	**440**	**376**	**429**
2.1, 2.2	Perform PDA system impact assessment and determine scaling requirements if needed.	80	80	64	75
2.3	Obtain configuration control board (CCB) approvals to implement changes.	80	80	64	75
3.1, 3.2	Procure hardware and software.	32	40	40	37

Table I-1. cont.

4.1, 4.2, 4.3, 4.4	Integrate and test new users at CBU.	80	80	80	80
4.5, 4.6, 4.7, 4.8	Integrate and test new users in operations.	80	80	80	80
4.9	Provide training to end users.	120	80	48	83
	Configuration management	**32**	**80**	**8**	**40**
2.3, 4.9	Provide CM support to draft configuration change request, obtain CCB approvals, modify system docs.	32	80	8	40
	Quality assurance	**16**	**80**	**8**	**35**
4.9	Provide QA support for test, configuration, and other affected system documentation.	16	80	8	35
	Labor hour totals	720	760	440	640
	Labor cost (dollars)	93,600	98,800	57,200	83,200
Goal	Estimate total cost of hardware and software w/ vendor support cost				
Unit	USD				
	Materials/services	Est. 1 (dollars)	Est. 2 (dollars)	Est. 3 (dollars)	Final Est. (dollars)
	ESPDS hardware/support	18,158	18,158	18,158	18,158
	ESPDS software/license	15,976	15,976	15,976	15,976
	Material cost totals	34,134	34,134	34,134	34,134
	Implementation cost	127,734	132,934	91,334	117,334

I.1.1.2 Operation and maintenance cost

The operation and maintenance (O&M) costs for this alternative are largely influenced by the assumption that additional labor will be required to manage 26 users who would be integrated with ESPDS. In general, the system is based on self-service, where users manage their accounts but OSPO intervention is often required to assist users with issues such as account access or failed data transfers. Table I-2 shows the O&M cost estimates for this alternative. The labor estimates account for an additional part-time analyst to assist users as required. The O&M tech refresh costs are based on the hardware implementation costs, averaged over a five-year period. The hardware support and software license costs were reduced during the first year of operations to reflect that those license and support contracts would begin at the time of hardware procurement and extend for a period of one year. Since this alternative is expected to complete development in three months, the license and support costs were reduced by 75% during the first year of operations.

Table I-2. O&M cost for DCS/ESPDS alternative architecture.

Goal	Estimate annual increase in system operational cost associated with scaling ESPDS					
Unit	Labor: Number of full time personnel required. Materials: USD					
	Labor	Year 1	Year 2	Year 3	Year 4	Year 5
	Additional personnel required to support operations.	0.5	0.5	0.5	0.5	0.5
	Labor totals (person-year)	0.5	0.5	0.5	0.5	0.5
	Labor cost totals (dollars)	96,000	96,000	96,000	96,000	96,000
	Materials/services	Year 1 (dollars)	Year 2 (dollars)	Year 3 (dollars)	Year 4 (dollars)	Year 5 (dollars)
	Annual hardware support cost	760	3,041	3,041	3,041	3,041
	Tech refresh cost	6,827	6,827	6,827	6,827	6,827
	Annual software support cost	3,994	15,976	15,976	15,976	15,976
	Material cost totals	11,581	25,843	25,843	25,843	25,843
	Annual O&M cost	107,581	121,843	121,843	121,843	121,843

I.1.1.3 Implementation schedule

Time to implement: Four months

The timeline to implement the DCS/ESPDS alternative architecture is expected to span a period of approximately four months. The bulk of the time is allocated to integration, test, and training for new users. Typically, it does not take long to perform the integration and test tasks, but users need to determine physical layer interfaces, obtain account approvals, and ensure their systems use a compatible protocol and are able to meet the authentication requirements for secure file transfer.

I.1.2 DCS/cloud alternative ROM cost

I.1.2.1 Implementation cost: User-initiated transfer

The cost of the cloud services for the UIx implementation is shown in Table I-3. These are based on costs obtained from the Amazon Web Services website and the SPRES projected data use. The service costs were used to estimate the implementation and O&M costs for this alternative. This table illustrates that since data transfer volumes are low, distribution comprises only about 3% of the cost.

Table I-3. Cost of DCS/cloud alternative services (UIx).

Service	Service pricing component	AWS cost (dollars)	Per unit	SPRES projected use	Unit	Monthly service cost (dollars)
Storage						
AWS S3 Standard - GovCloud (U.S.East)	Storage	0.04	GB/month	0.160	GB/month	0.01
	Requests (put/ copy/list/get)	0.01	1000 requests	17010000	Put/list-request	85.05
	Requests (get/select/all other)	0.0004	1000 requests	37113000	Get-requests	14.85
	Transfer (out to internet, <10 TB/month)	0.16	GB	124.98	GB/month	20.00
					Total monthly payment	119.91
Identity and access management						
AWS Directory Service for Microsoft AD, AD Connector - GovCloud (U.S.East)	Standard Edition (2-domain cont.)	0.19	hour	1460	hrs/month	275.94
					Total monthly payment	275.94
Logging and reporting						
AWS CloudTrail	Management events	2.00	100,000 events	100000	Management events	2.00
	Data events	0.10	100,000 events	185564700	Data requests/ month	185.56
	CloudTrail insights	0.35	100,000 write e	2536740	Puts/month	8.88
	Log file size	—	500 bytes/ event	188201440	Entries/ month: 87.638	
					Total monthly payment	196.44
					Total monthly cost	592.28
					Total annual cost	7,107.38

The implementation costs for the cloud service are shown in Table I-4. Approximately 54% of the labor costs are associated with development. This is due mainly to the expectation that developing policies and procedures for integrating cloud services into an operational system will require substantial coordination with operations and security staff. The material cost for the implementation period reflects the expected service costs that will be incurred during the implementation period. To generate this estimate, the costs are expected to rise linearly from the beginning of task 2.6 (month 2) until the end of the implementation period (month 9) when the full monthly cost shown in Table I-1 will be incurred.

Table I-4. Implementation cost for DCS/cloud alternative (UIx).

Goal	Estimate time to implement DCS/cloud alternative as described in UI-cloud scope sheet				
Unit	Hours				
WBS or task	Task name	Estimate 1	Estimate 2	Estimate 3	Final estimate
	Program management	**960**	**640**	**780**	**793**
1.1	Provide PM support to develop cloud alternative architecture, including design, test, and transition to operations.	720	480	312	504
1.2	Coordinate with NOAA to develop project planning, understand program requirements, conduct status reviews/reports.	240	160	468	289
	Development	**2649**	**2320**	**2512**	**2494**
2.1, 2.2	Determines in which NOAA system boundary the virtual private cloud will reside and how security control requirements will be met.	240	160	72	157
2.3, 2.4	Design of virtual private cloud and required services.	613	160	1280	684
2.5	Perform trade studies to select cloud service provider and optimize service implementation.	80	80	120	93
2.6	Instantiate a development VPC and begin characterizing design; deploy required software applications.	480	160	360	333
2.7	Test result analysis and scaling services for ops.	280	160	300	247
2.8	Conduct system lifecycle reviews as required (PDR through ORR).	676	1280	200	719
2.9	Develop/document SOPs/COPs to manage cloud services; establish roles and responsibilities for NOAA vs. CSP.	280	320	180	260
	Procurement	**331**	**320**	**154**	**268**
3.1	Specify services required and operating constraints.	187	160	58	135
3.2	Inventory and service utilization audit.	144	160	96	133
	Integrate and test	**1080**	**800**	**776**	**885**
4.1	Scale dev system to conduct performance testing; configure for integration with ESPDS I&T.	160	160	80	133
4.2, 4.3	Integrate with ESPDS I&T and begin V&V testing.	200	160	240	200
4.4	Cloud I&T instantiation begins transition to operational distribution system through integration with ESPDS CBU and ops environments.	240	160	240	213
4.5	External users are integrated with CSP.	240	160	104	168
4.6	V&V testing with external users.	160	160	80	133
4.7	End-user training required.	80	0	32	37
	Quality assurance	**144**	**240**	**200**	**195**
2.8, 2.9, 4.7	Provide QA support for reviews, testing, and other system documentation.	144	240	200	195
	Labor hour totals	5164	4320	4422	4635
	Labor cost (dollars)	671,320	561,600	574,860	602,593

Goal	Estimate total cost of software licensing and cloud services				
Unit	USD				
	Materials/services	(dollars)	(dollars)	(dollars)	(dollars)
	Services (see attached annual service cost sheet)	2,073	2,073	2,073	2,073
	Material cost totals	2,073	2,073	2,073	2,073
	Implementation cost	673,393	563,673	576,933	604,666

I.1.22 O&M cost: User-initiated transfer

The maintenance and operations costs are shown in Table I-5. The temporary personnel support during the first year of operations is intended to provide subject-matter experience in operation of the cloud environment as knowledge is transferred to the operations staff. Because this position is considered a subject-matter expert, it is billed at a rate of $130/hour. The full-time cloud service administrator is included with the expectation that this knowledge base does not currently exist in the OSPO operations staff. If additional cloud services are used to disseminate operational data to critical NOAA partners, then this O&M activity may be consolidated with those staff, resulting in a reduction in O&M cost of up to 96%.

Table I-5. O&M cost for DCS/cloud alternative (UIx).

Goal	Estimate annual operational cost						
Unit	Labor: Number of full-time personnel required. Materials: USD						
	Labor		Year 1	Year 2	Year 3	Year 4	Year 5
	Temporary personnel support during initial operations.	Arch/SE/I&T/ Sec/CM	1	—	—	—	—
	Additional personnel required to support operations due to cloud service implementation.	CSP administrator	1	1	1	1	1
	Man-year labor totals		2	1	1	1	1
	Annual labor cost (dollars)		441,600	192,000	192,000	192,000	192,000
	Materials/services		Year 1 (dollars)	Year 2 (dollars)	Year 3 (dollars)	Year 4 (dollars)	Year 5 (dollars)
	Annual cloud service cost.		5,452	5,452	5,452	5,452	5,452
	Material cost totals		5,452	5,452	5,452	5,452	5,452
	Annual O&M cost		447,052	197,452	97,452	197,452	197,452

I.1.23 Implementation schedule: User-initiated

Time to implement: Nine months

The time to implement the alternative is largely driven by the time needed to select and optimize appropriate cloud services to minimize cost while meeting the NESDIS security requirements and performance needs. During development, it may be necessary to establish empirical relationships to benchmark services to ensure the implementation will meet user requirements. Determining how cloud-provided services are integrated with a system security plan will likely take a considerable amount of collaboration between the development team and the system security office.

I.1.24 Implementation cost: NOAA-initiated transfer

To implement the NOAA-initiated transfer (NIx) service that will distribute objects to users immediately upon arrival in cloud storage, additional cloud services are required. The expectation is that NOAA will create and manage a database that will contain user information that will automate distribution of files to users without their intervention. The database will include necessary information to transfer the objects to users such as a destination address and file transfer service. The delivery mechanism is expected to be a secure FTP server, or something similar, running on an elastic cloud compute (EC2) instance. In order to size these additional services, the projected DCS data flows and ESPDS model outputs were used. The estimated service use rates and costs are shown in Table I-6.

Table I-6. NOAA operational distribution service cost.

Service	Service pricing component	AWS cost (dollars)	Per unit	SPRES projected use	Unit	Monthly service cost (dollars)
Storage						
AWS S3 Standard-GovCloud (US-East)	Storage	0.04	GB/month	0.16	GB/month	0.01
	Transfer (to EC2)	0.00	GB	124.98	GB/month	0.00
					Total monthly payment (S3)	0.01
Identity and access management						
AWS Directory Service for Microsoft AD, AD Connector-GovCloud (US-East)	Standard edition (2-domain control)	0.19	hour	1460	hrs/month	275.94
					Total monthly payment (AD)	275.94
Compute						
AWS EC2 Service-GovCloud (US-East)	m5.8xlarge	0.23	hour	730	hrs/month	164.98
	Transfer to internet (>150 TB/month)	0.16	GB	124.98	GB/month	19.37
					Total monthly payment (EC2)	184.35
Compute						
AWS EBS Service-GovCloud (US-East)	General purpose SSD, 8 GB	0.12	GB/month	8	GB	0.96
					Total monthly payment (EBS)	0.96
Relational database						
AWS RDS for Oracle-GovCloud (US-East)	db.t.large, SE2 (multi-AZ)	0.463	hour	730	hrs/month	337.99
					Total monthly payment (RDS)	337.99
Networking/compute						
AWS Elastic Load Balancer-GovCloud (US-East)	Classic load balancer	0.03	hour	730	hrs/month	23.36
	Data processing	0.01	GB	124.98	GB/month	1.25
					Total monthly payment (ELB)	24.61

Table I-6. cont.

Logging and reporting						
AWS CloudTrail	Management events	2.00	100,000 events	100000	Management event	2.00
	Data events	0.10	100,000 events	185564700	Data requests/yr	185.56
	CloudTrail insights	0.35	100,000 write e	2536740	Puts/month	8.88
	Log file size	500	Bytes/event	188201440	Entries/ month: 87,638	
Total monthly payment (CT)						196.44
Total monthly cost						1,020.30
Total annual cost						12,243.61

The implementation costs for the cloud NIx alternative are shown in Table I-7. Compared with the UIx implementation, the cost increased 25%. The material cost estimates include the Amazon Web Services costs expected to be incurred during the implementation phase. These costs were estimated by assuming a linear increase from the time service first begins implementation during task 2.6 through the completion of the implementation project when service costs must meet the projected operational utilization rates. The implementation cost variance was a maximum of 25% from the average.

Table I-7. Implementation cost for DCS/cloud alternative (NIx).

Goal	Estimate implementation cost of DCS/cloud alternative as described in the cloud DCS scope sheet					
Unit	Hours					
WBS or task	Task name	Resource type	Bill	Rich	Dan	Final estimate
	Program management		**1440**	**640**	**1040**	**1040**
1.1	Provide PM support to develop cloud alternative architecture, including design, test, and transition to operations. Perform project planning, risk, schedule, and resource management.	PM	480	312	416	459
1.2	Provision resources to accomplish tasks. Coordinate with NOAA to develop project planning, understand program requirements, conduct status reviews/ reports.	PM	960	160	624	581
	Development		**3376**	**2320**	**3416**	**3037**
2.1, 2.2	System/Security Architect determines in which NOAA system boundary the Virtual Private Could will reside and how security control requirements will be met (NOAA or Cloud Service Provide [CSP]).	ArchSec	240	160	80	160
2.3, 2.4	Design of Virtual Private Cloud and required services.	ArchSec/ SE/Dev	1146	160	1920	1075
2.5	Perform trade studies to select Cloud Service Provider and optimize service implementation.	ArchSec	80	80	120	93
2.6	Instantiate a development VPC w/minimal number services required to begin characterizing and refining design. Deploy required software applications.	DevI&T	400	160	480	347

Table I-7. cont.

