DISSERTATION

SYSTEM ENGINEERING FOR RADIO FREQUENCY COMMUNICATION CONSOLIDATION WITH PARABOLIC ANTENNA STACKING

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ABSTRACT

SYSTEM ENGINEERING FOR RADIO FREQUENCY COMMUNICATION CONSOLIDATION WITH PARABOLIC ANTENNA STACKING

This dissertation implements System Engineering (SE) practices while utilizing Model Based System Engineering (MBSE) methods through software applications for the design and development of a parabolic stacked antenna. Parabolic antenna stacking provides communication system consolidation by having multiple antennas on a single pedestal which reduces the number of U.S. Navy shipboard topside antennas. The dissertation begins with defining early phase system lifecycle processes and the correlation of these early processes to activities performed when the system is being developed. Performing SE practices with the assistance of MBSE, Agile, Lean methodologies and SE / engineering software applications reduces the likelihood of system failure, rework, schedule delays, and cost overruns. Using this approach, antenna system consolidation via parabolic antenna stacking is investigated while applying SE principles and utilizing SE software applications. SE / engineering software such as IBM Rational Software, Innoslate, Antenna Magus, ExtendSim, and CST Microwave Studio were used to perform SE activities denoted in ISO, IEC, and IEEE standards. A method to achieve multi-band capabilities on a single antenna pedestal in order to reduce the amount of U.S. Navy topside antennas is researched. An innovative approach of parabolic antenna stacking is presented to reduce the amount of antennas that take up physical space on shipboard platforms. Process simulation is presented to provide an approach to improve predicting delay times for operational availability measures and to identify process improvements through lean methodologies. Finally, this work concludes with a summary and suggestions for future work.

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1. Introduction

System Engineering (SE) involves the collaboration of various engineering disciplines to produce a service or product (system). A system contains a life cycle which begins with system requirements and ends with disposal of the system. Performing SE throughout the system life cycle is critical in delivering a quality product. Performing SE and planning in the early phases is especially important to prevent rework, schedule delays, and cost over runs. SE rigor is recommended to increase the chances of project success in terms of cost, schedule, and overall performance of a system. Model Based System Engineering (MBSE) is a form of SE that uses models as a backbone for engineering, and expands on improvements that can be made from a base lined model or simulation. Producing models can demonstrate current and future states of a process, concept, or operational view of a system. Molding a more efficient methodology from a base lined model can create a target (goal) that a team can work towards to accomplish successfully. Integrated models can show an entire engineering effort, and display potential risk areas for neighboring systems.

As technology brings forth new capabilities for Satellite Communication (SATCOM) and Line of Sight (LoS) systems, the need to incorporate these capabilities are desired especially with our military forces. Various frequency bands are accessed with antennas and satellites to make use of SATCOM and LoS capabilities. Developing consolidated SATCOM and LoS antenna systems can be complex, and require performing SE activities early in the system life cycle. Leveraging SE software applications and practices assist with producing state of the art consolidated SATCOM and LoS systems.

History has shown the importance of early phase system engineering through lessons learned. In December of 1982, an antenna was being hoisted on top of a 1,800 foot tower where a lifting mechanism failed. The antenna fell and severed a guy wire, bringing down the tower [1]. Not only did this catastrophe cause an antenna and tower to fall, but it cost the lives of 5 people. Consideration for lifting this type of antenna during the early phases of the system's life cycle may have prevented this tragedy. This particular antenna was unintentionally designed to include the microwave baskets being in the way of the lifting cables. The placement of the hoisting lugs allowed the antenna to be lifted horizontally off the delivery truck, but the baskets interfered with the lifting cables when the antenna was rotated to a vertical position [2]. This led to a separate hoisting mechanism to be fabricated in order to lift the antenna. The hoisting mechanism failed which resulted in an unfortunate chain of events. Early phase SE may have prevented this by identifying requirements for lifting. Requirement elicitation and collaboration among stakeholders prior to the actual design in regards to hoisting practices could have altered this design to account for specific lifting practices.

In October 1989 NASA launched a Jupiter bound Galileo space craft to obtain 60,000 photos of the planet. This space craft had high and low gain antennas aboard to relay these photos back to earth years later. The high gain antenna had been stowed behind a sun shield since Galileo's launch in October 1989, to avoid heat damage while the spacecraft flew closer to the sun than the orbit of Earth [3]. NASA officials noticed there was a failure when attempting to deploy the antenna as the space craft was heading towards Jupiter. Based on information received from the satellite and studies of a mock-up on Earth, engineers at NASA's Jet Propulsion Laboratory in Pasadena have concluded that three of the antenna's 18 graphite composite ribs are probably stuck in the folded position [4]. NASA officials believed that the stuck antenna could have been caused by a loss of lubrication during the transport of the equipment between Florida and California. Various engineers worked countless hours to come up with solutions to loosen the stuck antenna remotely. Attempts that included repeatedly having the motor turn on / off, spinning the spacecraft to its fastest rotation possible, turning the spacecraft sideways towards and away from the sun had no impact on the stuck antenna. An attempt was made to raise the acceleration around Jupiter to free the stuck antenna, but was unsuccessful. Utilizing the existing low gain antenna was the only option where efforts to get the most out this low speed antenna was made. Engineers developed data compression techniques, modulation efficiencies, intricate coding advancements, and improved S-Band signal to noise ratio antenna designs from the Galileo dilemma. Despite a failed high-gain antenna and a fussy tape recorder, more than 70% of the original Galileo Prime Mission science objectives were accomplished using the low gain antenna [5].

Software applications such as Rational DOORS, Rational Rhapsody, Innoslate, ExtendSIM, Antenna Magus, and CST Microwave Studio provide engineers tools that decrease the likelihood of system failure, rework, schedule delays, and cost overruns. These software tools enhance the development of SATCOM and LoS antenna systems. Utilizing these tools allow engineers to obtain and deliver information necessary to perform SE practices throughout the system life cycle. Rational Doors is a leading requirements management tool that makes it easy to capture, trace, analyze, and manage changes to information [6]. Rational Rhapsody provides a collaborative design, development and test environment for systems engineers and software engineers that supports UML, SysML and AUTOSAR [7]. The software Innoslate supports system engineers throughout the lifecycle by integrating requirements analysis and management, functional analysis and allocation, solution synthesis, test/evaluation, and simulation [8]. ExtendSIM is a software application for finding operational performance of any system using discrete event simulation [9]. Antenna Magus is a software tool to help accelerate the antenna design and modeling process. It increases efficiency by helping the engineer to make a more informed choice of antenna element, providing a good starting design [10]. Systems Engineering involves breaking a complex problem up into smaller, more manageable pieces [11]. CST Microwave Studio assists with modeling and simulation of antennas by providing metrics such as Voltage Standing Wave Ratio (VSWR) and radiation patterns. SE software applications aids in solving these manageable pieces.

Going through the SE development process allows engineers to prepare for later phases of the system life cycle. Leveraging SE and engineering software applications assist with document artifact composition. This dissertation specifies an approach for utilizing software applications and SE practices that support early phase SE and planning for consolidated SATCOM and LoS antenna system development.

1.1. Problem Statement

Various Radio Frequency (RF) capabilities are required for the military to meet mission requirements. The Navy wants to increase Fleet warfighting capability while reducing the number of single function RF systems required on Navy ships [12]. The need for the consolidation of RF antennas is vital to reduce cost, size, weight, and power consumption on shipboard platforms. The topside of Navy ships is crowded and the space available for new antennas, systems and capabilities is limited by the number of existing topside systems [13]. Figure 1 depicts numerous individual antennas performing unique functions.

Figure 1 Shipboard Antennas [14]

Various antennas are procured to perform specific capabilities for shipboard platforms. The Navy Multiband Terminal (NMT) manufactured by Raytheon, supports Extremely High Frequency (EHF) / Advanced EHF Low Data Rate /Medium Data Rate/Extended Data Rate, Super High Frequency, Military Ka (transmit/receive) and Global Broadcast Service (GBS) (receive-only) communications [15]. The Harris Commercial Band Satellite Program (CBSP) WSC-6 terminals operate in X and Ka band over DSCS/WGS or allied military satellites and C band over commercial satellites [16]. The Harris CBSP FLV SATCOM equipment involves 8.9-foot terminals with C- and Ku-band capabilities [17]. A LoS antenna that is used on shipboard platforms include Cubic's Sharklink Surface Data Terminal (SDT) which operates within the Ku band for directional LoS operations. The Cubic Sharklink SDT uses Common Data Link (CDL), the DoD intelligence, surveillance, and reconnaissance (ISR) data link standard [18]. The Cubic

SDT has a directional antenna along with an omni antenna. This research focuses on consolidating the directional portion of this type of LoS antenna. Obtaining replacement antenna's and components from different manufacturers is costly. Table 1 shows antennas being provided by different manufacturers to provide various RF features.

Table 1 Antennas with Manufacturers

Manufacturer	**Nomenclature**	**Frequency**	**Purpose**
Raytheon	NMT X/Ka, Q/KA	EHF,SHF	SATCOM
Harris	CBSP FLV, ULV, WSC-6	SHF	SATCOM
Cubic	SDT	SHF	LoS

Multiple RF systems have individual life cycle costs associated with them which require specific subject matter expertise to maintain which increase overall costs. This research documents existing systems for consolidation in order to fulfill the Navy's need to reduce costs along with reducing the amount of topside antennas. Having a joint RF system would reduce the number of antennas needed as well as unearth new enhanced capabilities.

1.2. Research Objectives

This dissertation proposal is focused on synthesizing antenna consolidation under a system engineering perspective. Performing early phase system engineering practices while considering system life cycle and cybersecurity criteria is critical on developing requirements for antenna development. An approach to reduce the number of top side antennas is necessary to minimize the amount of space consumed by various antennas on U.S. Navy shipboard platforms. Antenna consolidation synthesis involves research of different kinds of antennas to identify limitations as well as consider different alternatives to combine antenna capabilities to a single platform. NMT (Q / Ka, X / Ka), CBSP (FLV, ULV) and directional SDT antenna capabilities are investigated to propose a consolidated solution. Capabilities of these antennas are listed to establish a baseline for a platform that is able to operate at frequencies these various antennas achieve. Identifying constraints of antenna consolidation such as antenna type and size assisted with proposed antenna consolidation techniques. Antenna dish size and type limits the frequency capabilities and strength of a RF signal. The joint functional area includes integrating CBSP and NMT antennas. This will combine commercial and military RF band capabilities onto a single antenna pedestal. The range of military operations include LoS and SATCOM communications to include unclassified and classified capabilities such as NIPRNet, SIPRNet, voice over IP, and data transfer. Commercial satellite links are also required to provide quality of life technology access such as internet, email, chat, voice and data transfer services. The timeframe under consideration consists of approval of the Materiel Develop Decision NLT 15 years prior to the end of life of the NMT antenna.

The required capability of operating at L, C, X, Ku, K, Ka and Q band frequencies stem from existing operations that the antenna variants of the NMT, CBSP and SDT systems provide. Consolidating multiple antenna variants such as the NMT Q / Ka, NMT X / Ka, CBSP ULV, CBSP FLV and SDT directional antennas onto a single pedestal capable of operating at frequencies spanning across will reduce the number of antennas required on topside shipboard platforms. This capability is required to provide LoS and SATCOM links to the warfighter. Mission area contributions include military unclassified and classified LoS and SATCOM links along with commercial satellite links. The operational outcome the parabolic stacked antenna provides includes operating at L, C, X, Ku, K, Ka and Q band frequencies for communication capabilities. The parabolic stacked antenna would include multiple LoS and SATCOM communication groups to connect to this antenna for transmit and receive communication link purposes. This parabolic stacked antenna compliments the warfighting force by integrating multiple antennas that consume topside space onto a single pedestal capable of utilizing the same required frequency bands. To achieve desired operational outcomes, LoS and SATCOM communication groups would have to connect to the parabolic stacked antenna with a RF switch mechanism to access particular frequency bands required. The functions that cannot be performed currently includes a single pedestal antenna capable of providing communication links on L, C, X, Ku, K, Ka and Q RF bands. Different variant antennas which include the CBSP FLV, CBSP ULV, NMT Q / Ka, and NMT X / Ka antennas are required to support missions that use those particular RF bands for SATCOM and the directional SDT antenna for LoS operations. Due to the amount of antennas needed to provide these communication links, smaller shipboard platforms are left without the luxury of having some of these RF capabilities. Some of these ships may have a couple of antenna variants aboard that provide limited mission critical capabilities due to the amount of space available topside for RF antennas. The attributes of the desired capabilities include various operations that the CBSP, NMT and directional SDT RF system variants provide. These operations include imagery distribution, NIPRNet, SIPRNet, secure communications, VTC, legacy data transfer, file transfer services, file delivery, video / audio services, secure communications and protected communications. Providing these operational services through multiple communication links provide the war fighter a vast array of capabilities utilizing a multitude of RF bands. Cybersecurity implementation would have to be considered utilizing directives outlined in the DoDI 8510.01 Risk Management Framework (RMF). The RMF process allow the parabolic stacked antenna system to go through the required information assurance rigor needed to prevent any potential vulnerabilities. Potential vulnerabilities include RF signal jamming to shutdown communication capabilities, outdated virus / malware prevention software on client workstations, outdated firmware on devices such as firewalls, switches, routers, HAIPE, workstations, and RF equipment, password complexity, minimal access control, lack of device configuration backups, inadequate redundancy options / plans, and limited encryption on network connected devices [19]. These vulnerabilities would have to be considered throughout the design of the parabolic antenna system along with the communication groups that the antenna is connected to.

System engineering relating to the Defense Acquisition System (DAS) process is investigated to determine methodologies for parabolic antenna system development throughout the system life cycle. Methodologies to include process analysis is included to determine delay times of testing antenna equipment and to promote lean methods for process improvement. Analyzing and planning for process related testing events allow for accurate schedule estimating. Forecasting delay times also assists with Reliability, Availability, and Maintainability (RAM) metrics for measuring operational availability. Researching previous efforts and baselining costs is another research effort to assist with budgeting for overall life cycle costs of the parabolic stacked antenna. Life cycle costs would include activities within the DAS process with respect to the System Engineering Vee model, and incorporating Agile methodologies to decrease delivery times and cost. Use cases are depicted to illustrate various scenarios the parabolic stacked antenna would provide. An overall approach to develop a parabolic stacked antenna using system engineering methods is investigated and depicted within this research.

1.3. Dissertation Overview

Section 2 provides a background for the research of antenna consolidation. This section includes prior RF system consolidation efforts to include efforts by the Office of Naval Research (ONR) Integrated Topside (InTop) program and the Surface Electronic Warfare Improvement Program (SEWIP). The NMT antenna was another antenna consolidation effort which combined the EHF, SHF, and GBS antenna on a single pedestal. The CBSP antenna is also discussed which replaced the AN/WSC-8 C band antenna and integrated additional RF band capabilities. RF communication capabilities are identified and depicted to provide an overview of the RF spectrum. SATCOM and LoS capabilities along with NMT, CBSP and directional SDT RF band capabilities are defined to set a baseline for a consolidated SATCOM antenna.

In section 3, early phase system engineering is discussed to strategize an approach for developing a consolidated SATCOM antenna. The DAS process along with the SE Vee model is proposed to provide a process for the development of a parabolic stacked antenna which would combine NMT, CBSP and directional SDT antenna RF band capabilities. A parabolic stacked antenna system architecture is presented to depict various interfaces that the parabolic stacked antenna would be connected to. Various use cases and sequence diagrams for LoS and SATCOM operation are also illustrated to provide insight on potential mission applications. In addition, conceptual diagrams such as the parabolic stacked antenna OV-1 show antenna capabilities that can provide communication links to satellites and LoS operations to other antennas. Project planning using historical data from prior NMT efforts allowed for schedule and cost forecasts when developing a parabolic stacked antenna. Agile methodology is examined with the use of SE practices to reduce development costs and delivery times. Exploring various alternatives using the Pugh matrix provided a system engineering approach to selecting the parabolic stacked antenna as a solution. Performing early phase system engineering improves planning for the development of a parabolic stacked antenna.

Antenna consolidation via parabolic antenna stacking is researched in Section 4. Parabolic antenna stacking allows multiple antennas to be placed on a single pedestal to achieve multiple RF capabilities. Gregorian, Cassegrain and splash plate parabolic antennas were investigated to demonstrate multiband capabilities through simulation. Different configurations were proposed utilizing the parabolic stacking methodology. VSWR, gain values, radiation patterns, angular width, and side lobe levels were captured for parabolic antenna stacking analysis. Simulations were based off values captured from NMT, CBSP and directional SDT RF band capabilities shown in Section 2. Physical descriptions and simulation results of the parabolic stacked antenna configurations are listed to compare against one another. Risk reduction methods are discussed based off of identified risks for the parabolic stacked antenna system life cycle.

In Section 5, mid to late phase SE is considered to include planning for parabolic stacked antenna sustainment efforts. Process analysis is introduced to determine delay times of known process areas which support operational availability metrics. Simulating a PITCO process using triangular distribution probability methods demonstrated anticipated delay times to be used for process improvement. The simulation proved that schedule estimation accuracy is increased by predicting delays within the process as well as proposing lean methodologies for process improvement. Utilizing SE models such as a FFBD depicted a high level view for operation and sustainment activities.

Section 6 concludes with a summary of the research that was completed within this dissertation. The focus areas of the research objectives are presented and key points are identified. Future work is also recommended at the end of this section.

2. Background

Research was conducted to identify requirements for RF system consolidation. A Systems Engineering approach was conducted to assess requirements, define functional / physical characteristics, and provide a conceptual design. RF communication capabilities that are currently in use were assessed to incorporate within the consolidated RF system architecture. A consolidated antenna approach was proposed to meet the current and future needs of government and military entities. RF system standards along with non-functional and functional requirements assist with RF system design. Various communication links would be achieved by utilizing a single antenna with different assemblies and sub-assemblies.

Integrating RF communications systems provides the advantage of reducing overall antenna footprints, life cycle costs, multiple RF system maintenance, logistics support and procurement costs / lead times associated with acquiring various antenna systems / replacement parts from different vendors. Maintaining multiple RF antennas involves various Subject Matter Experts (SME), stakeholders and personnel associated with the system's program of records [20]. A methodology of RF system consolidation, requirements for design, and process planning considerations are gained from this research. Mission use cases along with proven feasibility are achieved for the RF system consolidation effort.

2.1 Prior RF System Consolidation Efforts

Various efforts have been performed to reduce the amount of antennas on U.S. Navy shipboard platforms. The Surface Electronic Warfare Improvement Program (SEWIP) intended to upgrade the AN/SLQ-32 system. The AN/SLQ-32 was a radar system that allowed U.S. Navy ships to defend themselves by detection of various threats. The US Navy's AN/SLQ-32 ECM

(Electronic Countermeasures) system used radar warning receivers, and in some cases active jamming, as the part of ships' self-defense system [21]. The SEWIP modernized various aspects of the AN/SLQ-32 system such as integrating an AN/SSX-1 specific emitter identification subsystem. Such success of system integration obtained from the SEWIP effort led to the Office of Naval Research (ONR) Integrated Topside (InTop) program. The ONR InTop program pursued to consolidate common sets of signal and data processing hardware and apertures. In 2004, the Advanced Multifunction Radio Frequency Concept used this common set to demonstrate that radar, electronic warfare, and communications functions could perform simultaneously [22].

NMT is another effort that consolidated various RF systems. EHF and SHF systems along with a GBS antenna was combined to perform multi-frequency capabilities. This consolidation reduced the need for three different antennas for the EHF, SHF and GBS systems along with reducing the EHF and SHF communications racks into one communications rack on shipboard platforms. The NMT Q / Ka antenna is capable of supporting Q and Ka band frequencies for EHF and SHF transmit / receive capabilities along with K band frequency reception for GBS capabilities. The NMT X / Ka antenna is capable of supporting X and Ka band frequencies along with reception of the K band frequency for GBS capabilities. This consolidation breakthrough reduced the overall topside space that the three antennas was consuming, life cycle costs for multiple systems, logistic support costs, power consumption and overall weight on shipboard platforms.

The CBSP system effort consolidated SATCOM systems as well. The CBSP was a rapid deployment capability acquisition to expedite replacement of Inmarsat B high speed data channel and Commercial Wideband SATCOM Program capabilities [23]. In addition, the CBSP antenna replaced Harris's AN/WSC-8 C band systems along with including adding other frequency capabilities such as X, Ka, and Ku bands. The CBSP antenna system allowed access to commercial and military satellite links. This equipment also provides access to military NIPRNET and SIPRNET data, secure telephones, afloat personal telecommunication, video teleconferencing, telemedicine and medical imagery, national primary image dissemination, and intelligence database and tactical imagery [17]. This antenna was capable of providing commercial and military SATCOM communications. The AN/WSC-6(V)9 SHF terminal installed on guided missile destroyers enabled the ability to also operate in the commercial C-band with a feed horn change out [24]. Swapping out feed horns was a CBSP solution to achieve multi-band frequencies utilizing a single antenna pedestal.

The effort to consolidate SATCOM antenna systems has been successful with prior endeavors. The NMT and CBSP antenna systems have consolidated five systems of record into just two systems. Multi-band frequency capable antennas have reduced the amount of space, weight, power and cost to operate multiple RF systems.

2.2 RF Communication Capabilities Analysis

LoS and SATCOM capabilities provide the advantage of sending and receiving information from remote locations. Satellites that are currently in orbit would drive the requirement of what signals are to be used on antennas for connectivity and current LoS frequencies that are in use would provide requirements for LoS operations. Designing an antenna that can span across various RF frequencies would save on costs for procuring multiple antenna systems from different vendors. Different satellites would have unique SATCOM band capabilities and LoS antennas would require a set frequency range to transmit / receive. This would require a rotatable antenna which can lock into different satellites or antennas to access various communications links. Frequencies for communication systems span over a broad range as shown in Figure 2. Each allocated frequency range provides unique capabilities.

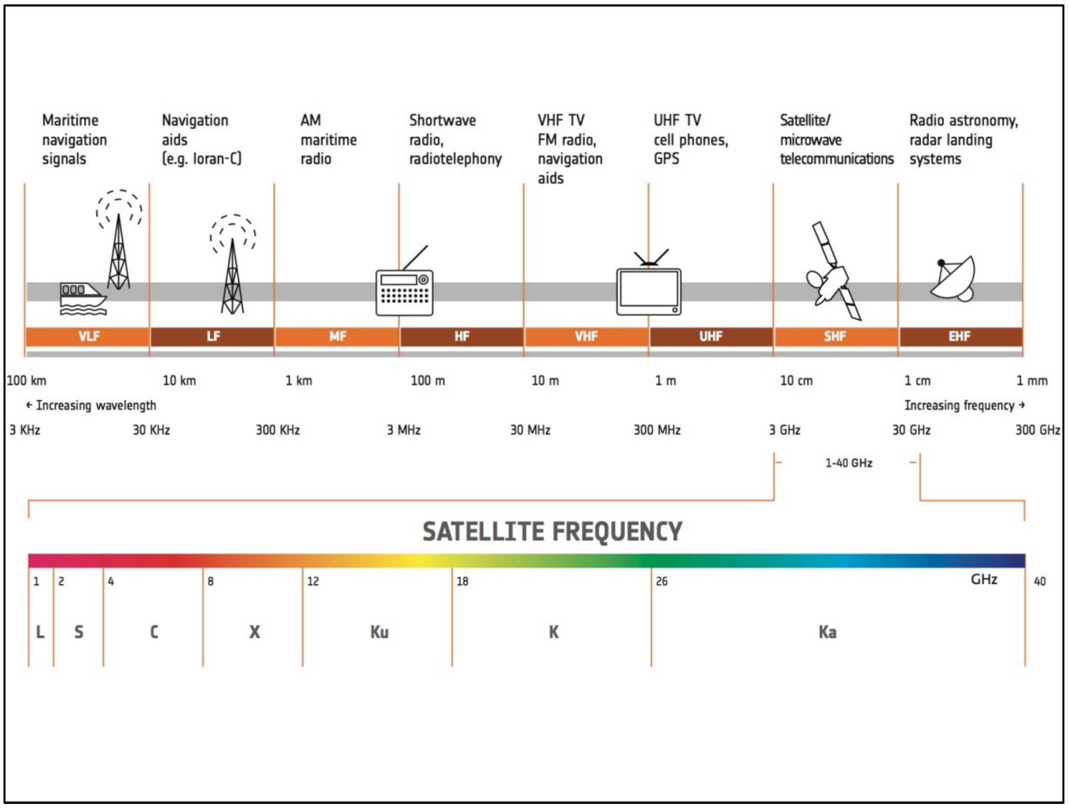


Figure 2 RF Communication Frequency Bands [25]

The lower in frequency, the larger the wavelength and, accordingly, the more resistant to fading and blocking a spectrum band will be [26]. Lower frequencies that are below 1 GHz are resistant against rain and are more tolerable in an urban / high foliage environment. Although lower frequencies are highly reliable, can travel farther, and can penetrate through objects, they have a disadvantage of having a lower bandwidth. Applications that do not require much bandwidth such as voice would be ideal for the lower frequency range. As frequencies increase, losses by free space, rain, and obstructions increase. Higher frequencies do have advantages by allowing applications to transmit and receive at higher data rates at a greater capacity.

RF system capabilities that are currently being used have to be considered to design a consolidated solution. LoS and SATCOM methods of communication are critical for remote military units / platforms. SATCOM provides transmit and receive services to platforms worldwide based on the satellite's location and spot beam while LoS capabilities provide data transfer between platforms directly.

2.3 Communications for LoS and SATCOM Antennas

There are various satellites that are available that are Government owned as well as commercially provided. Wideband Global SATCOM (WGS) system provides 4.875 GHz instantaneous switchable bandwidth, along with 500 MHz of X band and 1 GHz Ka band spectrum allocated to WGS [27]. Defense Satellite Communications System (DSCS) includes a payload of six-channel SHF transponder and system single channel transponder (X, cross band) [28]. The AEHF System is the follow-on to the MILSTAR system, augmenting and improving on the capabilities of MILSTAR, and expanding the military SATCOM architecture, and has onboard signal processing along with cross banded EHF/SHF communications capabilities [29]. The MILSTAR satellite can transmit 75 to 2,400 bps of data over 192 channels in the extremely high frequency (EHF) range [30]. Commercial satellites provide an alternative to Government owned satellites by providing additional bandwidth resources. Commercial satellites such as AMC, NSS, SES, INTELSAT, ASTRA, and INMARSAT have SATCOM resources ranging from L band, Ka band, Ku band, and C band. Table 2 depicts satellites with their respective frequency band capabilities. Considering these options assist with determining appropriate mission configuration settings applicable with the location of the beam coverage.

Table 2 SATCOM Capabilities

Satellite	Frequency Band Capabilities
WGS	X-Band, K-Band, Ka-Band [27]
DSCS	SHF, X-Band [28]
AEHF	EHF, SHF [29]
MILSTAR	EHF [31]
AMC, NSS (Commercial)	Ku-Band [30]
SES, INTELSAT (Commercial)	C-Band, Ku-Band [28] [32]
ASTRA (Commercial)	Ku-Band, Ka-Band [30]
INMARSAT-3 F3 (Commercial)	L-Band, C-Band [33]
INMARSAT-5 (Commercial)	Ka-Band [34]

The locations of these satellites determine the angle at which the antenna would need to be pointed to. Since the satellites are at various look angles the SATCOM capabilities would be linked via frequencies shown in Table 2. These satellites provide spot beams to certain locations around the world to provide services.

Antennas were assessed for SATCOM capabilities aboard U.S. Navy ships. CBSP and NMT antennas were identified as the major SATCOM antennas with multiple capabilities already. The CBSP antenna would have L, C, X, Ku and Ka band capabilities. The NMT antenna would have X, K, Ka and Q band capabilities. Consolidating these antennas would eliminate the need for buying different antennas from different manufacturers. The CBSP and NMT frequency band capabilities are shown in Table 3.

Table 3 CBSP and NMT Frequency Band Capabilities

Frequency	MHz / GHz	Transmit / Receive	Antenna	Band
7.25 to 7.75	GHz	Receive	CBSP ULV [35]	X
7.9 to 8.4	GHz	Transmit	CBSP ULV [35]	X
10.95 to 12.75	GHz	Receive	CBSP ULV [35]	Ku
13.75 to 14.5	GHz	Transmit	CBSP ULV [35]	Ku
29 to 31	GHz	Transmit	CBSP ULV [35]	Ka
3.7 to 4.2	GHz	Receive	CBSP FLV [36]	C
5.85 to 6.425	GHz	Transmit	CBSP FLV [36]	C
10.95 to 12.75	GHz	Receive	CBSP FLV [36]	Ku
13.75 to 14.5	GHz	Transmit	CBSP FLV [36]	Ku
950 to 2050	MHz	Transmit / Receive	CBSP FLV [36]	L
20.2 to 21.2	GHz	Receive	NMT [37]	K
30 to 31	GHz	Transmit	NMT [37]	Ka
7.25 to 7.75	GHz	Receive	NMT [37]	X
7.9 to 8.4	GHz	Transmit	NMT [37]	X
43.5 to 44.5	GHz	Transmit / Receive	NMT [38] [39]	Q

The CBSP FLV antennas provide IESS-601 standard G compliant beam patterns using a 2.74m reflector mounted on a high dynamics three-axis pedestal enclosed within a protective radome [17]. The CBSP FLV antennas continue to provide legacy operations with L band frequency capabilities. Most unit level access for frigates, mine countermeasures and coastal patrol ships accessed commercial Inmarsat satellite service with an Inmarsat terminal that operates strictly in the L-band portion of the RF spectrum, for nothing more than a 64 to 128 kilobyte per second (Kbps) data rate [40]. The CBSP FLV variant additionally provides C band and Ku band capabilities to provide access to commercial satellites for transmission and reception of files, web access, e-mail and voice over IP solutions.

The CBSP ULV antenna is capable of accessing military and commercial satellites depending on the mission and availability. The CBSP ULV antenna is capable of performing X, Ku and Ka operations. The X band frequency is intended for links to military satellites, the Ku band frequency is intended for links to commercial satellites, and the Ka band frequency is intended for communication links for both military and commercial satellites. Since the designation in the 1970s of a military satellite communications Ka-band (30-31 GHz uplink, 20.2-21.2 GHz downlink), these frequencies have held great potential to support US forces and requirements [41]. The CBSP ULV antenna (1.32 m) variant is smaller than the CBSP FLV antenna (2.74 m) variant. The CBSP ULV antenna variant is capable of supporting reception of files, web access, e-mail and voice over IP solutions like the CBSP FLV antenna along with having capabilities to support military missions with NIPRNet, SIPRNet, secure telecommunications and imagery service. The CBSP ULV does not support the L band, C band and Ku band frequencies that the CBSP FLV variant supports.

The NMT shipboard antenna variants consist of a large X / Ka antenna (2.44 m), a small X / Ka antenna (1.54 m) and a Q / Ka antenna (1.37 m). These antennas are utilized for military satellite links to provide EHF and SHF communications. In addition to X band, Ka band and Q band capabilities, these antennas support the reception of the K band frequency. The K band receive frequency is designated for the GBS capability. GBS is an extension of the Global Information Grid that provides worldwide, high capacity, one-way transmission of video (especially from Unmanned Aerial Vehicles), imagery and geospatial intelligence products, and other high-bandwidth information supporting the nation's command centers and joint combat forces in garrison, in transit, and deployed within global combat zones [42]. The NMT X / Ka and Q / Ka variants support multiband frequency capabilities and are placed on many military shipboard platforms.

LoS operations provide direct communication links to nearby entities to include shipboard, airborne, and ground units. The Common Data Link (CDL) protocol interconnects information from various intelligence, surveillance, and reconnaissance operations that joint military forces are involved in. This includes all military branches that provide information relevant to mission success. Information details can be captured by aircraft and relayed to nearby units such as ship and ground units to assist with strategic decisions. This integrated connection would also work other ways such as a ground unit relaying information to a nearby ship vessel or an aircraft. Point to point communication links allow data transfer to occur without the need for SATCOM. Data transfer to include voice, video and other intelligence information between the military forces in the air, on the ground and at sea provides situational awareness with real time data. Being able to share information expeditiously, promotes successful mission execution.

CDL systems typically consist of omnidirectional antennas and / or directional antennas. Omnidirectional antennas distribute the RF signal equally around the source. The RF signal would appear as a donut shape around the conductor. A directional antenna radiates energy in one direction rather than the omnidirectional antenna that distributes the RF energy in a 360 degree pattern. A directional antenna provides more gain since the RF energy is focused towards a particular location. The directional antenna provides support for long range operations whereas the omnidirectional antenna provides support for operations nearby. Typically automatic switching between the two antennas occur to adjust to mission needs. This research is focused on the directional antenna capability of LoS operations.

The CDL system is aboard aircraft, ground and shipboard platforms. Aircraft platforms include both manned and unmanned vessels. Unmanned vessels involve drones which can capture vital information from potential threats. Ground platforms entail mobile platforms whether it's vehicular or equipped on personnel and military stations. Unmanned vehicles are also considered to equip the CDL system to capture and transmit information. Shipboard platforms would use this information by connecting with other CDL systems to receive and transmit information.