2.7	Test result analysis and scaling services for ops.	SE/DevI&T	320	160	360	280
2.8	Conduct system lifecycle reviews as required (PDR through ORR).	ArchSec&T/ Sec/QA	790	1280	200	757
2.9	Establish roles and responsibilities for NOAA vs. CSP.	SE/QA/XM	400	320	256	325
	Procurement		**304**	**320**	**200**	**275**
3.1	Specify services required and operating constraints.	SE/Dev/Sec	160	160	80	133
3.2	Inventory and service utilization audit.	SE/Sec/CM	144	160	120	141
	Integrate and test		**1400**	**800**	**1072**	**1091**
4.1	Scale dev system to conduct performance testing. Configure for integration with ESPDS I&T.	Arch/SE/ DevI&T/Sec/ CM	160	160	80	133
4.2, 4.3	Integrate with ESPDS I&T and begin V&V testing.	DevI&T/	400	160	240	267
4.4	Cloud I&T instantiation begins transition to operational distribution system through integration with ESPDS CBU and ops environments.	SE/DevI&T/ Sec/CM	400	160	320	293
4.5	External users are integrated with CSP.	SE/I&T/Sec	160	160	208	176
4.6	V&V testing with external users.	I&T	200	160	160	173
4.7	End-user training required.	SE/QA	80	0	64	48
	Quality assurance		**160**	**240**	**416**	**272**
2.8, 4.7	Provide QA support for reviews, testing, and other system documentation.	QA/SPT	160	240	416	272
	Labor hour totals		6680	4320	6144	5715
	Labor cost (dollars)		868,400	561,600	798,720	742,907

I.1.2.5 O&M cost: NOAA-initiated

The O&M cost for NOAA-initiated service is shown in Table I-8. Since this implementation requires the use of compute resources, network traffic analysis, and database management, it is expected that another staff member would be added. Temporary operational support was also increased into a second year of initial operations due to increased implementation complexity. The O&M cost compared with the UIx implementation increased by 99%. If NESDIS implements additional cloud distribution services, it is expected that operational staff can be shared, thereby reducing the O&M costs for DCS distribution.

I.1.2.6 Implementation schedule: NOAA-initiated

Time to implement: 12 months

The additional time to implement this alternative is distributed among all phases of the development effort. In general, the labor increased by approximately 25%.

Table I-8. O&M cost for DCS/cloud alternative (NIx).

Goal	Estimate annual increase in system operational cost associated with scaling ESPDS					
Unit	Labor: Number of full-time personnel required. Materials: USD					
	Labor	Year 1	Year 2	Year 3	Year 4	Year 5
	Development personnel support during initial operations	2	1	—	—	—
	Computer analyst – cloud services	1	1	1	1	1
	Computer analyst – cloud VPN	1	1	1	1	1
	Man-year labor totals	4	3	2	2	2
	Annual labor cost (dollars)	883,200	633,600	384,000	384,000	384,000

	Materials/services	Year 1 (dollars)	Year 2 (dollars)	Year 3 (dollars)	Year 4 (dollars)	Year 5 (dollars)
	Annual cloud service cost	12,244	12,244	12,244	12,244	12,244
	Material cost totals	12,244	12,244	12,244	12,244	12,244
	Annual O&M cost	895,844	645,844	396,244	396,244	396,244

I.1.3 DCS/remote receiver alternative ROM cost

I.1.3.1 Implementation cost

The implementation cost for moving existing DCS equipment from NSOF to CBU is shown in Table I-9.

The material costs include provisions for additional network hardware that may be required to interface with the GOES-R antenna IF and the N-Wave WAN at CBU. The shipping cost estimates are based on moving four racks of equipment from NSOF to CBU containing Dual Pilot Control Module (DPCM), demodulators, DADDS, webservers, and network equipment. The shipping estimate includes insurance for the equipment valued at $250,000 per rack. The implementation cost variance was a maximum of 8%.

Table I-9. Implementation cost for DCS/remote receiver alternative (NIx).

Goal	Estimate time to implement alternative				
Unit	Hours				
WBS or task	Task name	Estimate 1	Estimate 2	Estimate 3	Final estimate
	Program management	**480**	**480**	**384**	**448**
1.1, 1.2	Provide PM support to transition DRGS receiver equipment from NSDF to CBU. Project activities include planning, impact assessment, hardware or software procurement, logistic support for implementation, and O&M testing new network interfaces and verifying end-to-end performance.	480	480	384	448
	System engineering/development/I&T	**1740**	**1760**	**2280**	**1927**
2.1	Perform impact assessment to determine which components should be moved to CBU.	240	320	160	240
2.2	Modify DADDS system as required to remotely locate the DRGS receiver equipment.	320	80	640	347
2.4	Conduct security impact assessments, implementation plan, test, plan, etc.	160	320	160	213
3.1	Procure needed hardware and software.	80	160	40	93
4.1	Move DCS system to CBU.	340	320	160	273
4.2	Integrate and test DRGS equipment at CBU.	240	320	640	400
4.3	Integrate DCS equipment with DRGS receiver equipment at CBU.	200	160	320	227
4.4	User integration with DCS distribution system located at CBU.	160	80	160	133
	Configuration management/SE	**160**	**240**	**128**	**176**
2.4	Provide CM support to draft CCRs, obtain CCB approvals, and modify affected system documentation.	160	240	128	176
	Quality assurance	**160**	**240**	**128**	**176**
2.4	Provide QA support for test, configuration, and other affected system documentation.	160	240	128	176
	Labor hour totals	2540	2720	2920	2727
	Labor cost (dollars)	330,200	353,600	379,600	354,467
Goal	Estimate total cost of hardware and sofware w/vendor support cost				
Unit	USD				
	Materials/services	(dollars)	(dollars)	(dollars)	(dollars)
	Hardware/software	24,900	50,000	24,900	33,267
	Shipping	12,000	12,000	12,000	12,000
	WAN service	1,500	1,500	1,500	1,500
	Material cost totals	38,400	63,500	38,400	46,767
	Implementation cost	368,600	417,100	418,000	401,233

I.1.3.2 O&M cost

O&M costs are shown in Table I-10. A staff position was added as a full-time system administrator at CBU, significantly increasing O&M cost. If the DCS system requires minimal physical interaction, two existing staff could travel to CBU at a cost of approximately $2,000/trip. The tech refresh costs refer to any additional networking equipment required to interface with the WAN service at NSOF. Although the need for WAN services are not expected, the cost was included to provide a more conservative estimate.

Table I-10. O&M cost for DCS remote receiver alternative.

Goal	Estimate annual increase in system operational cost associated with scaling ESPDS					
Unit	Labor: Number of full time personnel required. Materials: USD					
	Labor	Year 1	Year 2	Year 3	Year 4	Year 5
	Additional personnel required to support operations	1	1	1	1	1
	Labor totals, person/year	1	1	1	1	1
	Annual labor cost (dollars)	192,000	192,000	192,000	192,000	192,000
	Materials/services	Year 1 (dollars)	Year 2 (dollars)	Year 3 (dollars)	Year 4 (dollars)	Year 5 (dollars)
	Annual software support cost	1,200	1,200	1,200	1,200	1,200
	Tech refresh cost	4,980	4,980	4,980	4,980	4,980
	WAN service cost	3,600	3,600	3,600	3,600	3,600
	Material cost totals	9,780	9,780	9,780	9,780	9,780
	Annual O&M cost	201,780	201,780	201,780	201,780	201,780

I.1.3.3 Implementation schedule

Time to implement: Six months

Based on discussions with the DCS project, the time to disassemble and move equipment from NSOF to CBU and integrate it with the GOES-R IF feed would take less than one month. But planning the move to minimize impacts to operations may be more significant. An examination of the DADDS and LRGS system websites shows all webservers actively transmitting data. Therefore, data flows may have to be migrated off equipment, which is then moved in a phased approach, potentially extending the schedule and increasing cost. In any event, careful planning of equipment being taken offline to facilitate physical relocation may take considerable time.

I.1.4 DCS/DADDS alternative ROM cost

I.1.4.1 Implementation cost

The implementation costs for this alternative are shown in Table I-11. Verifying data distribution performance over the public internet accounted for approximately 38% of the labor required to implement this alternative. The variance in implementation costs was a maximum of 39%.

Table I-11. Implementation cost for DCS/DADDS alternative.

Goal	Estimate time (for example: requirements and design for release 1.1 of X)				
Unit	Hours				
WBS or task	Task name	Estimate 1	Estimate 2	Estimate 3	Final estimate
	Program management	**320**	**320**	**32**	**224**
1.1	Provide PM support to transition DADDS as the primary system for receiving DCS data. Project activities include planning, user outreach, testing new interfaces, and associated data distribution performance.	320	320	32	224
	System engineering/development/I&T	**480**	**560**	**400**	**480**
4.1	Ensure all DRGS users have DADDS accounts and are able to access the system over the internet.	80	160	160	133
4.2	Verify users can receive data over internet and the network performance is acceptable.	320	320	160	267
4.3	Ensure users are familiar with DADDS features.	80	80	80	80
	Labor hour totals	800	880	432	704
	Labor cost (dollars)	104,000	114,400	56,160	91,520
Goal	Estimate total cost of hardware and sofware w/vendor support cost				
Unit	USD				
	Materials/services	(dollars)	(dollars)	(dollars)	(dollars)
	Hardware	—	—	—	—
	Software/license cost	—	—	—	—
	Material cost totals	0	0	0	0
	Implementation cost	104,000	114,400	56,160	91,520

I.1.4.2 O&M cost

There are no expected increases in O&M costs if the DADDS alternative is implemented.

I.1.4.3 Implementation schedule

Time to implement: Four months

The time to implement the DADDS alternative is limited to verifying that the 26 DRGS users can obtain DCS data with acceptable performance over the internet. Benchmarking performance is not expected to take a long time; and for users with multiple internet service providers, this test may be conducted multiple times.

I.2 GRB Alternative Architecture ROM Costs

I.2.1 GRB/ESPDS alternative ROM cost

Table I-12. Implementation cost for GRB/ESPDS alternative.

Goal	Estimate time (for example: requirements and design for release 1.1 of X)				
Unit	Hours				
WBS or task	Task name	Estimate 1	Estimate 2	Estimate 3	Final estimate
	Program management	**350**	**96**	**320**	**255**
1.1	Provide PDA PM support to scale ESPDS in support of new users and associated data distribution.	280	80	320	227
1.2	Coordinate with NOAA to determine OSPO and development contractor responsibilities.	70	16	0	29
	System engineering/development/I&T	**760**	**572**	**880**	**737**
2.1, 2.2	Determine scaling requirements for hardware and software components to accommodate increased data flow.	180	80	160	133
3.1, 3.2, 3.3	PDA SE/Dev/Sec specify and procure required hardware and software for ops environments. Develop software release.	80	32	80	64
4.3, 4.5, 4.6, 4.7	Integrate, configure, and perform functional checkout of hardware and software components into ops.	180	120	160	147
4.4, 4.9, 4.10	SE/I&T/conduct testing, generate test reports and resolve deficiencies.	200	160	320	227
4.8, 4.11	SE/I&T/Sec perform network configuration changes, integrate end users, and conduct training.	160	180	160	167
	Configuration management/SE	**80**	**32**	**160**	**91**
2.3	Provide CM support to draft CCRs, obtain CCB approvals, and modify affected system documentation.	80	32	160	91
	Quality assurance	**40**	**32**	**160**	**77**
3.3, 4.9	Provide QA support for test, configuration, and other affected system documentation.	40	32	160	77
		1230	732	1520	1161
	(dollars)	159,900	95,160	197,600	150,887
Goal	Estimate total cost of hardware and sofware w/vendor support cost				
Unit	USD				
	Materials/services	(dollars)	(dollars)	(dollars)	(dollars)
	Hardware	193,899	193,899	193,899	193,899
	Software/license/support cost	31,952	31,952	31,952	31,952
		225,851	225,851	225,851	225,851
		385,751	321,011	423,451	376,738

I.2.1.1 Implementation cost

ESPDS was architected to enable scaling of the system to accommodate growth in the number of users and volume of data distributed. Based on the ESPDS model outputs, using data from Table I-6, the capacity of the compute and storage clusters will need to be increased. Cost of increasing capacity of the network hardware is also included in the material estimates. The effort required to scale and test the system is included in the implementation estimates shown in Table I-12. In addition, integrating and testing the user's ability to connect and retrieve the required data is also included. Although the process for integrating users has been well defined, it requires considerable coordination to ensure security and network configurations are implemented correctly. The implementation cost variance was a maximum of 15%.

I.2.1.2 O&M cost

The cost to operate ESPDS with the additional GRB users is shown in Table I-13. O&M labor costs are driven by OSPO's request for additional staff required to manage the additional 26 users that would be integrated with ESPDS. The O&M tech refresh costs are based on the hardware implementation costs, averaged over a five-year period. The hardware support and software license costs were reduced during the first year of operations to reflect that those license and support contracts would begin at the time of hardware procurement and extend for a period of one year. Since this alternative is expected to complete development in six months, the license and support cost were reduced by 50% during the first year of operations.

Table I-13. O&M cost for ESPDS/GRB alternative.

Goal	Estimate annual increase in system operational cost associated with scaling ESPDS					
Unit	Labor: Number of full-time personnel required. Materials: USD					
	Labor	Year 1	Year 2	Year 3	Year 4	Year 5
	PDA analyst	1	1	1	1	1
	Systems analyst	0.5	0.5	0.5	0.5	0.5
		1.5	1.5	1.5	1.5	1.5
	(dollars)	288,000	288,000	288,000	288,000	288,000

	Materials/services	Year 1 (dollars)	Year 2 (dollars)	Year 3 (dollars)	Year 4 (dollars)	Year 5 (dollars)
	Annual software support cost	39,732	79,463	79,463	79,463	79,463
	Tech refresh cost	38,780	38,780	38,780	38,780	38,780
		78,511	118,243	118,243	118,243	118,243
		366,511	406,243	406,243	406,243	406,243

I.21.3 Implementation schedule

Time to implement: Six months
The time to implement this alternative is divided between system scaling and user integration and test, with both activities being approximately three months in duration.

I.22 GRB/cloud alternative ROM cost

I.22.1 Implementation cost: User-initiated transfer

The cost of the cloud services for the UIx implementation is shown in Table I-14. This is based on costs obtained from the Amazon Web Services website and the SPRES projected data use. The service costs were used to estimate the implementation and O&M costs for this alternative. This

Table I-14. Cost of GRB/cloud alternative services (UIx).