The Light Airborne Multipurpose System (LAMPS) Hawklink is a high-speed, air-to-ground, digital data link that transmits reconnaissance and other data from MK III H-60 helicopters to their host surface ships, such as Arleigh Burke Class destroyers [43]. The AN/SRQ-4 Hawklink is the shipboard element of a situational awareness system that links the MH-60R helicopter with surface warships in the area [44]. The AN/SRQ-4 is another antenna that can be consolidated by parabolic antenna stacking for the directional antenna portion. The omni antenna would be separate to provide near range communication links. The AN/SRQ-4 system has CDL capabilities that assists surveillance missions and provides a link between neighboring platforms equipped with CDL technology. Capabilities include secure data transfer, data link operation, full motion video distribution, interoperability with CDL family of airborne terminals (fire scout, P-3, and P-8) [45]. Real time data to include imagery, and sensor data is also included to support mission requirements.

Cubic's Sharklink Surface Data Terminal (SDT) is a new, high performance surface data terminal that supports secure, long range, high data rate communications with airborne and shipboard platforms equipped with a DoD standard Common Data Link (CDL) data terminal [18]. LoS communications and beyond line of sight systems promotes a tactical communications environment. Cooperative Engagement Capability Data Distribution System CEC (CEC DDS) fuses high quality tracking data from participating sensors and distributes it to all other participants in a filtered and combined state, using identical algorithms to create a single, common air defense tactical display ("air picture") [46]. The CEC DDS operations use the C-Band frequency range, and CDL operations operate within the C and Ku band frequency range. The CDL capable SDT LoS directional antenna is investigated for consolidation purposes within this research and the frequency capabilities for this LoS antenna is shown in Table 4.

Table 4 Cubic Sharklink SDT LoS Antenna Capabilities

Frequency	MHz / GHz	Type	Antenna	Frequency Band
14.4 to 15.35	GHz	Directional	Sharklink Surface Data Terminal (SDT)	Ku
14.4 to 15.35	GHz	Omni	Sharklink Surface Data Terminal (SDT)	Ku
2.2 to 2.5	GHz	Omni	Sharklink Surface Data Terminal (SDT)	S
4.4 to 4.99	GHz	Omni	Sharklink Surface Data Terminal (SDT)	C

3. Early Phase System Engineering

In order to develop a new consolidated antenna, a planned System Engineering (SE) approach is required. Utilizing SE practices along with SE software within the early phases of the system life cycle increase the chances for success. SE includes many aspects such as technical planning, customer requirements, design, build / integrate, testing, production, deployment, and operations / sustainment. During this life cycle, system engineering would be needed to ensure processes are followed through in the most efficient manner while verifying that requirements are met. SE also includes SE architectures, modeling, technology assessment, capabilities engineering, as well as system integration.

Applying MBSE early in the life cycle is important to be able to provide models and simulations to meet system requirements. During the conceptual design phase, activities relating to design, analysis, verification and validation can be done using MBSE. Models are produced during the search for solutions & assessments to display alternative system concepts as well as assessment & concept trade off studies. Performing MBSE early in the life cycle can reduce the need to perform rework later on due to unforeseen system constraints. MBSE can support validation of operational behavior and functional performance during the design refinement & design validation phase. Visually seeing virtual interactions among system components or other systems within the environment would determine required interfaces as well as other systems that may be affected. Performing MBSE early on help provide more accurate cost estimates throughout the life cycle of the system. Displaying models that show neighboring entities as well as performance characteristics will help facilitate cost projections down the road. Simulations and models displaying physical constraints, operational constraints, environmental / operational factors, system synthesis models and simulations can encompass many areas of the system.

Determining quantitative values for these activities will tie into cost estimates to ensure adequate funding is available for the overall effort. Performing MBSE activities as well as Agile methodologies early on can help reduce cost, and promote the ability to deliver faster. Displaying a functional and physical architecture of a system is a start to MBSE where these architectures are expanded upon from system requirements. Determining any constraints or tradeoffs early in the life cycle will reduce the need to reassess the system later on in the future. Determining issues early using MBSE and Agile methodologies will help reduce delays in schedule due to rework, increase cost projection accuracy, and ensure the system is meeting operational needs.

The CBSP, NMT and directional SDT antennas were researched and explored to identify current frequency band requirements along with satellite connection points for the CBSP and NMT antennas in section 2.3. Requirements for this antenna design is provided along with a concept of operations throughout this research. A high level design with simulation results is also provided within this research. The objective includes following SE practices to propose a consolidated antenna capable of utilizing frequencies of CBSP, NMT and SDT antennas. High level requirements were defined to identify functional and non-functional characteristics of the consolidated antenna.

Boundaries include designing the antenna itself and including the interconnections of the systems correlating to various existing antennas. Schedule was estimated to identify major milestones and a budget was estimated for planning purposes. Assumptions, constraints and risks was identified to account for details relating to the design of the consolidated antenna. Certain roles and responsibilities were depicted for budget estimation and resource identification needs for future development.

SE has many different fields where incorporating different domains would allow different SE approaches to be successful when developing a system. SE standards such as the ISO 15288 provides guidance for SE life cycle processes. The processes listed in the ISO 15288 provide direction on how to perform SE activities. Not all processes listed creates a one size fits all solution, but does give a way forward for the system engineer to tailor one's need to accomplish a SE objective. The SE V Model is an iterative set of processes that depicts the system's life cycle from beginning to end.

DoD instruction 5000.02 defines the operation of the Defense Acquisition System (DAS). The DAS consists of 5 phases of major activities. This can be cross walked with the SE V model. The major activities include material solution analysis, technology maturation & risk reduction, engineering & manufacturing development, production & deployment, and operations & support. Various decision points are also included such as the Material Development Decision (MDD), Capability Development Document (CDD), Request for Proposal (RFP), and the Full Rate Production (FRP) decision. Major reviews would include the Preliminary Design Review (PDR), Critical Design Review (CDR), and Production Readiness Review (PRR). These reviews assist with obtaining the status of the current development of the system as well as making any major decisions on changes relating to the cost, schedule and performance of the system. Major milestone decisions are labeled A, B, and C and are shown in Figure 3 which depicts the DAS process aligning to the SE Vee model.

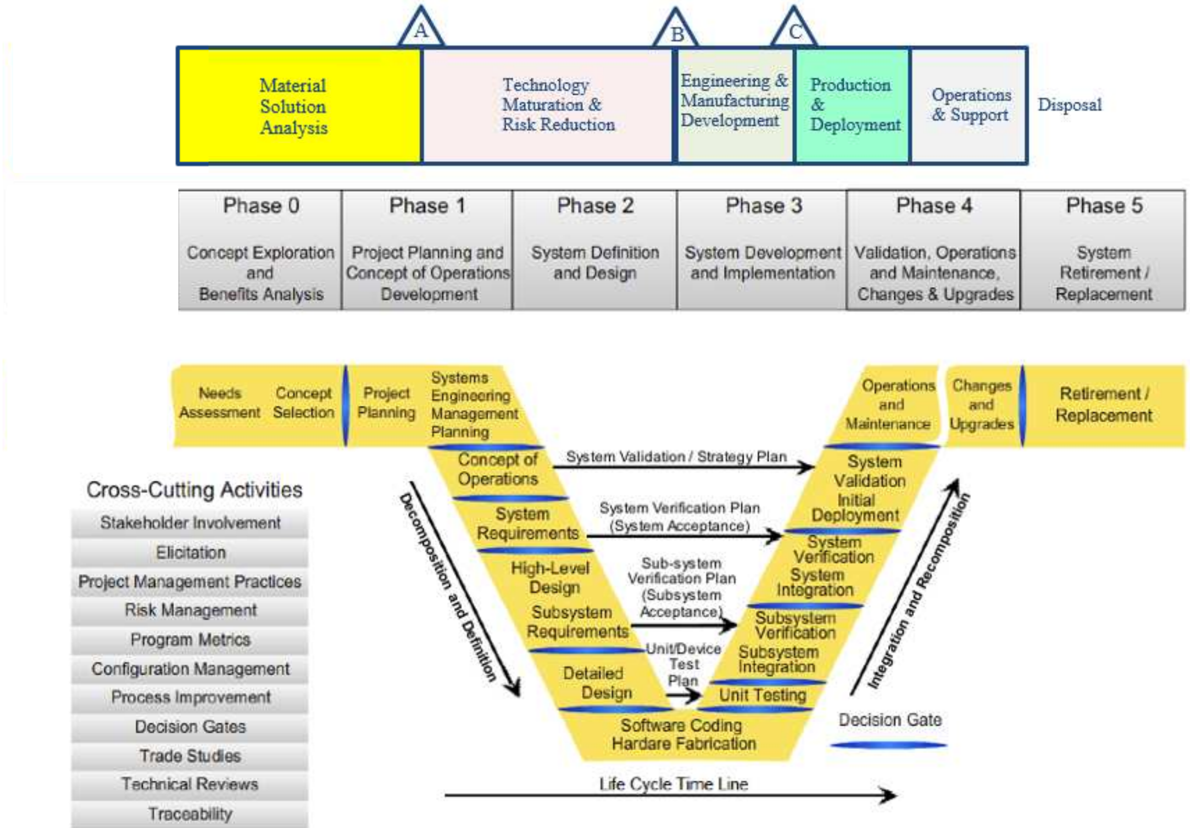


Figure 3 SE V Model with DAS (after [47] , [67])

The Material Solution Analysis phase is the basis of the Defense Acquisition System process which sets up the acquisition strategy, goals, and provides an analysis of alternatives. Initially, the Initial Capabilities Document (ICD) specifies the need to fill a capability gap with a materiel and / or service solution. The ICD includes a Concept of Operations (CONOPS) summary that depicts how a system would operate. A high level depiction of the system with high level requirements describes the objectives of the system. Different use case scenarios would be presented to demonstrate how the system would function in a particular environment. A description of operational outcomes with how the capabilities would satisfy those objectives is required. The required capability and capability gaps would be presented in the ICD. Capability gaps occur when an existing capability is not sufficient, needing to be replaced or does not exist.

At times, redundant capabilities may be present creating inefficiencies. The Material Development Decision is the formal decision made to move forward with the Materiel Solution Analysis phase. This decision point recognizes the need and / or capability gap. In addition, providing the necessary resources to staff and fund engineering and programmatic tasking is made. This decision is made based off of the ICD and any other evidence that demonstrates that the approach would satisfy the need. The schedule would be discussed to show when the capability can be available and what can be done in the time being to address the need until the system is fielded.

The Material Solutions Analysis (MSA) phase determines potential solutions for a need. This need would typically come from a technology gap or a new capability that would benefit mission requirements. An Analysis of Alternatives (AoA) method assists with solution selection. Listing potential solutions identifies feasible options to choose based off of the selection criteria. Comparisons would be made off of the solution being operational effective, cost effective, suitable and meeting the selection criteria parameters. A preliminary acquisition strategy is included to identify various contract avenues, sustainment plans, program schedule, risk areas, design considerations, cost information, resource needs, test strategies and other relevant acquisition requirements. Avenues for material and service contracts would be identified in the acquisition strategy. A decision would have to be made to determine what material would have to be procured whether it is COTS or custom made. Contractor services would have to be considered to supplement the required expertise to assist with the development of the system. Initial plans for sustainment would be included in the acquisition strategy to include support and maintenance concepts which would be linked to the Life Cycle Sustainment Plan (LCSP). These sustainment details provide insight to design considerations that would be required.

Milestone A refers to a decision where stakeholders would have to commit resources required to develop the intended system. Risks would be identified and mitigated prior to Milestone A in order to obtain stakeholder concurrence. Certain risks may not be easily mitigated by Milestone A and stakeholders would have to accept certain risks in order to move forward with the Technology Maturation & Risk Reduction (TMRR) phase. Justifying the preferred system solution would have to be discussed during the Milestone A decision review. Various alternatives that were vetted prior to the review would assist with the justification and to demonstrate the feasibility of the system. The cost, schedule, performance and risks associated with the planned system would also be reviewed and agree upon during the Milestone A decision review. Requirements along with the scope of the work involved to develop the system would provide a common understanding of the magnitude of the entailed effort. The acquisition strategy would also be discussed to include contracts for both material and services in order to determine how effective and efficient the strategy is. Overall the approach, assumptions, acquisition strategies, technology development requirements, affordability, and risks with mitigation activities would increase approval to move to the next phase after the Milestone A decision review. Written determination, market research, affordability analysis, AoA, Draft CDD, core logistics determination / core logistics and sustaining workloads estimate, economic analysis, SE Plan to be revised are activities performed by Milestone B.

3.1 Interfacing with Planning and Architecture

Modeling architecture takes place in the early planning stages of the system's life cycle. During this planning area, interconnecting links are identified. The interconnecting links would include other systems or components that interface with the system being developed. For a consolidated antenna being developed, various interconnecting systems would be identified.

These interconnecting systems would have various system owners that would have to be collaborated with. Obtaining historical architectures would assist with integration activities and design. System architecture would depict various interfaces and data elements of the system. The data elements would show various types of information exchanged between the systems. The architecture assists with defining the system's scope and identifying requirements. The architecture identifies the integration opportunities that should be considered and provides a head start for the systems engineering analysis [47]. If historical architecture artifacts are unavailable, developing an architecture to depict the system with interfaces connecting to other systems is recommended.

A system architecture can be achieved from MBSE. MBSE establishing a common language to communicate better through MBSE software tools are essential. SysML is a visual modeling language that MBSE SMEs use to develop intricate models. This modeling language fills the gap between system engineering fields of practice. Having a common language whether it is system engineering, project management, or MBSE can promote better communication between team members to accomplish the tasks at hand.

A common language for model based system engineers improves collaboration and cohesion among team members. SysML standards assist MBSE communities to share information amongst one another to expand on ideas. Receiving help on a common language such as SysML is easier than obtaining peer support from a proprietary vendor that developed their own language. MBSE software tools such as IBM Rational Rhapsody, uses SysML to display robust models for system engineers. SysML modeling would allow insight into complex diagrams where important decisions can be made from stakeholders. A common language will reduce the need to translate different languages when integrating models. A scenario where a software tool uses one language that is not compatible with another can force one software language to be manipulated to cater to the preferred MBSE tool.

Communication gaps can be filled with having a common language when applying MBSE practices. Having consistency with a common language and capabilities to address issues when performing MBSE, can promote a cohesive project team. The team being able to communicate with each other using a common MBSE language can add value to the overall progress for a MBSE modeling effort. To be able to clearly communicate with all stakeholders using a common language will allow team members to be on the same page with decision makers. Not being able to communicate about a MBSE language can cause confusion and loss of interest amongst members of a team.

The MBSE primer states there is a need for a "systems language" to avoid the natural ambiguity of language and to enable specialists involved in the SE effort to communicate outside of their own group [48]. Common language of MBSE would keep everyone on the team on the same page. Methodologies, thoughts, decisions, and rationale of the way forward on an MBSE effort will promote a cohesive team that performs efficiently. Reducing MBSE interpretation issues can be done by defining MBSE related terminology. A common language would be able to have decision makers determine unavoidable tradeoffs visually depicted by a MBSE model. Having a common language is significant to the application of MBSE by reducing interpretation discrepancies which may lead to rework, improving cohesion with views amongst team members, and the ability to persuade decision makers to select the most cost effective solution.

The existing architecture includes the SDT, CBSP FLV, CBSP ULV, GBS, NMT Q / Ka, and NMT X / Ka system variants on U.S. Navy shipboard platforms. Depending on the size of the ship and the amount of space availability, various configurations exist with different combinations of these CBSP, NMT and SDT variants. Some ships may not have all the antenna variants available to them and are limited to only a select few that are mission critical. Each antenna variant would have their own unique communications group which would have its' own set of operations they perform. The NMT antenna systems have an ability to connect to the GBS communications group to receive files, video, audio and other data elements. Communication groups would have their own RF capability values associated with them. Some communications groups have the same RF capability values along with the same system operations. Although this provides a redundant backup to one another, it increases costs with maintaining multiple systems. Combining antenna variants would reduce the amount of antennas needing to be maintained. A parabolic stacked antenna solution would eliminate the need for multiple antenna variants and provide the same SATCOM capability that CBSP FLV, CBSP ULV, NMT Q / Ka, and NMT X / Ka antenna variants currently provide along with the LoS directional capability that the SDT antenna provides. The parabolic stacked antenna system architecture is depicted in Figure 4 using existing RF communication groups.

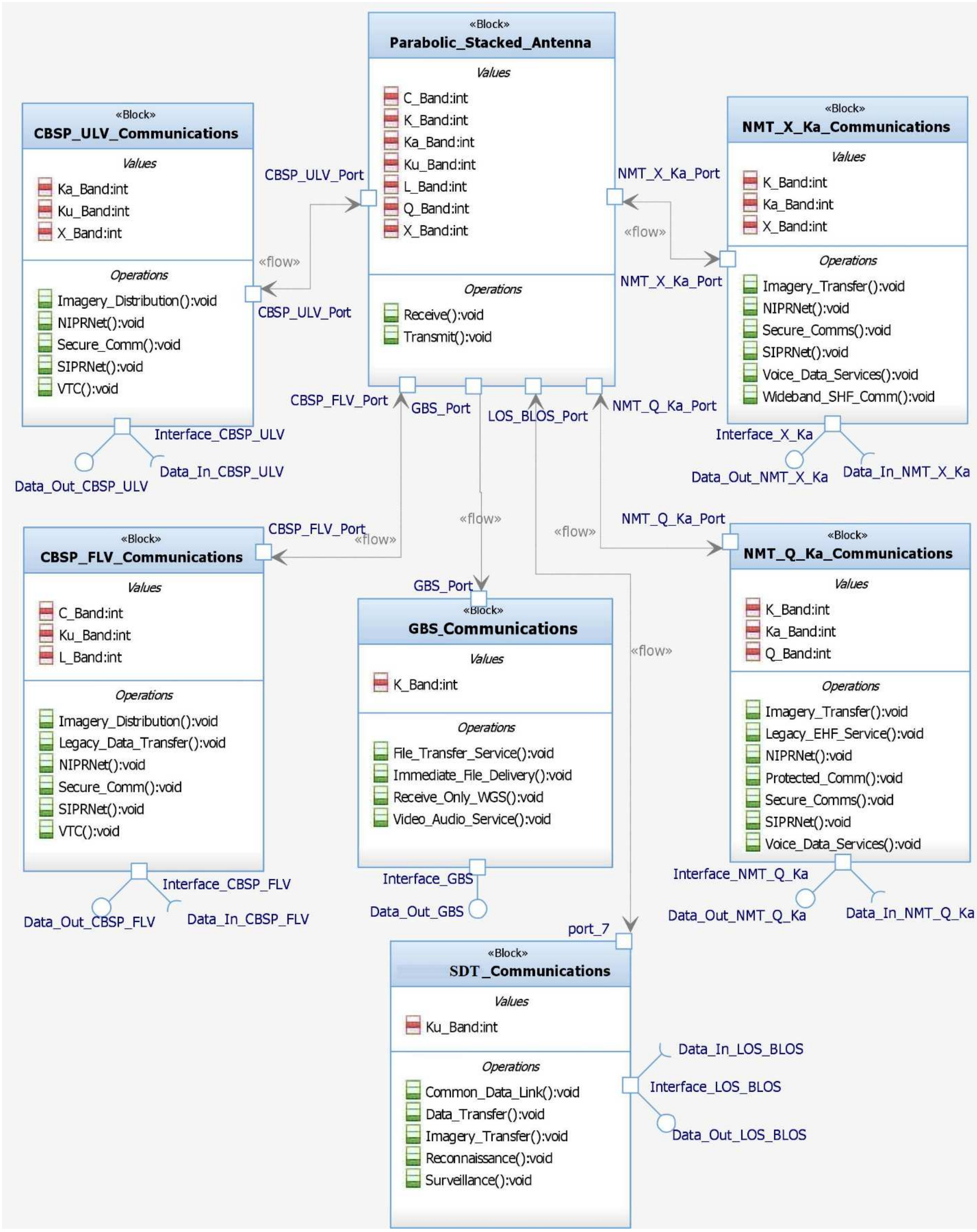


Figure 4 Parabolic Stacked Antenna System Architecture

NMT and CBSP variant communication groups have operational capabilities that provide required data to the warfighter. The NMT and CBSP variants have similar operational capabilities such as NIPRNet, SIPRNet, secure communications, voice, imagery, and other data transfer services on the MILSATCOM side. These capabilities are used with both NMT and CBSP variant antennas which occupies space on the topside of U.S. Navy shipboard platforms. The parabolic stacked antenna would take the place of currently installed NMT and CBSP antenna variants, and be capable of interfacing with existing communication groups to provide communication services to the war fighter.

The reference sequence diagram was created to depict a high-level activity flow between the operator and the external source. This diagram generalizes the parabolic stacked antenna system where typical concepts of operations are shown. This sequence diagram includes the operator requesting desired information from the external source through the operator's internal network, COMSEC devices, and parabolic stacked antenna system as shown in Figure 5.

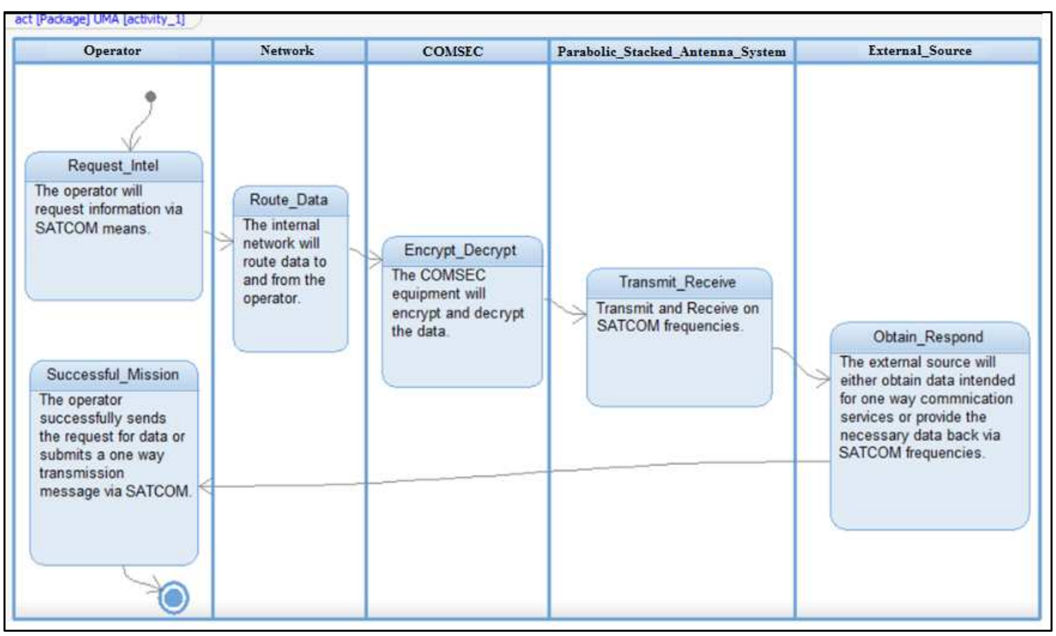


Figure 5 Behavioral Model of the Parabolic Stacked Antenna Sequence Diagram

The reference sequence diagram was created to depict a high level activity flow between the operator and the external source for SATCOM systems. This diagram generalizes the parabolic stacked antenna system where typical concepts of operations are shown. This use case includes the operator requesting desired information from the external source through the operator's internal network, COMSEC devices, and parabolic stacked antenna system.

The sequence diagram shown in Figure 6 displays the events of transmitting and receiving data via the parabolic stacked antenna system. The parabolic stacked antenna would have the capability of utilizing a SATCOM signal. The operator would send and request data while the internal network would encrypt the data using COMSEC devices and sending the data to the consolidated antenna system. The parabolic stacked antenna system converts the Internet Protocol (IP) data into a RF signal via modulation. The RF signal would be encrypted and sent to the distant end with about 500ms latency. The receive signal is obtained by the consolidated antenna system around the same latency, decrypted and demodulated prior to converting the signal to the IP format. The IP traffic would be decrypted and sent to the operator. Latency times are approximations where weather, bandwidth, configurations, assemblies and the type of applications being used would alter these values.

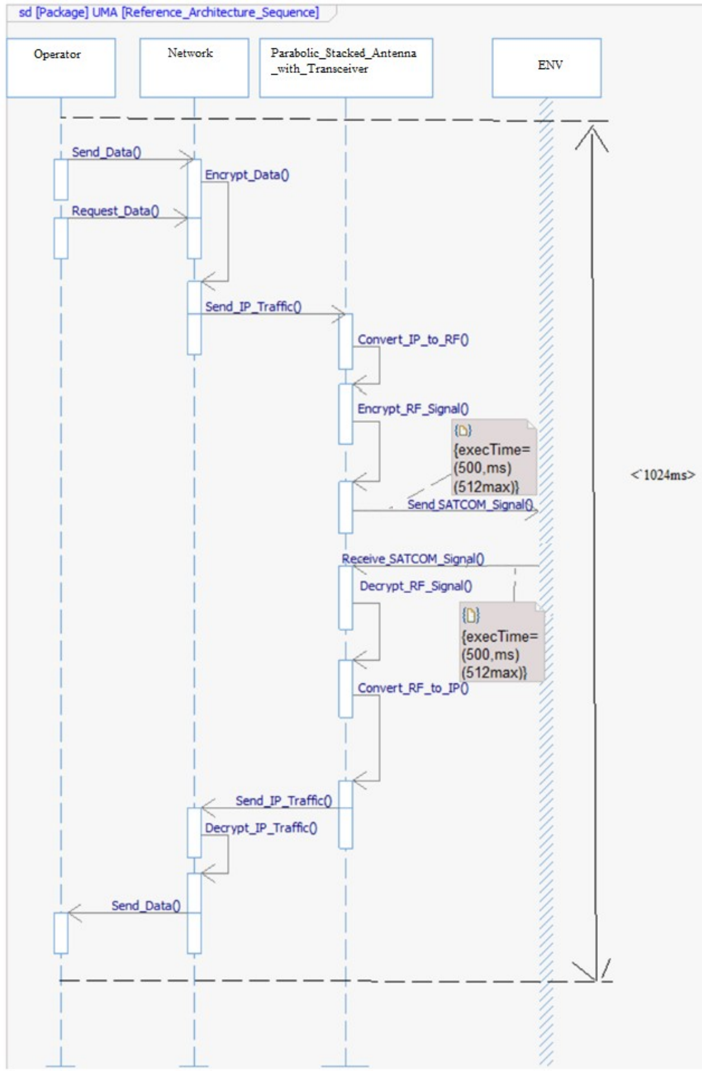


Figure 6 Consolidated Antenna Reference Sequence Diagram

The GBS capability provides high-speed broadcast of large-volume information products such as video, imagery, maps and weather data to deployed tactical operations centers and garrisoned forces worldwide [49]. The land-based platform video distribution source would transmit the streaming video via the consolidated antenna using the Ka band frequency to the WGS satellite. A parabolic stacked antenna could also be used on the land-based platform to perform multiband capabilities. The WGS satellite would forward the streaming video to a shipboard platform using the K band capability of the parabolic stacked antenna configured to receive the required video depicted in Figure 7.

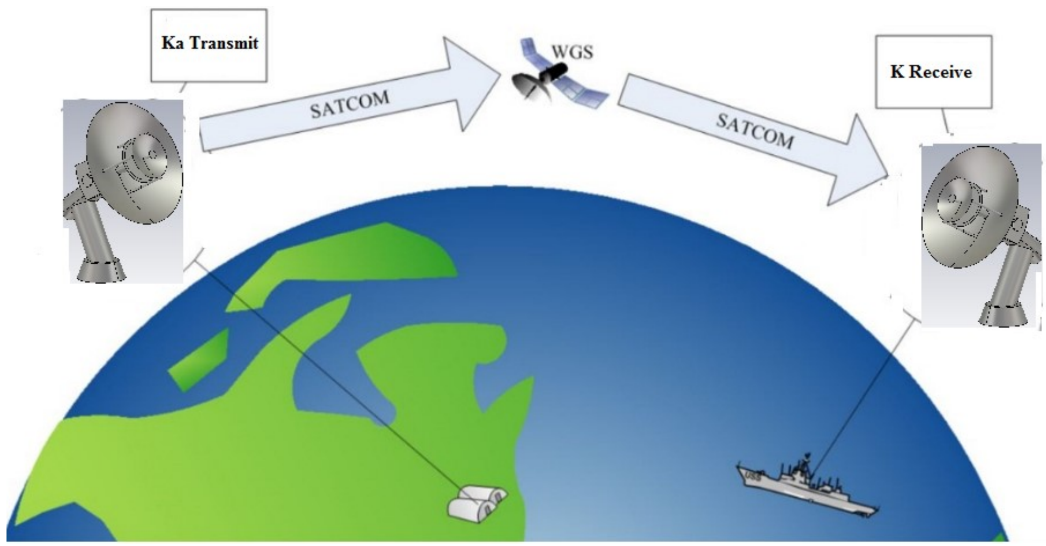


Figure 7 GBS SATCOM Video Transmission OV-1 Diagram

Interactions among the various entities as well as actions that occur that transform inputs to outputs independently is shown in Figure 8. This sequence diagram illustrates video streaming from the source to a distant end via SATCOM. Video feeds are essential when performing a mission to distribute vital intelligence. Observing the sequence diagram to ensure near real time video streaming is being conducted is useful for timing and performance analysis. GBS operates as a one-way broadcast capability supporting timely delivery of video products, unclassified & classified data for mission support and theater info transfer [50].

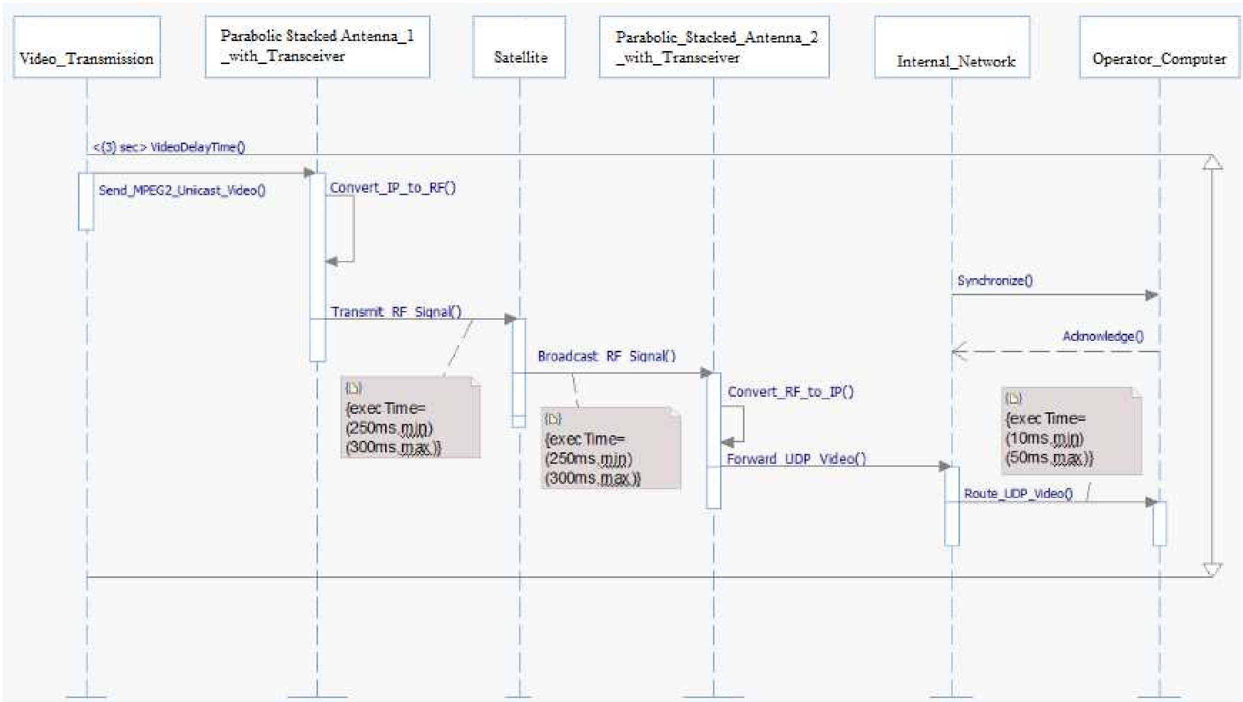


Figure 8 Consolidated Video Transmission Sequence Diagram

The operator at the distant end would configure the parabolic stacked antenna Ka / Ku configuration to track, and acquire the signal from the satellite. The parabolic stacked antenna would acquire the signal to make the connection. Once the connection is made, the parabolic stacked antenna will receive the streaming video. The video would then be distributed through the internal network. The video would be in the User Datagram Protocol (UDP) format for one way reception.

A mission thread was modeled which included a shipboard platform, operations center, and a mobile communications unit. The shipboard platform requested mobile communications data in order to assess battleground intelligence in a remote location. This SHF connectivity between the platforms is shown in Figure 9.