Service	Service pricing component	AWS cost (dollars)	Per unit	SPRES projected use	Unit	Monthly service cost (dollars)
Storage						
AWS S3 Standard-GovCloud (U.S.-East)	Storage	0.04	GB/month	7,948	GB/month	309.98
	Requests (put/copy/list/ get)	0.01	1000 requests	39650000	Put/list-request	198.25
	Requests (get/select/all other)	0.00	1000 requests	37113000	Get-requests	14.85
	Transfer (out to internet, >150 TB/month	0.07	GB	238448.64	GB/month	15,499.16
Total monthly payment (S3)						16,022.24
Identity and access management						
AWS Directory Service for Microsoft AD, AD Connector-GovCloud (U.S.-East)	Standard edition (2-domain control)	$0.19	hour	1460	hrs/month	$275.94
Total monthly payment (AD) (dollars)						275.94
Logging and reporting						
AWS CloudTrail	Management events	$2.00	1000 events	100000	Management events	$2.00
	Data events	$0.10	1000 events	185564700	GB/month	$185.56
	CloudTrail insights	$0.35	1000 write e	2536740	Puts/month	$8.88
	Log file size	500	Bytes/event	188201440	Entries/month: 87,638	
Total monthly payment (CT) (dollars)						196.44
Total monthly cost (dollars)						16,494.62
Total annual cost (dollars)						197,935.48

table illustrates considerable cost of transferring data out of cloud storage via the internet, comprising about 94% of the total cloud service cost. It is possible that this cost could be reduced by implementing Amazon Web Services direct connect. This service routes data directly from Amazon Web Services to the user rather than by traversing the public internet. The storage costs are kept low by deleting products from storage after 24 hours.

The cost to implement this alternative are given in Table I-15. The labor is focused on development, which accounts for approximately 52% of the labor cost. As with the DCS system, considerable effort is expected to be required to ensure that the information assurance requirements are met and that the system performance meets users' requirements. The service costs associated with implementation are based on a procurement cycle beginning during task 2.6 and extending to the end of implementation. The assumption is that service costs will increase linearly over this six-month period, from zero to the monthly operational service cost. Although the majority of ESPDS distribution load is transitioned to the cloud, additional compute and storage cluster capacity is required. The associated cost to scale ESPDS to support the data loading is included in Table I-15. The variance in implementation costs for the GRB/cloud-UIx alternative was a maximum of 29%.

Table I-15. Implementation cost for GRB/cloud (UIx) alternative.

Goal	Estimate time to (for example: establish requirements and design for release 1.1 of X)				
Unit	Hours				
WBS or task	Task name	Estimate 1	Estimate 2	Estimate 3	Final estimate
	Program management	**1320**	**1040**	**780**	**1047**
1.1	Provide PDA support to develop cloud alternative architecture, including design, test, and translation to operations. Perform project planning, risk, schedule, and resource management.	880	720	312	637
1.2	Provision resources to accomplish tasks. Coordinate with NOAA to develop project planning, understand program requirements, conduct status reviews/reports.	440	320	468	409
	Development	**3680**	**4320**	**2512**	**3504**
2.1, 2.2	System/security architect determines in which NOAA system boundary the Virtual Private Cloud will reside and how security control requirements will be met (NOAA or cloud service provider [CSP]).	160	160	72	131
2.3, 2.4	Design of virtual private cloud service provider and optimize service implementation.	1120	480	1280	960
2.5	Perform trade studies to select cloud service provider and optimize service implementation.	160	160	120	147
2.6	Instantiate a development VPC w/minimal number services required to begin characterizing and refining design. Deploy required software applications.	480	320	360	387
2.7	Test result analysis and scaling services for ops.	240	320	300	267
2.8	Conduct system lifecycle reviews as required (PDR through ORR).	1200	2560	200	1320
2.9	Develop/document SOPs/COPs to manage cloud services. Establish roles and responsibilities for NOAA vs. CSP.	320	320	180	273

Table I-15. cont.

	Procurement	**560**	**320**	**154**	**345**
3.1	Specify services required and operating constraints.	240	160	58	153
3.2	Inventory and service utilization audit.	320	160	96	192
	Integrate and test	**2264**	**1920**	**776**	**1653**
4.1	Scale dev system to conduct performance testing. Configure for integration with ESPDSI&T.	351	320	80	250
4.2, 4.3	Integrate with ESPDSI&T and begin V&V testing.	320	320	240	293
4.4	Cloud I&T installation begins transition to operational distribution system through integration with ESPDS ops.	531	320	240	364
4.5	External users are integrated with CSP.	360	320	104	261
4.6	V&V testing with external users.	222	320	80	207
4.7	End-user training required.	480	320	32	277
	Quality assurance	**160**	**160**	**200**	**173**
2.7, 2.8, 4.7	Provide QA support for reviews, testing, and other system documentation.	160	160	200	173
	Labor hour totals	7484	7760	4422	6722
	Labor cost (dollars)	1,037,920	1,008,800	574,860	873,860
Goal	Estimate total cost of cloud services				
Unit	USD				
	Materials/services	(dollars)	(dollars)	(dollars)	(dollars)
	Annual cloud service cost	53,159	53,159	53,159	53,159
	ESPDS materials	93,134	93,134	93,134	93,134
	Material cost totals:	146,293	146,293	146,293	146,293
	NRE cost totals:	1,184,213	1,155,093	721,153	1,020,153

I.2.2.2 O&M cost: User-initiated transfer

The operations and maintenance costs for the GRB/cloud–UIx alternative are shown in Table I-16. The temporary personnel support during the first two years of operations is intended to provide subject-matter experience in operation of the cloud environment as knowledge is transferred to the operations staff. Because this position is considered senior-level or subject-matter expert, it is billed at a rate of $130/hour. The full-time cloud service administrator is included, with the expectation that this knowledge base does not currently exist in the OSPO operations staff. If additional cloud services are used to disseminate operational data to critical NOAA partners, then this O&M activity may be consolidated with those staff, resulting in a reduction in O&M cost of up to a 61%.

Table I-16. O&M cost for GRB/cloud alternative (UIx).

Goal	Estimate annual increase in system operational cost associated with scaling ESPDS					
Unit	Labor: Number of full-time personnel required.					
	Labor	Year 1	Year 2	Year 3	Year 4	Year 5
	Temporary personnel support during initial operations.	2	1			
	Additional personnel required to support operations due to cloud service implementation.	1	1	1	1	1
		1	1	1	1	1
	Labor totals (person/year)	4	3	2	2	2
	Labor cost totals (dollars)	883,200	633,600	384,000	384,000	384,000

	Materials/services	Year 1 (dollars)	Year 2 (dollars)	Year 3 (dollars)	Year 4 (dollars)	Year 5 (dollars)
	Annual cloud service cost	197,935	197,935	197,935	197,935	197,935
	ESPDS tech refresh	18,627	18,627	18,627	18,627	18,627
	Annual license/support	15,696	31,392	31,392	31,392	31,392
	Material service cost totals	232,258	247,954	247,954	247,954	247,954
	Annual cost totals	1,115,458	881,554	631,954	631,954	631,954

I.2.2.3 Implementation schedule: User-initiated transfer

Timeline to implement: 11 months

The time to implement this alternative is largely driven by the development and integration and test phases. Development is expected to take about six months, with integration and test taking the last five months. During development, it may be necessary to establish empirical relationships to benchmark services to ensure the implementation will meet user requirements. Determining how cloud-provided services are integrated with a system security plan will likely take a considerable amount of collaboration between the development team and the system security office.

I.2.2.4 Implementation cost: NOAA-initiated transfer

To implement the NIx service that will distribute objects to users immediately upon arrival in cloud storage, additional cloud services are required. The expectation is that NOAA will create a database that will contain user information, including an object identifier that will determine which users receive specific products. The database will also include necessary information to transfer the objects to users, such as a destination address and file transfer protocol. The delivery mechanism is expected to be a secure FTP server, or something similar, running on an elastic cloud compute (EC2) instance. In order to size these additional services, the projected GRB data flows and ESPDS model outputs were used. The estimated service use rates and costs are shown in Table I-17. The cloud service cost is increased by 33%. Therefore, the performance advantages of using non-native cloud distribution services should be considered along with benchmarking UIx and NIx implementation performance.

Table I-17. Cost of GRB/cloud (NIx) alternative cloud services.

Service	Service pricing component	AWS cost (dollars)	Per unit	SPRES projected use	Unit	Monthly service cost (dollars)
Storage						
AWS S3 Standard-GovCloud (U.S.-East)	Storage	0.04	GB/month	7,948	GB/month	309.98
	Transfer (to EC2)	0.00	GB	238448.64	GB/month	0.00
					Total monthly payment (S3)	309.98
Identity and access management						
AWS Directory Service for Microsoft AD, AD Connector-GovCloud (U.S.-East)	Standard edition (2-domain control)	0.19	hour	1460	hours/month	275.94
					Total monthly payment (AD)	275.94
Compute						
AWS EC2 Service-GovCloud (U.S.-East)	m5.8xlarge	1.46	hour	1460	hrs/month	2,133.06
	Transfer to internet (>150 TB/month)	0.07	GB	238448.64	GB/month	15,499.16
					Total monthly payment (EC2)	17,632.22
Compute						
AWS EBS Service-GovCloud (U.S.-East)	General purpose SSD, 1 TB	0.12	GB/month	2048	GB	245.76
					Total monthly payment (EBS)	245.76
Relational database						
AWS RDS for Oracle	db.m5.xlarge, SE2 (multi-AZ)	1.212	hour	730	hrs/month	884.76
					Total monthly payment (RDS)	884.76
Networking/compute						
AWS Elastic Load Balancer-AWS GovCloud (U.S.-East)	Classic load balancer	0.03	hour	730	hrs/month	23.36
	Data processing	0.01	GB	124.98	GB/month	2,384.49
					Total monthly payment (ELB)	2,407.85
Logging and reporting						
AWS CloudTrail	Management events	2.00	100,000 events	100000	Management events	2.00
	Data events	0.10	100,000 events	185564700	Data requests/ yr	185.56
	CloudTrail insights	0.35	100,000 write e	2536740	Puts/month	8.88
	Log file size	500	Bytes/event	188201440	Entries/month: 87,638	
					Total monthly payment (CT) (dollars)	196.44
					Total monthly cost (dollars)	21,952.95
					Total annual cost (dollars)	263,435.45

The implementation costs for the cloud NIx alternative are shown in Table I-18. It was assumed that existing database schemas and FTP clients could be migrated from the ESPDS system to the Amazon Web Services RDS and EC2 instances. This is expected to reduce development labor required to implement the NIx solution. The material cost estimates include the Amazon Web Services costs expected to be incurred during the implementation phase. These costs were estimated by assuming a linear increase from the time service first begins implementation during task 2.6 through the completion of the implementation project when service costs must meet the projected operational utilization rates. The complexity of the additional services is expected to increase development level of effort and total implementation cost by approximately 15% compared with the GRB/cloud–UIx implementation. The maximum implementation cost variance was 17%.

Table I-18. Implementation cost for GRB/cloud (NIx) alternative.

Goal	Estimate time to (for example: establish requirements and design for release 1.1 of X)				
Unit	Hours				
WBS or task	Task name	Estimate 1	Estimate 2	Estimate 3	Final estimate
	Program management	**1440**	**1040**	**1040**	**1173**
1.1	Provide PDA support to develop cloud alternative architecture, including design, test, and translation to operations. Perform project planning, risk, schedule, and resource management.	960	720	416	699
1.2	Provision resources to accomplish tasks. Coordinate with NOAA to develop project planning, understand program requirements, conduct status reviews/reports.	480	320	624	475
	Development	**4432**	**4320**	**3416**	**4056**
2.1, 2.2	System/security architect determines in which NOAA system boundary the virtual private cloud will reside and how security control requirements will be met (NOAA or cloud service provider [CSP]).	240	160	80	160
2.3, 2.4	Design of virtual private cloud service provider and optimize service implementation.	1760	480	1920	1387
2.5	Perform trade studies to select cloud service provider and optimize service implementation.	160	160	120	147
2.6	Instantiate a development VPC w/minimal number services required to begin characterizing and refining design. Deploy required software applications.	440	320	480	413
2.7	Test result analysis and scaling services for ops.	400	320	360	360
2.8	Conduct system lifecycle reviews as required (PDR through ORR).	1252	2560	200	1337
2.9	Develop/document SOPs/COPs to manage cloud services. Establish roles and responsibilities for NOAA vs. CSP.	180	320	256	252
	Procurement	**560**	**320**	**200**	**360**
3.1	Specify services required and operating constraints.	240	160	80	160
3.2	Inventory and service utilization audit.	320	160	120	200

Table I-18. cont.

	Integrate and test	2278	1920	1052	1757
4.1	Scale dev system to conduct performance testing. Configure for integration with ESPDS I&T.	480	320	80	293
4.2, 4.3	Integrate with ESPDS I&T and begin V&V testing.	320	320	240	293
4.4	Cloud I&T installation begins transition to operational distribution system through integration with ESPDS OPS.	792	320	320	477
4.5	External users are integrated with CSP.	240	320	208	256
4.6	V&V testing with external users.	222	320	160	234
4.7	End-user training required.	224	320	64	203
	Quality assurance	**192**	**360**	**416**	**323**
2.7, 2.8, 4.7	Provide QA support for reviews, testing, and other system documentation.	192	360	416	323
	Labor hour totals	8902	7960	6144	7669
	Labor cost (dollars)	1,157,260	1,034,800	798,720	996,927
Goal	Estimate total cost of software licensing				
Unit	USD				
	Materials/services	(dollars)	(dollars)	(dollars)	(dollars)
	Services	87,812	87,812	87,812	87,812
	ESPDS materials	93,134	93,134	93,134	93,134
	Material cost totals	180,946	180,946	180,946	180,946
	Implementation cost	1,338,206	1,215,746	979,666	1,177,872

I.2.2.5 O&M cost: NOAA-initiated

As with the UIx implementation, temporary cloud support resources are expected to be required during the initial operating period of three years. The first year provides four members of the development team to assist in administration, auditing, monitoring, and optimizing service performance. The support requirements could be reduced if expertise in implementing and administering cloud services in an operational environment is acquired during implementation of other NOAA cloud initiatives. This estimate assumes that skillset does not exist in the operations staff.

Table I-19. O&M cost for GRB/cloud (NIx) alternative.

Goal	Estimate annual increase in system operational cost associated with cloud service provider (CSP)					
Unit	Labor: Number of full-time personnel required.					
	Labor	Year 1	Year 2	Year 3	Year 4	Year 5
	Temporary personnel support during initial operations.	4	1	1	—	—
	Additional personnel required to support operations due to cloud service implementation.	1	1	1	1	1
		1	1	1	1	1
		1	1	1	1	1
	Labor totals (person/year)	7	4	4	3	3
	Labor cost totals (dollars)	1,574,400	825,600	825,600	576,000	576,000

	Materials/services	Year 1 (dollars)	Year 2 (dollars)	Year 3 (dollars)	Year 4 (dollars)	Year 5 (dollars)
	Annual cloud service cost	263,435	263,435	263,435	263,435	263,435
	Annual license/support cost	18,311	31,391	31,391	31,391	31,391
	ESPDS tech refresh	18,627	18,627	18,627	18,627	18,627
	Material service cost totals	300,374	313,453	313,453	313,453	313,453
	Annual cost totals	1,874,774	1,139,053	1,139,053	889,453	889,453

I.2.2.6 Implementation schedule: NOAA-initiated

Timeline to implement: 13 months

The timeline to implement this alternative is approximately 18% (two months) longer when compared with the GRB/cloud–UIx implementation. This is due to increased service complexity. Performance testing should be used to determine whether the additional schedule is worthwhile when compared with UIx.

I.2.3 GRB/remote receiver alternative ROM cost

I.2.3.1 Implementation cost

The cost to implement the GRB/remote receiver alternative is given in Table I-20. Provisions have been made to implement networking hardware if required to improve terrestrial link availability or increase its performance. The estimates are limited to additional transceivers and fiber-optic cabling, confined to the CBU, WCDAS, and NSOF facilities. Cost also includes network service to transmit data between the three facilities. Based on previous quotes, data transmit capacity is expected to be limited to $1,500/month for 1 Gbps and 99.9% service availability. The implementation cost variance was a maximum of 12%.

Table I-20. Implementation cost for GRB/remote receiver alternative.

Goal	Estimate time to (for example: establish requirements and design for release 1.1 of X)				
Unit	Hours				
WBS or task	Task name	Estimate 1	Estimate 2	Estimate 3	Final estimate
	Program management	**480**	**320**	**384**	**395**
1.1, 1.2	Provide PM support to operationalize the existing test data links between WCDAS/CBU and NSOF. Project activities include planning, impact assessment, hardware or software procurement, and test new interfaces and associated data distribution.	480	320	384	395
	System engineering/development/I&T	**1160**	**800**	**1160**	**1040**
2.1	Perform GOES-R GS system impact (assessment).	320	320	160	267
2.2	Obtain necessary approvals for configuration changes.	280	80	40	133
3.1, 4.1, 4.2	Integrate and configure necessary hardware.	320	320	320	320
4.3	Conduct V&V testing.	240	80	640	320
	Configuration management/SE	**128**	**160**	**80**	**123**
2.2, 4.3	Provide CM support to draft CCRs, obtain CCB approvals, and modify affected system documentation.	128	160	80	123
	Quality assurance	**64**	**160**	**40**	**88**
2.2, 4.3	Provide QA support for test, configuration, and other affected system documentation.	64	160	40	88
	Labor hours totals	1832	1440	1664	1645
	Labor cost (dollars)	238,160	187,200	216,320	213,893
Goal	Estimate total cost of hardware and sofware w/vendor support cost				
Unit	USD				
	Materials/services	(dollars)	(dollars)	(dollars)	(dollars)
	Added WAM capacity	9,000	9,000	9,000	9,000
	Hardware	5,800	5,800	5,800	5,800
	Material cost totals	14,800	14,800	14,800	14,800
	Implementation cost	252,960	202,000	231,120	228,693

I.2.3.2 O&M cost

The O&M cost for this GRB/remote receiver is shown in Table I-21. Costs are associated with WAN service augmentation and quarterly travel to CBU to maintain equipment. WAN service costs were estimated at $1,500 per month. Travel costs include two personnel driving to Fairmont, West Virginia, for one week. This includes two days for travel and three days of on-site work. There is no expected additional labor required to support the GRB/remote receiver alternative.

Table I-21. O&M cost for GRB/remote receiver alternative.

Goal	Estimate annual increase in system operational cost associated with operationalizing test link over N-wave					
Unit	Labor: Number of full-time personnel required. Materials: USD					
	Materials/services/travel	Year 1 (dollars)	Year 2 (dollars)	Year 3 (dollars)	Year 4 (dollars)	Year 5 (dollars)
	WAN network costs	18,000	18,000	18,000	18,000	18,000
	Travel	6,820	6,820	6,820	6,820	6,820
	Material cost totals	24,820	24,820	24,820	24,820	24,820
	Annual O&M cost	24,820	24,820	24,820	24,820	24,820

I.2.3.3 Implementation schedule

Timeline to implement: Six months

The estimated time to implement this alternative is six months and accounts for terrestrial link performance testing and time to resolve minor performance issues.

I.3 Decision Analysis and Resolution Form Reevaluation

The decision analysis and resolution (DAR) form serves as a method of determining which alternative is most capable of meeting NOAA's objectives

The DAR form created during Project 3 was reevaluated using data that was obtained during Projects 4 and 5. This was an opportunity to replace the qualitative cost, schedule, and performance metrics that were used to evaluate that trade study in Project 3 with quantitative cost and schedule data from Project 4, as well as with availability and latency metrics that were obtained during Project 5.

I.3.1 DCS alternative DAR form

The DCS DAR form is shown in Table I-22. The DADDS system remains the highest-scoring alternative, and inclusion of higher-fidelity scores for schedule, cost, and performance have widened the margins since Project 3. As with the GRB alternative, the remote DCS receiver alternative was investigated to mitigate RFI risk at NOAA downlink sites, where data could subsequently be distributed via other terrestrial methods. The margin between DADDS and the ESPDS alternative was increased from 14% to 33%. The margin between the DADDS and cloud alternatives increased from 24% to 37%. The weighted score changes were due to the evaluation criteria shown in Table I-22.

Table I-22. SPRES DCS alternative DAR form scores.

		Alt. 1: Cloud			Alt. 2: ESPDS			Alt. 3: Remote DCS receiver			Alt. 4: DADDS		
Evaluation criteria	***Weight (percent)***	***Base***	***Low***	***High***	***Base***	***Low***	***High***	***Base***	***Low***	***High***	***Base***	***Low***	***High***
Technical	20	2.25	2.18	2.25	2.25	2.25	2.25	1.50	1.50	1.58	2.50	2.50	2.50
Schedule	10	1.33	1.33	1.33	2.00	2.00	2.00	2.00	2.00	2.00	3.00	3.00	3.00
Operational	10	2.50	2.43	2.58	2.50	2.35	2.50	2.25	2.10	2.33	2.75	2.75	2.83
Security	20	2.50	2.50	2.58	3.00	3.00	3.00	1.75	1.90	2.00	3.00	3.00	3.00
Cost	20	1.75	1.75	1.75	1.50	1.50	1.50	1.50	1.50	1.50	3.00	3.00	3.00
Scalability	10	3.00	3.00	3.00	2.50	2.35	2.65	2.50	2.35	2.50	3.00	2.70	3.00
Performance	10	2.00	2.00	2.00	2.00	2.00	2.00	2.75	2.75	2.75	3.00	3.00	3.00
Total weighted score		2.18	2.16	2.21	2.25	2.22	2.27	1.90	1.90	1.97	2.88	2.85	2.88
Project 3 weighted score		2.43	2.35	2.49	2.61	2.55	2.64	1.76	1.76	1.85	2.88	2.79	2.88

Schedule

The cloud schedule score was reduced by 1 point. This was mainly driven by the schedule required to receive approval, specify, and test services from a cloud provider that has not been successfully implemented in ESPC operations at this point. If one of NOAA's existing cloud initiatives enters into operations, it will reduce the schedule risk of implementing the cloud alternative.

The ESPDS alternative experienced a net decrease in schedule score of 0.33. This was due to the fact that unexpected system procurement was required to support the additional DRGS users. In addition, the reluctance to approve user accounts on ESPDS is expected to cause schedule delays. These schedule risks were offset by a relatively short implementation and test schedule compared with the other alternatives.

The schedule for the remote DCS receiver was improved based on the understanding that CBU would be used as a remote receiver site. Since the receive equipment at NSOF is compatible with the ground station at CBU, the procurement of equipment is expected to be minimal. Since the operational staff is already familiar with the resulting receiver configuration, the expectation is that implementation and testing time could be reduced as well.

Cost

The cloud alternative cost score was reduced by 0.5. This was due to the labor costs to implement this alternative, as well as the O&M costs. The O&M costs were dominated by the staffing required to support cloud service use. The cost of distribution services was not a significant factor due to the small volume of DCS data being distributed.

ESPDS alternative cost score was lowered from 2.75 to 1.5. This significant reduction was largely due to the additional hardware and software required to support the DRGS users. In addition, recurring license and support staffing requirements increased the projected operational cost for this alternative.

Scores for the remote receiver and DADDS alternatives did not change between Projects 3 and 4.

Performance

The cloud alternative score was reduced from 2.5 to 2.0. The reduction was largely driven by the latency the system adds to the distribution of data and reduced availability as a result of its series arrangement with ESPDS.

ESPDS score was reduced by 0.75 due largely to the fact that the system availability of 99.44% does not currently meet users' stated availability requirements of 99.98%.

The performance score for the remote receiver alternative was increased by 0.75, mostly driven by a better understanding of the feasibility of duplicating (or relocating) the DCS system at NSOF, at CBU. The expectation is that that system would closely replicate the DRGS receiver at WCDAS and operate with similar performance characteristics.

I.3.2 GRB alternative DAR form

The reevaluated GRB DAR form scores are shown in Table I-23. There was a change to the total weighted score for Alt. 3. However, this alternative mitigates the RFI risk only at NSOF. In order to mitigate the RFI risk to users, a second distribution alternative needs to be considered. Two systems are capable of transmitting data to end users, the cloud and the ESPDS alternative. Looking at the total weighted scores presented in Table I-23, the margin between the ESPDS and the cloud increased from 9.5%, as scored during Project 3, to 23.2%. This was due to the evaluation factors shown in Table I-23.

Table I-23. SPRES GRB alternative DAR scores.

		Alt. 1: Cloud			Alt. 2: ESPDS			Alt. 3: Remote GRB receiver		
Evaluation criteria	***Weight. (percent)***	***Base***	***Low***	***High***	***Base***	***Low***	***High***	***Base***	***Low***	***High***
Technical	20	2.75	2.53	2.75	2.50	2.50	2.50	2.00	1.85	2.00
Schedule	10	1.33	1.33	1.33	2.33	2.33	2.33	3.00	3.00	3.00
Operational	10	2.50	2.43	2.50	2.75	2.60	2.75	2.75	2.75	2.83
Security	20	2.50	2.67	2.67	3.00	3.00	3.00	3.00	2.90	3.00
Cost	20	1.25	1.25	1.25	2.00	2.00	2.00	3.00	3.00	3.00
Scalability	10	2.50	2.50	2.50	2.50	2.50	2.65	2.00	2.00	2.15
Performance	10	2.25	2.25	2.25	2.50	2.50	2.50	2.50	2.50	2.50
Total weighted score		2.16	2.14	2.19	2.51	2.49	2.52	2.63	2.58	2.65
Project 3 weighted score		2.51	2.45	2.56	2.69	2.63	2.73	2.19	2.10	2.26

Schedule

The schedule for implementing the cloud alternative was estimated to be approximately 12 months, compared to four months for the ESPDS alternative. The complexity involved in selecting, testing, and optimizing cloud services capable of meeting the users' requirements contributed to a longer implementation schedule. If cloud services are integrated into ESPC operations through current NOAA initiatives such as secure ingest or PG in the cloud projects, this schedule could be reduced considerably. It is expected that integration of cloud services into operations while continuing to meet the system security requirements will be a challenging part of implementation, and that the ability to leverage previous success will result in significant schedule savings.

To a lesser extent, ESPDS also lost points on schedule due to the fact that NESDIS is currently not approving new user accounts on ESPDS. During the SPRES program, OSPO indicated that new user accounts are not being permitted because the current system capacity has already been allocated to existing users. If ESPDS is scaled to accommodate the projected GRB data use, as proposed in this study, it should relieve this freeze for existing GRB users that rely on NOAA to provide mission-critical weather data.

The NOAA remote receiver alternative improved its schedule score by 1.33. Since NOAA is planning to transition to a terrestrial link between the GRB data generation and uplink sites in Wallops Island, Virginia, and Fairmont, West Virginia, this will eliminate the RFI risk to GRB down-link at NSOF. This effectively eliminates the need for NOAA to install a remote receiver at another location. The terrestrial link is in place and has been used for testing purposes by the GOES-R program. That link is scheduled to become operational in 2021. Therefore, the score factors relating to authorization, procurement, and testing used to evaluate schedule risk were given an improved score.

Cost

Cost for the cloud alternative dropped a full point. This change was driven by two major factors: transfer service cost and the need for operations support. The cost of getting data transferred out of the cloud over the public internet to a user is expensive. There are opportunities to reduce that cost through direct connect interfaces with Amazon Web Services that eliminate the need to transfer data over the public internet, but availability and cost savings is dependent on geographic location.

The cost score for ESPDS was also reduced by 0.75 due to high hardware cost associated with system scaling, the recurring license and support cost, and the need to increase the operations staffing to support additional users and data flows.

The score for the remote receiver increased from a previous score of 1.5. This increase was due to the decision to transfer GRB data over a terrestrial link between WCDAS, CBU, and NSOF. Rather than install a GRB receiver at a remote site, data will be transferred over terrestrial link to NSOF for subsequent distribution by one of the other SPRES data distribution alternatives. In addition, plans are already in place to decommission the GRB receivers at NSOF and implement a terrestrial link. If that transition is successful, future funding will not be necessary to complete this work. Costs associated with operationalizing the existing terrestrial link are considered minimal, and operational costs are expected to decrease as a result of decommissioning the GRB receive equipment at NSOF.

Performance

The score for the cloud alternative performance was decreased by 0.5. This was driven by latency and availability. The cloud is expected to double the latency of data that it receives from PDA. In addition, the availability of data in the cloud is adversely impacted by the series arrangement it is in with PDA, resulting in a reduced performance score.

Appendix J. Report Addendum: Clarifications, Updates, and Additional Information

Since the completion of the SPRES final report, the DOC/National Telecommunications and Information Administration (NTIA) requested additional information and clarification regarding certain technical report content. This content includes protection thresholds, ducting prediction, propagation modeling, and ground site-specific performance requirements. In addition, NOAA has identified variances in performance and sensitivity among GOES receivers. As a result, Appendix J was created to capture the additional information, any related revised analyses and explanation, and to connect these updates to the relevant report sections.

In order to present the reader with a single set of current results, relevant results in the report were also updated or replaced, including Tables 3.2-3, 3.3-3, 4.7-3, 4.7-4, 4.7-5, and 4.7-6, and Figures 4.7-13, -14, and -15.

J.1 Interference Threshold and Link Budget Variables: SPRES Report Section 3.2.2

The initial protection thresholds used in the report were first-order assumptions wherein LNA/LNB values for GRB were assumed to be the same for DCS, and installation-specific implementation details (certain receive chain losses, antenna noise, etc.) were not included. DCS and GRB receiver-, and installation-specific, LNA/LNB and system noise temperatures have since been found to be sufficiently unique to justify revised threshold computations and protection distance calculations. The threshold computations are presented in this section.