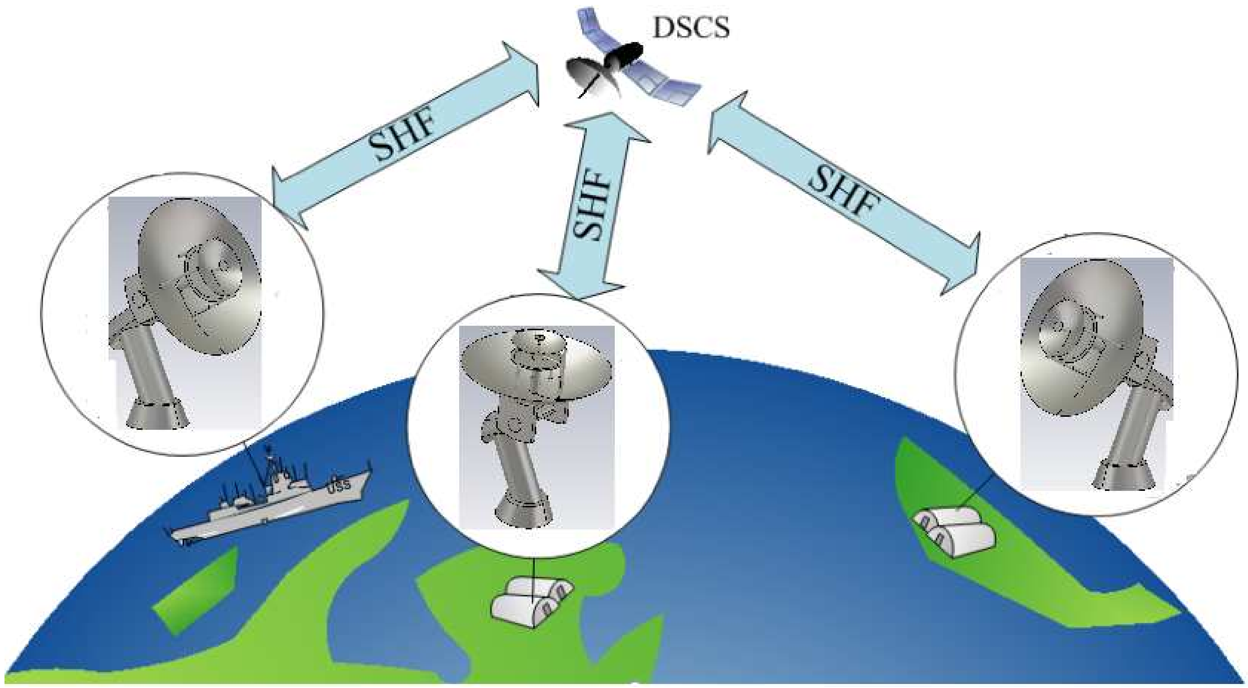


Figure 9 SHF Parabolic Stacked Antenna OV-1

The shipboard platform would send a request to the operations center for intelligence data from a mobile communications unit. The mobile communications unit in this use case is a temporary base set up at a remote location. The operations center would approve or deny the request while notifying the mobile communications unit. The mobile communications unit would acknowledge the request for the data and transmit via SHF back to the operations center. The operations center would forward the mobile communications data to the shipboard platform.

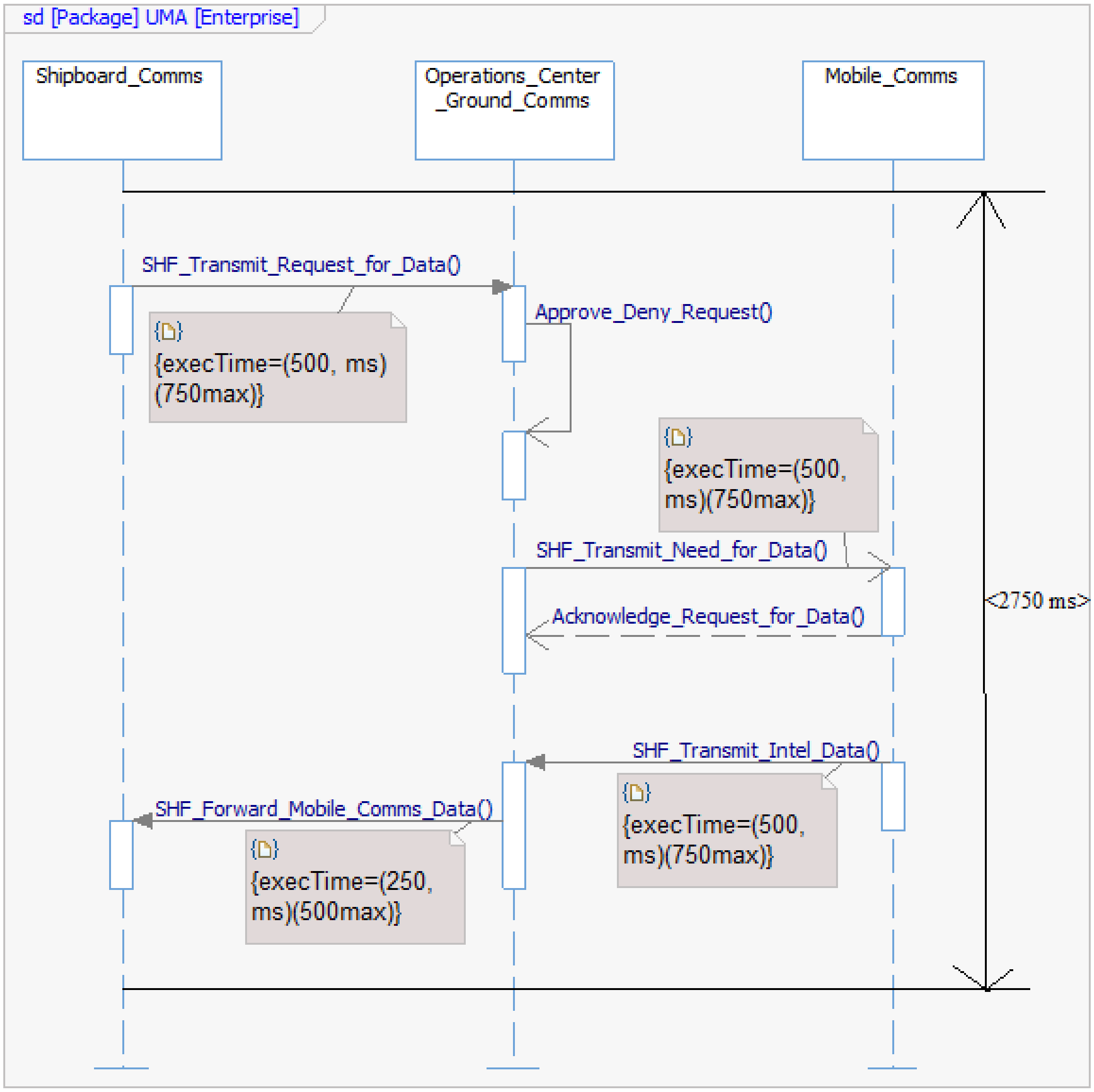


Figure 10 SHF Parabolic Stacked Antenna Sequence Diagram

A sequence diagram showing message exchanges among systems was modeled in Figure 10. This sequence diagram annotated approximate timing aspects involving multiple platforms. The operations center would be the authoritative source to approve or deny a communications transmission request based on mission requirements, bandwidth resources, and prioritization.

3.2 Project Planning and Concept of Operations Development

Project planning is a critical phase where the foundation of guidelines and way forward is presented on the system being developed. Aspects of cost, schedule, performance, and risks are identified along with information how the project will be managed. A project management plan would provide an initial baseline for the expectations of the overall project. A project charter assists with providing a high level overview of the project along with concurrence to have the project move forward. A project charter would include elements such as the need, scope, schedule, cost, stakeholders, roles / responsibilities, assumptions, constraints and risks. This planning phase artifact would be referenced or incorporated into the project management plan.

The need for antenna consolidation on afloat Navy platforms is ongoing where space is limited due to the amount of various antennas staged topside. Consolidating these antennas would free up topside space along with reducing power consumed and the weight that excess antennas provide. Previous efforts have taken place such as the NMT antenna that consolidated multiple antennas that supported EHF, SHF, and GBS capabilities. An approach and design for consolidating existing LoS and SATCOM antennas was researched and an Operational View (OV-1) is depicted in Figure 11 .

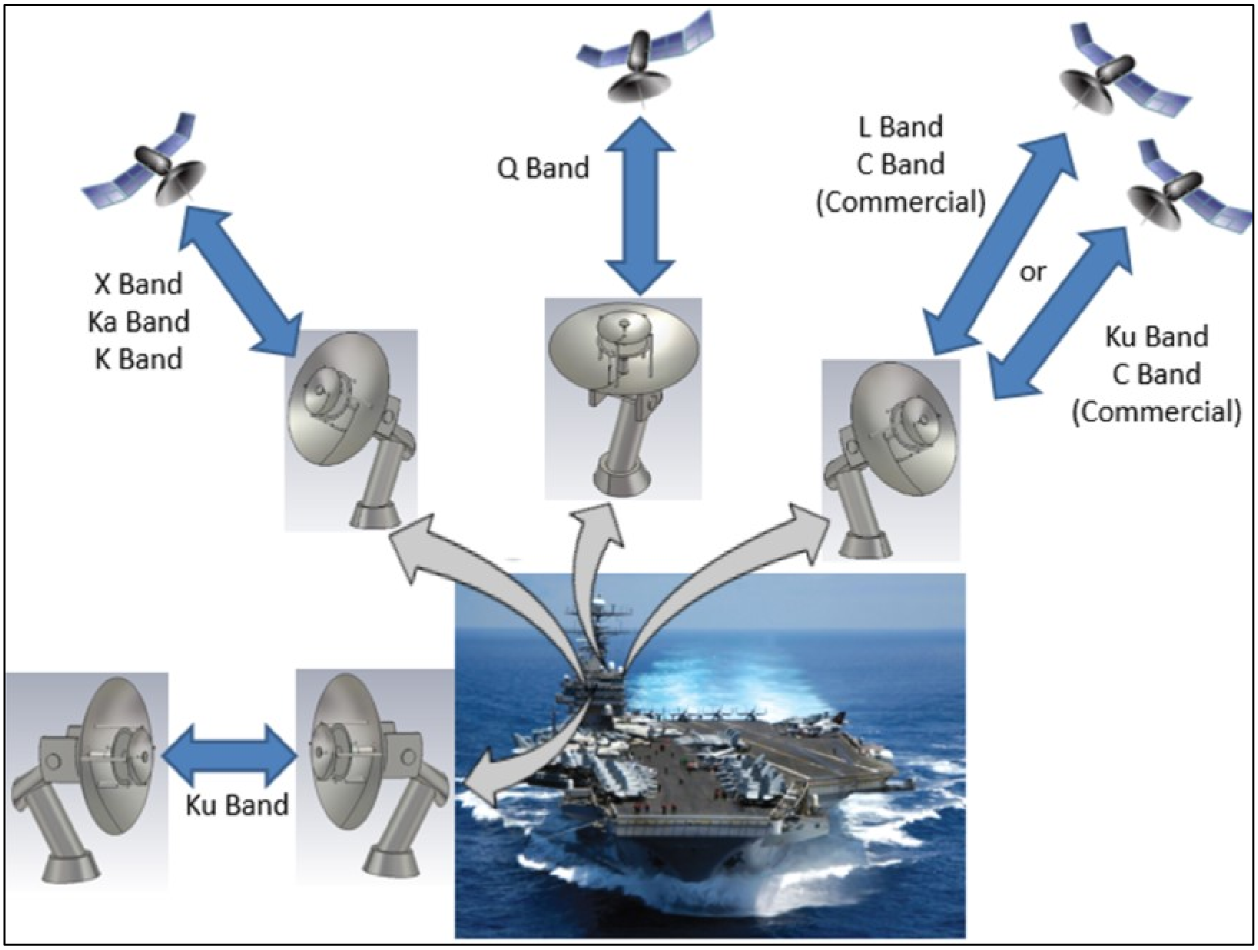


Figure 11 OV-1 Parabolic Stacked Antenna Configuration on U.S. Navy Carrier (after [51])

Project planning for the parabolic stacked antenna involves managing the scope of work. Scope management includes the processes required to ensure the project includes all the work required, and only the work required, to complete the project successfully [52]. Details of tasks required and a methodology for change control management assists with progression of development. A change control process has to be identified early on to address changes in scope. Any change in scope, whether it's adding, removing, or changing requirements have to be documented and agreed upon amongst stakeholders. Without a change control process, the scope of any effort could potentially be derailed. Scope creep occurs during a project where requirements are added by stakeholders which then has a negative effect on cost and schedule with respect to system deliverables. A Work Breakdown Structure (WBS) would assist with defining tasks to accomplish specific deliverables for the system. Practicing scope management would involve planning while collecting requirements, defining the scope, creating the WBS, validating the scope and controlling the scope. Product scope is the details that characterize a system while the project scope details the work performed to deliver the product. Project planning and SE management planning includes the scope of the effort for the design, development and fielding of the system. The SE approach would include identifying RF antennas used on shipboard platforms / tactical environments. Defining specific attributes and characteristics of these RF antennas is necessary to identify commonalities and differences between them. Researching previous RF consolidation efforts would be performed in order to identify constraints encountered by prior efforts. These constraints would define limitations of combining certain RF antennas. SE management planning assists with preparing SE activities throughout the antenna system's life cycle.

Scheduling SE tasks to establish a target is necessary to forecast activities required to develop the parabolic stacked antenna system. The Materiel Solution Analysis phase would last approximately 2 years to include various activities to support the development of the system. These activities provide the foundation for the parabolic stacked antenna system, and provide necessary deliverable documentation needed for follow on process phase initiatives. The Materiel Solution Analysis schedule is shown in Figure 12.

Task Name	Duration	Start	Finish	Prec	Resource Names
Defense Acquisition Strategy (DAS) Process	**8117 days**	**Fri 8/20/21**	**Mon 9/30/52**		
Initial Capabilities Document (ICD)	30 days	Fri 8/20/21	Thu 9/30/21		Eng
Materiel Development Decision (MDD)	0 days	Thu 9/30/21	Thu 9/30/21		
Materiel Solution Analysis	**265 days**	**Fri 10/1/21**	**Thu 10/6/22**		
Develop an preliminary acquisition strategy	30 days	Fri 10/1/21	Thu 11/11/21		Eng
Develop a Technology Development Strategy	30 days	Fri 11/12/21	Thu 12/23/21	5	Eng,Dev
Develop goals for technology	20 days	Fri 12/24/21	Thu 1/20/22	6	PM,Eng,Dev
Alternative Systems Review	0 days	Thu 1/20/22	Thu 1/20/22		
Perform an Analysis of Alternatives	30 days	Fri 1/21/22	Thu 3/3/22	7	PM,Eng,Dev
Develop a draft Capabilities Development Document (CDD)	30 days	Fri 3/4/22	Thu 4/14/22	9	Eng,Dev
Develop a Systems Engineering Plan (SEP)	30 days	Fri 4/15/22	Thu 5/26/22	10	Eng,Dev
Develop Inital Support and Maintenance Concepts (Life - Cycle Sustainment Plan)	45 days	Fri 5/27/22	Thu 7/28/22	11	Eng,Log
Develop the Life-Cycle Signature Support Plan (LSSP)	30 days	Fri 7/29/22	Thu 9/8/22	12	Eng,Log
Understand Research and Development Costs	20 days	Fri 9/9/22	Thu 10/6/22	13	PM,Eng,Dev,Log
Milestone A	0 days	Thu 10/6/22	Thu 10/6/22		
Technology Maturation & Risk Reduction	**321 days**	**Thu 10/6/22**	**Fri 12/29/23**		
Engineering & Manufacturing Development	**1301 days**	**Mon 1/1/24**	**Mon 12/25/28**		
Production and Deployment	**4105 days**	**Wed 1/3/29**	**Tue 9/27/44**		
Operations and Support	5480 days	Tue 9/30/31	Mon 9/30/52		

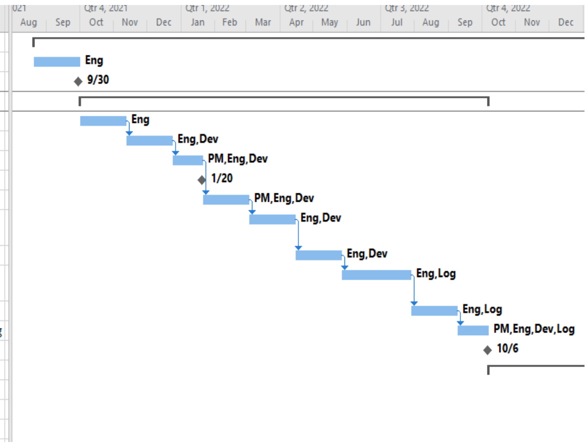
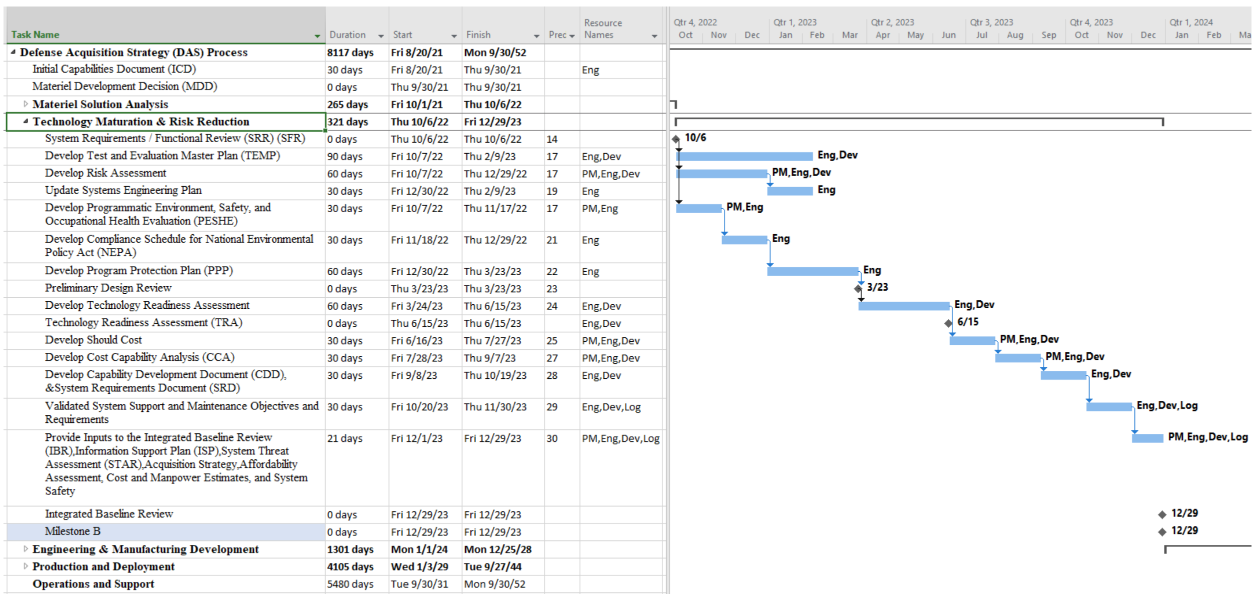


Figure 12 Materiel Solution Analysis Schedule

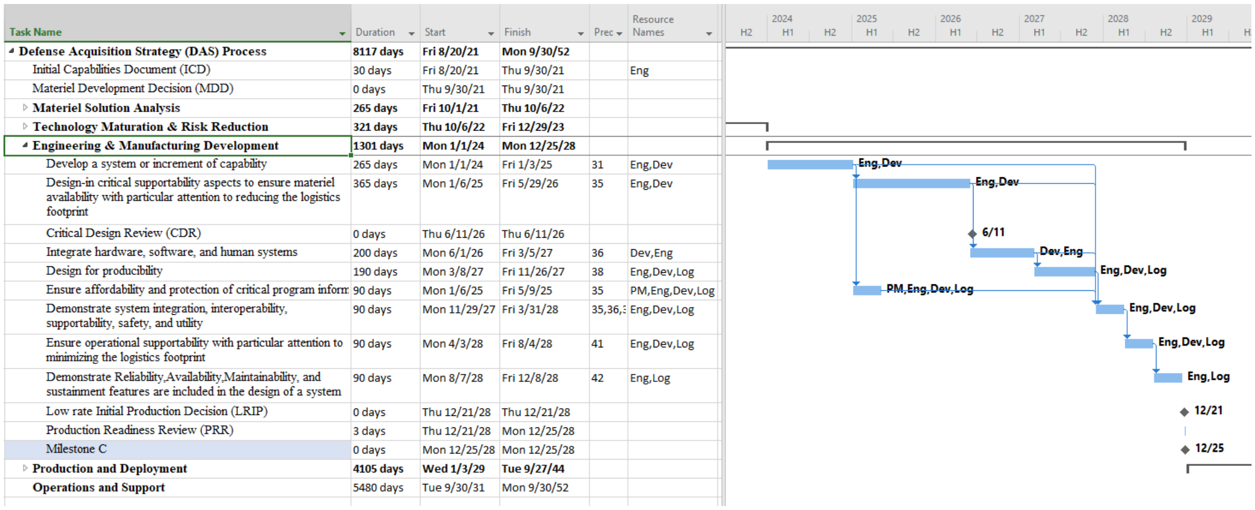
The Technology Maturation and Risk Reduction phase is estimated to be a 2 year effort. Reviewing system requirements to verify that the system is being designed within the specifications would be performed during this phase. Developing a test and evaluation master plan would begin in this phase as well. Producing guidance on how to perform testing allows how the integrated product team would go about testing the system at a high level. Risk management would continue through this phase to identify and mitigate risks. System engineering plan updates would be completed along with developing safety documentation with respect to personnel and the environment. A program protection plan entails how sensitive information is contained along with any cyber security parameters. The PDR would occur to review the design and gain concurrence from stakeholders. Another review would be the Technology Readiness Assessment where the new technology would be analyzed to ensure the technology developed is mature and feasible. Developing life cycle costs would depict estimated costs amongst the phases. The system requirements document and the capability development document captures the system information needed to establish the project to support the effort. Validating system support along with maintenance objective requirements provide input to the integrated baseline review and support plans. Additional inputs would be required for system threat assessments, the overall acquisition strategy, affordability assessments and system safety documentation. The integrated baseline review would occur to establish a collaborative concurrence amongst industry contractor partners on system development. Completing these activities would reach Milestone B as shown in Figure 13.



Task Name	Duration	Start	Finish	Prec	Resource Names
Defense Acquisition Strategy (DAS) Process	**8117 days**	**Fri 8/20/21**	**Mon 9/30/52**		
Initial Capabilities Document (ICD)	30 days	Fri 8/20/21	Thu 9/30/21		Eng
Materiel Development Decision (MDD)	0 days	Thu 9/30/21	Thu 9/30/21		
Materiel Solution Analysis	**265 days**	**Fri 10/1/21**	**Thu 10/6/22**		
Technology Maturation & Risk Reduction	**321 days**	**Thu 10/6/22**	**Fri 12/29/23**		
System Requirements / Functional Review (SRR) (SFR)	0 days	Thu 10/6/22	Thu 10/6/22	14	
Develop Test and Evaluation Master Plan (TEMP)	90 days	Fri 10/7/22	Thu 2/9/23	17	Eng,Dev
Develop Risk Assessment	60 days	Fri 10/7/22	Thu 12/29/22	17	PM,Eng,Dev
Update Systems Engineering Plan	30 days	Fri 12/30/22	Thu 2/9/23	19	Eng
Develop Programmatic Environment, Safety, and Occupational Health Evaluation (PESHE)	30 days	Fri 10/7/22	Thu 11/17/22	17	PM,Eng
Develop Compliance Schedule for National Environmental Policy Act (NEPA)	30 days	Fri 11/18/22	Thu 12/29/22	21	Eng
Develop Program Protection Plan (PPP)	60 days	Fri 12/30/22	Thu 3/23/23	22	Eng
Preliminary Design Review	0 days	Thu 3/23/23	Thu 3/23/23	23	
Develop Technology Readiness Assessment	60 days	Fri 3/24/23	Thu 6/15/23	24	Eng,Dev
Technology Readiness Assessment (TRA)	0 days	Thu 6/15/23	Thu 6/15/23		Eng,Dev
Develop Should Cost	30 days	Fri 6/16/23	Thu 7/27/23	25	PM,Eng,Dev
Develop Cost Capability Analysis (CCA)	30 days	Fri 7/28/23	Thu 9/7/23	27	PM,Eng,Dev
Develop Capability Development Document (CDD), &System Requirements Document (SRD)	30 days	Fri 9/8/23	Thu 10/19/23	28	Eng,Dev
Validated System Support and Maintenance Objectives and Requirements	30 days	Fri 10/20/23	Thu 11/30/23	29	Eng,Dev,Log
Provide Inputs to the Integrated Baseline Review (IBR),Information Support Plan (ISP),System Threat Assessment (STAR),Acquisition Strategy,Affordability Assessment, Cost and Manpower Estimates, and System Safety	21 days	Fri 12/1/23	Fri 12/29/23	30	PM,Eng,Dev,Log
Integrated Baseline Review	0 days	Fri 12/29/23	Fri 12/29/23		
Milestone B	0 days	Fri 12/29/23	Fri 12/29/23		
Engineering & Manufacturing Development	**1301 days**	**Mon 1/1/24**	**Mon 12/25/28**		
Production and Deployment	**4105 days**	**Wed 1/3/29**	**Tue 9/27/44**		
Operations and Support	5480 days	Tue 9/30/31	Mon 9/30/52		

Figure 13 Technology Maturation & Risk Reduction Schedule

The Engineering and Manufacturing Development phase is projected to span over 5 years. This is a reduction of 3 years compared to the NMT project. Reducing schedule by 33% can be forecasted by using Agile methodologies during the Engineering and Manufacturing Development phase. A minimum range of a 9% to a median range of 33% schedule reduction was realized from return on investment data gathered from over 300 scholarly articles [53]. The 33% schedule reduction is used for the Engineering and Manufacturing Development phase for the parabolic stacked antenna development to set a benchmark for project planning. Cost savings would be realized with the amount of time required to deliver being reduced. During this phase, the system is being designed and developed. Integration of various hardware, software and human systems occur to produce the desired capabilities. Demonstrating the integration, interoperability, supportability, safety and utility of the system through simulation and prototypes allow stakeholders to observe system operation. Producibility is assessed to ensure the complexity to manufacture the system is as low as possible. Determining the producibility complexity will ensure that the system is affordable to produce. In addition to affordability, supportability of the system would be assessed for operations and sustainment of the system. Demonstrating RAM of the system provides insight to overall life cycle costs and sustainment needs. A Critical Design Review (CDR) would be performed within the Engineering and Manufacturing Development phase to gain concurrence to proceed to fabricate the design and create a prototype. The system baseline would be established at the CDR and entail initial hardware specifications. The Production Readiness Review (PRR) provides approval that the design is ready to be manufactured. A Low Rate Initial Production (LRIP) can be agreed upon to begin producing an initial set of systems. These activities would satisfy requirements needed to meet Milestone C as shown in Figure 14.



Task Name	Duration	Start	Finish	Prec	Resource Names
Defense Acquisition Strategy (DAS) Process	**8117 days**	**Fri 8/20/21**	**Mon 9/30/52**		
Initial Capabilities Document (ICD)	30 days	Fri 8/20/21	Thu 9/30/21		Eng
Materiel Development Decision (MDD)	0 days	Thu 9/30/21	Thu 9/30/21		
Materiel Solution Analysis	**265 days**	**Fri 10/1/21**	**Thu 10/6/22**		
Technology Maturation & Risk Reduction	**321 days**	**Thu 10/6/22**	**Fri 12/29/23**		
Engineering & Manufacturing Development	**1301 days**	**Mon 1/1/24**	**Mon 12/25/28**		
Develop a system or increment of capability	265 days	Mon 1/1/24	Fri 1/3/25	31	Eng,Dev
Design-in critical supportability aspects to ensure materiel availability with particular attention to reducing the logistics footprint	365 days	Mon 1/6/25	Fri 5/29/26	35	Eng,Dev
Critical Design Review (CDR)	0 days	Thu 6/11/26	Thu 6/11/26		
Integrate hardware, software, and human systems	200 days	Mon 6/1/26	Fri 3/5/27	36	Dev,Eng
Design for producibility	190 days	Mon 3/8/27	Fri 11/26/27	38	Eng,Dev,Log
Ensure affordability and protection of critical program inforn	90 days	Mon 1/6/25	Fri 5/9/25	35	PM,Eng,Dev,Log
Demonstrate system integration, interoperability, supportability, safety, and utility	90 days	Mon 11/29/27	Fri 3/31/28	35,36,3	Eng,Dev,Log
Ensure operational supportability with particular attention to minimizing the logistics footprint	90 days	Mon 4/3/28	Fri 8/4/28	41	Eng,Dev,Log
Demonstrate Reliability,Availability,Maintainability, and sustainment features are included in the design of a system	90 days	Mon 8/7/28	Fri 12/8/28	42	Eng,Log
Low rate Initial Production Decision (LRIP)	0 days	Thu 12/21/28	Thu 12/21/28		
Production Readiness Review (PRR)	3 days	Thu 12/21/28	Mon 12/25/28		
Milestone C	0 days	Mon 12/25/28	Mon 12/25/28		
Production and Deployment	**4105 days**	**Wed 1/3/29**	**Tue 9/27/44**		
Operations and Support	5480 days	Tue 9/30/31	Mon 9/30/52		

Figure 14 Engineering and Manufacturing Deployment Schedule

Implementing Agile methodologies during the Engineering and Manufacturing Deployment phase can reduce the time and costs during this particular phase. Agile is proven to save on time and costs with software efforts. Performing agile practices reduces overall schedule by a median of 33% compared to the traditional waterfall approach [54]. With the Framework, SEI cut initial planning time by 28 percent [55]. The Fitbit company reported that velocity has increased 33 percent in 2016 [56]. Agile strives to reduce documentation to useful artifacts vice extensive documentation that has little value. The goal on agile projects is to keep documentation as simple as possible, relying on roadmaps, overviews and concepts rather than enterprise-focused details [57].

Agile software development is based on an incremental, iterative approach. Instead of in-depth planning at the beginning of the project, Agile methodologies are open to changing requirements over time and encourages constant feedback from the end users [58]. Agile focuses on small, frequent capability releases, valuing working software over comprehensive documentation, responding rapidly to changes in operations, technology, and budgets, actively involving users throughout development to ensure high operational value [59]. Releasing software in increments allow the customer to evaluate, provide feedback and allow developers to make adjustments. This strategy decreases the cost of overall changes made since the changes are done early on rather than when an entire build is released.

The Agile Manifesto was created by seventeen developers and representatives from areas such as Extreme Programming (XP), Scrum, Dynamic Systems Development Method (DSDM), Adaptive Software Development, Crystal, Feature-Driven Development (FDD) and Pragmatic Programming on February 11-13 of 2001. The goal was to find an alternative to documentation driven, heavyweight software development processes [60]. The four values and twelve principles that the agile manifesto included is listed in Table 5 below.

Table 5 Agile Manifesto [60]

Values	
1	Individuals and interactions over processes and tools
2	Working software over comprehensive documentation
3	Customer collaboration over contract negotiation
4	Responding to change over following a plan
Principles	
1	Our highest priority is to satisfy the customer through early and continuous delivery of valuable software.
2	Welcome changing requirements, even late in development. Agile processes harness change for the customer's competitive advantage.
3	Deliver working software frequently, from a couple of weeks to a couple of months, with a preference to the shorter timescale.
4	Business people and developers must work together daily throughout the project.

5	Build projects around motivated individuals. Give them the environment and support they need, and trust them to get the job done.
6	The most efficient and effective method of conveying information to and within a development team is face-to-face conversation.
7	Working software is the primary measure of progress.
8	Agile processes promote sustainable development. The sponsors, developers, and users should be able to maintain a constant pace indefinitely.
9	Continuous attention to technical excellence and good design enhances agility.
10	Simplicity--the art of maximizing the amount of work not done--is essential.
11	The best architectures, requirements, and designs emerge from self-organizing teams.
12	At regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behavior accordingly.

The Agile Manifesto helped with creating a mindset for software development. Different frameworks and methods can be used with this mindset to deliver software to the customer fast and efficiently. Agile refers to various approaches such as Kanban, Scrum, XP, FDD, DSDM, ScrumBan, and Agile Unified Process (AUP). A method is determined by what is best suited for the team and the task involved. Kanban and agile are descendants of lean where they have shared attributes. This shared heritage is very similar and focuses on delivering value, respect for people, minimizing waste, being transparent, adapting to change and continuously improving [60]. Figure 15 depicts agile approaches for software development.

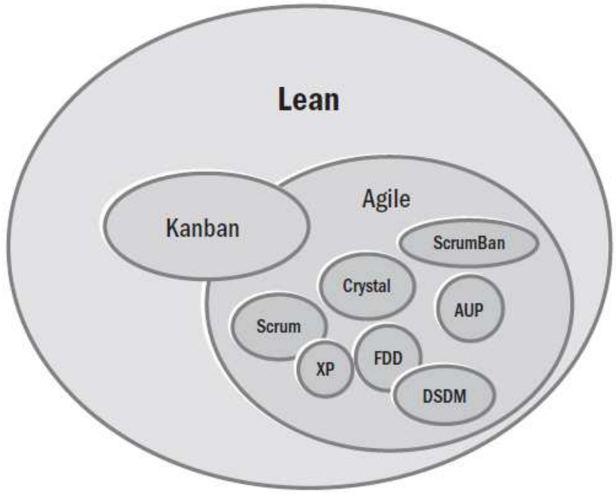


Figure 15 Agile Approaches [60]

Lean provides concepts such as eliminating waste, decreasing the amount of work queues and delivering as much value as possible through value streams. Eliminating waste would include assessing a particular process, and improving process areas to reduce the amount of work exerted to accomplish a task which provides more value to the customer. Lean focuses on reducing wasteful process steps and potentially reallocate resources to other quality work. Value is determined by the customer with respect to the product or service being delivered and being whether it is executed correctly. Identifying steps within a process while determining if that step provides value and the customer is willing to pay for it is essential in reducing waste. Inefficiencies in process areas can include information processing where automation could resolve excessive time being spent to complete a task. Redundant process steps or steps that doesn't add value to the overall product or service should be reduced to save on time and costs. Personnel and facility resources are also areas that can be assessed to reduce or eliminate waste. Bottlenecks that hinder the flow of the process should be identified and assessed for potential process improvement initiatives. The process should move in a continuous fashion and as fast as possible.