Interference protection thresholds are derived below using characteristics obtained from the GOES receiver manufacturers. These thresholds are specific to classes of sites, as identified, based on their receiver and antenna implementation. This replaces the general values previously identified in SPRES Report Section 3.2.2.

J 1.1 Determination of receiver sensitivity using amplifier and antenna contributions to system noise temperature for GOES DRGS and GRB receive systems

There are four different known LNB specifications for the DCS DRGS configurations:

1. NOAA Wallops CDAS and NOAA Fairmont CBU ground station locations.
    a. NTIA Spectrum Certification: "GOES-R DCPR WCDAS Receiver."
    b. Receiver has a 1.4 dB Noise Figure (NF) and 110 Kelvin (K) system noise temperature (NT).
    c. These sites have 16.4 m reflector/antenna.
2. NOAA Suitland MD NSOF ground station
    a. NTIA Spectrum Certification: "DCPR Receiver NSOF."
    b. 1.45 dB NF and 115 K system NT.
    c. This site has 9.1 m reflector/antenna).
3. User Direct Receive Ground Station (DRGS)
    a. Identified on the NTIA Spectrum Certification as: "US&P use."
    b. Usually implemented with 5 m antenna and Quorum low noise block (LNB) L-band Downconverter (model ESD/G2-DCS with part number 99R014003).
    c. 1.0 dB NF (system noise temperature is antenna dependent).
4. The USGS EDDN Sioux Falls DCS ground station site is an outlier with a low noise amplifier (LNA) or LNB that is no longer made. That LNB was custom designed and has a wider RF passband (and hence different noise bandwidth) than used in item 3 above.

Table J-1. (Reserved)

Additionally, data provided for the GOES-R NTIA Spectrum Certification applies only to the NSOF site (i.e., specifically the 1.45 dB NF). The NOAA CDAS ground stations, and the fielded user systems, including those at NOAA user sites, utilize receive equipment with different system noise performance. The performance values and resultant protection threshold computations for the specific DCS and GRB equipment installed at NOAA Wallops CDAS and NOAA Fairmont CBU, NOAA NSOF Suitland, and at user DRGS sites are shown below.

The DCS system DCPR channel is not a single contiguous signal, but rather consists of 533 individual narrow-band (750 Hz) channels, each uniquely vulnerable to loss from RFI. Therefore, the revised and expanded table below includes the computations for the entire 400 kHz DCPR band and each 750 Hz channel within DCPR. The DCPR also includes two "pilot channels" used for receiver tuning and lockup. If a pilot channel received harmful interference, its loss would disrupt reception of all the other DCS/DCPR channels and content.

Table J-2. Receive sensitivity calculations.

		CDAS	NSOF	User sites		
	Units	Both	Both	GRB	DRGS	
Antenna diameter	meters	16.4	9.1	6.5	5.0	
L-band antenna gain	dBi	47.5	40.7	39.3	37.0	Note 1
Antenna noise (clear sky, >5° El, 23°C)	K	87	125	140	145	Note 2
LNA or LNB noise temperature	K	23	30	25	75	Note 3
System noise temperature (K)	K	110	155	165	220	
System noise temperature (dB-K)	dB-K	20.4	21.9	22.2	23.4	
System G/T	dB/K	27.1	18.8	17.1	13.6	
Averaged measured G/T	dB/K	27.5				Note 4
System noise temperature	dB-K	20.4	21.9	22.2	23.4	
Boltzmann's constant	dBm/Hz	−198.6	−198.6	−198.6	−198.6	
Rcv noise density floor	dBm/Hz	−178.2	−176.7	−176.4	−175.2	
Relative I/N level	dB	−6.0	−6.0	−6.0	−6.0	
Interference density threshold	dBm/Hz	−184.2	−182.7	−182.4	−181.2	
Threshold in 1 kHz bandwidth	dBm/kHz	−154.2	−152.7	−152.4	−151.2	
Theshold in 10.9 MHz bandwidth	dBm/BW	−113.8	−112.3	−112.0	NA	For GRB
Threshold in 300 Hz bandwidth	dBm/BW	−155.4	−153.9	NA	−152.4	For DCS
Theshold in 400kHz bandwidth	dBm/BW	−128.2	−126.7	NA	−125.2	For DCS

Note 1. Factory measurements for WCDAS and NSOF, calculated from antenna diameter for users. "Both" indicates WCDAS and NSOF parameters apply to both GRB and DRGS.

Note 2. Factory measurements for WCDAS and NSOF, estimated from antenna diameter for users. Based on DCS antenna at >5° elevation, and includes all components/losses from the antenna to the LNA/LNB.

Note 3. Factory measurements for WCDAS and NSOF, Quorum brochure published values for users.

Note 4. Avereage of 45 measurements using Cassiopeia A, each measurement with 100 averages. This was conducted only on the WCDAS antenna.

In the examples above:

- The factory measurements account for all antenna characteristics taken together and use 5° elevation to determine the antenna noise temperature. Higher elevation angles would reduce that noise temperature but not have a major effect on the threshold.
- The CDAS column refers to the NOAA stations at Wallops Island, Virginia, and Fairmont, West Virginia.
- The NSOF column refers to the NOAA station at Suitland, Maryland.
- The user GRB station is the model that was integrated and sold by L3 Harris with a 6.5 m dish antenna.
- The DRGS column refers to the non-NOAA DRGS user stations, which are assumed to be using a 5-m antenna.

To summarize the calculations

- The interference threshold for Wallops or Fairmont in a 750 Hz bandwidth is −155.4 dBm.
- The interference threshold for NSOF Suitland in a 750 Hz bandwidth is −153.9 dBm.
- The interference threshold for DCS user sites (US&P) is −152.4 dBm/750 Hz.

J.1.2 Reconciliation of differences between calculated and measured GOES receiver performance results: SPRES Report Table 4.9-4

Data Collection System (DCS)

Table 4.9-4 of the SPRES final report contains measured interference thresholds for the MicroCom™ DCS receiver (the receiver typically installed at user sites). A reported downlink (LTE) value of −147 dBm/kHz (Row 1/2) (as measured at the LNB input) was found to cause the onset of interference to the DCS communication signals. Converting this to the stated DCS bandwidth of 400 kHz requires an adjustment of 26 dB, yielding −121 dBm/400 kHz (DCS BW). An interference protection margin of −6 dB (i.e., I/N = −6 dB) is applied, yielding −127 dBm/400 kHz. This value compares favorably with the calculated value of −125.2 dB/400 kHz, provided in the SPRES table above. Table 8-3 of NTIA Report 05-432 (see reference #11) suggests the use of −194 dBW/100 Hz for long-term interference to Geostationary Orbit (GSO) data collection satellite systems operating in 1670–1690 MHz. Adjusted for a 400 kHz bandwidth and units of decibels per milliwatt (dBm), this equates to −128 dBm/400 kHz.

Table J-3. Comparison of IPC derivations for the DCS communication channels.

Method/Source	Value (dBm/400 kHz)
Calculated using kTB values applicable to Microcom receiver / Quorum LNB equipped customer sites	−125.2
Calculated using kTB values applicable to CDAS/CBU (NOAA) sites	−128.2
Measured on Microcom Receiver / Quorum LNB customer equipment	−127
Calculated using NTIA Report 05-432 for GSO data collection platforms	−128

GOES Rebroadcast (GRB)

Similar analysis / comparison for the GRB signal (see Table 4.9-5) is more difficult due to measurement variation and signal-structure differences. The GRB signal, which is actually two ~11 MHz signals in the same bandwidth separated by polarization (one is right-hand-circularly-polarized, the other left), uses two levels of error detection and correction (inner and outer) as stipulated in the Digital Video Broadcasting – Satellite Second Generation (DVB-S2 format). The DVB-S2 standard improves robustness in the presence of low signal-to-noise and interference level. Depending upon the information display available from the receiver, the use of DVB-S2 can also make it challenging to detect when RFI is affecting the signal until complete loss occurs. The table below shows both calculated and measured data from the SPRES final report, as well as reference interference protection criteria (IPC) from NTIA Report 05-432 (see reference #11). The approximately 20 dB difference is mostly explained by signal margin. The antenna gain (G) of the 16.4 m parabolic antenna at CDAS Wallops is 47.6 dB, while the minimum required antenna size is about 3.8 m; corresponding to a gain of 34 dB. Additional differences may have come from characterization of the LNB and other gains/losses prior to the receiver, which were estimated and could not be measured directly. The data loss threshold in row 4 (as opposed to the onset of data corruption), which was the only metric obtainable from the Quorum receiver, is a further 19 dB higher. Much of this difference is explained by DVB-S2 coding gain.

Table J-4. Comparison of IPC derivations for the GRB channel.

Method/Source	IPC value (dBm/10.9 MHz)	IPC source value/source
Calculated: kTB values for customer site/ receiver (Quorum receiver)	−112.0	Computations table J-2 above
Calculated: kTB values for WCDAS/CBU (NOAA) (RT Logic 400 receiver)	−113.8	Computations table J-2 above
Measured: Wallops (NOAA ground station)	−91.6 (data corruption threshold	Table 4.9-7, SPRES Final Report: −89 dBm/5 MHz; add 3.39 dB (convert 5 MHz to 10.9 MHz) + I/N = −6 dB
Measured: College Park (NCWCP, NOAA Center for Weather and Climate Prediction)	−72.6 (data loss threshold) −92.6 (Subtract ~20 dB for onset of RFI)	Table 4.9-8, SPRES Final Report: −70 dBm/5 MHz; add 3.39 (convert 5 MHz to 10.9 MHz) + I/N = −6 dB
NTIA Report 05-432, Data dissemination	−116.4	Table 8-3, NTIA Report 05-432: −153.4 dBW/2.11 MHz for Hi-Gain ant., long term; convert in same manner

J.1.3 Data availability as a consideration for interference threshold

The operational availability requirement for the GOES-R ground system was defined as 99.988% (see SPRES Report Section 4.3.4). In Project 1, user surveys generally identified the same data availability requirement as NOAA's. Users designed their network implementations with redundancy to overcome expected outages on any single delivery path from ground equipment failures or loss of internet access. Other than the qualitative analysis of user impacts covered in Project 1 and elsewhere, no analysis was conducted for RFI impacts on system performance parameters such as data availability.

J.1.4 Information statements and references

1. GOES Protection Requirements, Protection Criteria, and Protection Zone Analysis, SPRES Preliminary Insights and Project 7 Analysis Approach, Version 1.0 (FINAL); Presentation to NTIA Tech Panel, October 3, 2019.
2. This analysis addresses only the signal, noise, and interference energies that reach the demodulators of the referenced desired signals, i.e., in-band interference.
3. All NOAA receive systems (Wallops/Fairmont/Suitland) are designed such that the S/N+I ratio at the demodulator input is identical to the S/N+I ratio at the LNA input.
4. All NOAA receive systems use the input to the LNA as the reference point for all antenna gain and system noise temperature measurements. Therefore, measurement of the noise floor, i.e., noise when interference is not present, provides the best possible reference for determining the damaging effects of interference when it does occur.

5. NOAA has high-accuracy measurements made by General Dynamics Mission Systems (GDMS) in their Kilgore, Texas, facility during Factory Acceptance Tests (FAT) of the GOES-R 16.4-m (at Wallops and Fairmont) and 9.1-m antennas (at Suitland). (Vendor ownership note: GDMS is now part of CPI.)
6. NOAA also has high-accuracy measurements made by Satellink (vendor) of all of the LNAs used in these receive systems cited in note 6.
7. NOAA has made many G/T measurements using Cassiopeia A and the three 16.4-m antennas at Wallops. In the computations table above, note the close agreement of those measurements and the G/T values derived from FAT measurements by the equipment manufacturers.
8. Comparison of simultaneous S/N+I measurements at the user receiving sites can show the validity of their G/T values—and hence the receive noise density floor—for the receiving sites using antennas too small for Cassiopeia A measurements to be performed.
9. Sky Brightness Temperature Values: Chen Xiaoming, "Study of System Noise Temperature from 50 MHz to 15 GHz with Application to ELEVEN Antenna," Antenna Group, Department of Signals and Systems, Chalmers University of Technology Gothenburg, Sweden, 2007 (master's thesis). See Figure 2.4: Sky brightness temperature. http://publications.lib.chalmers.se/records/fulltext/67232.pdf
10. EL-CID document supporting doc# 41947-1, Certification of Spectrum Support for the GOES-R Series Meteorological Satellite, Stage 4, dated 20 April 2016.
11. NTIA Report 05-432, Interference Protection Critera, Phase 1—Compilation from Existing Sources, October 2005, as found on the Internet at https://www.ntia.doc.gov/files/ntia/publications/ipc_phase_1_report.pdf

J.2 Propagation Analysis Approach and Parameters: SPRES Report Paragraphs 3.2.3, 4.8.3, and Various Paragraphs in Section 4.7

This section provides additional detail on the application of the Advanced Propagation Model (APM), and use of the Irregular Terrain Model (ITM) as a means of validating the APM analysis results where feasible.

J.2.1 APM and troposcatter

The study used APM's default troposcatter model. This model implements forward scattering using the parabolic equation. Access to the specific APM troposcatter model was not available, but the following paper provides an analysis of a troposcatter model using the parabolic equation that likely forms the basis of APM's tropo model: Hitney, H.V., "A Practical Tropospheric Scatter Model Using the Parabolic Equation," IEEE Transactions on Antennas and Propagation, Vol. 41, No. 7, July 1993. https://ieeexplore.ieee.org/document/237621.

An alternative approach for implementing troposcatter is to inject the appropriate perturbations in the vertical refractivity profile to provide a forward scattering effect. This approach requires more detailed data regarding troposcatter conditions that was not readily available for this SPRES project.

J.2.2 APM and refractivity profiles

Running three years of individual refractivity profiles through the APM for all locations in all directions around each site is computationally expensive. The study therefore developed a three-step approach:

1. Characterize the propagation impacts of all refractivity profiles at a NOAA site using a sampling approach. Produce a statistical characterization of propagation loss and identify representative refractivity profiles for percentile ranges to be used in the interference analysis.
2. Calculate the propagation loss extending from the NOAA site out to 1000 km in 0.1° intervals using the set of representative refractivity profiles.
3. Conduct RFI analysis using the propagation loss data and Monte Carlo iterations across the various probabilistic parameters.

J.2.3 Preparing refractivity profiles for use in the interference analysis

The process described above characterized the propagation loss impacts of each refractivity profile based on APM results in a subset of directions around each site, generated a histogram of propagation impacts from each profile, and associated each profile with a percentile range.