Kanban is a method for defining, managing, and improving services that deliver knowledge work, such as professional services, creative endeavors, and the design of both physical and software products [61]. Kanban improves communication and increases efficiencies within a project through participation on a Kanban board. Kanban utilizes a visual board that has cards that show tasks that can be worked on to deliver features to the customer. The visual board depicts what tasks are in the backlog, are being working on, is in testing and is complete. These tasks that are written on cards in the form of user stories move across the visual board to depict progress from the beginning to the end. Team members are assigned on each task card to identify the individual or individuals working the task. An example would include a Kanban board containing columns for ready, develop and unit test, dev-done, system test and done as shown in Figure 16. This methodology provides a visual depiction of status on particular tasking. Metrics can be derived from Kanban such as cycle time of tasks, delivery rate and work in progress limitations.

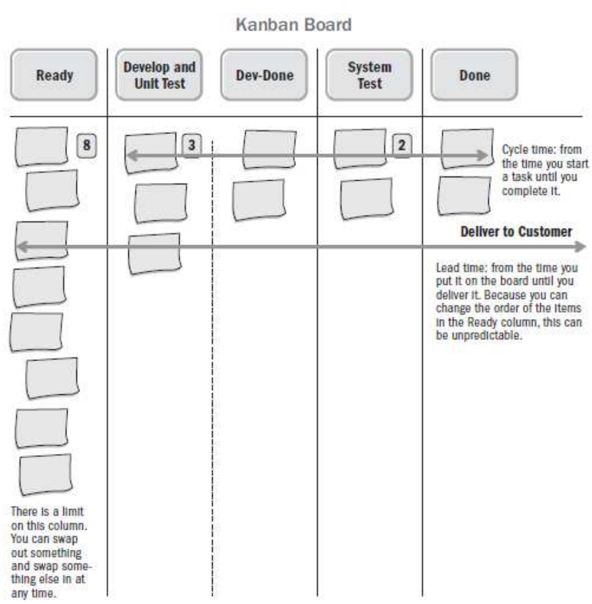


Figure 16 Kanban Board Example [61]

Scrum is a framework within which people can address complex adaptive problems, while productively and creatively delivering products of the highest possible value [62]. An agile scrum team consists of main roles such as the product owner, scrum master and development team. The product owner is the authoritative source that prioritizes / manages the backlog along with communicating with the development team on the progress of their work. The scrum master supports the product owner and ensures agile processes are being followed by the team. The development team self organizes and works together to complete required tasks. A sprint is a short, time-boxed period when a scrum team works to complete a set amount of work [63]. Breaking down large sized tasking into smaller manageable sprints allows for products to be released faster with the intent of receiving feedback sooner. Receiving feedback sooner allows changes to the product to be made sooner which makes change management more efficient. Waiting to receive feedback once a product is fully designed and finished potentially creates a costly change modification. Sprint planning begins with the team getting together to strategize how they will be able complete a particular task and deliver a product. This planning would include the amount of time the task is going to take, the objective, how the task is going to be complete, who will be completing the task, and any dependencies required for the task to be completed. A product backlog would contain a prioritized list of tasks that need to be completed. This backlog of tasks is pulled by the team when the team members have capacity for it. These tasks are called user stories which describes a user requirement. An epic is a group of stories which represent a larger task. An initiative is a group of epics that focuses on a common objective. A theme is the overarching focus area that represents a high-level effort. The daily scrum occurs in the beginning of the day where the team, scrum master, and product owner discuss the tasking they completed the previous day, the tasks they will be working on that day and if there are any issues or blockages that are preventing them from making progress. A sprint review is conducted to depict the work the team has produced for feedback and recognition. The sprint retrospective allows the team to discuss what went well, what didn't go so well and what areas needs improvements. The product owner owns the product backlog while the sprint backlog is owned by the team. These backlogs are prioritized and adjusted by the respective owners. The scrum and sprint cycle is shown in Figure 17.

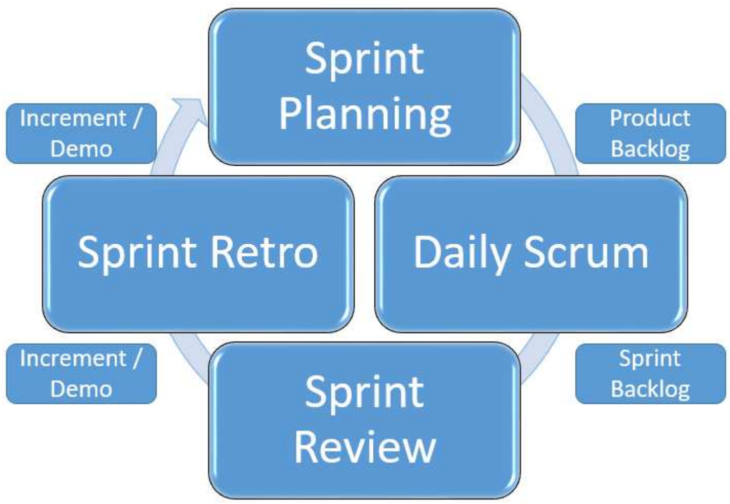


Figure 17 Scrum Sprint Cycle (after [64])

Development Operations (DevOps) is another methodology that promotes a collaborative environment for developers, operators, and quality assurance personnel to work together. This type of environment increases communication and builds trust between developers and operators. Having this collaborative environment allows operator personnel to provide direct feedback to developers early in the DevOps process. Defining and automating these processes decreases the time for any software changes / releases. This collaborative environment assists with depicting the lifecycle of the software from development to production. Quality assurance is an important role that not only inspects the quality of the product but the quality of the processes to provide the most efficient product as well. The DevOps methodology provides automated testing, continuous integration, and continuous delivery. Deploying the software and receiving feedback improves the software and the deployment of this software. Reducing rework and overhead will reduce time which in turn saves on overall costs.

Scaled Agile Framework (SAFe) is for large organizations that operate at the portfolio, program and team levels. With the metrics that SAFe provides combined with regularly reporting, velocity has increased 33 percent [65]. With the Framework, the company SEI also cut initial planning time by 28 percent, realized $30M in savings, shipped more than 350 production releases, completed 22 PSIs over 125 sprints and delivered 250 features [55]. Organizations have realized these benefits at a high level where lower levels within the organization would perform Agile methods to deliver. The team level follows agile methods that deliver working software releases over various sprints. The team meets every day during daily scrums as well as during spring planning, sprint reviews, and sprint retrospective meetings. The program level consists of multiple teams that deliver a larger software product. Program Increment (PI) Planning is a cadence-based, face-to-face event that serves as the heartbeat of the Agile Release Train (ART), aligning all the teams on the ART to a shared mission and Vision [66]. PI planning consists of teams that get together to discuss the overall vision, business context, roadmap, features of the product and the way forward. Establishing SAFe at a high level promotes collaboration amongst multiple projects with multiple stakeholders which creates easier integration in efforts to deliver a product faster and cheaper.

There are pros and cons for both waterfall and Agile methodologies. Using a waterfall methodology such as the DAS process delineates schedule milestones. This can be used to better estimate costs and depict a predictable schedule. Each phase of the waterfall requires specific deliverables in order to proceed to the next phase which is typically determined by a review gate. The waterfall methodology specifies certain document deliverables that are necessary to create historical artifacts for future projects to use as a guide and to adopt lessons learned. These documented deliverables provide updates to stakeholders on the progression of the project itself. The waterfall method is well known throughout industry which would decrease the learning curve for managing project efforts. The benefits of using Agile includes the project being flexible and able to adapt due to shorter development cycles. These shorter development cycles allow for stakeholder feedback to be received earlier on. This feedback would allow for changes to be made immediately rather than later on which would potentially cause delay and increase cost of the overall effort. Due to engineering a solution in increments via Agile sprints, unit tests can be administered which verifies the overall solution. Quality is then increased due to the cycle of engineering tests performed at each increment. In addition to a quality product, collaboration amongst stakeholders is practiced throughout system development which increases productivity.

Agile unit tests allow engineering efforts to be verified and possibly adjusted with the early phases of the system lifecycle. The waterfall approach has the potential to inadequately test a product due to stringent schedule milestones. Inadequate testing can lead to a faulty system when fielded. Tests that fail early on can be recovered easier using the Agile approach since a failed test can be evaluated early on in development rather than producing and testing a larger deliverable using the waterfall approach. Being able to change and catch issues as early as possible based on stakeholder feedback can save costs and time using the Agile approach. The Agile approach is acknowledged to provide rapid delivery of increments which would decrease delivery times. The Agile approach increases stakeholder collaboration which increases overall productivity, but in turn requires the commitment of time amongst stakeholders. The waterfall approach does have benefits by having predictive schedule milestones with associated documented deliverables. Being able to predict engineering efforts using the waterfall method enables easier budgeting for overall efforts. Documented deliverables within a waterfall method demonstrates progress made to stakeholders along with benefiting future endeavors of similar projects. The waterfall approach requires gathering requirements early on which has the potential to create risk to cost and schedule if a change is needed later on. The waterfall approach is well known and practiced throughout industry while the Agile method may require additional training and buy in from stakeholders.

A combination of both waterfall and Agile methods is recommended to develop and deploy a parabolic stacked antenna. The waterfall approach would be used to provide an overall predicted schedule with an estimated budget. This estimated budget and time line is necessary for DoD programs to allocate necessary resources for forecasted operational requirements such as replacement of end of life systems and system consolidation efforts. Documentation requirements shall be considered and tailored out to include vital information critical to project success and future endeavors. Agile methods shall be used during early phases of the system life cycle to include modeling, simulation, software development and integration activities. Stakeholder commitment would have to be established early on by mutually acknowledging the benefits of Agile and learning Agile methodologies.

The DoD instruction 5000.02 specifies management strategies and tailoring projects to meet hardware and software product needs. A hybrid waterfall and Agile methodology can provide much benefit. Hybrid approaches are introduced to account for parallel efforts regarding hardware and software design and development. Software development would have to align with the hardware being developed in order to have successful integration prior to Milestone C. Various software builds would be planned based on the features required for the overall system. During the technology maturation & risk reduction phase software would begin to be developed in increments. The Engineering & Manufacturing Development phase would incorporate multiple software builds to be incorporated and tested with the hardware platform. Later software releases would occur during the production and deployment phase for any updates required when feedback was received when the initial units were fielded. Figure 18 depicts a hybrid hardware / software DAS process which does not depict updates during the operations and support phase of the life cycle.

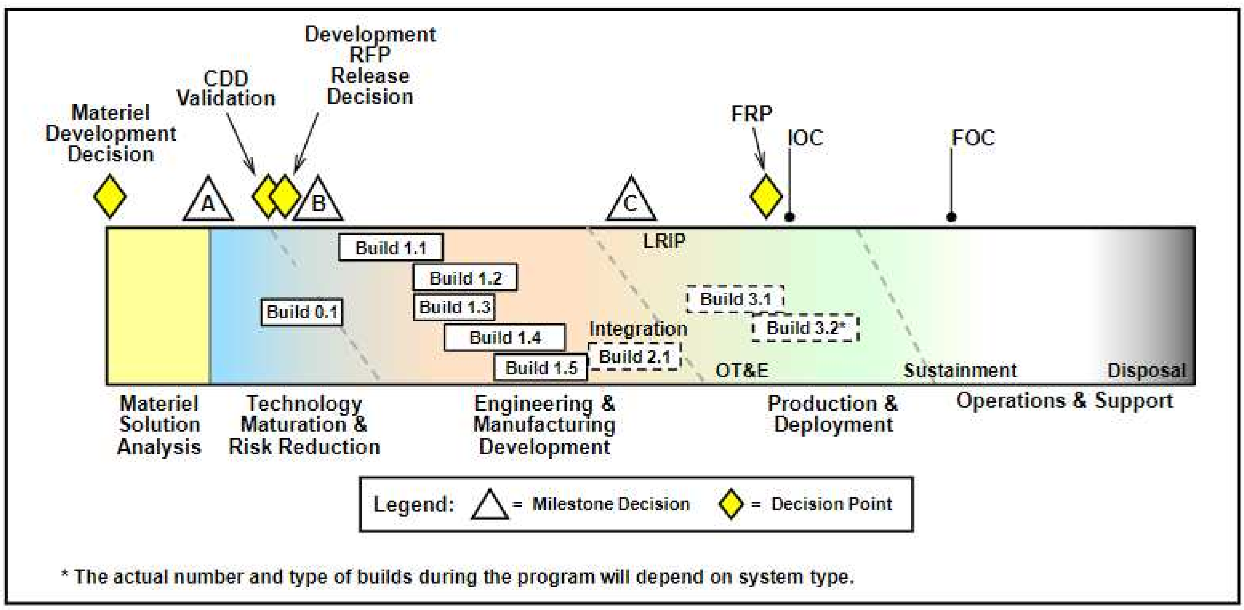


Figure 18 Hybrid Program [67]

Software and hardware updates would be performed during the operations and support phase. These updates would be initiated by cyber security needs, RAM events or additional capability features that are introduced over time. Disadvantages of the waterfall process includes any new requirements or miscommunications of requirements will cost more by having to restart the development process. Agile allows programmers to develop and provide prototypes to the customer rapidly which gains immediate feedback which in turn reduces costly change requests. The customer can provide feedback to the prototypes and the developers can make adjustments as required.

Incorporating MBSE with Agile methods decreases the amount of time for design. Releasing simulation results early on promotes obtaining sponsor feedback early on. By receiving feedback from the customer early on, the design can continue or any changes that need to occur can be made with minimal impact. If an iterative agile approach is not practiced, there is a chance for increased risk that a major change may be required after the initial design is completed. Simulations assist with learning about the system itself. By testing and validating system characteristics early, models facilitate timely learning of properties and behaviors, enabling fast feedback on requirements and design decisions [68]. During Program Increments (PI), simulations can be produced to obtain results for further analysis. Figure 19 depicts MBSE incorporated within an Agile fashion.

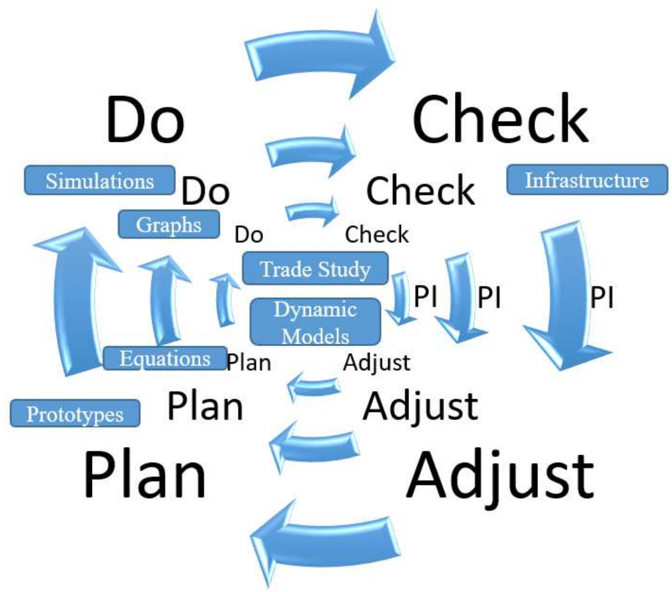


Figure 19 Models and Learning Cycles (after [68])

MBSE supports traceability, quality assurance, compliance verification, test results for analysis / acceptance and depictions for interlinked dependencies. Producing MBSE models and simulations for review while performing agile practices promote feedback to make any necessary adjustments early on. Integrating the physical and virtual worlds validates virtual models and helps engineers improve system analysis, better predict failures or downtime, and provide for more accurate maintenance schedules [68]. Incorporating MBSE within an Agile framework reduces the amount of time to develop and deliver designs.

Executing the DoD's DAS process with respect to DoDI 5000.02 can be challenging when incorporating Agile methodologies. Typical system engineering technical reviews can be replaced with more frequent small reviews. Greater frequency allows key decision makers and other stakeholders to become more familiar and comfortable with processes in the Agile environment, which enables a more collaborative and productive review process [59]. The same amount of engineering rigor is applied and allows for more frequent feedback in order to reduce the likelihood of costly change requests. A change made early on can significantly be less costly and less time consuming than a change made further down the process. Figure 20 depicts the correlation between the DAS process and Agile methodologies.

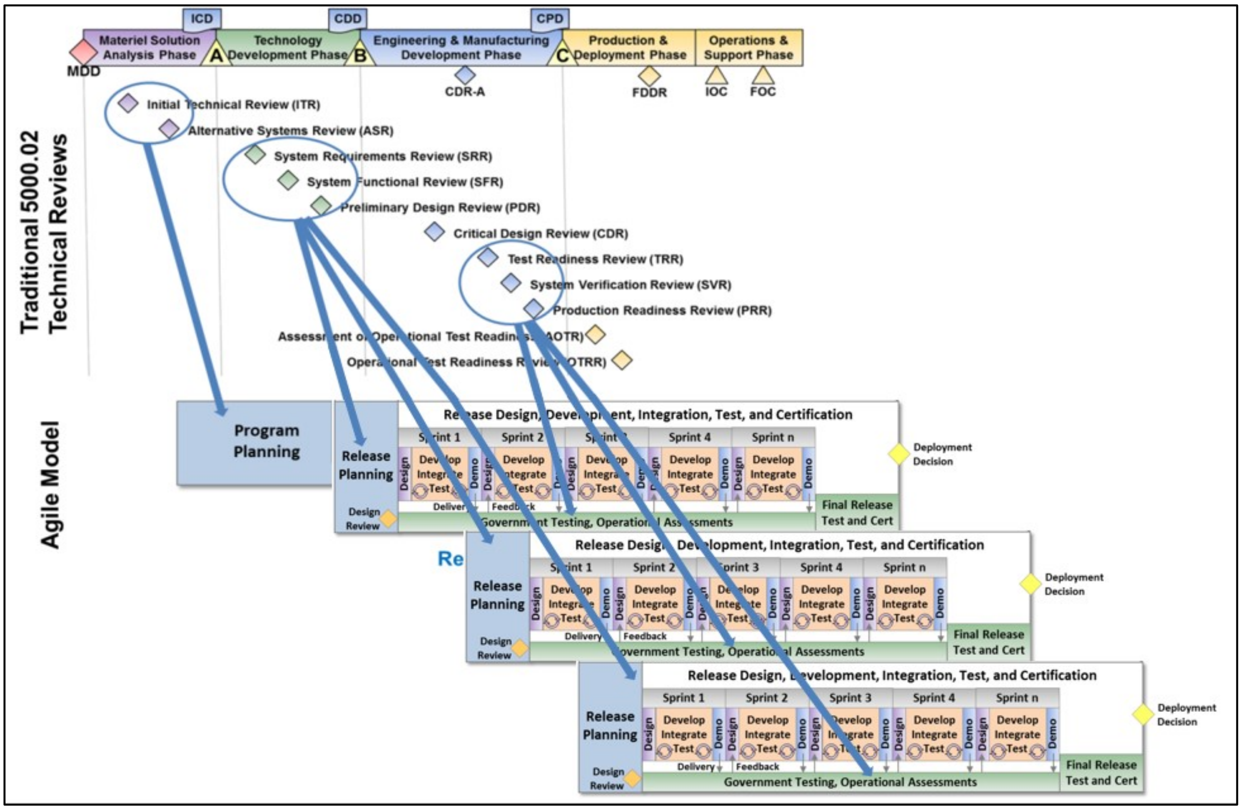


Figure 20 DAS Process WRT Agile Methodologies [59]

Incorporating Agile methodologies within the DAS process can increase key stakeholder collaboration, steer the direction the program is going and reduce time and cost with early change requests. The waterfall approach provides a predictive schedule with a budget that can be requested for in advance. Engineering rigor will still be in place by executing a hybrid approach using waterfall and Agile methods. Cost and time savings can be realized by receiving stakeholder feedback early on and making changes sooner than later. These cost and time savings can also be realized by incremental testing using Agile practices which would capture issues early on as well as increasing the quality of the system delivered.

The Production and Deployment phase would last for 8 years where the systems would be manufactured and fielded during that time frame. This is a decrease of 3 years from the NMT program's production and deployment schedule. Reducing planned procurement actions required for additional spares and antenna upgrades by procuring them in advance would assist with decreasing the scheduled phase. Lessons learned and implementation of lean process improvement initiatives allows for the reduction of the amount of years producing and deploying systems. During this phase, various updates are implemented such as the product baseline, test and evaluation plan, life cycle sustainment plan, safety plans, system engineering plan and cost data for budgeting purposes. The Full Rate Production Decision review takes place to obtain concurrence from stakeholders to proceed with manufacturing the systems at a large scale. Based off of lessons learned and adjustments made after the initial set of systems were produced during the LRIP, more refined systems are produced at a more efficient rate. The Production and Deployment schedule is show in Figure 21.

Task Name	Duration	Start	Finish	Prec	Resource Names
Defense Acquisition Strategy (DAS) Process	**8117 days**	**Fri 8/20/21**	**Mon 9/30/52**		
Initial Capabilities Document (ICD)	30 days	Fri 8/20/21	Thu 9/30/21		Eng
Materiel Development Decision (MDD)	0 days	Thu 9/30/21	Thu 9/30/21		
Materiel Solution Analysis	**265 days**	**Fri 10/1/21**	**Thu 10/6/22**		
Technology Maturation & Risk Reduction	**321 days**	**Thu 10/6/22**	**Fri 12/29/23**		
Engineering & Manufacturing Development	**1301 days**	**Mon 1/1/24**	**Mon 12/25/28**		
Production and Deployment	**4105 days**	**Wed 1/3/29**	**Tue 9/27/44**		
Update Product Baseline	180 days	Wed 1/3/29	Tue 9/11/29	45FS+6	PM,Eng,Dev,Log
Update Test and Evaluation Plan	180 days	Wed 1/3/29	Tue 9/11/29	45FS+6	Eng,Dev
Conduct a Risk Assessment	4053 days	Wed 1/3/29	Fri 7/15/44	45FS+6	PM,Eng,Dev,Log
Update the Life-Cycle Sustainment Plan	180 days	Wed 1/3/29	Tue 9/11/29	45FS+6	Eng,Log
Ensure Programmatic Environment, Safety, and Occupational Health Evaluation (PESHE)	30 days	Wed 1/3/29	Tue 2/13/29	45FS+6 days	Eng,Log
Compliance ScheduleforNational Environmental Policy Act (	30 days	Wed 1/3/29	Tue 2/13/29	45FS+6	Eng,Log
Update the Systems Engineering Plan (SEP)	180 days	Wed 1/3/29	Tue 9/11/29	45FS+6	Eng
Provide Inputs to Cost and Manpower Estimate	261 days	Wed 1/3/29	Wed 1/2/30	45FS+6	PM,Eng
Update System Safety Analyses to include finalizing hazard :	261 days	Wed 1/3/29	Wed 1/2/30	45FS+6	Eng
Full Rate Production Decision Review (FRDR)	0 days	Mon 9/30/30	Mon 9/30/30		
Produce and Deploy Antenna Systems	3652 days	Mon 9/30/30	Tue 9/27/44	57	
Operations and Support	5480 days	Tue 9/30/31	Mon 9/30/52		

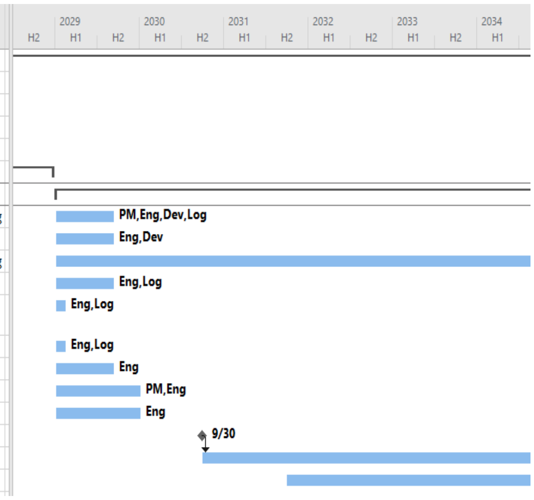


Figure 21 Production and Deployment Schedule

The Operations and Support phase spans out for 22 years which will be the life of system, and is equivalent to the life span of the NMT system. This phase will begin after the system is fielded and operational. System operations along with maintenance and upgrades are performed to meet mission requirements. Help desk support would be available within this phase to assist with issues that surface during the life of the system. Metrics would be captured on issues encountered to help alleviate recurring problems. Training would be provided during the operations and support phase to enable system users to operate and maintain the system. Upgrades and updates would be deployed or installed by SMEs based on complexity. Recurring system checks are necessary to ensure the system is maintained and fully operational.

Average costs for the Technology Maturation & Risk Reduction phase is estimated at $5M per year of RDT&E funding over 2 years based off of the NMT system cost data. The Engineering & Manufacturing Development phase estimated at about $69.9M per year for RDT&E funding over 8 years and $61.6M per year for procurement funding over a year. The Production and Deployment phase had an estimated average value of $21.3M per year of RDT&E funding over

14 years and $72.6M per year of procurement funding over 18 years. The Production and Deployment phase introduced Operating and Sustainment costs which began once the systems were fielded. Using the average $87.6k per system fielded cost value the costs for performing operation and sustainment tasks would reach $21.9M per year when 250 systems were fielded.

The estimated life cycle cost to develop and field the parabolic stacked antenna would be $2227.2M which is $419.2M less than the NMT system. The NMT program had 2 years for the Technology Maturation and Risk Reduction phase, 8 years for the Engineering & Manufacturing Development phase, and 18 years for the Production and Deployment phase. The Operations and Support phase overlaps a portion of the Production and Deployment phase and continues for 22 years which is approximately the life the NMT system. A recommended approach would include utilizing key personnel that have been part of the NMT, CBSP and SDT programs to review lessons learned and implement continuing process improvement recommendations to reduce the amount of time to develop and field the parabolic stacked antenna. Implementing Agile methodologies would reduce engineering costs and time lines by 33% which would potentially reduce the 8 year amount that the NMT project operated within to approximately 5 years. The Production and Deployment phase would be reduced by reducing the planned procurement actions required for additional spares and antenna upgrades. Planning for shipboard availability and having the personnel available to execute fielding actions is also essential for reducing costs and time. Reduction of times would include reducing the Engineering & Manufacturing Development phase by 3 years, and reducing the Production and Deployment phase by 3 years as well. The Technology Maturation and Risk Reduction phase will be kept at 2 years and the Operations and Support phase will be kept at 22 years to account for the life of the parabolic stacked antenna system as well. Using average values of costs by the NMT program per year and per phase the approximate costs were slated for each phase increment. Due to the reduction of time, and a phased system deployment approach cost savings were realized. The Technology Maturation & Risk Reduction phase would endure RDT&E costs of $10M, and the Engineering & Manufacturing Development phase would endure RDT&E costs of $349.5M. The Production and Deployment phase would endure RDT&E costs of $395.4 and $1089M of procurement costs. The RDT&E costs during the production and deployment phase will support continuous improvement efforts required with the system. The costs for the operations and support phase would be $383.3M which is lower than the previous NMT program's budget due to the amount of systems fielded at a slower rate. The more systems fielded initially early on in the operations and support phase the more costs are required to perform operations and support tasks. The approximate life cycle costs for the parabolic stacked antenna system is shown in Table 6.

Table 6 Approximate Life Cycle Costs for the Parabolic Stacked Antenna System

Year	RDT&E Costs	Procurement Costs	Operations and Sustainment Costs	Systems Ordered QTY	Systems Fielded Per Year	Process Phase	
2021	-	-	-	-	-	Materiel Solution Analysis	
Milestone A							
2022	5	-	-	-	-	Technology Maturation & Risk Reduction	
2023	5	-	-	-	-		
Milestone B							
2024	69.9	-	-	-	-	Engineering & Manufacturing Development	
2025	69.9	-	-	-	-		
CDR							
2026	69.9	-	-	-	-		
2027	69.9	-	-	-	-		
Operational Assessment / LRIP							
2028	69.9	-	-	-	-		
Milestone C							
2029	69.9	-	-	-	-	Production and Deployment	
IOC							
2030	69.9	72.6	-	25			

Full Rate Production Decision Review							
2031	21.3	72.6	2.2	25	25		
2032	21.3	72.6	4.4	25	50		
2033	21.3	72.6	6.6	25	75		
2034	21.3	72.6	8.8	25	100		
2035	21.3	72.6	11.0	25	125		
2036	21.3	72.6	13.1	25	150		
2037	21.3	72.6	15.3	25	175		
2038	21.3	72.6	17.5	25	200		
2039	21.3	72.6	19.7	25	225		
2040	21.3	72.6	21.9	-	250		
2041	21.3	72.6	21.9	-	-		Operations & Support
2042	21.3	72.6	21.9	-	-		
2043	-	72.6	21.9	-	-		
2044	-	72.6	21.9	-	-		
2045	-	-	21.9	-	-		
2046	-	-	21.9	-	-		
2047	-	-	21.9	-	-		
2048	-	-	21.9	-	-		
2049	-	-	21.9	-	-		
2050	-	-	21.9	-	-		
2051	-	-	21.9	-	-		
2052	-	-	21.9	-	-		
Total	754.9	1089	383.3	250			
Total Costs ($M)	2227.2						

The service life for the NMT system is planned to be in operation for 22 years (FY 2012-FY 2032) [69]. The DAS process was followed throughout time for to field NMT systems. Planning for the next generation of multiband antennas that utilize the parabolic stacking methodology to incorporate both NMT, CBSP and SDT operating frequency capabilities is recommended to start in the near future. Historical and future planned amounts for the NMT system included expending a total of $868.6M over 15 years. This included Research, Development, Test and Evaluation activities throughout the DAS process. The DAS process included the phases of Materiel Solution Analysis, Technology Maturation & Risk Reduction, Engineering & Manufacturing Development and Production and Deployment. The Technology Maturation & Risk Reduction phase begun after the Materiel Solution Analysis phase was complete (Milestone A) in 2001. This led to a two year endeavor of Technology Maturation & Risk Reduction tasking that valued at approximately $10M. Upon completion of the Technology Maturation & Risk Reduction phase (Milestone B) in 2003, the Engineering & Manufacturing Development phase begun to perform engineering activities until 2010. The Engineering & Manufacturing Development phase was completed at Milestone C expending approximately $559M. The completion of Milestone C consisted of the decision to begin Low Rate Initial Production to begin fielding NMT systems. This decision led to the Production and Deployment phase of the DAS process which expended approximately $217M of costs until 2019. The Production and Deployment phase is still continuing until 2024 and has budgeted $81M throughout the remaining years of this phase. Table 7 depicts annual RDT&E costs for the NMT system throughout the DAS process.

Table 7 Annual RDT&E Costs for the NMT System (after [69])

Year -- -- -- -- -- Cost $M	Process Phase
2000	Materiel Solution Analysis
Milestone A	
2001 -- -- -- -- -- -- 3.4	Technology Maturation & Risk Reduction
2002 -- -- -- -- -- -- 6.6	
Milestone B	
2003 -- -- -- -- -- -- 29.4	Engineering & Manufacturing Development
2004 -- -- -- -- -- -- 64.1	
2005 -- -- -- -- -- -- 58.1	
CDR	
2006 -- -- -- -- -- -- 55.4	
2007 -- -- -- -- -- -- 77.7	
2008 -- -- -- -- -- -- 87.7	
2009 -- -- -- -- -- -- 108.7	

Operational Assessment / LRIP	
2010 -- -- -- -- -- -- 78.8	
Milestone C	
2011 -- -- -- -- -- -- 18.1	Production and Deployment
IOC	
2012 -- -- -- -- -- -- 17.5	
Full Rate Production Decision Review	
2013 -- -- -- -- -- -- 28.1	
2014 -- -- -- -- -- -- 19.8	
2015 -- -- -- -- -- -- 18.2	
2016 -- -- -- -- -- -- 28.0	
2017 -- -- -- -- -- -- 21.1	
2018 -- -- -- -- -- -- 32.1	
2019 -- -- -- -- -- -- 34.8	
2020 -- -- -- -- -- -- 30.8	
2021 -- -- -- -- -- -- 10.3	
2022 -- -- -- -- -- -- 9.0	
2023 -- -- -- -- -- -- 16.2	
2024 -- -- -- -- -- -- 14.7	
Total -- -- -- -- -- --868.6	

Procurement costs include procuring the system from the manufacturer and installing the system on the intended platform. The NMT system consisted of an antenna (s) and communication group (s). Some variants included a group of antennas with one communication group rack, while others consisted of a single antenna with a single communication group rack. The approximate value of $1368M entails production and deployment costs associated with the NMT system. A total of 250 systems were desired to be procured from 2010 where the LRIP was approved. The quantities were spread out over 10 years to be funded incrementally. The production and deployment phase only consisted of production and deployment efforts and did not include RDT&E efforts which was separately budgeted in Table 8. The production and deployment phase included tasks such as procuring the NMT system, procuring associated components (cables, connectors, radomes, ancillaries, etc.), verifying system operation, installing the system, and performing verification tests after the system was fielded. These efforts spanned across the years of 2010 through 2028. The unit cost to produce and deploy a NMT system had an approximate value of $5.5M per system when dividing the total value of $1368.4M over 250 systems.

Table 8 Annual Procurement Costs for the NMT System (after [69])

Year -- -- -- -- -- Cost $M	System QTY	Process Phase
Operational Assessment / LRIP		Engineering & Manufacturing Development
2010 -- -- -- -- -- -- 61.6	33	
Milestone C		
2011 -- -- -- -- -- -- 111.5	54	Production and Deployment
IOC		
2012 -- -- -- -- -- -- 107.3	26	
Full Rate Production Decision Review		
2013 -- -- -- -- -- -- 156.2	34	
2014 -- -- -- -- -- -- 183.6	41	
2015 -- -- -- -- -- -- 233.2	17	
2016 -- -- -- -- -- -- 118.1	12	
2017 -- -- -- -- -- -- 38.4	2	
2018 -- -- -- -- -- -- 68.1	8	
2019 -- -- -- -- -- -- 95	10	
2020 -- -- -- -- -- -- 71.4	13	
2021 -- -- -- -- -- -- 11.1	-	
2022 -- -- -- -- -- -- 25.5	-	
2023 -- -- -- -- -- -- 14.4	-	
2024 -- -- -- -- -- -- 20.7	-	
2025 -- -- -- -- -- -- 17.4	-	
2026 -- -- -- -- -- -- 14.7	-	
2027 -- -- -- -- -- -- 12.7	-	
2028 -- -- -- -- -- -- 7.5	-	
Total -- -- -- -- -- --1368.4	250	

Operation and sustainment costs involves maintenance for hardware and software components of the NMT system. Depot maintenance with respect to sparing and repairs are included in the operation and sustainment costs. These costs represent the NMT system to include the antennas, communication groups and ancillaries associated with the system itself. Help desk support is incorporated in to the operation and sustainment costs to provide onsite and offsite troubleshooting support. Warehousing functions and storage costs for spares would include having a stock of maintenance parts along with applicable spares for high failure rate items, and items that are identified as single points of failure. Support for system life cycle testing would be included to detect potential risk areas with hardware and software components. The annual costs for each NMT system would be approximately $87.6k, while the annual cost to sustain the total amount of 250 systems would be approximately $21.9M. Assuming the CBSP sustainment cost mirrors the NMT sustainment cost per system, a savings of $16.6M can be realized annually as shown in Table 9.

Table 9 Annual Operation and Sustainment Cost for the NMT System (after [69])

Cost Element	Cost per system NMT $k	Cost for 250 NMT systems $M	Cost for 190 CBSP systems $M
Unit-Level Manpower	39.4	9.9	7.5
Maintenance	2.3	0.6	0.4
Sustaining Support	21.9	5.5	4.2
Indirect Support	24	6.0	4.6
Total	**87.6**	**21.9**	**16.6**

The total cost to develop and field the NMT system was estimated to be $2646.4M. This total value included RDT&E, procurement, and operations and sustainment costs throughout a span of approximately 32 years. The DAS process was followed to deliver the NMT capability to the warfighter. The RDT&E costs ($868.6M) ranged from 2001 through 2024. The procurement costs ($1368.4M) ranged from 2010 to 2028. Operations and sustainment costs ($409.4M) ranged from 2011 to 2032. The total amount of systems ordered per year began in 2010 through 2020. Giving a one year lag for the systems to be fielded from the prior ordering year provided an estimated fielding range for years 2011 through 2021. The overall costs throughout the DAS process over time for the NMT system is shown in Table 10.

Table 10 Approximate Life Cycle Costs for the NMT System (after [69])

Year	RDT&E Costs	Procurement Costs	Operations and Sustainment Costs	Systems Ordered QTY	Systems Fielded Per Year	Process Phase	
-	-	-	-	-	-	Materiel Solution Analysis	
Milestone A							
2001	3.4	-	-	-	-	Technology Maturation & Risk Reduction	
2002	6.6	-	-	-	-		
Milestone B							
2003	29.4	-	-	-	-	Engineering & Manufacturing Development	
2004	64.1	-	-	-	-		
2005	58.1	-	-	-	-		
CDR							
2006	55.4	-	-	-	-		
2007	77.7	-	-	-	-		
2008	87.7	-	-	-	-		
2009	108.7	-	-	-	-		
Operational Assessment / LRIP							
2010	78.8	61.6	-	33	-		
Milestone C							
2011	18.1	111.5	2.9	54	33	Production and Deployment	Operations and Support
IOC							
2012	17.5	107.3	7.6	26	87		
Full Rate Production Decision Review							
2013	28.1	156.2	9.9	34	113		
2014	19.8	183.6	12.9	41	147		
2015	18.2	233.2	16.5	17	188		
2016	28	118.1	18.0	12	205		
2017	21.1	38.4	19.0	2	217		
2018	32.1	68.1	19.2	8	219		
2019	34.8	95	19.9	10	227		

2020	30.8	71.4	20.8	13	237
2021	10.3	11.1	21.9	-	250
2022	9	25.5	21.9	-	-
2023	16.2	14.4	21.9	-	-
2024	14.7	20.7	21.9	-	-
2025	-	17.4	21.9	-	-
2026	-	14.7	21.9	-	-
2027	-	12.7	21.9	-	-
2028	-	7.5	21.9	-	-
2029	-	-	21.9	-	-
2030	-	-	21.9	-	-
2031	-	-	21.9	-	-
2032	-	-	21.9	-	-
Total	868.6	1368.4	409.4	250	
Total Costs ($M)	2646.4				

Considering the similarities between the CBSP system and the NMT system, the total life cycle costs for the CBSP system should be similar as well. In 2014, Harris was awarded an eight-year $133 million contract from the U.S. Navy to provide 120 shipboard terminals on top of the 70 that were already provided that give access to high-bandwidth voice and data communications [70]. 49 terminals initially were placed on Navy ships in 2009, and there were plans to issue an additional 201 systems to the fleet after that [71]. The CBSP systems would consist of 190 fielded systems on U.S. Navy platforms along with 250 NMT fielded systems. Operation and sustainment costs in itself can be significantly reduced by fielding a parabolic stacked antenna capable of functions that include SATCOM capabilities. Using the 22 year SATCOM system life cycle value and assuming the sustainment costs for the CBSP system is the same as the NMT system, the annual operation and sustainment costs for the NMT and CBSP systems with projected incremental fielding is shown in Table 11.

Table 11 Annual Operation and Sustainment Costs for the NMT and CBSP Systems with Incremental Fielding (after [69])

System Service Year	# of NMT Systems Fielded	Cost ($M)	# of CBSP Systems Fielded	Cost ($M)
1	25	2.19	25	2.19
2	50	4.38	50	4.38
3	75	6.57	75	6.57
4	100	8.76	100	8.76
5	125	10.95	125	10.95
6	150	13.14	150	13.14
7	175	15.33	175	15.33
8	200	17.52	190	16.644
9	225	19.71	190	16.644
10	250	21.9	190	16.644
11	250	21.9	190	16.644
12	250	21.9	190	16.644
13	250	21.9	190	16.644
14	250	21.9	190	16.644
15	250	21.9	190	16.644
16	250	21.9	190	16.644
17	250	21.9	190	16.644
18	250	21.9	190	16.644
19	250	21.9	190	16.644
20	250	21.9	190	16.644
21	250	21.9	190	16.644
21	250	21.9	190	16.644
Total Cost over 22 Years		383.25		310.98

A cost savings of approximately $310.98M over 22 years can be realized in sustainment costs alone if the NMT and CBSP systems were consolidated. This assumes that the systems including the communication groups were consolidated and half the labor hours would be required for maintaining one system vice two systems. Developing a parabolic stacked antenna system capable of operating with both NMT and CBSP system capabilities would reduce costs. The approximate life cycle costs for the parabolic stacked antenna system was $2,227.2M over 32 years. Considering life cycle costs for two systems would amount to approximately $4,454.4M over 32 years. A life cycle cost savings of ~$2B over 32 years would be potentially realized by developing one consolidated system vice two individual systems.

3.3 Requirements Engineering

IEEE 29148:2011 states that requirements engineering is concerned with discovering, eliciting, developing, analyzing, determining verification methods, validating, communicating, documenting and managing requirements [72]. The results of requirements engineering include a set of high-level requirements decomposed into lower level requirements which can be verified, validated, implemented and understood amongst various stakeholders. Discovering requirements would include finding a need for improvement of an existing system / capability or a need for a new system / capability. The need for topside antenna consolidation is an ongoing effort where new capabilities are introduced to support the warfighter which require various types of antennas. Elicitation of requirements consists of collaborating with stakeholders to establish a common understanding, gain concurrence, and document requirements. Requirement elicitation would have to take place where meetings may assist with acquiring high level requirements and the overall vision. Documenting goals, objectives, and needs during these meetings would formulate stakeholder requirements. Other requirement gathering techniques would include reviewing current or historical documentation of a similar system. For antenna consolidation, reviewing documentation on similar past engineering efforts included the development of Raytheon's NMT and Harris's CBSP consolidated antennas. Any known existing engineering efforts would be researched to potentially obtain information that can assist with developing the system. Simulations, prototypes and modeling of the system promote requirement development as well.

Requirements would include the system along with the system's life cycle. Developing requirements would correlate to the overall need along with constraints, system objectives, environment, operational scenarios, and interactions between users / systems with consideration on the system's life cycle. Analyzing elicited requirements would include reviewing the requirements to ensure the requirements are complete, consistent, verifiable and unambiguous. Identifying any requirement conflicts are also performed when analyzing. Trade-offs and prioritization of requirements may need to occur in order to realistically achieve the required criteria. Collaboration amongst stakeholders while capturing feedback and gaining concurrence would ensure a common understanding of the requirements. Choosing a requirements management tool assists with storing requirements within a central location along with traceability of the requirements tend to be volatile, or additional requirements are added throughout the life cycle. Rational DOORS Next Generation provides a smarter way to define, trace, analyze, and manage requirements while complying with industry standards and regulations [73]. The Rational DOORS Next Generation requirements management tool promotes understanding of requirements, scope, and the associated costs. A centralized location to store and track requirements is necessary for the life cycle of the system as shown in Figure 22.

ID	Name	Description
208610	The consolidated antenna shall provide GBS services by transmitting video from a remote location and receiving the video on a consolidated antenna at a remote platform	Functional
208609	On a monthly basis, the consolidated antenna shall prompt the user for required maintenance actions needed to be performed within 2 months	Functional
208607	On a monthly basis, the consolidated antenna shall update the system's firmware over a SATCOM link	Functional
208606	The consolidated antenna shall acquire SATCOM links within 20 seconds	Functional
208605	During the startup process, the consolidated antenna shall track satellite locations within 1 minute	Functional
208604	The consolidated antenna shall cut over to a neighboring consolidated antenna upon signal loss or failure	Functional
208603	The consolidated antenna shall have redundancy features to maintain a .985 operational availability	Functional
208602	The consolidated antenna shall maintain a constant operating temperature by having cooling / heating capabilities	Functional
208601	The consolidated antenna shall perform fault analysis by displaying internal diagnostic faults on a Graphical User Interface (GUI)	Functional
208599	The consolidated antenna shall transmit and receive with other consolidated antennas and legacy antennas via satellites	Functional
208598	The consolidated antenna shall transmit and receive on SATCOM frequency bands to include L, C, X, Ku, K, Ka, and Q bands that current NMT and CBSP antennas operate under	Functional
208597	The consolidated antenna shall be developed using RF system standards	Non-functional
208596	The consolidated antenna shall be fabricated using anti-corrosive materials	Non-functional
208595	The consolidated antenna shall have the same mounting bolt pattern as the existing CBSP and NMT antennas on shipboard platforms	Non-functional
208594	The consolidated antenna shall have a base mount to operate on a shipboard platform	Non-functional
208593	The consolidated antenna shall have a base mount to operate on a shore platform	Non-functional
208592	The consolidated antenna system shall be developed and manufactured within the approved budget	Non-functional
208590	The consolidated antenna system shall support Classified and Unclassified missions using SATCOM frequencies	Non-functional
208587	The consolidated antenna system shall operate within the temperature ranges of -62.2 and 54 degrees Celsius	Non-functional

Figure 22 Rational DOORS Next Generation Requirements Management Tool

Non-functional and functional requirements were listed to describe the system to be designed to. Functional requirements define the functions of the system. Non-functional requirements define the overall qualities or attributes of the resulting system [74]. Functional requirements define the functions of the system. This requirements management tool has features to track any adjustments and / or modifications made by placing a time stamp along with the user that adjusted that requirement. Permissions to add, change, and delete requirements would be made to manage control. The Rational DOORS Next Generation tool allows each requirement to contain additional data. For instance, requirement 208597 would contain the RF antenna standards profile shown in Table 12 within the database.

Table 12 RF Antenna Standards Profile [20]

Standards Categories	***Typical Standards***
RF Transfer: - Frequency Range and Rate - Noise limits - RF Exposure - EMI Control	**Goal: Operate within RF rules and protocol** - Broadcast standards - Signal to noise ratio standards - FCC Regulations, IEEE C95.1 - MIL-STD-461G, IEEE C63.12-2015, IEEE C63.2-2009, IEEE C37.90.2-2004
Information Assurance: - RF COMSEC - Network Security - Physical Security - Software Security	**Goal: Capable of passing an IA audit** - PKI, EKMS standards and protocol - DISA Information Assurance Support Environment Reqs. - TEMPEST physical security standards - ISO/IEC 27034
RF Testing: - Standard Test Procedures for Antennas - Sites performing Emission testing - Compliance of Transmitters - Electrostatic Discharge - Environmental - RF Absorption	**Goal: Perfrom and meet outlined test procedures** - IEEE 149-1977 - IEEE C63.7-2015, IEEE C63.7-2005 - IEEE C63.36-2015 - IEEE C63.16-2016 - IEEE 1613.1-2013 - IEEE 1128-1998
Emissisons: - FM and TV Broadcast Receivers - Land-Mobile Transmitters - Low Voltage Electrical Equipment	**Goal: Stay within acceptable RF emissions boundaries** - IEEE 187-2003 - IEEE 377-1980 - IEEE C63.4-2014
Safety: - RF Safety Program 3kHz to 300GHz - Human Exposure to EMI	**Goal: Adhere to RF safety precautions** - IEEE C95.7-2014 - IEEE C95.7-2014, IEEE C95.1-2005, IEEE C95.3.1-2010
Disturbance: - Radio and IT Equipment - Radio Noise	**Goal: Meet acceptable signal to noise ratio requirements** - IEEE C63.022-1996, IEEE C63.011-2000 - IEEE C63.5-2006, IEEE C63.4-2003

There are times on complex systems that some requirements may be overlooked or misunderstood. These requirements would need to be identified as early as possible to prevent rework, system development delays, cost over runs, performance issues, or safety concerns. Baselining requirements and ensuring configuration control practices are implemented is necessary to prevent scope creep. Scope creep can occur when requirements are not well understood initially, change control would have to be implemented in order to clearly indicate the impacts of requirements that were unforeseen at the beginning. Figure 23 depicts the Requirements Definition and Management Process.

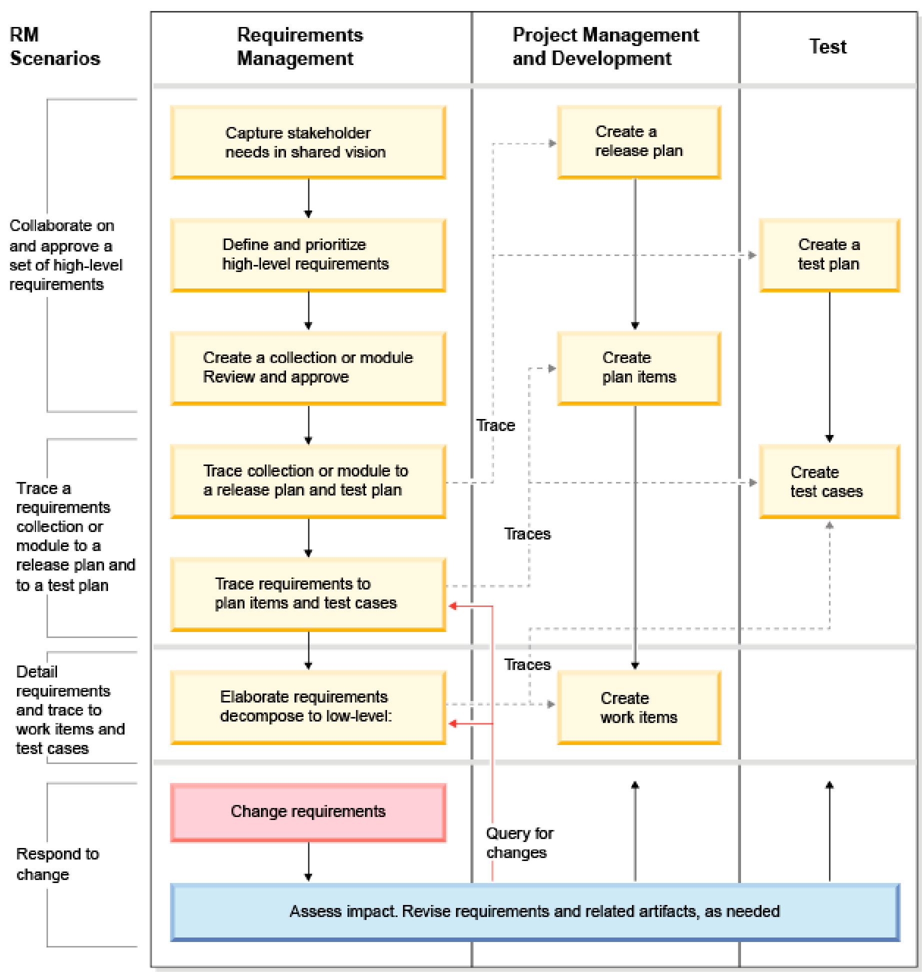


Figure 23 Requirements Definition and Management Process [75]

Requirements would be developed from particular needs. These needs would come from strategic goals an organization or stakeholder envisions. Taking these needs and transforming them into detailed requirements is necessary. A requirement is verifiable and is linked with fulfilling a need. Measurable requirements are desired to determine if the objective has met a specific threshold.

Identifying the RF antennas on a shipboard platform assisted with defining requirements. Decomposed requirements to lower levels would specify antenna design criteria. Researching prior antenna consolidation efforts defined limitations and constraints. Operational scenarios with interfaces depicted interconnecting systems. System life cycle process concepts supported identifying functional and non-functional requirements. Design requirements would include the capability to create SATCOM and LoS links between systems. Cybersecurity requirements were documented to ensure RF design compliancy was met. Cybersecurity requirements are important to define early as well in the system's lifecycle to prevent signal interception, jamming, and intelligence data leaks. A newly designed fielded system that didn't consider cybersecurity requirements initially would cost more to mitigate than a system that is in the early stages of the system's life cycle.

Functional definition and analysis included translating requirements into functions. These functions were grouped and allocated within specific groups associated with their frequency band. Determining the nature of use for the parabolic stacked antenna system assisted with defining the required functions. RF capabilities that operate concurrently with each other were specified along with known interference problems of specified RF frequencies. Functional constraints identified were defined for consideration during the design process. Testability needs were assessed for future stand alone, integration, and operational verification.

Physical attributes were described and analyzed for form, fit, and function criteria. Developing a system architecture model depicted the physical systems and platforms that interconnected with one another. Identifying various assemblies and sub-assemblies described mission parameters that the consolidated solution would be composed of. Each mission package provides the operator specific RF communication capabilities. Design validation ensured the proposed conceptual design aligned with system requirements. Simulating the RF solution proved the benefit of having a consolidated antenna versus multiple antennas at different stages of the system's life cycle to perform common operations. Developing use case scenarios would further prove required capabilities been met.

Cybersecurity risk management would involve identifying risks along with reducing the likelihood and impact over a period of time. Designing the parabolic stacked antenna requires consideration to the operational availability of the system. Anti-jamming measures would have to take place to ensure RF communication services stay operational [19]. Incorporating a Low Probability of Intercept / Low Probability of Detection (LPI / LPD) design is also essential to maintain continuous communication links. Recurring audits would be required to ensure compliancy of the system once it's fielded. These audits would involve software, firmware, Communication Security (COMSEC) equipment, and physical checks to ensure there are no vulnerabilities or incidents present. Considerations for these checks would be documented during the design of the parabolic stacked antenna. Security is essential when transmitting and receiving sensitive data. As hackers and unauthorized users are attempting to cause malicious intent, security measures are required to be put in place. A list of security features and functions applicable to the parabolic stacked system are shown in Table 13.

Table 13 Security Features and Functions

System Element	Security Feature	Security Function
RF Parabolic Stacked Antenna System	EKMS, PKI, and Encryption/ Decryption capabilities	Encrypt from the source and decrypt at the distant end
Internal Network	Router Access Lists, Firewall Prevention, Encryption / Decryption capabilities	Prevent un-authorized IP Traffic from penetrating the network. Encrypt the data at the IP level and decrypt the data at the distant end
Operator's Computer	Antivirus Protection, Malware Protection, Host intrusion prevention	Identify, isolate, and prevent viruses and malware from affecting the computer. The Host intrusion prevention would block any type of IP based unauthorized user from accessing the operator's computer
Video Imagery	Video Encryption/Decryption	Encrypt video at the source and allow the video to be decrypted at the receiving end

The security structural diagram showing security features and functions is shown to include streaming video coming in through a RF signal initially. This data is sent to a full motion video distribution unit which distributes the video stream to a networking source and finally to the operators computer. COMSEC components are associated with the RF parabolic stacked antenna system along with the video distribution unit and the networking source. Access control components are associated with the networking source along with the operator’s computer. This diagram includes the components of structure that would handle sensitive video imagery. The security behavior diagram is shown in Figure 24. This diagram shows an incoming one way path of sensitive imagery that is sent to the operator’s workstation.

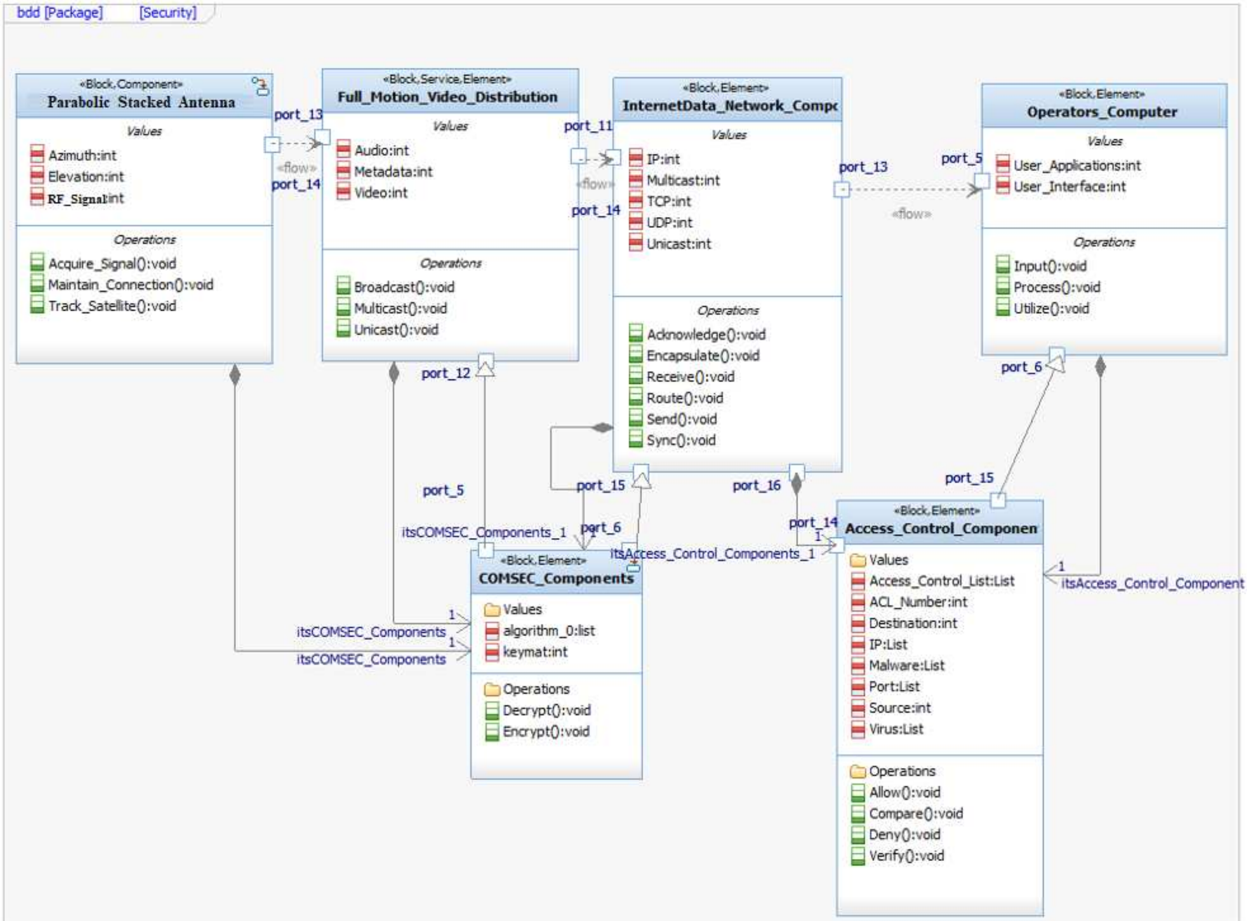


Figure 24 Security Structural Diagram

The security behavior diagram in Figure 25 displays one way traffic of incoming video data. The parabolic stacked antenna received encrypted video traffic and is decrypted by COMSEC devices. The IP traffic within the encrypted RF signal is passed through the firewall which permits or denies the incoming traffic. A network encrypt / decrypt device would remove the encryption that encapsulated the data. The application security software would either accept or deny the video then pass the video stream to the operator's computer via UDP.

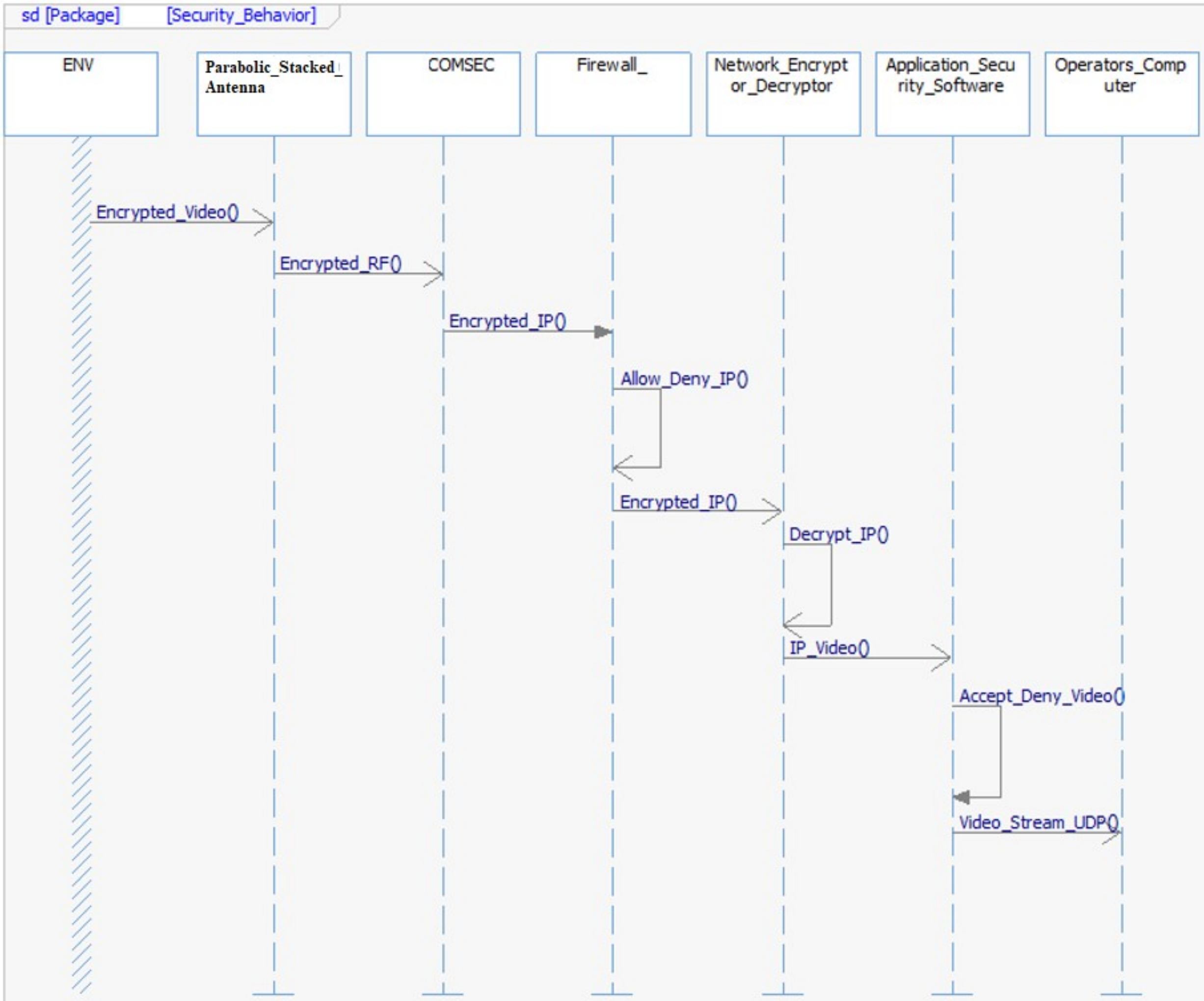


Figure 25 Security Behavior Model

The administrative portion with respect to security for the system includes risk reduction, risk assignment, risk avoidance, and risk assessment which is handled by the communications team. The communication team would be divided into sub-teams where the RF security, network security, and workstation administrators assist with safeguarding sensitive information. The RF security team would handle all the EKMS and PKI equipment necessary to ensure RF security is met. Keying the equipment monthly would be required. Metrics such as the timeliness of keying the COMSEC equipment monthly would be considered to identify any potential interruption of services. This would reduce the risk of loss of service and assign the RF security team this duty. The RF security team would avoid the risk of any malicious data by allowing the network security and workstation administrative teams to account for any mishaps. The risk is accepted by the organization to assume each sub-team performs their due diligence. The network team would be responsible of updating access control lists and firewall entries. Metrics of the amount of malicious data encountered would be assessed in order to tighten up the data security measures as necessary. This would reduce the risk of any intrusions the network may have. The RF security portion is avoided by the network security team by having the RF security team perform their duties. Accepting this risk ensures SMEs are performing their functions within their team's boundary. The workstation administrative team would update security features for the operator's computer system. Metrics for the amount of malware encountered will be accessed and updated onto the operator's workstation. This would reduce the risk of malware being placed on the operator's workstation. The workstation administrative team would be assigned these duties and avoid the risk of any RF or network related information assurance concerns by policing their functional area. The organization would accept all risks with having these teams perform their duties in order to have a safe information transferring system that is able to pass sensitive video to the operator's workstation securely. Security quality attributes have been documented within Table 14. The assessment factors are shown to score the system's security parameters is also listed. The potential issues are described to identify any shortfalls that may be encountered.

Table 14 Security Quality Attributes

Quality Attribute	Scoring System	Potential Issues
Predictability	Updating security technical information guidelines parameters monthly in order to predict potential intrusions, and malicious intent to do harm on the system. A 0 would indicate a poor job of predicting attacks where a 10 would indicate no attacks seen monthly.	Potential issues may include the security technical information guideline database is inoperable to obtain the latest information on how to protect the system.
Upgradability	Upgradability would ensure all systems have the latest software patches needed to maintain compliance with all RF, Network, and computer appliances. A 0 would indicate outdated versions of software loaded on these appliances, where as a 10 would indicated all RF, Network, and computer appliances are up to date during an audit.	Potential issues could include licensing fees that may or may not be funded to upgrade to the latest version of any RF, Network or computer appliance. Another potential issue could be due to contract related limitations.
Effectiveness	Effectiveness of the security would indicate if the system can safely pass data to the operator securely. A 0 would indicate frequent intrusions, attacks, viruses, and service discontinuations caused by malicious intent. A 10 would indicate no issues encountered related to the data security parameters.	Potential issues could include insider threat, where someone that has access to internal components may be able to breach the system.
Responsiveness	Responsiveness would be scored by the timeliness of the RF, Network, or workstation administrative team reacts to a malicious encounter or breach. A 0 would indicate that there are numerous breaches with slow reaction times by the RF, Network or workstation administrative security teams. A 10 would indicate immediate responsiveness by the teams when a problem arises.	Potential issues could include lack of staff and / or funding to include the necessary SMEs to respond to issues within a timely manner.
Recoverability	Recoverability would include the notion that if a security parameter is breached, how fast the system can be recovered back to a functioning state. A 0 would indicate an excessive outage for over a day. A 10 would indicate an outage for less than an hour.	Potential issues could include lack of trained staff, or equipment that would need to be completely replaced without having a spare on hand.

Designing RF systems to meet ongoing cybersecurity needs early will reduce or eliminate the need for rework later in the system's life cycle. Maintaining consistent continuity between RF links while preventing malicious adversarial threats is critical for information assurance. Performing ongoing risk management throughout the system's life cycle is also beneficial to cost, schedule, and performance parameters.

Identifying requirements early on will save on costs and prevent schedule delays at later stages of the system life cycle. If requirements are not documented and agreed upon early, change requests may be implemented in the future to satisfy the customer. This can affect a planned budget, resource availability, and the planned schedule.