To illustrate this, the figure below represents the sectors established for evaluating each refractivity profile's propagation loss impact around WCDAS. These sectors were defined based on terrain effects and LTE transmitter density surrounding the WCDAS. The radials in red, blue, green, and cyan represent the terrain characteristics that are fed into the APM at the LTE center frequency (1677 MHz). Histograms and probability distributions of the propagation loss statistics returned from the APM were then created at distances of 50 km, 100 km, 200 km, and 500 km from the Federal site. Figure J-2 presents an example histogram. Each refractivity profile analyzed was associated with a probability percentile range and select refractivity profiles were identified to effectively represent the probability of a duct at a given region. Per Federal site, six probability bins were identified where each probability bin consisted of four refractivity profiles, resulting in a total of 24 refractivity profiles. The six probability bins are: 0%–1% (the worst ducting case and it occurs 1% of the time), 1%–5%, 5%–10%, 10%–25%, 25%–50%, and 50%–100% (this is standard atmosphere).

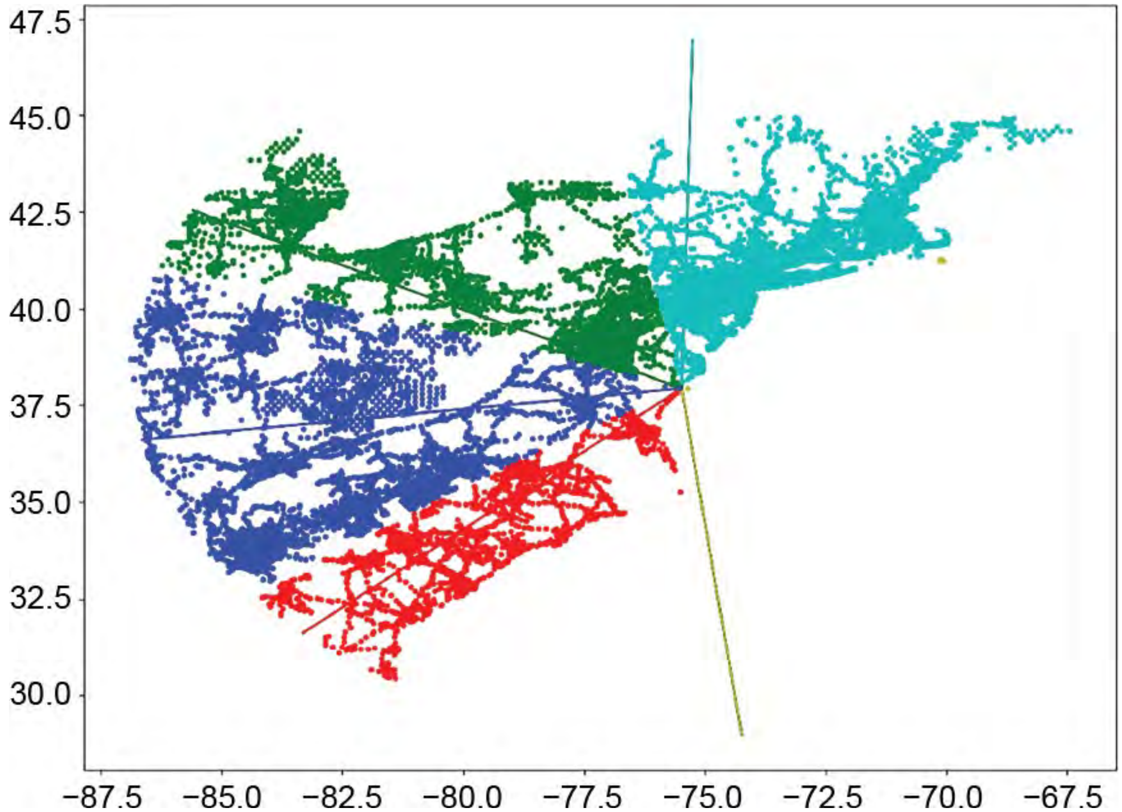

Figure J-1. Sectors of analysis based on terrain and LTE density effects to identify ducting occurrence at WCDAS.

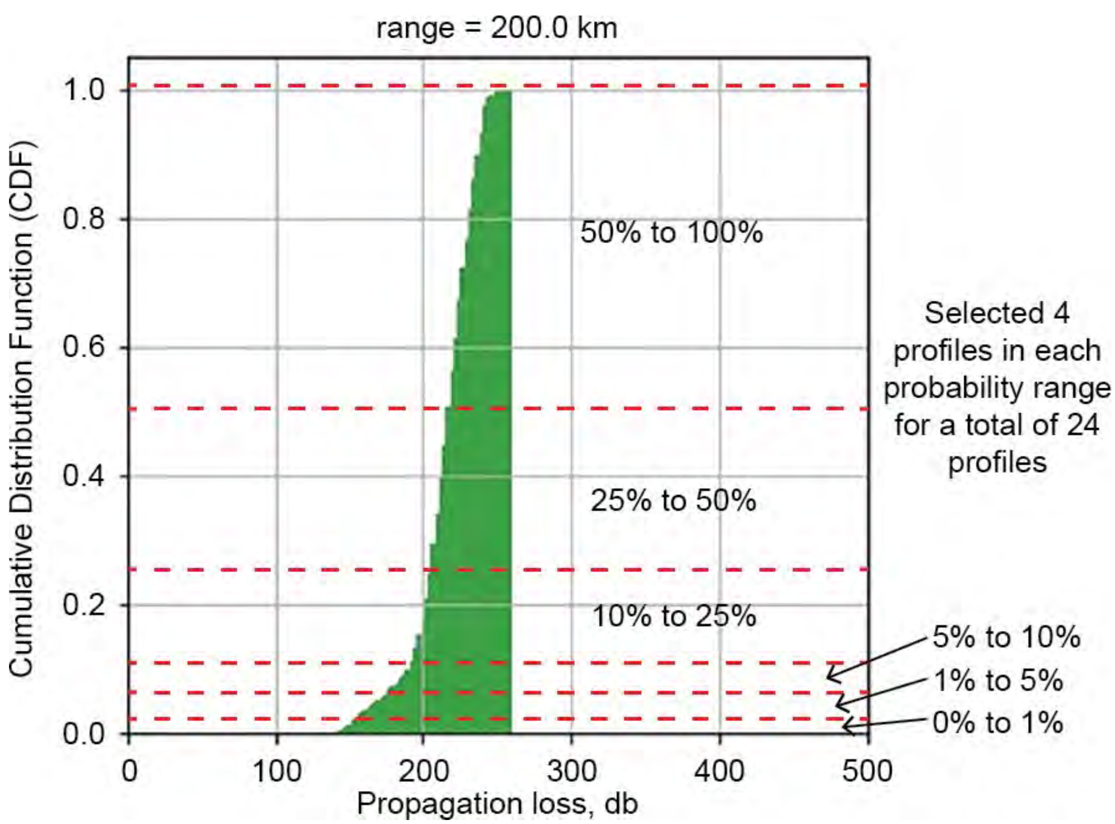

Figure J-2. Refractivity profile analysis produced a histogram that characterized propagation loss probabilities.

J.2.3.1 Calculating propagation loss in APM

The simulation and analysis for assessing interference potential used the selected refractivity profiles from the distribution as inputs to APM. To make computation manageable, propagation loss calculations were conducted in all directions around a NOAA ground station at 0.1° intervals out to the maximum study range of 1000 km.

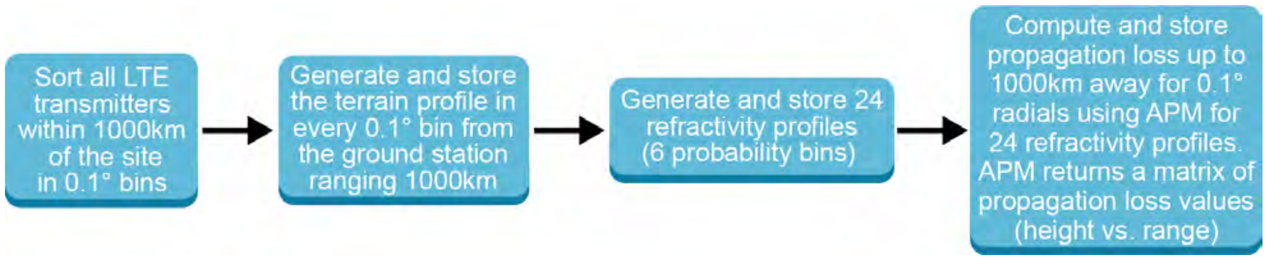

Figure J-3. APM calculation process.

J.2.3.2 Conducting the interference analysis

The interference analysis approach was conducted as follows:

1. Determine all LTE transmitters within 1000 km of the ground station.
    a. Compute the distance and bearing angle from the ground station to each LTE transmitter.
2. Randomly select the ducting spatial size to be used for the current iteration.
3. Randomly select a refractivity profile based on the binning of refractivity profiles and identify the corresponding APM outputs for LTE transmitters of interest.
    a. Index the APM output in range, distance, and azimuth to accurately identify the locations of each LTE transmitter.
    b. For any LTE transmitters beyond the duct size, assume an infinite propagation loss across the link.
4. Randomly select clutter loss values from the clutter loss distributions in 10° bins around the ground station.
    a. Identify clutter loss per LTE transmitter and add the clutter loss to the losses outputted from the APM.
5. Randomly set the pointing angle of the LTE transmitters. Determine the gain of each LTE transmitter relative to the ground station and compute the gain of the ground station relative to each LTE transmitter.
6. Integrate the RFI for the current Monte Carlo trial to obtain the aggregate RFI experienced at the ground station.
7. Repeat Steps 2 through 6 N times

There were N=10,000 iterations at each site. We varied the number of iterations for Wallops as an exercise, which produced the same results. All random variables in the simulation were treated as independent from each other. Random draws for each step in the process and each Monte Carlo trial were conducted independent of all other random variables.

Table J-5. Variables used in the interference analysis.

Variable	Application
Duct sizes	Duct size exceedance probability estimation based on pair-wise correlations of radiosonde readings of all continental U.S. radiosonde locations.
Duct strength	Representative profiles to represent the time variability of anomalous propagation (four refractivity profiles per time variability range, and a total of six time variability ranges).
Clutter losses	Normal distributions generated per site.
LTE base station sector pointing	Three sector sites maintained 120 degrees apart. Uniformly generated pointing angles.
UE power	UE EIRP normal distribution curve (distinct distributions for urban and suburban environments).
UE location	Uniform randomization X km from base station; X is driven by the footprint of the cell in urban/suburban/rural environments.

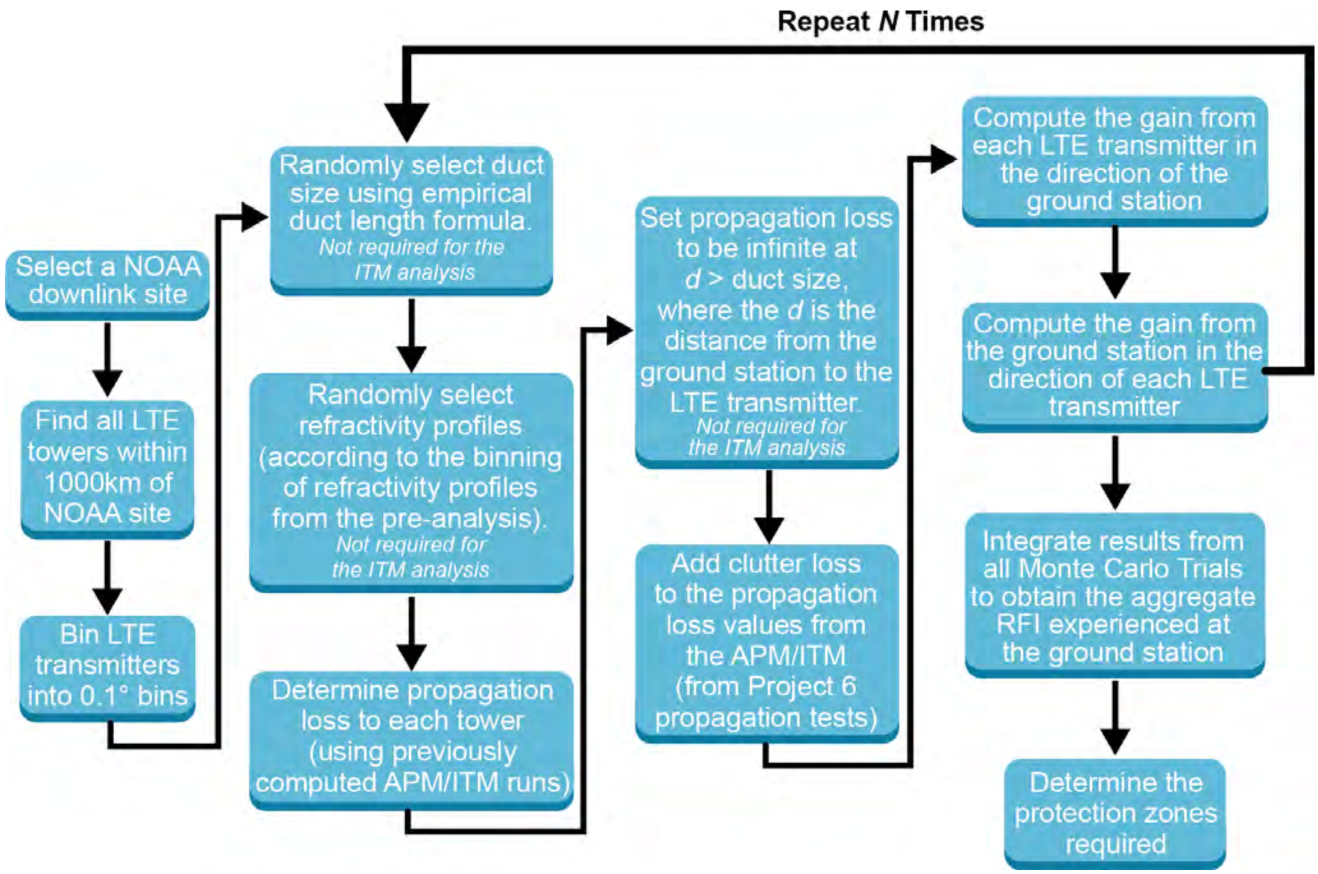

Figure J-4. High-level flow diagram of the RFI analysis phase.

A couple of clarifications on the algorithm are provided:

1. The analysis always assumed infinite path loss for LTE transmitters outside the randomly selected duct size (step 3b in the above algorithm). This assumption may underestimate RFI levels in the specific case of no/weak ducting and the selection of a small duct size. However, the MC process coupled with the duct size distribution (minimum duct size of 50 km; mean duct size of ~120 km) mitigate these cases from having any measurable impact on the overall result.

2. The aggregate RFI calculations are performed in the context of a particular protection distance or protection zone. The protection distance calculations such as those shown in Figure 4.7-13 aggregate RFI power from all LTE transmitters beyond the exclusion distance. In general, the effect is a monotonic reduction in RFI with exclusion distance. Dense population centers and significant terrain features create irregular features in the curves.

J24 Determining duct size

A major interference factor is the spatial extent of ducting conditions. As the propagation loss changes slowly with distance during ducting conditions, there is a direct relationship between the duct extent, the quantity of LTE transmitters included in the summation of total RF energy, and the projected interference at the affected Federal ground stations. The APM does not, by itself, take the ducting spatial size into account; thus, in the absence of terrain blockage, a surface duct would be assumed to extend out greater than 1000 km in all directions. In reality, ducting conditions and ducts extend over finite distances. The precise extent of the duct is difficult to estimate due to the sparse number of radiosonde locations in the United States, and the limited ability of remote sensors to directly measure the index of refractions in three dimensions.

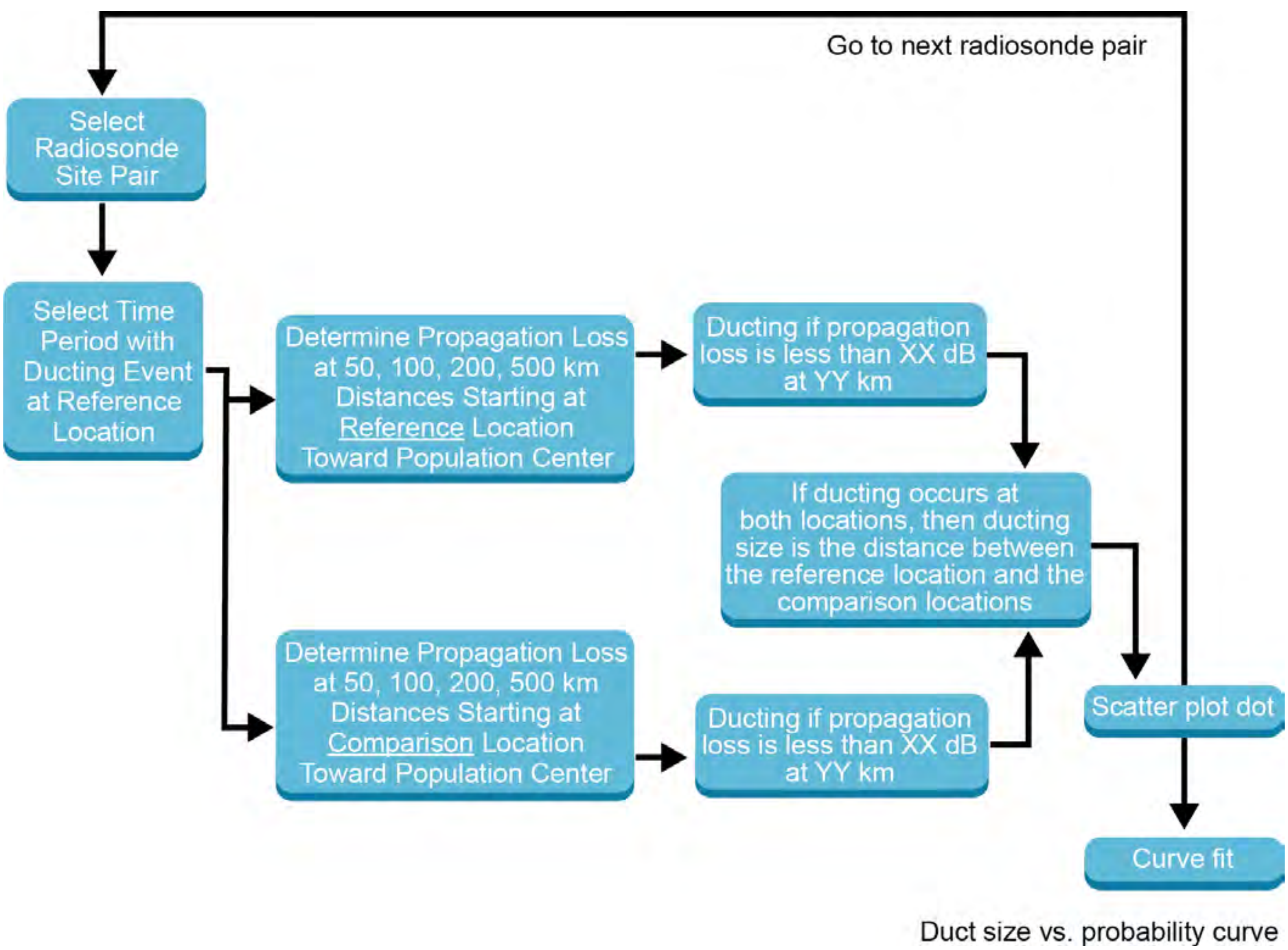

Figure J-5. Duct size analysis methodology correlating radiosonde data from multiple sites to estimate the duct size.

Therefore, a method to assay duct spatial extent was added to the RFI estimation process. The figure below shows the approach of approximating the spatial size. The process involved selecting a radiosonde location and identifying the presence of a duct. Readings from radiosondes at nearby locations were analyzed for the same time period to determine if they also experienced a duct. The statistics regarding the coexistence of ducting conditions between pairs of radiosonde sites were identified to produce an assessment of duct size probability as a function of distance.

Figure J-6 provides an example of a correlation analysis between Wallops Island and the Dulles International Airport (DIA). The plot presents the predicted propagation loss versus distance at distance of 50 km, 100 km, 200 km, and 500 km. This example selected some of the strong ducting events based on the Wallops Island radiosonde data and compares propagation losses with DIA radiosonde data for the same periods. Solid curves represent the Wallops Island data while the dashed curves represent the DIA data. Colors represent a radiosonde measurement date/time. For a correlated ducting condition, the solid and dashed curves having the same color must present similar trends in propagation loss versus distance. In most cases, these two locations differ and do not present simultaneously ducting events. This difference implies that the duct size was less than the distance from the Wallops Island and the DIA radiosonde locations (209 km).

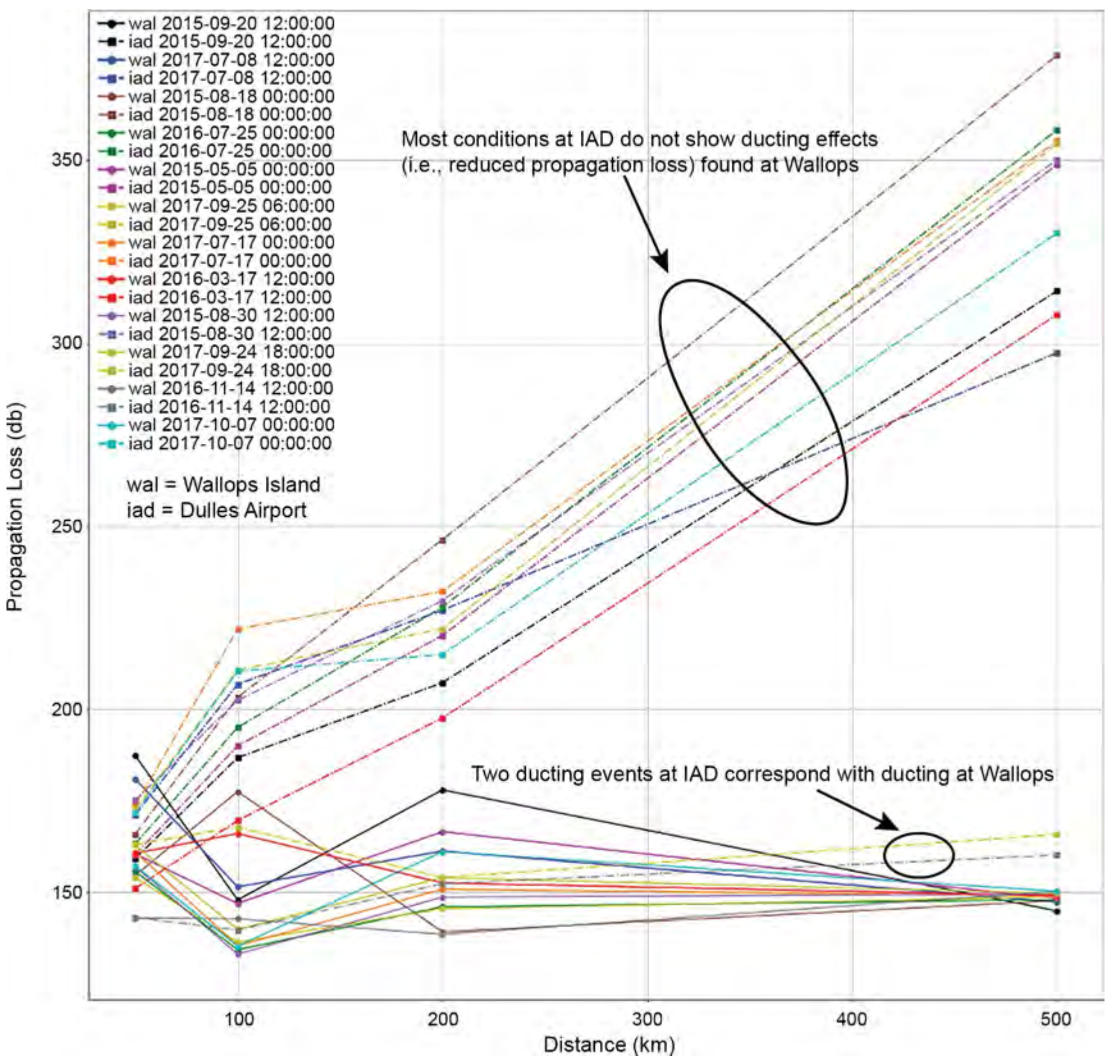

Figure J-6. Correlation of propagation loss versus distance between Wallops Island and the Dulles International Airport.

However, two ducting events are present at both sites during the same times. These events show significant reductions in propagation loss similar to what is found in the Wallops cases for the same date/time.

The process was repeated with all radiosonde locations in the continental United States to create the scatter plot shown below (copy of Figure 4.7-11). This plot displays the fraction of time a correlation event was experienced versus the distance between two radiosonde locations. The curve shows the probability that a duct is at least as large as the distance indicated (given that a duct was detected).

The significant distance between adjacent radiosonde locations limits the quantifiable resolution of the duct size (see Figure J-7). There were no radiosonde separations of less than 180 km; thus, all observations were at 180 km and greater. To ensure that a minimum duct size is maintained, a duct size of 50 km was assumed at 100% total probability (i.e., all ducts are at least 50 km in size). Further, a maximum duct size of 1000 km was enforced to ensure that the probability distribution properly terminated. Many of the locations have distances greater than 600 km and are not shown in the scatter plot.

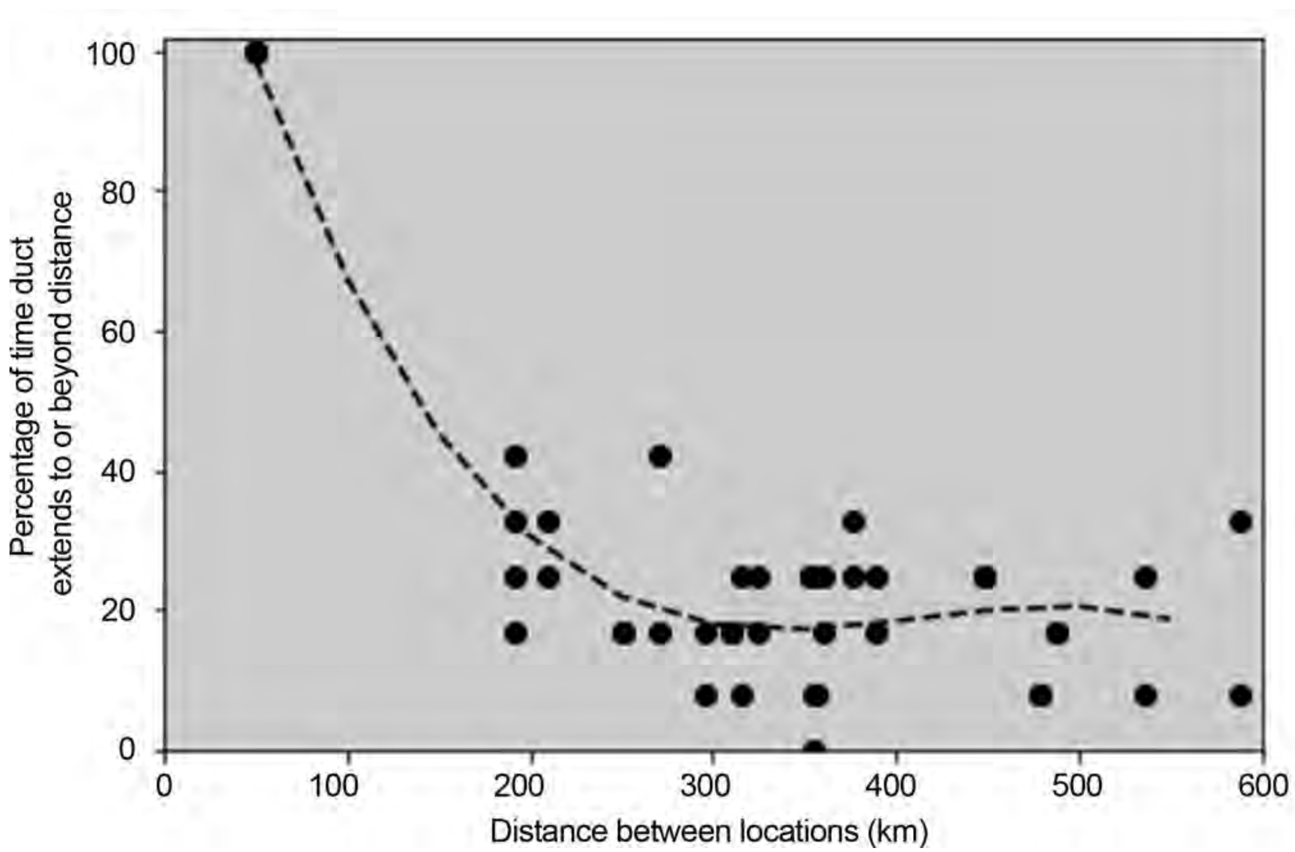

Figure 4.7-11. Duct size exceedance probability estimation based on pair-wise correlations of radiosonde readings of all continental U.S. radiosonde locations.