3.4 Concept Exploration and Benefits Analysis Phase

Needs assessment is an early phase SE activity area where real world needs are collaborated with various stakeholders. Identifying these stakeholders that have an interest in the system would take place to discuss needs which would be transformed into requirements. These stakeholders includes, but is not limited to, users, operators, supporters, developers, producers, trainers, maintainers, disposers, acquirer and supplier organizations, parties responsible for external interfacing entities or enabling systems, regulatory bodies and members of society [72]. Collaborating with stakeholders requires different techniques to extract information relevant for the system in need. Activities such as meetings, reviewing current / historical documents, market analysis, modeling and simulating the system provides important information to capture needs for requirement development.

Concept selection compares various alternatives with stakeholders to decide the best Course of Action (COA) to take. Multiple COAs to be investigated are possible when potential solutions are apparent amongst the alternatives. Concept selection is a recurring event throughout the system's life cycle that narrows down a set of potential solutions. Based off of the needs captured from stakeholders, an assessment is performed to produce concepts that are feasible to the design and development of the system. These concepts should be reviewed and analyzed for trade off studies. When the needs are met with multiple concepts, criteria such as cost, schedule, performance and risk would be researched to select the appropriate solution.

Producing a weighted matrix with these concepts where stakeholders would provide a score to what they feel meets each need would narrow down a COA. Group decision making amongst stakeholders assists not only with team cohesion but with selecting the best concept to move forward with. Concurrence with selection criteria and applicable concepts lead to a concept selected amongst stakeholders that acknowledges the risk and path to take. A concept screening and weighted matrix assists a team with selecting the best concept to choose. This type of selection process is repeated several times throughout the system's life cycle when alternatives are present to pose as a viable solution. This concept screening and weighted matrix provides an artifact to refer to when future questions arise on how a concept, course of action or solution was selected. A concept screening matrix would assist with various concepts for selecting the most feasible solution. The concepts would be listed in the upper columns while the selection criteria would be listed to the left most column. The selection criteria is tied to high level requirements and prioritized. Comparing these concepts would eliminate concepts that would not meet the selection criteria.

The remaining concepts would be evaluated with weights. These weights depict the importance of each selection criterion. Ratings are assigned to each concept corresponding with the selection criterion. The team would select the appropriate rating based on their own and SME judgement. The ratings and weights are multiplied to produce a value to compare. These values would be compared amongst the concepts to select the highest value. If there are concepts that produce the same overall value when comparing, additional selection criteria may be added to select the most feasible concept. A closer look at these concepts may reveal additional facts. Selection criteria associated certain customer needs may not include factors such as part availability, ease of production, ease of design, specific details on how to produce the concept and so on. Risks can be introduced to further down select or choose a concept. New technology can pose risk when data on the life cycle of a new technology may be minimum.

The Pugh Matrix is a type of matrix diagram that allows for the comparison of a number of design candidates leading ultimately to which best meets a set of criteria [76]. Table 15 depicts design concepts to meet the requirements for a consolidated antenna. A fully adjustable dish with a fully adjustable feed antenna system was set as the baseline within the Pugh Matrix. This design would satisfy the requirements; however other solutions are applicable to meet the criteria. A fully adjustable dish with multiple feeds would satisfy requirements as well as multiple non-adjustable dishes with multiple feeds. These designs were compared within the Pugh matrix to determine which concept is better than the other. This type of matrix is recommended to be performed with appropriate stakeholders to obtain concurrence on the best course of action. The fully adjustable dish and fully adjustable feed antenna system was set as the baseline where an “S” was placed in each criteria. A “+” or “++” was used to show if the design concept was better / much better than the baseline. A “-” or “- -” was used to show if the design concept was worse / much worse than the baseline. Weights were assigned to express the importance of specific selection criteria. The total value added the amount of “+” or “-” shown with each design concept with respect to multiplying the applicable weights.

Table 15 Pugh Matrix for Antenna Design Concept Selection

		Design Concepts		
	Weight	Fully Adjustable Dish and Fully Adjustable Feed Antenna System	Fully Adjustable Dish and Multiple Feed Antenna System	Multiple Non-Adjustable Dishes and Multiple Feed Antenna Systems (Parabolic Stacked Antenna)
Selection Criteria				
Operate on L,C, X, Ku, Ka, and Q Bands	4	S	S	S
Single dish able to accommodate multiple RF bands	5	S	S	--
Single feed able to accommodate multiple RF bands	3	S	--	--
Ease of design	4	S	+	++
Minimal time to design	2	S	+	++
Minimal number of parts	2	S	-	--
Low number of moving parts	2	S	+	++
Low cost of design	3	S	--	++
Ease of production	3	S	+	++
Low Cost of production	4	S	-	+
Minimal time to produce and deploy	4	S	-	--
Low maintenance	3	S	+	++
Total +		0	5	13
Total -		0	7	8
Total Score		0	-2	2
Weighted Total +		0	16	38
Weighted Total -		0	22	28
Weighted Total		0	-5	10

A parabolic stacked antenna would be the best concept that meets the weighted selection criteria. This method would be performed amongst various stakeholders and the matrix itself would be kept as an artifact to resolve any concerns that may arise when a particular concept selected is questioned. Comparing the concepts with associated weights allows a group of stakeholders to collaboratively select a particular concept.

The parabolic stacked antenna system would provide various beneficial service features to the warfighter. Services to include internet, voice, data, and real time imagery would allow the user to accomplish mission objectives. Using these capabilities the warfighter would be able to upload and download data along with other functions such as search, view, store as well as send and receive various types of information to include encrypted voice or data. Mission services include the communication plan which identifies the communication requirements of the user. These communication requirements define what satellite the user is needing to connect to along with other relevant configurations. The communication plan is submitted to the appropriate approval authority to provide access to a particular satellite. Data links between SATCOM and LoS operations are established to achieve operational mission requirements. LoS operations using the CDL protocol would allow information sharing for surveillance and reconnaissance operations. Enterprise services would provide overarching mission services across multiple entities. Enterprise services provide cross domain, interoperable solutions consisting of multiple capabilities. The parabolic stacked antenna capable of providing SATCOM and LoS operations assist with providing enterprise capabilities that span across multi-platform mission operations.

Mission services provide various data transfer operations such as COMSEC, RF, Networking, and video streaming. RF services would include wireless links to satellites or other antennas capable of LoS. This entails transmitting and receiving information over relevant RF bands. In addition to RF services, COMSEC services is critical to encrypt and decrypt data traffic. Keying Material (KEYMAT) is typically used on data to protect sensitive information from adversaries. The source and destination would have corresponding KEYMAT to unlock the data that is transferred. This KEYMAT is changed periodically which is based on COMSEC policy to secure data. Networking services is also involved with communication systems by routing data using IP addresses and other routing protocols. Video streaming services would utilize networking and COMSEC services in order to deliver live imagery to the user securely. Infrastructure resources such as COMSEC, networking, video distribution, and RF equipment is used to provide services to the user.

A layered architecture was developed to show interacting interfaces among layers. Dependencies of lower echelon services are shown in Figure 26. The services included user, mission, system (COMSEC, RF, Network, Video Stream), and enterprise. The infrastructure resources were also included in this model.

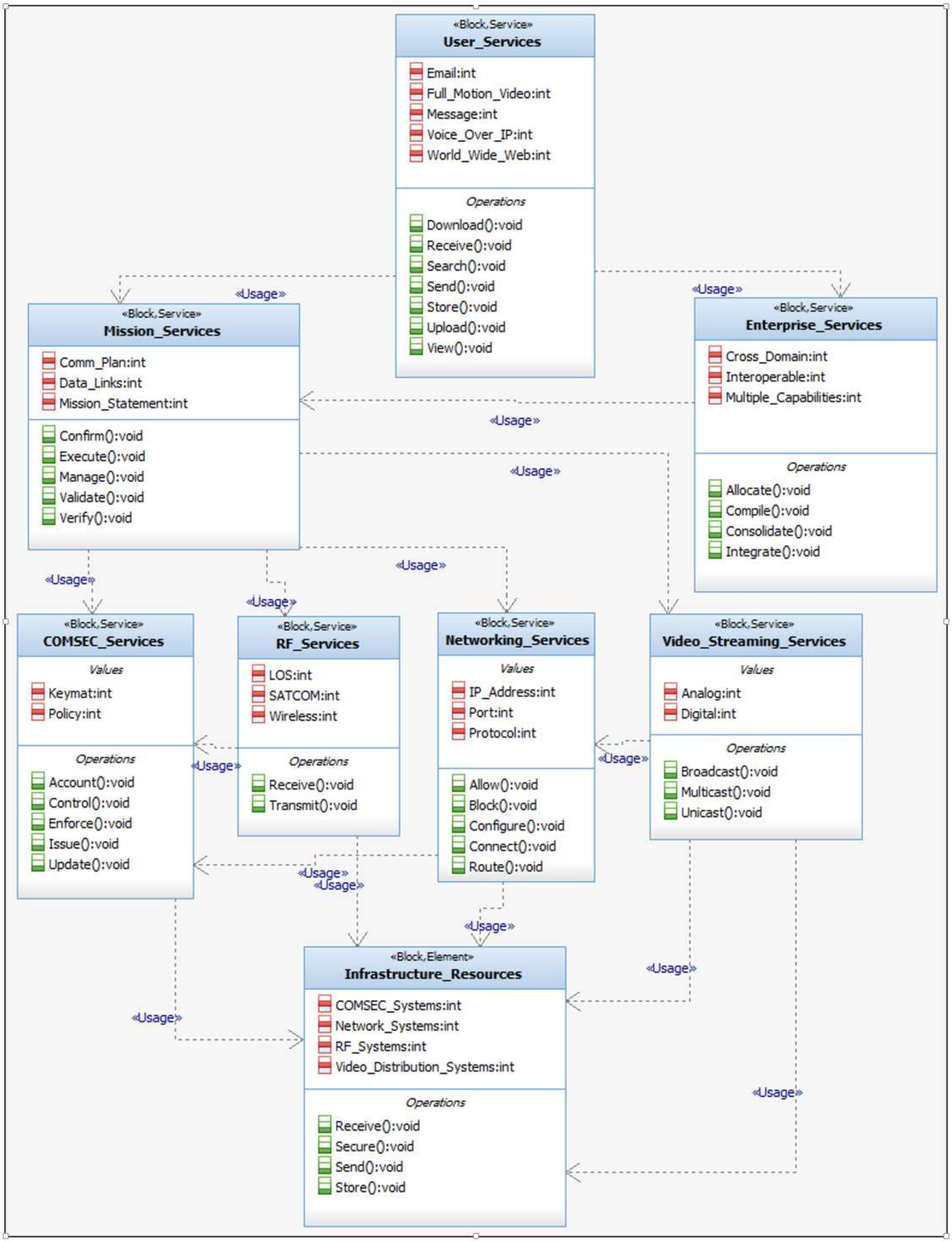


Figure 26 Parabolic Stacked Antenna Layered Service Architecture

The service taxonomy was composed to list services for three domains. The three domains included Ground_Comms, Shipboard_Comms, Mobile_Comms. These domains have services in which communication among them would have to occur in order to accomplish mission requirements. Values and operations were added to the parabolic stacked antenna service taxonomy to depict the characteristics of the system service. The parabolic stacked antenna service taxonomy is shown in Table 16.

Table 16 Parabolic Stacked Antenna Service Taxonomy

System Service	Use Cases	Domains	Domain Services	Values	Operations
Communications:: Establish a connection with a satellite to send and receive data	Obtain SATCOM connection	Ground Comms Shipboard Comms Mobile Comms	Transmit Data Receive Data Acquire Satellite Track Satellite	LoS SATCOM Wireless	Receive Transmit
Internet::Establish a connection with the internet	Utilize Internet Traffic	Ground Comms Shipboard Comms Mobile Comms	Access WWW Use Email Transfer Files View Videos	IP_Address Port Protocol	Allow Block Configure Connect Route
Full Motion Video (FMV) Distribution: Video distributed during a mission	Streaming FMV over a line of sight (LoS) connection	Ground Comms	Establish LoS connection Send video Receive video	Audio Metadata Video	Broadcast Multicast Unicast

The contextual perspective diagram was developed to depict the relationships of full motion video distribution. Operators in various domains would utilize interconnecting services in order to achieve the capability of sending and receiving video. This video would be analyzed and used to evaluate potential strategies to accomplish mission objectives. This context diagram is shown in Figure 27.

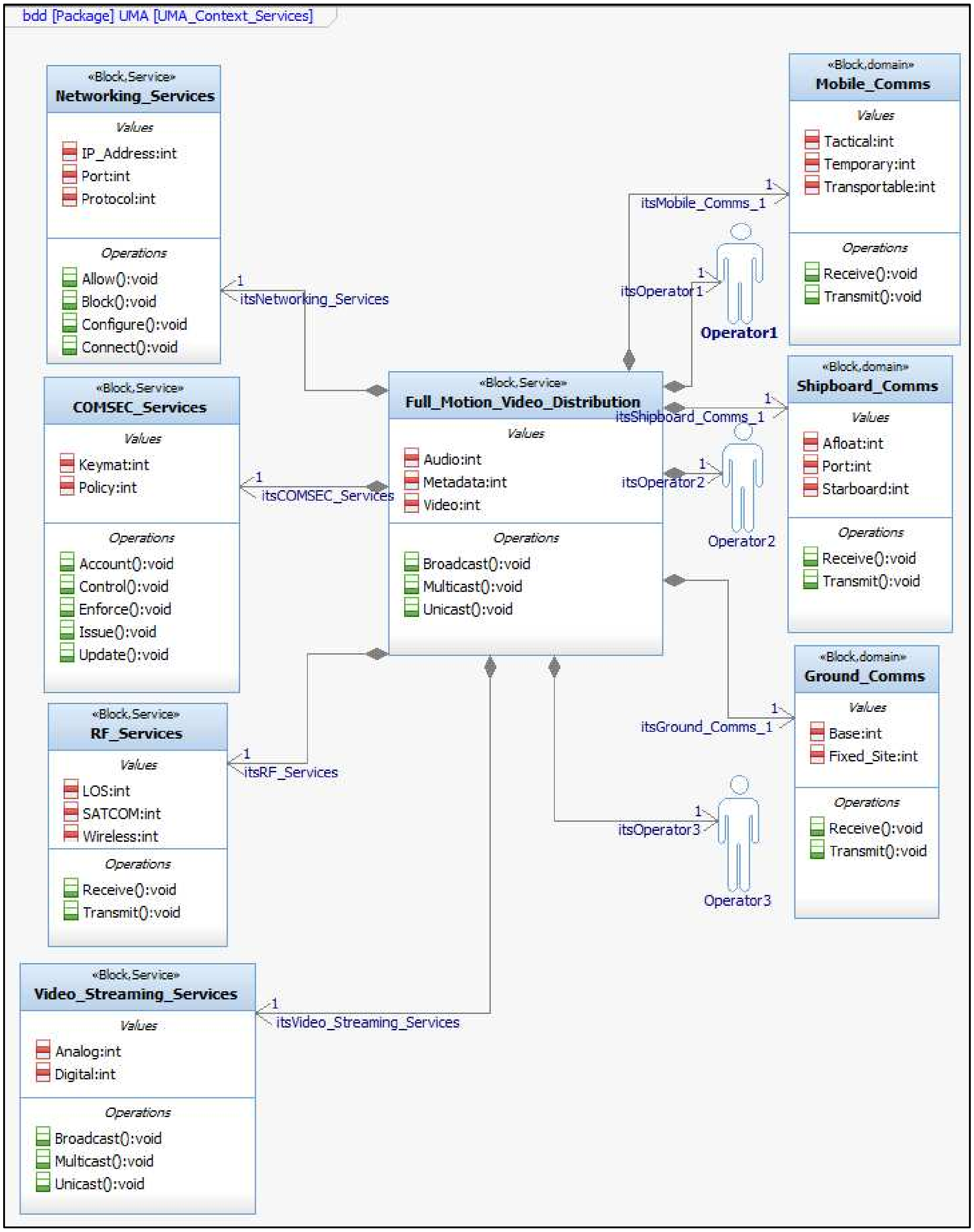


Figure 27 FMV Distribution Service Context Diagram

MBSE played a key role in early phase system engineering. Utilizing MBSE SysML contributed to developing parabolic stacked antenna service architectures, context diagrams, sequence diagrams and system architectures. Context diagrams depicted interconnecting services with communication platforms in relation with operators to illustrate mission objectives. Sequence diagrams provided various activities for the parabolic stacked antenna which were mapped to particular entities performing these functions. Service architectures provided a decomposed view of operations that is required by the user for both the mission and the enterprise level. These models assisted with determining parabolic stacked antenna design requirements, assessing interconnections among RF systems and parabolic stacked antenna project planning considerations. In addition, developing these models assisted with identifying similar capabilities between SATCOM systems currently fielded. The MBSE SysML system architecture shown in Figure 4 in Section 3.1 identified that the CBSP and NMT communication groups had similar operational services such as NIPRNet, SIPRNet, secure communications and imagery distribution. This diagram also identified that the CBSP and NMT communication groups both have the capability of operating at K, Ka and X band frequencies. Identifying these redundant capabilities amongst different antenna systems further stresses the need to consolidate antennas to reduce antenna overcrowding on the topside of U.S. Navy shipboard platforms. MBSE assisted with identifying antenna system operating frequency bands of the CBSP, NMT and the directional SDT antenna system variants which were used to simulate with parabolic stacked antenna configurations in Section 4.

4. Antenna Consolidation via Parabolic Antenna Stacking Synthesis

Parabolic antenna stacking combines multiple RF antennas on a single pedestal. Performing this method eliminates the need for multiple antennas on multiple pedestals. In a space constrained environment such as military shipboard platforms, the need to consolidate RF antennas is desired. A combined L-Band (1-2 GHz) and Ka-Band (20-30 GHz) antenna was patented in January 2013 that consisted of a dual-reflector antenna comprising a backfire helix using the sub-reflector as its reflector [77]. This combined antenna allowed multiple frequency capabilities to be achieved. This concept proved that stacking parabolic antennas in front of one another would successfully achieve multiband frequency needs for a space constrained environment. Six types of antenna configurations are investigated and compared against using the parabolic stacked antenna method. These antenna configurations included the Cassegrain with Gregorian parabolic stacked antenna, Gregorian with splash plate parabolic stacked antenna, the dual Gregorian parabolic stacked antenna, the dual splash plate parabolic stacked antenna, triple Cassegrain parabolic stacked antenna and the dual Cassegrain with splash plate antenna. These parabolic stacked antenna configurations were modeled through Antenna Magus software to obtain the physical parameters and simulated through CST Microwave Studio software to obtain VSWR, gain, radiation pattern, side lobe and angular width (3 dB) results.

The Cassegrain antenna has a primary and secondary reflector and is capable of reaching high RF signal gains. The feed horn extrudes out of the center of the primary parabolic dish transmitting and receiving RF signals. Advantages of the Cassegrain antenna include the feed radiator is more easily supported, the antenna is geometrically compact, and it provides minimum losses as the receiver can be mounted directly near the horn [78]. The physical dimensions of the Cassegrain antenna is shown in Figure 28.

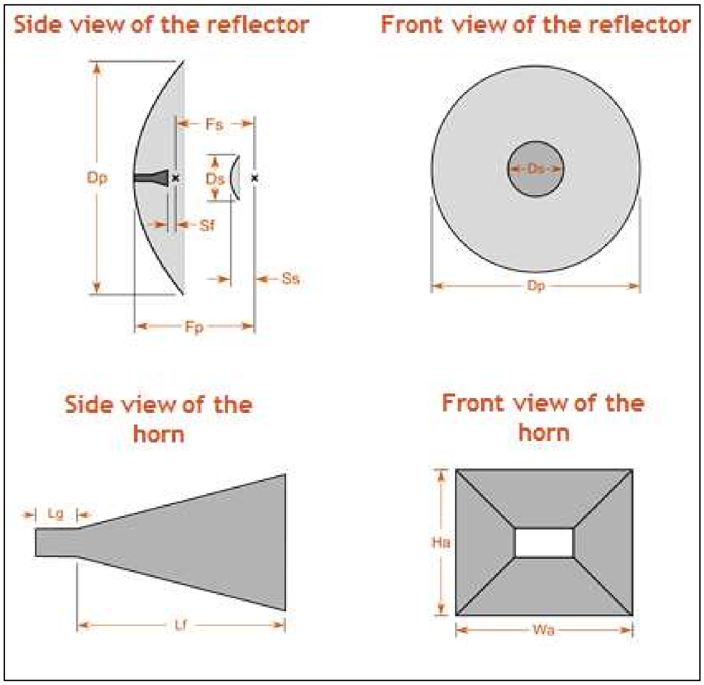


Figure 28 Physical Dimensions of a Cassegrain Antenna [79]

The feed of the antenna is placed in the center of the main parabolic dish and is connected to the rear of the dish in which the RF signal is provided. The RF signal is reflected off of the secondary reflector dish and sent back to the primary parabolic dish where the RF beam is formed. The RF beam is formed with the RF signal sent out of the feed horn at an angle against the secondary parabolic dish reflecting the signal to the primary parabolic dish forming a beam as shown with parallel lines in Figure 29.

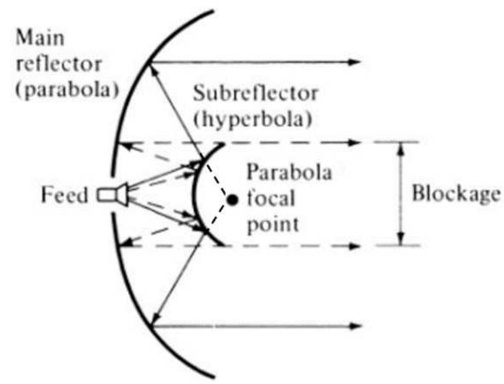


Figure 29 Cassegrain Antenna Ray Collimation after [80]

The blockage area shown in front of the sub-reflector on the Cassegrain antenna identifies space that can be allocated for another parabolic antenna to stack. Other antennas can use the same methodology as long as they incorporate some sort of sub-reflector. The sub-reflector reflects the signals coming from the feed where a virtual feed shown as the parabola focal point in Figure 29 can provide the same signal pattern if the sub-reflector was not physically there denoted by the dotted lines coming from the parabola focal point. The parabolic focal point is calculated by the diameter of the dish *D* and the depth of the dish *d*.

$$\boldsymbol{f_o = \frac{D^2}{16d}} \tag{1}$$

The Gregorian antenna is a parabolic antenna that was researched for the parabolic antenna stacking methodology as well. This dual reflector antenna is similar to the Cassegrain antenna where the main difference is the shape of the sub-reflector. The sub-reflector for the Gregorian antenna concaves inward toward the primary dish while the sub-reflector for the Cassegrain antenna has a convex sub-reflector that curves outward as shown in Figure 30. The reflection pattern from the sub-reflector for each of the Cassegrain and Gregorian antenna would produce slightly different reflection patterns due to the shape of their sub-reflectors.

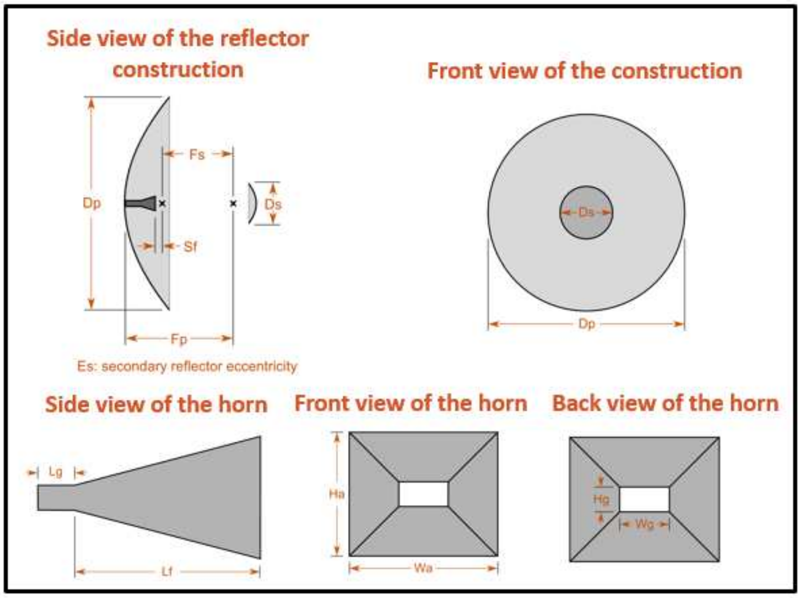


Figure 30 Physical Dimensions of a Gregorian Antenna [81]

The feed of the Gregorian parabolic antenna is placed in front of the dish where part of the feed goes through the primary dish to the rear of antenna. The concave sub-reflector reflects the signal back to the primary dish to be sent to the distant end. The Gregorian antenna transforms the low to medium gain radiation of the feed horn to a high-gain pencil beam [81]. Similar to the Cassegrain antenna, the sub-reflector of the Gregorian antenna creates a blockage area where another antenna can be stacked in front to utilize the blocked area. Figure 31 depicts the Gregorian antenna ray collimation.

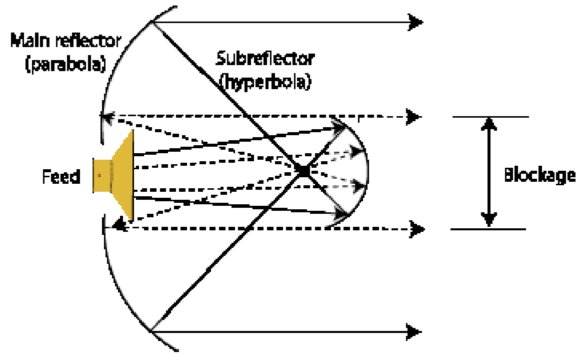


Figure 31 Gregorian Antenna Ray Collimation [82]

The splash plate antenna is another parabolic antenna that can be used for parabolic antenna stacking. The splash plate antenna (also known as the hat fed parabolic antenna) was investigated to provide multi-band frequency capabilities. The splash plate antenna is fed from behind the reflector dish reducing the amount of blockage that other parabolic reflector antennas have. The splash plate is easy to install, has low aperture blocking and is cheap to produce [83]. In Very Small Aperture Terminal (VSAT) communications, the use of splash plate antennas has been increasing due to its' compactness [84]. With this compactness feature, multiple splash plate antennas would be used on a single antenna pedestal to provide multiple frequency capabilities. The splash plate parabolic antenna is comprised of a primary dish reflector, waveguide, dielectric lens and sub-reflector. The dielectric lens supports the sub-reflector which reduces interference which other antenna aperture structures may introduce. Dielectrics such as Teflon polytetrafluoroethylene (PTFE) would be used due to is temperature stability of -260°C to +260°C, loss tangent (δ) of .0004, and dielectric constant (ε_r) of 2.1 [85]. Dielectric constant represents a material's ability to store electrostatic energy in an applied electric field [86]. Dielectric materials have characteristics of having the ability of becoming polarized and are poor electric conductors. The higher the value of the dielectric constant, the lower the gain and bandwidth [87]. In addition to the dielectric constant of material, the materials' loss tangent is important as well. As the loss tangent of the material increases, the antenna gain decreases [88]. The strength of the PTFE varies with temperature. The colder the temperature the stronger the material is. Teflon by DuPont resin may be chosen in preference to other materials because of its better chemical resistance, heat resistance, friction coefficient, dielectric strength, toughness, weather resistance, or combination of such properties [89]. Figure 32 lists the PTFE dielectric material strength associated with its corresponding temperature value.

Temperature, °C (°F)	*Teflon®* PTFE Yield Strength, MPa (psi)
−251 (−420)	131 (19,000)
−196 (−320)	110 (16,000)
−129 (−200)	79.3 (11,500)
−73 (−100)	53.1 (7,700)
−56 (−68)	26.2 (3,800)
0 (32)	12.4 (1,800)
23 (73)	9.0 (1,300)
70 (158)	5.5 (800)
121 (250)	3.4 (500)

Figure 32 PTFE Dielectric Strength at Various Temperatures [89]

The splash plate secondary reflector is held by the dielectric material to reflect the RF signal back to the main dish which is reflected outward. The splash plate antenna is similar to the Gregorian and Cassegrain antenna where signals are reflected off of the secondary dish, and the secondary dish creating a blockage zone on the non-reflecting side. The splash plate antenna ray collimation shown in Figure 33 depicts the RF signal reflection off of the parabolic dish.

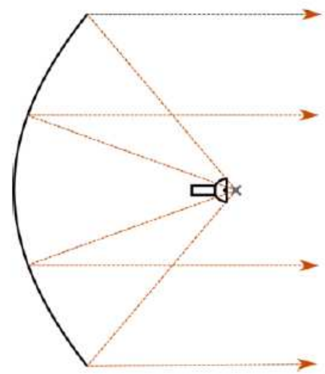


Figure 33 Splash Plate Antenna Ray Collimation [10]

Engineering software for antenna design assists with modeling and simulation. Antenna Magus is a software tool to help accelerate the antenna design and modeling process [90]. The software provides alternatives as well as adjusting physical aspects of an antenna based off of specifications entered in. A splash plate antenna was used to demonstrate Antenna Magus's and CST Microwave Studio's capability to produce an antenna to support various frequencies. Frequencies used by the CBSP, NMT and directional SDT antennas were entered into the software to obtain physical and logical outputs for a splash plate antenna. The physical parameters for the splash plate antenna as shown in Figure 34.

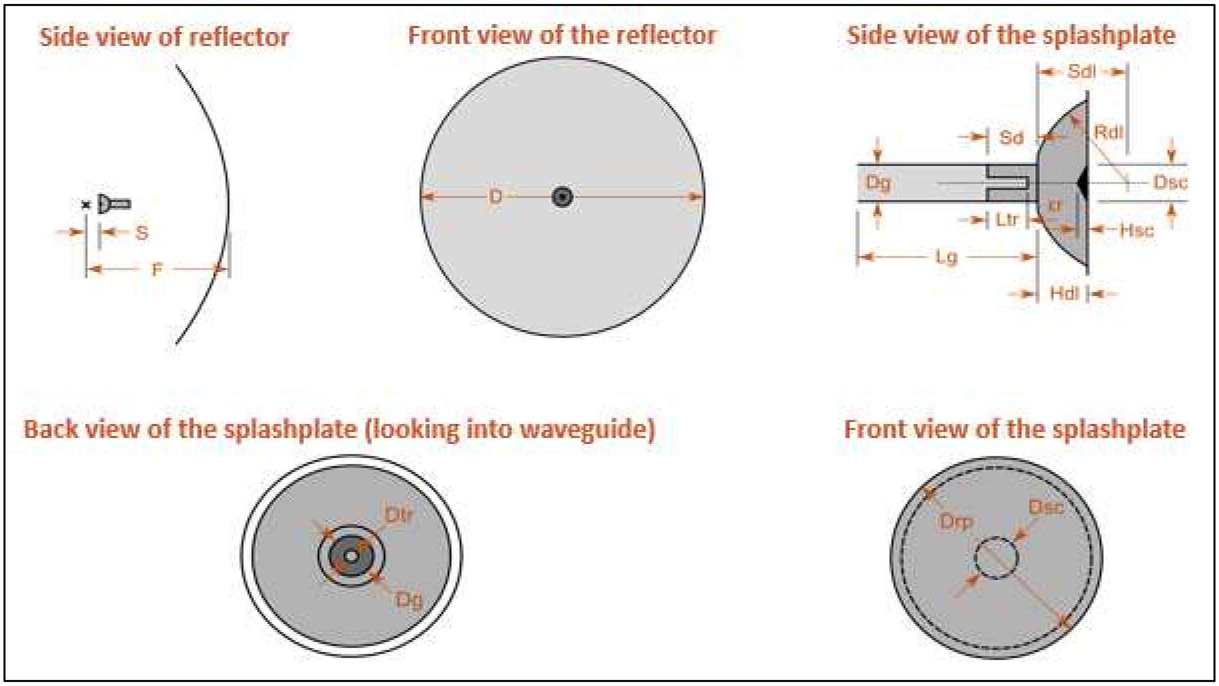


Figure 34 Physical Dimensions of a Splash Plate Antenna [91]

The splash plate feed uses backfire radiation to illuminate the dish, and the feeder waveguide doubles as a feed/support structure [92]. This is a compact reflector topology with the feed positioned close to the main reflector requiring no additional support struts. Another advantage is that the feed antenna can be fed from behind the main reflector, reducing unwanted aperture blockage. Antenna Magus and CST Microwave Studio was used to obtain VSWR values and radiation pattern information for the frequencies that the NMT, CBSP and directional SDT antennas support. As the frequencies increase, the size of the antenna decreases to conform to NMT, CBSP and directional SDT frequency capabilities.

Various metrics were obtained to assess antenna characteristics. The VSWR values, gain, radiation pattern, side lobe values and angular width (3 dB) values for each parabolic stacked antenna configuration were captured after simulating each arrangement in CST Microwave Studio.