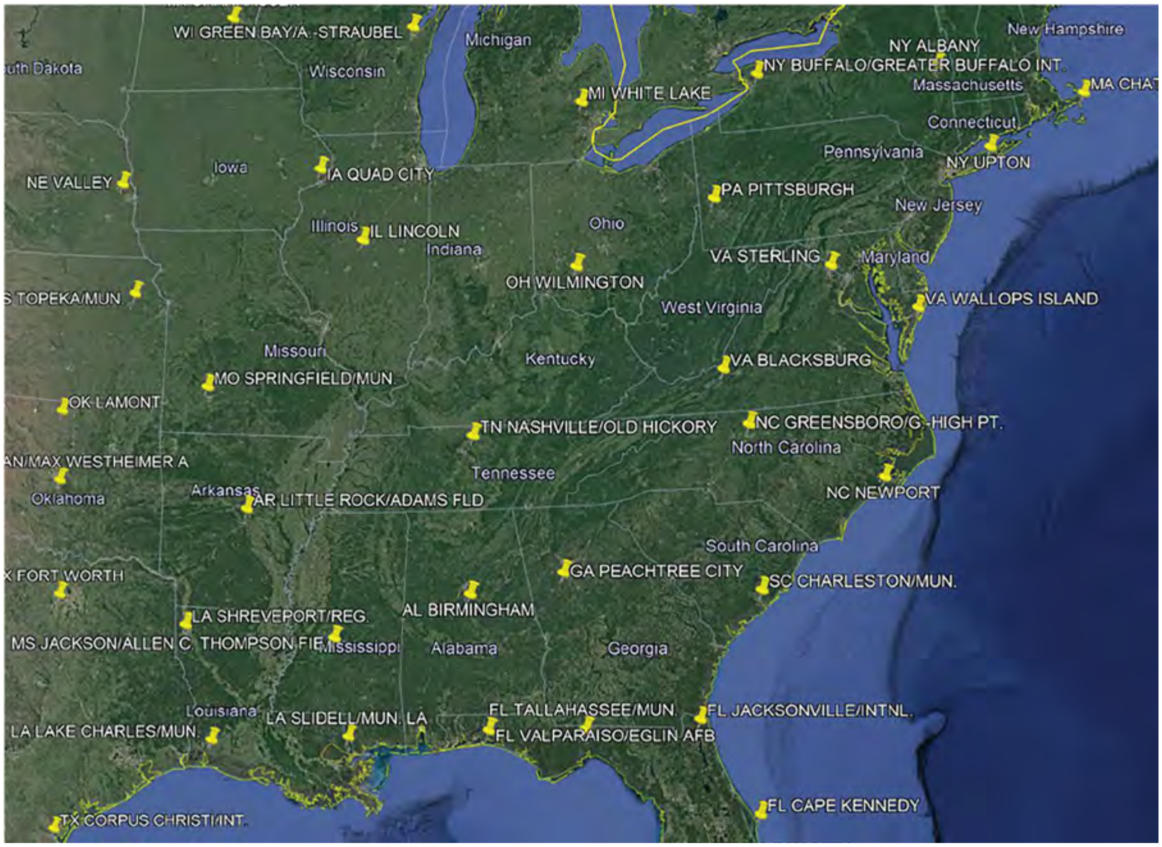

Figure J-7. Radiosonde locations in the eastern United States

J.2.5 Validation of APM propagation loss using other known models

Per Figure 4.7-6, propagation losses calculated using the APM, Terrain Integrated Rough Earth Model (TIREM), and Irregular Terrain Model (ITM) all vary with distance. ITM shows higher propagation loss than APM and TIREM, between 50 and 120 km, while APM shows greater propagation loss at distances greater than 125 km. This greater loss by APM under standard atmosphere assumptions produces smaller protection distances / zones. Further, APM provides modeling for anomalous propagation based on measured atmosphere data, which pro-vides a stronger link to actual conditions observed around each GOES earth station location.

J.3 LTE Deployment and Operating Scenario: SPRES Report Paragraph 4.7.5.3.2.1

J.3.1 Clutter and antenna height considerations

The final study analysis used clutter model assumptions based on the ITU-R P.2108 clutter model logic combined with site-specific clutter data. The ITU model applies clutter impacts at each terminal independently and demonstrates that clutter losses saturate from each terminal after a few kilometers. The model considers height gain corrections, and clutter losses are not applied to terminals above the effective clutter height relative to the radio horizon. As a result, the study always applied clutter to the NOAA GOES receiver, but applied clutter to the LTE transmitter based on radio horizon.

The table below defines the various cases. Uplink-sharing scenarios applied clutter loss to both terminals (i.e., UE transmitter and NOAA receiver) because both are always below the effective clutter height. Downlink sharing required further analysis of the LTE eNodeB height relative to the effective radio horizon. The effective radio horizon was determined using bare-earth and geometric calculation for standard atmospheric conditions. The study further assumes that ducting extends the radio horizon beyond the geometric horizon, so clutter was not applied to towers within the ducting region. The launch angle for surface ducting is shallow, so clutter is still a factor for the NOAA receiver under all ducting conditions.

Table J-6. Clutter cases under various sharing scenarios and distances.

Sharing scenario	Distance relative to radio Horizon	Propagation	Clutter loss application	Comment
Downlink sharing	Less than	All	NOAA receiver only	Line of sight
	Greater than	Standard	NOAA receiver and LTE Tx	Both stations experience clutter loss
		Anomalous	NOAA receiver only	Duct extends radio horizon
Uplink sharing	All	All	NOAA receiver and LTE Tx	UE is always in clutter

Clutter values were derived from propagation loss data collected in Project 6. The clutter data captures site-specific obstructions in all directions that cannot be addressed by any generalized clutter model. The data was collected in a ground-to-ground link, so half the clutter is attributed to each end of the link. The clutter data captures site-specific obstructions in all directions that cannot be addressed by a generalized clutter model. The data included directional information, allowing clutter to be applied in a directionally dependent manner. Data was grouped into 10-degree azimuths and applied to the study propagation data.

J.3.2 Additional considerations for tower density

The LTE Base Station (eNobeB) locations were obtained from the Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 5 “Randomized Real” model that were filtered slightly. This dataset includes 68,139 towers. Tower heights in the study were applied based on the morphology of the tower. Towers in dense urban, urban, suburban, or rural regions were assigned antenna mount heights of 25 m, 35 m, 45 m, or 55 m, respectively. The heights were determined through demographic (U.S. census) and land-use (USGS) data of the surrounding area. To provide higher capacity in urban areas, towers are placed at closer distances to each other than in rural areas. As a result, antenna heights are kept at lower heights to control the coverage footprint to avoid causing interference with neighboring towers. In rural areas, the tower density is less; thus, towers of higher heights are used to provide a larger coverage. Demographic classification of population density was primarily used to classify the surrounding areas as dense urban, urban, suburban, and rural. The classifications were filtered additionally through the use of the USGS land cover data.

The population density was defined around each tower as followed:

Table J-7. LTE tower morphology and height identification.

Tower morphology designation	Minimum population density (per square mile)	Maximum population density (per square mile)	Assigned antenna mount/tower height (meters)
Dense urban	8,500	Any	25
Urban	4,500	8,500	35
Suburban	1,000	4,500	45
Rural	0	1,000	55

No additional tower locations were added for the large-cell analyses. A few (<30) towers in the model that were over water were removed. That is how the value of 68,139 was obtained. The referenced modifications were made by those who generated the CSMAC dataset. Additional small-cell tower locations (as part of a small-cell deployment analysis) were the only tower locations generated within the study.

For the small-cell scenarios, additional towers were added, with appropriate heights and densities based on population density to ensure sufficient capacity. Antenna heights are lower in urban/dense urban areas to control the coverage footprint and provide user capacity to avoid causing interference with neighboring towers. In rural areas, the cells are larger because population density is lower.

- Dense urban: grid layout with a 0.5 km coverage radius.
- Urban: grid layout with a 1 km coverage radius.
- Suburban: grid layout with a 2 km coverage radius.

These assumptions are consistent with planning values that engineering staff have used in network deployment studies with commercial providers.

Note that CellMapper was evaluated as an alternative data source compared to CSMAC. The evaluation compared CellMapper and CSMAC tower data for a subset of GOES locations and assessed tower densities between the two datasets. The analysis showed that CellMapper did not provide nationwide coverage and was poorly populated outside of urban areas. Ultimately, CSMAC data was used in all final analyses as it has the pedigree of having been used for prior spectrum sharing analyses.

The study assumed that 3 UEs per LTE sector were operating simultaneously. This is consistent with 5 MHz LTE network assumptions used in the CMSAC Working Group 3 analysis for their 1755–1850 MHz study. (See “Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 3 (WG 3) Report on 1755-1850 MHz Satellite Control and Electronic Warfare,” Table 4.2.1-9, page 27.)

J.3.3 Clarification on LTE user equipment EIRP

The study used a range of EIRP values for LTE UEs in the uplink interference analyses. The EIRP values include transmit power and antenna gain. The study applied a normal distribution between −37 dBm to 23 dBm for urban and suburban environments (see Table 4.11-3) to capture the variation in operating conditions of UEs (e.g., outdoor and indoor). The handset gain value specified in the table was not used in the study calculation.

J.3.4 GOES antenna gain pattern application to interference power calculations

The study applied an azimuthal-dependent GOES ground station antenna pattern. This pattern was based on antenna range pattern measurements for a 9.1 m antenna (see Figure 4.11-1). An azimuthal pattern was calculated for each GOES ground station using the antenna pattern data and the GOES antenna pointing angle. The analysis applied a GOES antenna gain corresponding to the azimuthal direction of each LTE tower in addition to the LTE antenna gain in the direction of the GOES ground station.

J.3.5 Carrier ID traffic analysis

The traffic analysis applied to the carrier ID analysis (see Appendix H.4) was developed specifically for the carrier ID analysis. The traffic analysis produced the number of simultaneous LTE signals present at a carrier ID receiver, which in turn provides the signal-to-interference-plus-noise ratio (SINR) of each LTE signal. This traffic-based assessment was used only for the carrier ID study; it was not applied to the interference analysis for deriving interference risks and protection criteria.

J.3.6 Link budget for field strength protection analysis

The link budget presented for discussing the field strength protection approach (Section 4.7.5.3.2.1) provides a simplified model. Its intent is to capture the main elements of the interference calculation and provide clarity to the discussion of the field strength protection approach. Factors such as clutter loss, polarization loss, and (RF filter) insertion loss are not presented in this discussion but were applied in the interference assessment. These factors are not germane to the discussion, but should be included when providing a complete treatment of all factors affecting interference power levels.

J.4. DCS Site Identification and Applications: SPRES Report Sections 3.1.2.1, 3.1.2.3, and 4.1.1

In May 2020, NOAA's DCS program office had 659 users each with a signed user agreement (SUA). The SUA identifies that a user has agreed to share data from their sensor platforms (DCPs) with other users while mutually protecting data confidentiality.

The overwhelming majority (99%) of these users obtain their data indirectly, after it has been received at the NOAA or USGS DCS ingest sites. These users query servers at NOAA or USGS via the internet, or retrieve it via the GOES HRIT service, which rebroadcasts data stored at NOAA (see Sections 3.1.2.1 and 4.1.1).

However, in the continental United States, eight users, NOAA, and two developers maintain 26 DCPR Direct Reception Ground Stations (DRGS) at 19 sites. The two NOAA ground station sites and a USGS ground station site, prioritized at the top of Table J-8 below, are primary DCS reception sites where all customer data is received and stored for retrieval. While there is partial overlap and redundancy among these ground stations, harmful interference at any of these three ingest sites can result in irretrievable loss of customer data. At the 14 operational sites, of which 10 are Federal and four state owned, customers operate protection of life and property applications that demand high reliability and low latency (<1 minute). These customers utilize DRGS receivers for primary DCS reception, with terrestrial retrieval of NOAA or USGS data as a backup, and in most cases, reception via HRIT as a further backup option.

Through extensive experience, these customers have found terrestrial last-mile internet service to be unreliable during weather events (when DCS data can be most needed) and therefore primarily rely on satellite data delivery, including HRIT as one backup method.

As noted, DCS users with signed SUAs have agreed to share data with all other DCS users. As a result, if radio frequency interference concerns cause a non-Federal user to withdraw from the DCS system, that gage data would be denied to the NWS and other users. As noted in SPRES report paragraph 3.1.2.3.1, the NWS develops flood warnings from gage data obtained from the DADDS database to support the Hydrometeorological Automated Data System (HADS). NWS uses data from over 12,000 non-NOAA owned/maintained gages, all of which report data via GOES DCS. This same DCP gage data is input into numerical weather prediction models as a check on precipitation levels.

NOAA has been rebroadcasting digitized/aggregated DCS data since 2006 over the LRIT (and since 2018 over the HRIT/EMWIN) signal. Until 2020, this method was generally considered to have excessive delay for applications that were latency sensitive. The DCS data latency performance of the HRIT signal has been dramatically improved via recent (2019–20) NOAA ground-processing system enhancements. In May 2020, the following performance levels were observed:

- 99.96% messages delivered in <30 seconds
- 0.04% delivered with 30–60 second latency
- Maximum latency: 62.6 seconds

Therefore, DCS data reception via HRIT as a primary method may be an option for more users.

Table J-8. DRGS sites and applications.

US DRGS operators	Site location	# DRGS	Application
NOAA WCDAS	Wallops Island, VA	2	Primary ingest site for DADDS and NOAA LRGS server, DCS system quality test/monitoring
NOAA NSOF	Suitland, MD	2	Backup ingest site for DADDS and LRGS server
USGS EDDN	Sioux Falls, SD	3	Primary ingest site for USGS LRGS for internal and registered public use
U.S. Army Corp of Engineers (US ACE)	Rock Island, IL	2	Waterway level monitor and control (safe navigation)
U.S. Bureau of Reclamation	Boise, ID	1	Irrigation and reservoir monitor and control
National Interagency Fire Center (NIFC)	Boise, ID	1	Fire condition monitoring necessary for wildfire fire management and firefighter safety of life
Florida Department of Transportation (FDOT)	Lake City, FL	1	Water levels and overpass wind speed monitor for road storm closure
Florida Department of Transportation	Tallahassee, FL	1	Water levels and overpass wind speed monitor for road storm closure
U.S. Army Corp of Engineers	Cincinnati, OH	1	Waterway level monitor and control (safe navigation and dam safety)
U.S. Army Corp of Engineers	Columbus Lake, AL	1	Waterway level monitor and control (safe navigation and dam safety)
U.S. Army Corp of Engineers	Omaha, NE	1	Waterway level monitor and control (safe navigation and dam safety)
U.S. Army Corp of Engineers	Sacramento, CA	1	Waterway level monitor and control (safe navigation and dam safety)
U.S. Army Corp of Engineers	St. Louis, MO	1	Waterway level monitor and control (safe navigation and dam safety)
U.S. Army Corp of Engineers	Vicksburg, MS	1	Waterway level monitor and control (safe navigation and dam safety)
South Florida Water Management District	West Palm Beach, FL	1	Water quality monitor (water safety)
Microcom	Hunt Valley, MD	2	Development/test and backup DADDS support
Alion Science & Technology	Annapolis Junction, MD	1	Development/test
International Boundary and Water Commission (DoS)	Del Rio, TX	1	Discharge monitoring for treaty compliance verification
State of New Hampshire Dam Bureau	Concord, NH	2	Reservoir level monitor and control (dam safety)
Total	19	26	

National Oceanic and Atmospheric Administration
U.S. Department of Commerce