VSWR is an indication of the amount of mismatch between an antenna and the feed line connecting to it, and a VSWR value under 2 is considered suitable for most antenna applications [93]. VSWR (2) is solved by incorporating the reflection coefficient Γ, where the reflection coefficient (3) involves the relationship between the reflected power P_{ref} and forward power P_{fwd}. In the context of antennas and feeders, the reflection coefficient is defined as the figure that quantifies how much of an electromagnetic wave is reflected by an impedance discontinuity in the transmission medium [94].

$$\boldsymbol{VSWR} = \frac{\mathbf{1+|\Gamma|}}{\mathbf{1-|\Gamma|}} \tag{2}$$

$$\mathbf{\Gamma} = \sqrt{\frac{\mathbf{Pref}}{\mathbf{Pfwd}}} \tag{3}$$

The antenna gain was captured during the simulations to assess the strength of the RF signal. The antenna gain G is over an isotropic source and is denoted as dBi. Antenna gain is the relative measure of an antenna's ability to direct or concentrate radio frequency (RF) energy in a specific direction or pattern [95]. The antenna gain (4) relates to antenna efficiency $\boldsymbol{k}$ measured as a percentage, diameter of the parabolic reflector D measured in meters, and wavelength $\boldsymbol{\lambda}$ which is measured in meters as well. Antenna efficiency (5) correlates to the wavelength, diameter of the parabolic dish, and gain.

$$\mathbf{G} = \mathbf{10log_{10}}\, \boldsymbol{k} \left(\frac{\mathbf{\pi D}}{\boldsymbol{\lambda}}\right)^{\mathbf{2}} \tag{4}$$

$$\boldsymbol{k} = \left(\frac{\boldsymbol{\lambda}}{\mathbf{\pi D}}\right)^{\mathbf{2}} (\mathbf{10})^{\frac{\mathbf{G}}{\mathbf{10}}} \tag{5}$$

CST Microwave studio was able to produce antenna efficiency results in dB. To convert the dB value to a percentage formula (6) is used to obtain the value. Consequently, to convert the antenna efficiency percentage back to a dB value equation (7) is used.

$$\boldsymbol{k_{per} = (10)^{\frac{k_{dB}}{10}}} \tag{6}$$

$$\boldsymbol{k_{dB} = 10\log_{10}(k_{per})} \tag{7}$$

Side lobe data was recorded with each parabolic stacked antenna configuration. Side lobes are usually radiation in undesired directions which can never be completely eliminated [96]. Another value recorded was the angular width (3 dB) of the output signal. The 3 dB, or half power, beam width of the antenna is defined as the angular width of the radiation pattern, including beam peak maximum, between points 3 dB down from maximum beam level (beam peak) [97]. As the gain of the antenna increases the beam width decreases. The beam width at half power BW_{HP} also known as angular width (3 dB) relates to wavelength $\boldsymbol{\lambda}$ and parabolic antenna diameter D as shown in equation (8).

$$\boldsymbol{BW_{HP} = \frac{70\lambda}{D}} \tag{8}$$

Signal transmission characteristics were captured using CST Microwave Studio while Antenna Magus software was able to capture the physical parameters of the parabolic antennas. Consolidating antennas via parabolic antenna stacking allows multi-frequency capabilities to be achieved on a single antenna pedestal. The Cassegrain, Gregorian and splash plate antennas are analyzed to propose parabolic stacked antenna configurations. The Cassegrain, Gregorian and splash plate antenna were researched to provide a single pedestal solution for consolidating the CBSP, NMT and directional SDT variant antennas. The Cassegrain, Gregorian and splash plate antenna have unique characteristics to operate at various frequencies. Details on their physical parameters and signal transmission characteristics are described in this section.

Parabolic antenna stacking involves using the blockage area that a parabolic antenna with sub-reflector produces. Additional antennas is used within these blockage areas to support multiple antennas on a single pedestal to achieve multi-frequency capabilities. The diameter of the large parabolic antenna sub-reflector $\boldsymbol{D_{n_{sub}}}$would be greater than or equal to the diameter of the smaller main parabolic antenna dish $\boldsymbol{D_{n_{main}}}$. Multiple antennas would be stacked in front of one another as far as the blockage area permits on each parabolic reflector antenna as shown in equation (9).

$$\begin{aligned} \boldsymbol{D_{1_{sub}}} &\geq \boldsymbol{D_{2_{main}}} \\ \boldsymbol{D_{2_{sub}}} &\geq \boldsymbol{D_{3_{main}}} \\ \boldsymbol{D_{3_{sub}}} &\geq \boldsymbol{D_{n_{main}}} \dots \end{aligned} \tag{9}$$

4.1 Cassegrain with Gregorian Parabolic Stacked Antenna

The Cassegrain with Gregorian parabolic stacked antenna provides SATCOM and LoS frequency band operations. These frequencies are operated within currently fielded NMT Q / Ka, NMT X / Ka and SDT antennas. This configuration also achieves CBSP antenna capable frequencies with the exception the L band frequency range (.95 GHz to 2.05 GHz) and the C band frequency range (3.7 GHz to 4.2 GHz). A large Cassegrain antenna is used to operate at lower frequency bands while a smaller Gregorian antenna is stacked in front of the Cassegrain antenna's sub-reflector to operate within higher frequency bands. The parabolic stacked antenna geometry is shown in Figure 35.

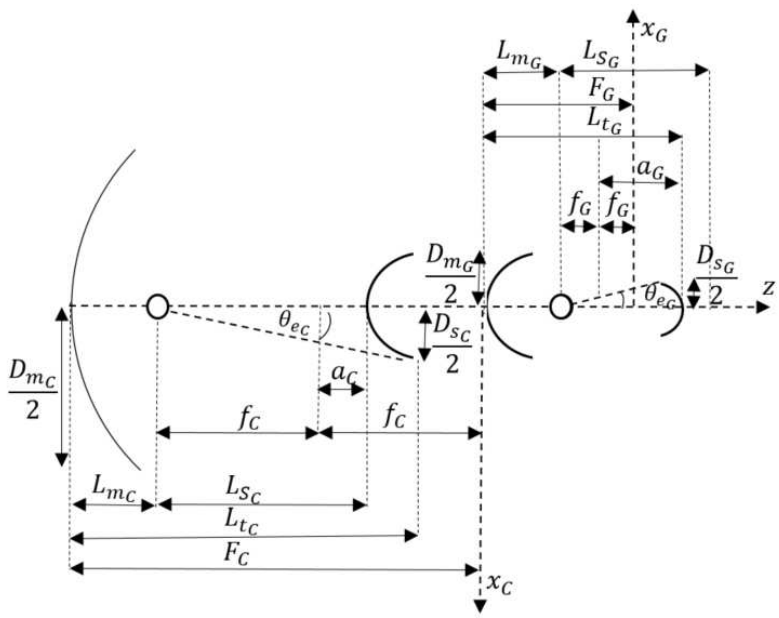


Figure 35 Cassegrain and Gregorian Parabolic Stacked Antenna Geometric Properties

The Cassegrain antenna's total length L_{t_C} incorporates the diameter of the sub-reflector D_{S_C}, distance between the main dish and foci F_C, half of the major axis of the ellipse a_C, and half of the distance between the foci f_C [98].

$$L_{t_C} = F_C + a_C\sqrt{1 + \frac{{D_{S_C}}^2}{4({f_C}^2 - {a_C}^2)}} - f_C \quad (10)$$

Half of the distance between the foci f_C for the Cassegrain antenna is determined by the diameter of the main parabolic dish D_{m_C} , position of the secondary focus L_{s_C}, angle to the edge ray of the sub-reflector $\theta_{e_C}$and the distance between the main dish and foci F_C [98].

$$\boldsymbol{f_C = \frac{L_{s_C}\left[-D_{m_C} - 4F_C \tan\frac{\theta_{e_C}}{2}\right]}{2\sigma D_{m_C}}} \tag{11}$$

The total length of the Cassegrain antenna L_{t_C} with respect to the main parabolic dish and sub-reflector is found by incorporating equation (11) into equation (10).

$$\boldsymbol{L_{t_C} = F_C + a_C\sqrt{1 + \frac{{D_{S_C}}^2}{4({f_C}^2 - {a_C}^2)}} - \frac{L_{s_C}\left[-D_{m_C} - 4F_C \tan\frac{\theta_{e_C}}{2}\right]}{-2D_{m_C}}} \tag{12}$$

The Gregorian antenna's total length L_{t_G} incorporates half the major axis of the ellipse a_G, distance between the main dish and foci F_G, and half the distance between the foci f_G [98].

$$\boldsymbol{L_{t_G} = F_G + a_G - f_G} \tag{13}$$

The Gregorian's sub-reflector diameter D_{S_G} includes the main parabolic dish D_{m_G}, distance from the main dish to the foci F_G , position of the secondary focus L_{s_G}, angle to the edge ray of the sub-reflector θ_{e_G} and half the distance between the foci f_G [98].

$$\boldsymbol{D_{S_G} = \frac{4\left(L_{s_G} - f_G\right)}{\frac{1}{\sin\theta_{e_G}} + \frac{\left(16{F_G}^2 + {D_{m_G}}^2\right)}{8F_G D_{m_G}}}} \tag{14}$$

Solving for half the distance between the foci f_G using equation (14) provides the following:

$$\boldsymbol{f_G} = -\left[\left(\frac{\mathbf{1}}{\sin\boldsymbol{\theta_{e_G}}} + \frac{\left(\mathbf{16}\boldsymbol{F_G}^{\mathbf{2}} + \boldsymbol{D_{m_G}}^{\mathbf{2}}\right)}{\mathbf{8}\boldsymbol{F_G}\boldsymbol{D_{m_G}}}\right)\left(\frac{\mathbf{1}}{\mathbf{4}}\right) + \boldsymbol{L_{S_G}}\right] \tag{15}$$

To solve for the total length of the Gregorian antenna incorporating the main dish and sub-reflector, equation (15) is used with equation (13).

$$\boldsymbol{L_{t_G}} = \boldsymbol{F_G} + \boldsymbol{a_G} + \left[\boldsymbol{D_{S_G}}\left(\frac{\mathbf{1}}{\sin\boldsymbol{\theta_{e_G}}} + \frac{\left(\mathbf{16}\boldsymbol{F_G}^{\mathbf{2}} + \boldsymbol{D_{m_G}}^{\mathbf{2}}\right)}{\mathbf{8}\boldsymbol{F_G}\boldsymbol{D_{m_G}}}\right)\left(\frac{\mathbf{1}}{\mathbf{4}}\right)\right] - \boldsymbol{L_{S_G}} \tag{16}$$

The Cassegrain and Gregorian antenna has a total length of 0.56m and has mounts to support the large Cassegrain's sub-refector and the small Gregorian antenna stacked in front of it. The waveguide from the Gregorian antenna is routed behind the Gregorian antenna's main reflector, along the blockage area of the Cassegrain's sub-reflector and through the rear of the large Cassegrain antenna's main reflector. The Cassegrain and Gregorian parabolic stacked antenna side view is shown in Figure 36.

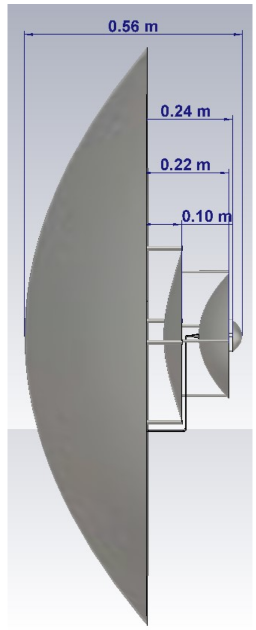


Figure 36 Side view of the Cassegrain and Gregorian parabolic stacked antenna

The physical parameters of the Cassegrain antenna of the parabolic stacked antenna configuration consists of a primary reflector diameter of 1.5m and a secondary reflector diameter of 447.3mm. The physical parameters of the Gregorian antenna of the parabolic stacked antenna configuration consists of a primary reflector diameter of 325.9mm and a secondary reflector diameter of 81.47mm. The Gregorian antenna utilizes the blockage area that the large Cassegrain's sub-reflector produces. A horn feed is used for both antennas of this parabolic stacked antenna configuration. Table 17 and Table 18 lists the physical parameters of the Cassegrain and Gregorian antennas in the parabolic stacked antenna configuration.

Table 17 Physical Parameters of the Cassegrain Antenna of the Parabolic Stacked Antenna

Description	Short Name	Value
Primary reflector diameter	Dp	1.5 m

Primary reflector focal length	Fp	444.0 mm
Secondary reflector diameter	Ds	447.3 mm
Secondary reflector focal length	Fs	257.4 mm
Horn aperture to focal point offset	Sf	0 m
Waveguide length	Lg	36.78 mm
Flare length	Lf	80.98 mm
Aperture height	Ha	35.58 mm
Aperture width	Wa	45.40 mm
Waveguide height	Hg	14.44 mm
Waveguide width	Wg	28.88 mm

Table 18 Physical Parameters of the Gregorian Antenna of the Parabolic Stacked Antenna

Description	Short Name	Value
Primary reflector diameter	Dp	325.9 mm
Primary reflector focal length	Fp	85.64 mm
Secondary reflector diameter	Ds	81.47 mm
Secondary reflector focal length	Fs	68.51 mm
Waveguide length	Lg	14.48 mm
Flare length	Lf	50.00 mm
Aperture height	Ha	21.02 mm
Aperture width	Wa	28.99 mm
Waveguide height	Hg	5.684 mm
Waveguide width	Wg	11.37 mm

VSWR values were captured through CST microwave studio for the Cassegrain and Gregorian parabolic stacked antenna. NMT Q / Ka, NMT X / Ka, directional SDT and CBSP frequencies were simulated to verify functionality. Certain CBSP frequencies were unable to operate with the Cassegrain and Gregorian parabolic stacked antenna which include the L band frequency range (.95 GHz to 2.05 GHz) and the C band frequency range (3.7 GHz to 4.2 GHz). VSWR values ranged from 1.34:1 to 2.21:1 which is slightly higher than the 2:1 VSWR benchmark. Figure 37 (a) through (i) depicts results from the C, X, Ku, K, Ka and Q band frequency range.

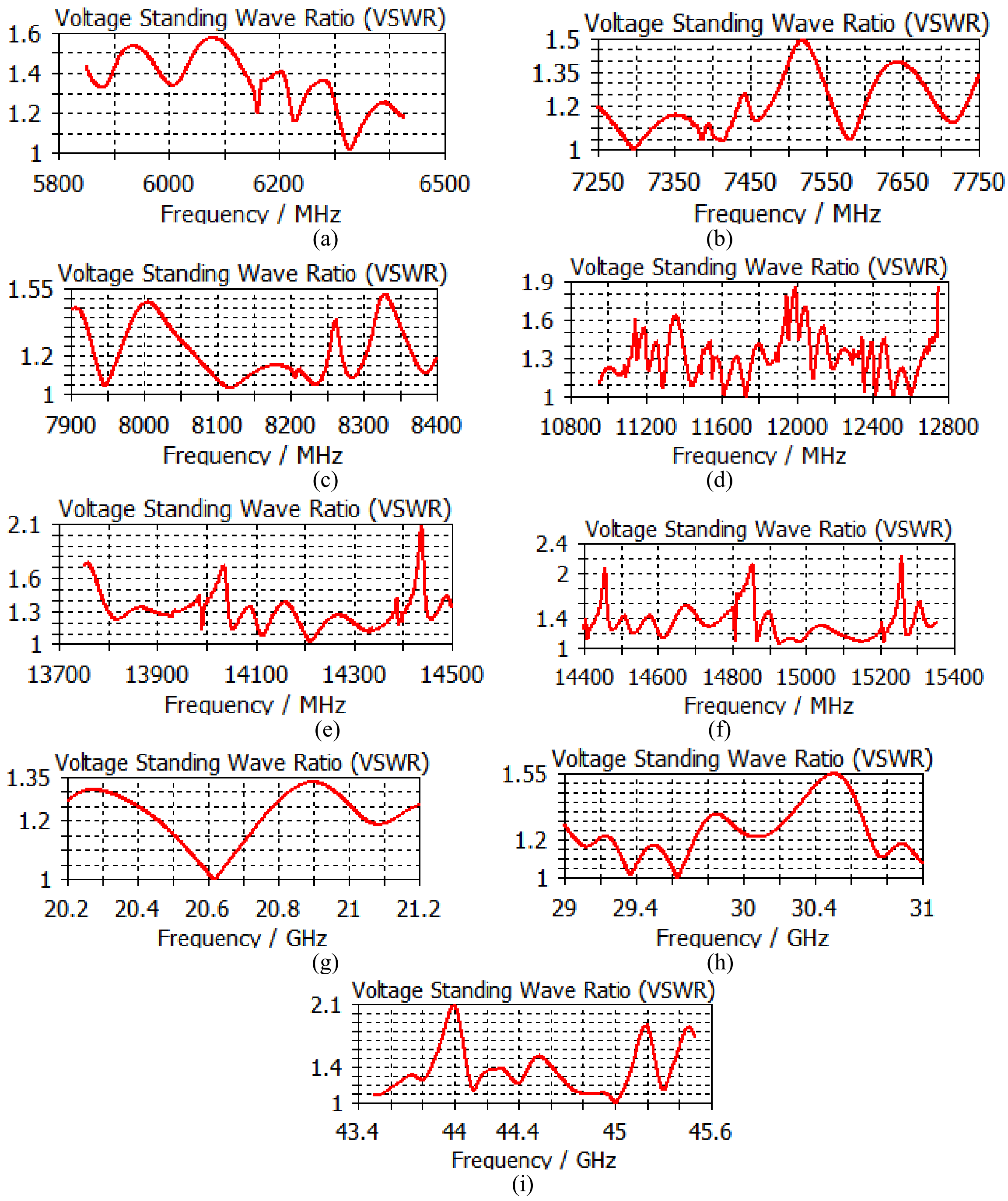
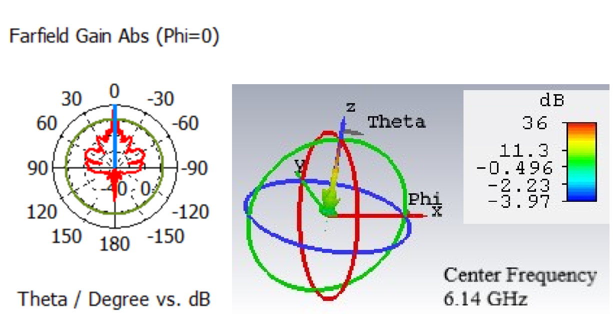
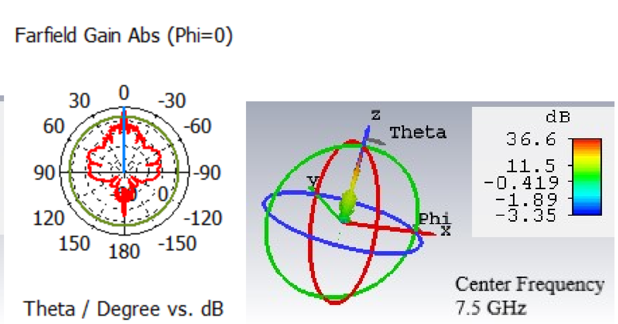


Figure 37 Cassegrain and Gregorian VSWR Values. (a) C band (5.85 GHz to 6.425 GHz). (b) X band (7.25 GHz to 7.75 GHz). (c) X band (7.9 GHz to 8.4 GHz). (d) Ku band (10.95 GHz to 12.75 GHz). (e) Ku band (13.75 GHz to 14.5 GHz). (f) Ku band (14.4 GHz to 15.35 GHz. (g) K band (20.2 GHz to 21.2 GHz). (h) Ka band (29 GHz to 31 GHz). (i) Q band (43.5 GHz to 45.5 GHz)

Radiation patterns, gain, side lobe levels and angular width (3 dB) were captured through simulation using CST microwave studio. Figure 38 (a) through (i) depicts the frequency band results for the C, X, Ku, K, Ka and Q band frequency range. The C band center frequency of 6.14 GHz had a gain of 36 dB with an angular width (3 dB) of 2 degrees and a side lobe level of -14.1 dB. The X band center frequency of 7.5 GHz had a gain of 36.6 dB with an angular width (3 dB) of 1.1 degrees and a side lobe level of -11.7 dB. The X band center frequency of 8.15 GHz had a gain of 39.2 dB with an angular width (3 dB) of 1.2 degrees and a side lobe level of -15.1 dB. The Ku band center frequency of 11.9 GHz had a gain of 40.9 GHz with an angular width (3 dB) of 0.6 degrees and a side lobe level of -26.3 dB. The Ku band center frequency of 14.1 GHz had a gain of 39.3 dB with an angular width (3 dB) of 0.3 degrees and a side lobe level of -13.1 dB. The Ku band center frequency of 14.875 GHz had a gain of 40.1 dB with an angular width (3 dB) of 0.4 degrees and a side lobe level of -12 dB. The K band center frequency of 20.7 GHz had a gain of 33.4 GHz with an angular width (3 dB) of 2.8 degrees and a side lobe level of -15.5 dB. The Ka band center frequency of 30 GHz had a gain of 36.8 dB with an angular width (3 dB) of 2.1 degrees and a side lobe level -14.7 dB. The Q band center frequency of 44.5 GHz had a gain of 39.1 dB with an angular width (3 dB) of 1 degree and a side lobe level of -29.4 dB. These frequencies represented the operating frequencies that the NMT Q / Ka, NMT X / Ka, directional SDT and a limited set of operating frequencies of the CBSP antenna variants operated within.



(a)



(b)

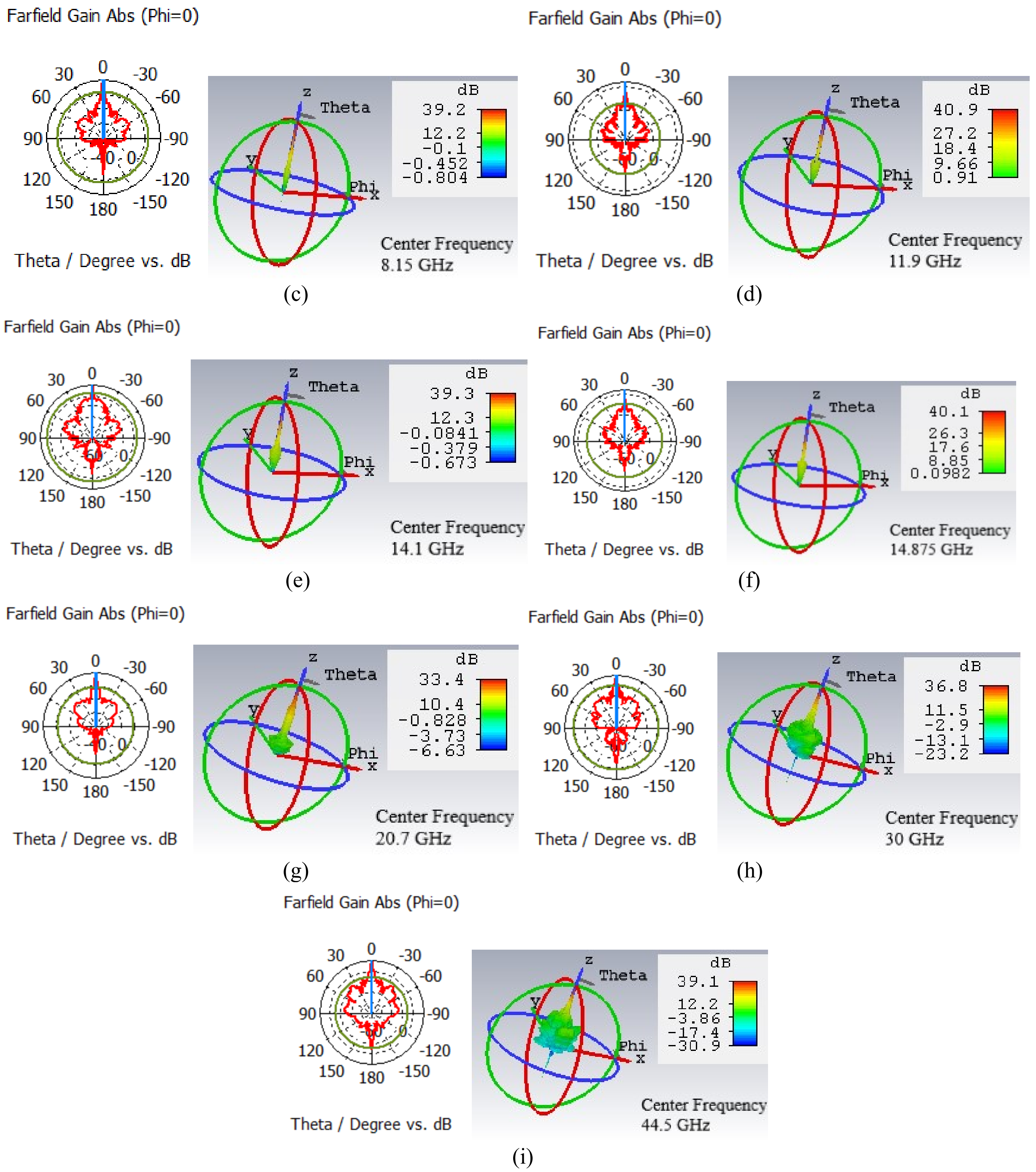


Figure 38 Radiation Pattern for the Cassegrain and Gregorian Parabolic Stacked Antenna. (a) C band (6.14 GHz). (b) X band (7.5 GHz). (c) X band (8.15 GHz). (d) Ku band (11.9 GHz). (e) Ku band (14.1 GHz). (f) Ku band (14.875 GHz). (g) K band (20.7 GHz). (h) Ka band (30 GHz). (i) Q band (44.5 GHz)

4.2 Gregorian with Splash Plate Antenna

The Gregorian with splash plate antenna operates within the frequency range of the NMT Q / Ka, NMT X / Ka and SDT antennas. Additionally, this configuration allows for other frequencies that the CBSP variants operate within except for the L band frequency range (.95 GHz to 2.05 GHz) and the C band frequency range (3.7 GHz to 4.2 GHz). Utilizing the blockage area that the Gregorian antenna produces, the splash plate antenna is able to be stacked in front of the Gregorian antenna's secondary reflector. The geometry of the Gregorian and splash plate antenna is shown in Figure 39.

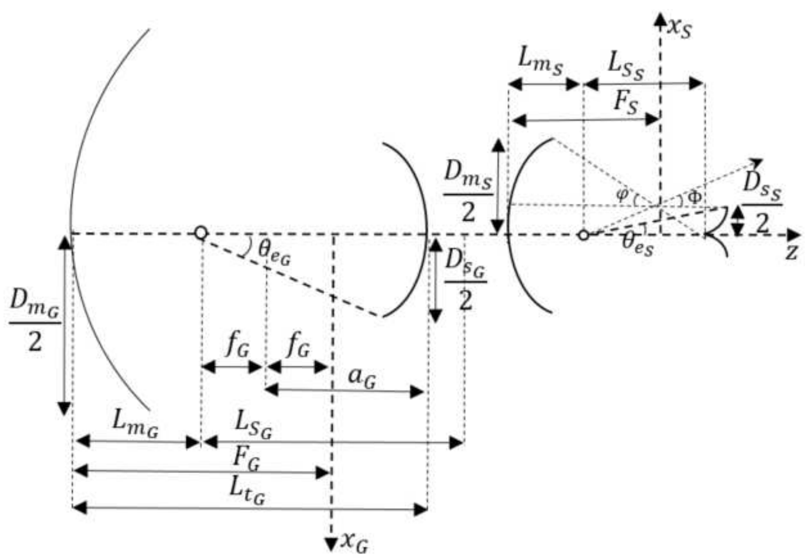


Figure 39 Gregorian and Splash Plate Stacked Antenna Geometric Properties

The splash plate antenna feed is a self-supported hat-fed system with a sub-reflector attached with the shape of an axially displaced ellipsoid [99]. A displaced axis Gregorian antenna with a single offset has geometric properties that the main reflector is parabolic while the sub-reflector is a portion of an ellipse [100]. L_{m_S} is the distance between the back of the main reflector and the focus while L_{S_S} is the distance between the focus and the edge of the sub-reflector. F_S is the focal distance of the main reflector, D_{m_S} is the diameter of the main splash plate reflector, D_{S_S} is the diameter of the splash plate sub-reflector, and θ_{e_S} is the angle between the Z axis and the ray emanating from the focus [100]. Equation (17) depicts the distance between the back of the main reflector and the focus with relationship between the splash plate main reflector dish and splash plate sub-reflector.

$$\boldsymbol{L_{m_S} = \frac{F_S D_{m_S}}{D_{m_S} - D_{S_S}} - \frac{D_{S_S}}{4}\left(\frac{\cos\theta_{e_S} + 1}{\sin\theta_{e_S}}\right)} \tag{17}$$

Equation (18) displays the distance between the edge of the splash plate sub-reflector and the focus.

$$\boldsymbol{L_{s_S} = 2\cos\Phi\left(\frac{D_{S_S}}{4\sin\Phi}\right) + \frac{D_{s_S}}{2\tan\varphi}} \tag{18}$$

Φ is the angle from the axis of the main splash plate reflector coordinate system to the top edge of the main splash plate reflector as shown

$$\boldsymbol{\tan\Phi = \frac{2}{\frac{\cos\theta_{e_S} + 1}{\sin\theta_{e_S}} - \frac{4F_S}{D_{m_S} - D_{S_S}}}} \tag{19}$$

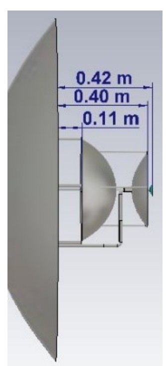
φ is the offset angle of the main splash plate reflector coordinate system and the splash plate sub-reflector coordinate system as shown

$$\boldsymbol{\tan\varphi = \frac{8F_S\left(D_{m_S} - D_{S_S}\right)}{\left(D_{m_S} - D_{S_S}\right)^2 - 16F_S^2}} \tag{20}$$

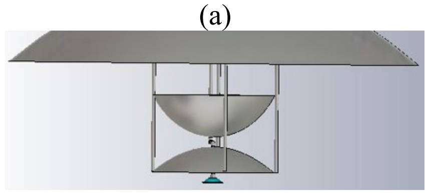
Using equation (19), the diameter of the splash plate sub-reflector with relation to the main splash plate reflector is shown as

$$D_{S_S} = D_{m_S} - \frac{4F_S \tan\Phi}{\tan\Phi\left(\frac{\cos\theta_{e_S}+1}{\sin\theta_{e_S}}\right)-2} \tag{21}$$

The splash plate antenna is smaller than the sub-reflector of the larger Gregorian antenna and is mounted in front while utilizing the blockage area that the sub-reflector produces. The feed from the splash plate antenna is routed behind the splash plate antenna's main parabolic dish, along the front of the larger Gregorian sub-reflector and through the rear of the larger Gregorian's main parabolic dish. The side view and top view of the Gregorian and splash plate parabolic stacked antenna is shown in Figure 40.



(a)



(b)

Figure 40 Gregorian and Splash Plate Parabolic Stacked Antenna. (a) Side View. (b) Top View

The Gregorian and splash plate parabolic stacked antenna had a Gregorian antenna with a primary dish size of 1.5 m and a splash plate antenna stacked in front of the reflecting dish with a primary dish size of 325.9 mm. The diameter of the Gregorian antenna is slightly smaller than the

NMT Q / Ka antenna that is currently fielded. Antenna Magus software was used to obtain the physical parameters of each antenna and CST Microwave studio software integrated these two antennas in a parabolic stack configuration. The physical parameter of the Gregorian and splash plate parabolic stacked antenna is shown in Table 19 and Table 20.

Table 19 Physical Parameters of the Gregorian Antenna of the Parabolic Stacked Antenna

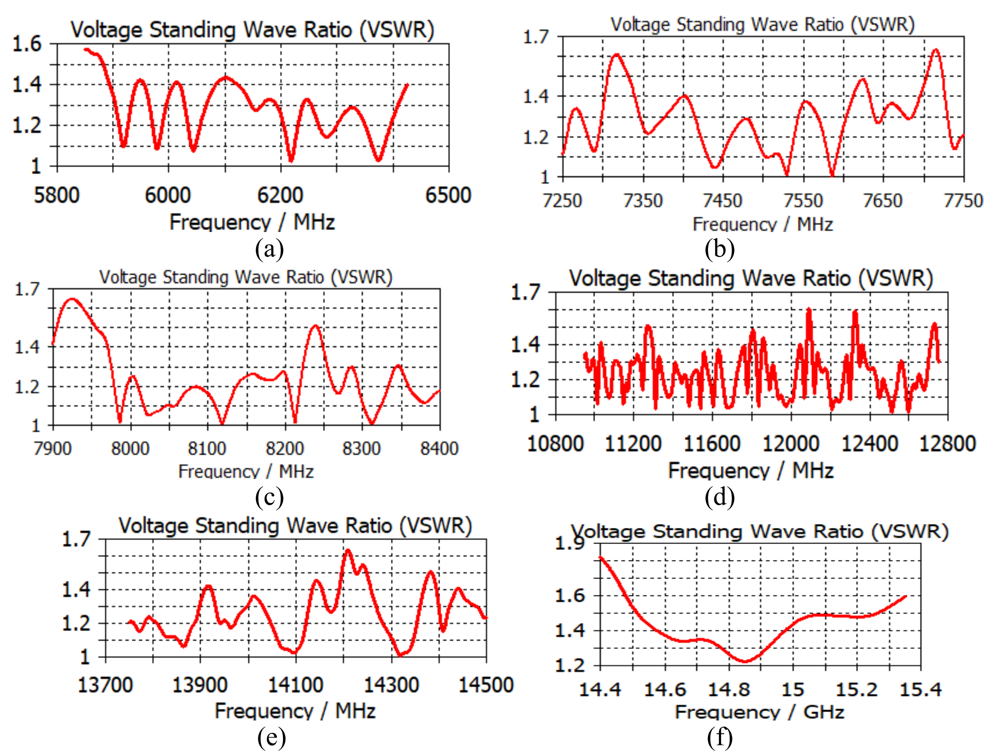
Description	Short Name	Value
Primary reflector diameter	Dp	1.5 m
Primary reflector focal length	Fp	443.6 mm
Secondary reflector diameter	Ds	447.3 mm
Secondary reflector focal length	Fs	354.9 mm
Horn aperture to focal point offset	Sf	0 m
Waveguide length	Lg	36.78 mm
Flare length	Lf	127 mm
Aperture height	Ha	53.38 mm
Aperture width	Wa	73.62 mm
Waveguide height	Hg	14.44 mm
Waveguide width	Wg	28.88 mm

Table 20 Physical Parameters of the Splash Plate Antenna of the Parabolic Stacked Antenna

Description	Short Name	Value
Dish diameter	D	325.9 mm
Focal depth	F	97.76 mm
Feed offset from focal point	S	5.314 mm
Waveguide diameter	Dg	10.02 mm
Waveguide length	Lg	30.05 mm
Length of tuning roller	Ltr	10.27 mm
Diameter of tuning roller	Dtr	3.706 mm
Radius of dielectric lens	Rdl	32.06 mm
Offset of dielectric lens	Sdl	30.55 mm
Height of dielectric lens	Hdl	11.02 mm
Diameter of reflecting plane	Drp	54.09 mm
Diameter of spherical cap	Dsc	12.02 mm

Height of spherical cap	Hsc	1.503 mm
Inset / extension of dielectric into waveguide	Sd	11.02 mm

The VSWR values for this configuration displayed results that were under the 2:1 VSWR value. This parabolic stacked antenna configuration was capable of operating within frequency bands C, X, Ku, K, Ka, and Q. The results depict operational capability to function within frequencies corresponding to current capabilities of the NMT Q / Ka, NMT X / Ka, SDT and certain frequencies that the CBSP antenna variants are capable of. The Gregorian antenna was capable of operating within the C, X and Ku bands while the splash plate antenna was capable of operating within the K, Ka, and Q bands. The maximum VSWR that was observed was within the Ka band frequency range of 1.85:1. The VSWR values shown in Figure 41 (a)-(f) represented the large Gregorian antenna values while the VSWR values shown in Figure 41 (g)-(i) were the results of the small splash plate antenna.



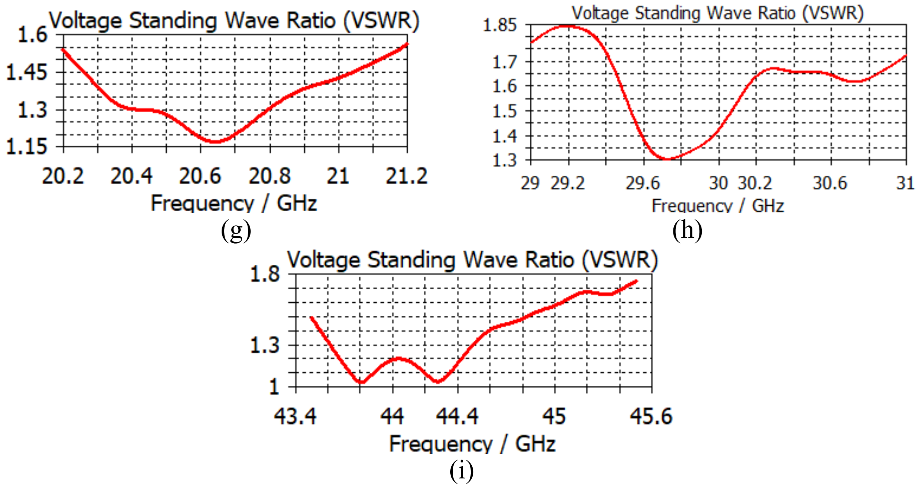
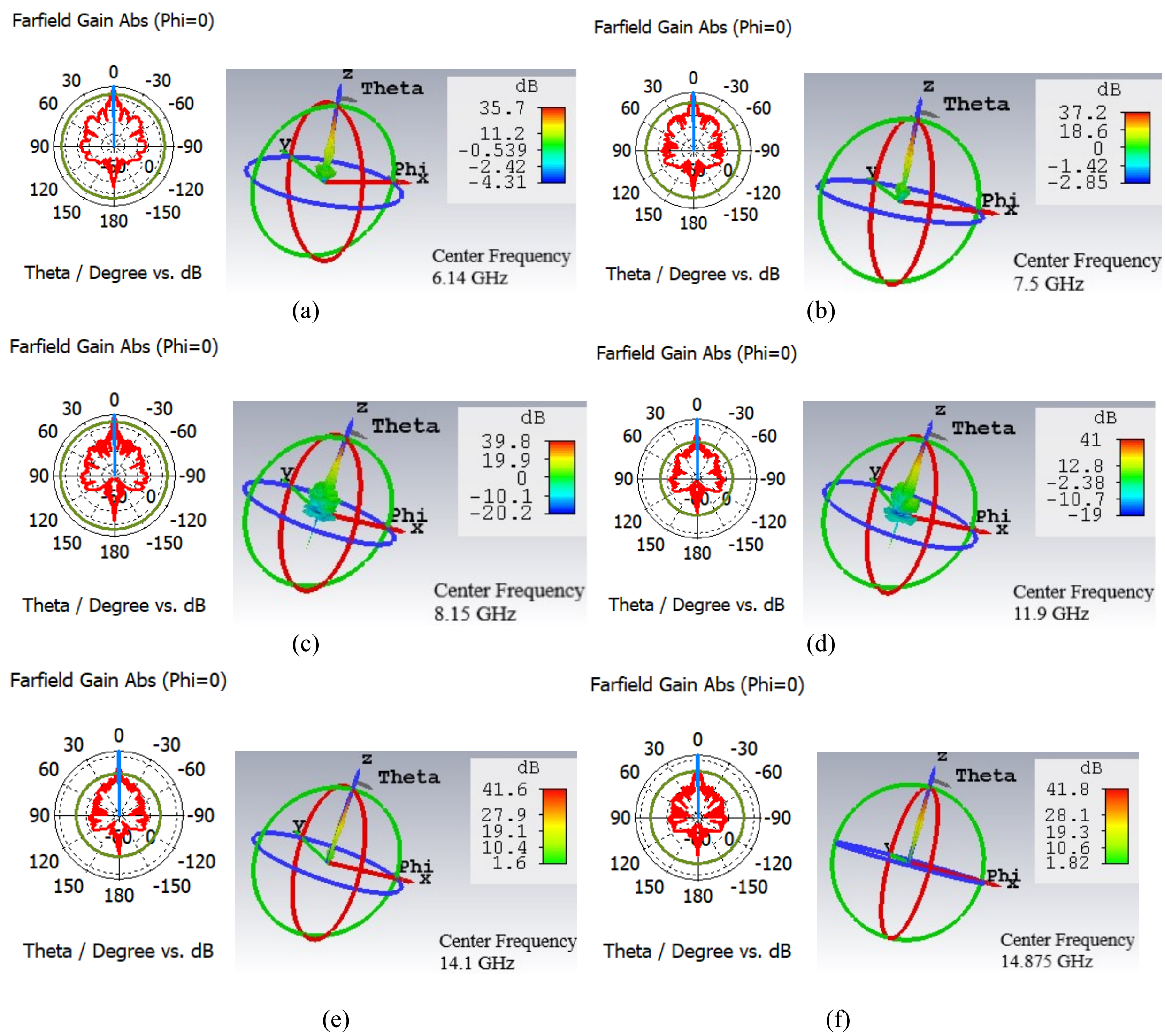
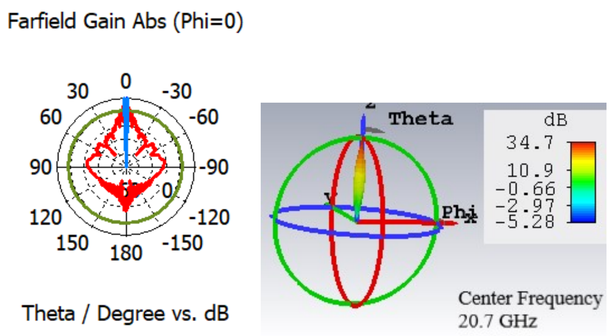


Figure 41 Gregorian and Splash Plate VSWR Values. (a) C band (5.85 GHz to 6.425 GHz). (b) X band (7.25 GHz to 7.75 GHz). (c) X band (7.9 GHz to 8.4 GHz). (d) Ku band (10.95 GHz to 12.75 GHz). (e) Ku band (13.75 GHz to 14.5 GHz). (f) Ku band (14.4 GHz to 15.35 GHz). (g) K band (20.2 GHz to 21.2 GHz). (h) Ka band (29 GHz to 31 GHz). (i) Q band (43.5 GHz to 45.5 GHz)

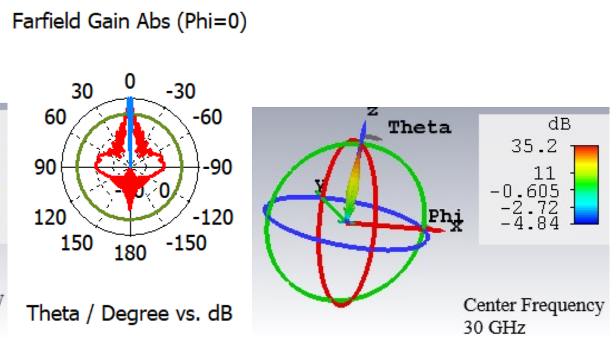
Radiation patterns, gain values and side lobe levels for the C, X, Ku, K, Ka, and Q frequency bands were captured for the Gregorian splash plate parabolic stacked antenna. The C band center frequency of 6.14 GHz was used to depict a gain of 35.7 dB, side lobe level of -8.9 dB and an angular width (3 dB) of 1.4 degrees. The X band center frequency of 7.5 GHz was simulated to obtain results of a gain value of 37.2 dB, side lobe level of -11.1 dB and an angular width (3 dB) of 1.3 degrees. Center frequency 8.15 GHz which is also within the X band frequency range produced results of 39.8 dB of gain, side lobe level of -24.9 dB and an angular width (3 dB) of 1.0 degrees. Ku band center frequency 11.9 GHz demonstrated a gain value of 41 dB, side lobe level of -26.7 dB and an angular width (3 dB) of 0.5 degrees. The Ku band center frequency of 14.1 GHz produced a gain of 41.6 GHz, side lobe level of -22.9 dB and an angular width (3 dB) of 0.4 degrees. The LoS Ku band center frequency of 14.875 GHz had a gain of 34.6 dB, side lobe level of -12.1 dB and an angular width (3 dB) of 2.9 degrees. Figure 42 (a)-(f) displayed gain and radiation patterns of the large Gregorian antenna of this parabolic stacked antenna configuration.

The smaller splash plate antenna was capable of operating at the K, Ka and Q band frequencies. The K band center frequency of 20.7 GHz was simulated to achieve a gain of 34.7 dB, side lobe level of -12.4 dB and an angular width (3 dB) of 2.9 degrees. The Ka band center frequency of 30 GHz produced a gain of 35.2 dB, side lobe level of -13.5 dB and an angular width (3 dB) of 2.2 degrees. The Q band center frequency of 44.5 GHz had a gain of 34.6 dB, side lobe level of -6.2 dB and an angular width of 1.7 degrees. Figure 42 (g)-(i) displayed gain and radiation patterns of the small splash plate antenna of this parabolic stacked antenna configuration.

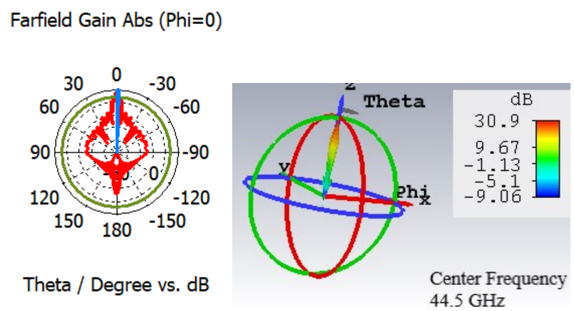




(g)



(h)



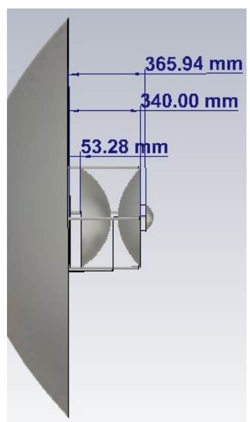
(i)

Figure 42 Radiation Pattern for the Gregorian and Splash Plate Parabolic Stacked Antenna. (a) C band (6.14 GHz). (b) X band (7.5 GHz). (c) X band (8.15 GHz). (d) Ku band (11.9 GHz). (e) Ku band (14.1 GHz). (f) Ku band (14.875 GHz). (g) K band (20.7 GHz). (h) Ka band (30 GHz). (i) Q band (44.5 GHz)

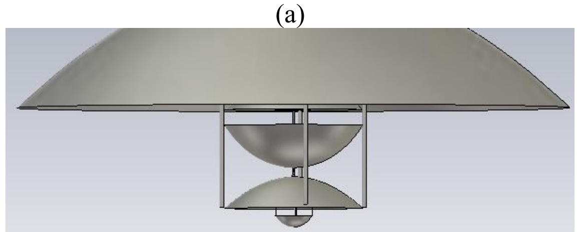
The Gregorian and splash plate parabolic stacked antenna was similar in size to the diameter of the NMT Q / Ka antenna of 1.5m. Capable frequencies ranged from frequency bands C, X, Ku, K, Ka and Q. The Gregorian antenna was able to operate within frequency bands C, X and Ku while the smaller splash plate antenna which had a diameter of 325.9mm operated at K, Ka and Q band frequencies. VSWR values peaked at 1.85:1 within the Ka band frequency range while gain values peaked within the Ku band frequency range at 41.8 dB. Considerations for this parabolic stacked antenna configuration included being able to have a similar size to the NMT Q / Ka antenna in order to replace the currently fielded antenna at the end of its system life cycle. The Gregorian and splash plate parabolic stacked antenna configuration was capable of operating at frequencies equivalent to the NMT Q / Ka, NMT X / Ka and the directional portion of the SDT antenna along with a portion of frequencies that the CBSP variants currently operate within.

4.3 Dual Gregorian Parabolic Stacked Antenna

A dual Gregorian parabolic stacked antenna provides capabilities that both NMT Q / Ka and NMT X / Ka antennas operate within [101]. In addition to the NMT antennas variants, the SDT directional antenna and certain frequencies that the CBSP antenna variants operate within are also capable with this parabolic antenna stacking configuration. This parabolic stacking configuration provides operation modes within the C, X, Ku, K, Ka, and Q band frequency range. The C, X and Ku band frequencies are met with the larger dish within this configuration while the smaller dish supports the K, Ka and Q band frequency ranges. The side view [101] and top view of the dual Gregorian parabolic stacked antenna is shown in Figure 43.



(a)



(b)

Figure 43 Dual Gregorian Parabolic Stacked Antenna. (a) Side View [101]. (b) Top View

The dual Gregorian parabolic stacked antenna had a large parabolic dish of 1.921m and a medium parabolic dish of 480mm. The larger Gregorian antenna had a dish diameter of 1.921m with a sub-reflector size of 480mm which is 20% smaller than the fielded large NMT X / Ka antenna. These antennas were stacked in front of one another utilizing the blockage space created by the larger antenna's secondary reflector. Antenna Magus software was used to obtain the physical parameters of each Gregorian antenna to simulate within CST Microwave studio in a parabolic stacked configuration. The physical parameters of the dual Gregorian parabolic stacked antenna is shown in Table 21.

Table 21 Dual Gregorian Parabolic Stacked Antenna Physical Parameters

Gregorian Parabolic Stacked Antenna Physical Description	Short Name	Large Gregorian Antenna Values	Medium Gregorian Antenna Values
Primary reflector diameter	Dp	1.921 m	480 mm
Primary reflector focal length	Fp	504.8 mm	132.1 mm
Secondary reflector diameter	Ds	480.2 mm	125.7 mm
Secondary reflector focal length	Fs	403.8 mm	105.7 mm
Secondary reflector eccentricity	Es	0.5604	0.5604
Horn aperture to focal point offset	Sf	0 m	0 m
Waveguide length	Lg	39.97 mm	9.993 mm
Flare length	Lf	138.0 mm	34.50 mm
Aperture height	Ha	58.00 mm	14.50 mm
Aperture width	Wa	80.00 mm	20.00 mm
Waveguide height	Hg	15.69 mm	3.922 mm
Waveguide width	Wg	31.38 mm	7.845 mm

VSWR values that operate within the NMT Q / Ka and NMT X / Ka frequency ranges were assessed. The VSWR values for this configuration displayed results that were under the 2:1 VSWR value with a maximum VSWR value of 1.68:1. The VSWR values for the X band frequency range 7.25 GHz to 7.75 GHz displayed values ranging up to 1.5:1. Similar results were shown for X band frequencies 7.9 GHz to 8.4 GHz with values ranging up to 1.49:1. K band frequencies 20.2 GHz to 21.2 GHz depicted VSWR results of up to 1.48:1. Frequencies 29 GHz to 31GHz which reside on the Ka band had VSWR values up to 1.45:1. The Q band frequency range of 43.5 GHz GHz to 45.5 GHz had VSWR values up to 1.68:1. VSWR values for the triple Gregorian parabolic stacked antenna are shown in Figure 44.

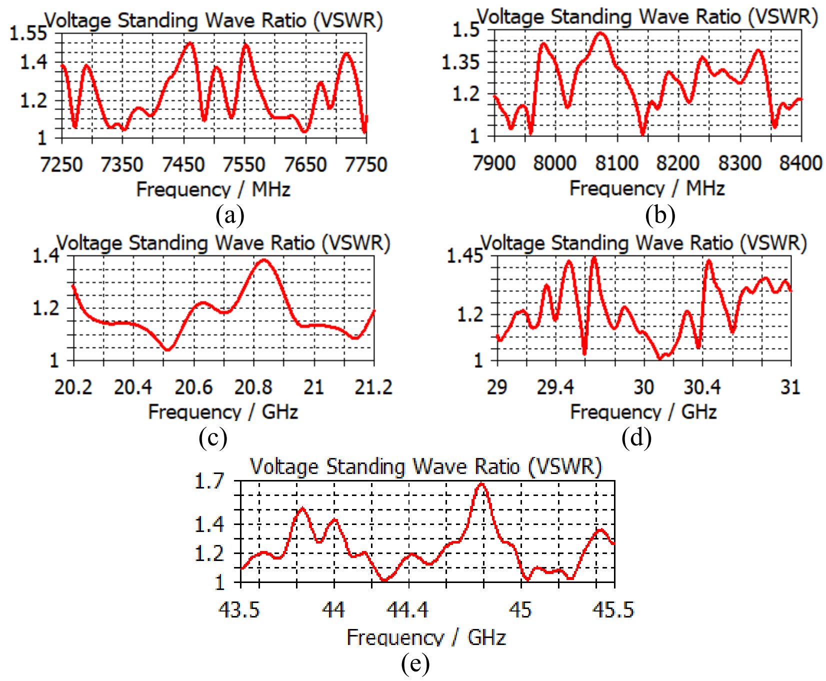
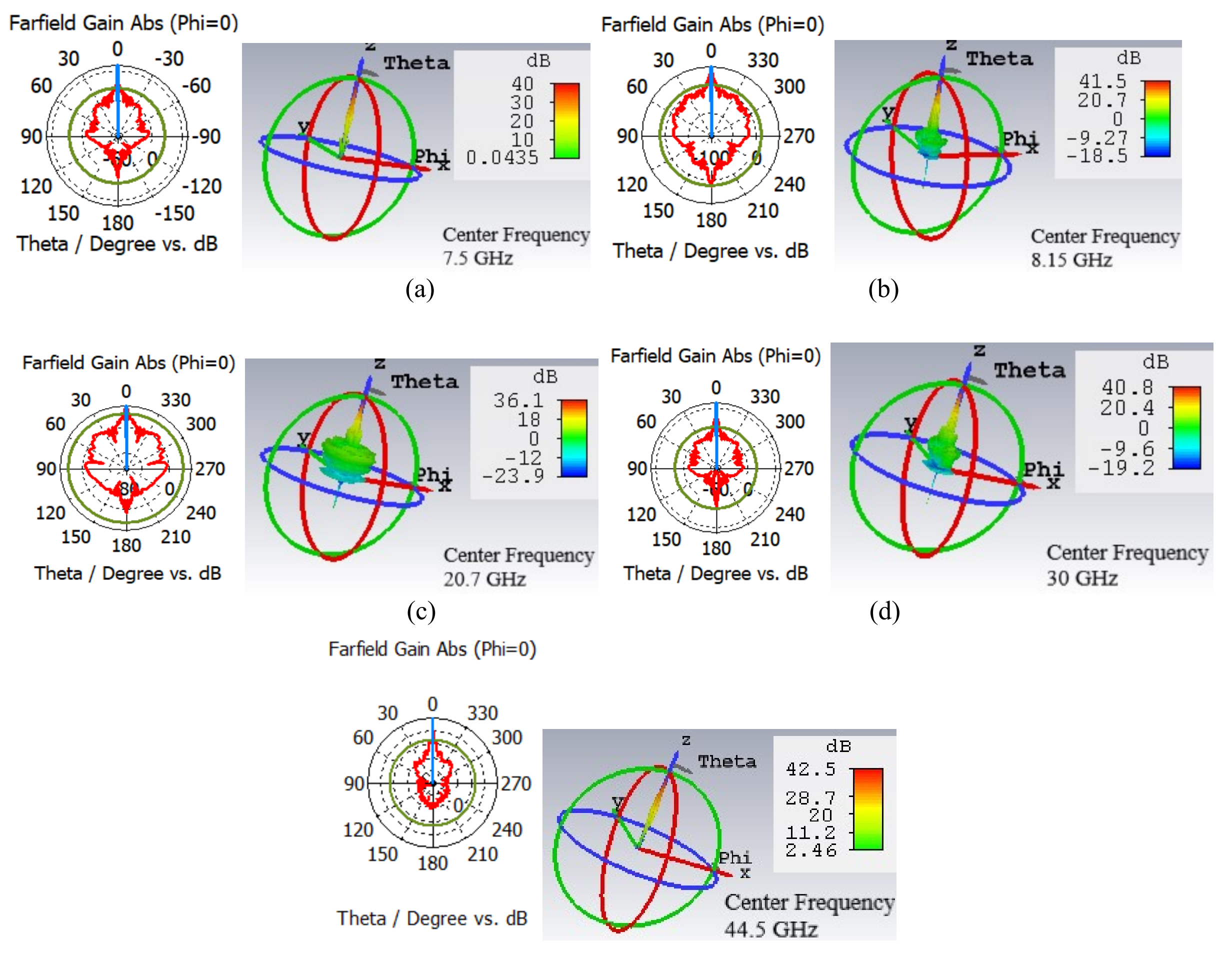


Figure 44 VSWR of the Gregorian Parabolic Stacked Antenna. (a) X band (7.25 GHz – 7.75 GHz). (b) X band (7.9 GHz – 8.4 GHz). (c) K band (20.2 GHz – 21.2 GHz). (d) Ka band (29 GHz – 31 GHz). (e) Q band (43.5 – 45.5 GHz)

Radiation patterns, gain values and side lobe levels for the X, K, Ka and Q frequency bands which the NMT Q / Ka and NMT X / Ka variant antennas operate within were captured for the dual Gregorian parabolic stacked antenna. The X band center frequency of 7.5 GHz was used to depict a gain of 40 dB, side lobe level of -24.1 dB and an angular width (3 dB) of 0.8 degrees. Center frequency 8.15 GHz which is also within the X band frequency range produced results of 41.5 dB of gain, side lobe level of -30 dB and an angular width (3 dB) of 0.7 degrees. K band center frequency of 20.7 GHz was simulated to produce values of 36.1 dB of gain, side lobe level of -14.1 dB and an angular width (3 dB) of 1.7 degrees. Ka band center frequency of 30 GHz produced results of 40.8 dB of gain, side lobe level of -24.9 dB and an angular width (3 dB) of 0.6 degrees. The Q band center frequency of 44.5 GHz resulted in the gain value of 42.5 dB. This Q band center frequency produced a side lobe level of -13.5 dB and an angular width (3 dB) of 3.7 degrees. Radiation patterns, gain values, and side lobe levels for these frequencies are shown in Figure 45 (a)-(e).



(e)

Figure 45 Radiation patterns of the Gregorian parabolic stacked antenna. (a) X band (7.5 GHz). (b) X band (8.15 GHz). (c) K band (20.7 GHz). (d) Ka band (30 GHz). (e) Q band (44.5 GHz)

The larger Gregorian antenna of the dual Gregorian parabolic stacked antenna configuration was also capable of operating within limited CBSP antenna and the directional SDT antenna variant frequency ranges. C band frequency range of 5.85 GHz to 6.425 GHz and Ku band frequency ranges of 10.95 GHz to 12.75 GHz, 13.75 GHz to 14.5 GHz and 14.4 GHz to 15.35 GHz were simulated to obtain VSWR, radiation pattern, gain, side lobe level (3 dB) and angular width results. The 5.85 GHz to 6.425 GHz CBSP frequency range is used for transmitting purposes for CBSP operations. The Ku band 10.95 GHz to 12.8 GHz range is used for receiving purposes while the 13.75 GHz to 14.5 GHz range is used to transmit. The SDT directional antenna uses the Ku band frequency range of 14.4 GHz to 15.35 GHz for LoS transmit and receive functions. The VSWR values for the C and Ku band frequency ranges were able to operate below the VSWR value of 1.58:1 as shown in Figure 46 (a)-(d).

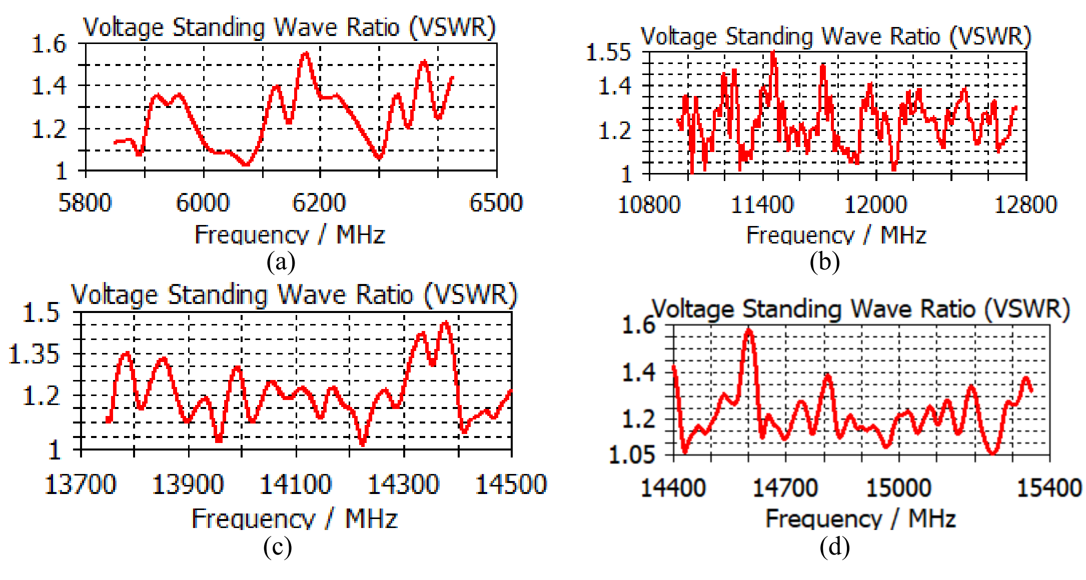


Figure 46 VSWR of the Gregorian parabolic stacked antenna. (a) C band (5.8 GHz – 6.5 GHz). (b) Ku band (10.8 GHz – 12.8 GHz). (c) Ku band (13.75 GHz – 14.5 GHz). (d) Ku band (14.4 GHz – 15.35 GHz)

Radiation patterns, gain values and side lobe levels for the C and Ku frequency bands were captured for the dual Gregorian parabolic stacked antenna. The C band center frequency of 6.14

GHz was used to depict a gain of 38.4 dB, side lobe level of -15.6 dB and an angular width (3 dB) of 1.4 degrees. Ku band center frequency of 11.9 GHz was simulated to produce values of 42.4 dB of gain, side lobe level of -23 dB and an angular width (3 dB) of 0.5 degrees. The Ku band center frequency of 14.1 GHz provided simulation results of 42.4 dB of gain, side lobe level of -29.3 dB and an angular width (3 dB) of 0.7 degrees. The Ku band center frequency of 14.875 GHz depicted a gain of 42.3 dB, side lobe level of -22.3 dB and an angular width (3 dB) of 0.4 degrees. Radiation patterns, gain values, and side lobe levels for certain CBSP frequencies as well as the directional SDT antenna capability are shown in Figure 47 (a)-(d).

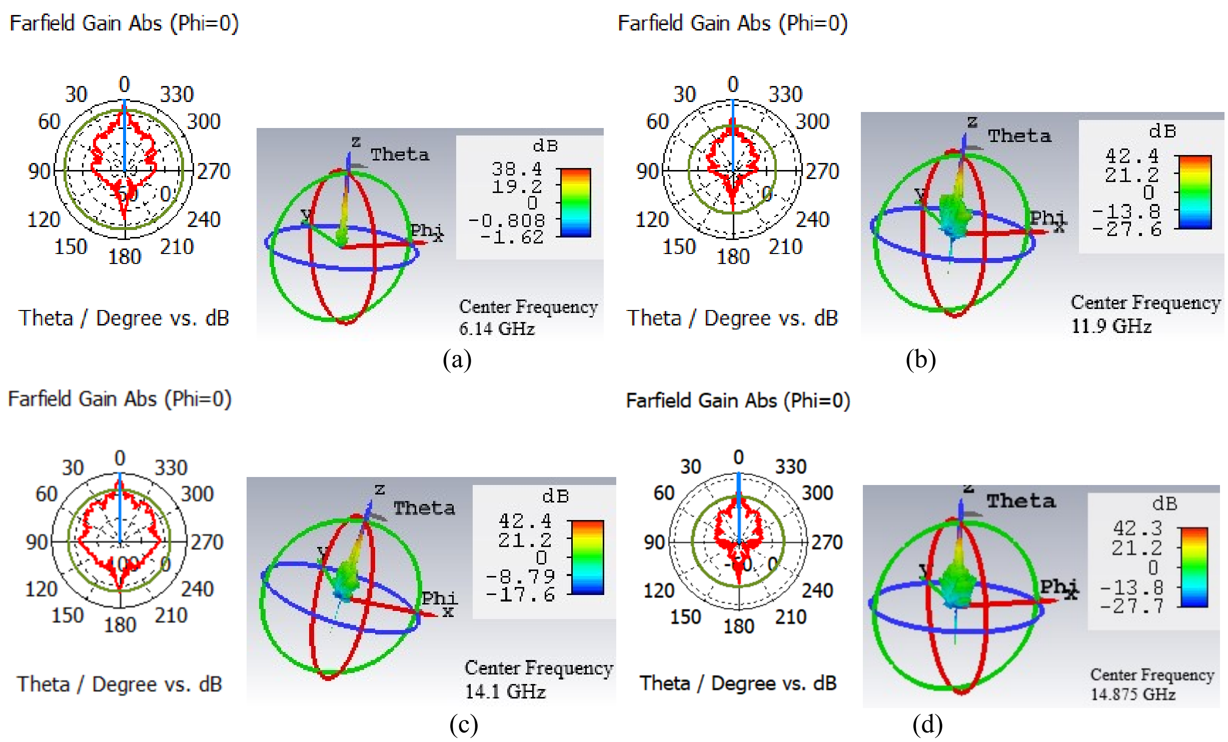
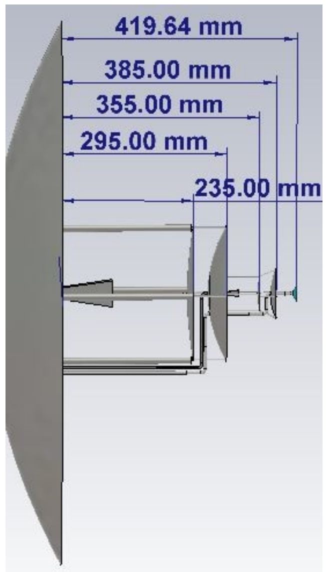


Figure 47 Radiation patterns of the Gregorian parabolic stacked antenna. (a) C band (6.14 GHz). (b) Ku band (11.9 GHz). (c) Ku band (14.1 GHz). (d) Ku band (14.875 GHz)

The dual Gregorian parabolic stacked antenna contained two Gregorian antennas stacked in front of one another to operate at the C, X, Ku, K, Ka and Q band frequencies. Results shown gain values of that peaked at 42.5 dB at the Q band frequency range. Overall VSWR values were under 2:1 with a maximum VSWR peaking at 1.68:1. This parabolic stacked antenna had additional C and Ku band capabilities that the CBSP antenna provided as well as the directional SDT LoS operating frequency range. The dual Gregorian parabolic stacked antenna is an efficient solution for consolidating the NMT Q / Ka, NMT X / Ka and directional SDT antenna variants.

4.4 Dual Cassegrain with Splash Plate Parabolic Stacked Antenna

An improvement need was presented to field tri-band antennas (Q, Ka, X) to reduce topside volume and antenna count [102]. The need for a tri-band antenna was referencing the NMT Q / Ka and X / Ka antennas. Having a singular antenna that can operate at Q, Ka, and X band frequencies would eliminate the need for two different NMT variant antennas. A tri-band parabolic stacked antenna was focused on providing a Q, Ka and X band capable solution on a single antenna pedestal [103]. This tri-band parabolic stacked antenna consisted of two Cassegrain antennas and a splash plate antenna to operate within the Q, K, Ka and X band frequencies. This parabolic stacked antenna had three antennas on a single pedestal to provide multiband frequency capabilities. Additional frequency operation simulation testing revealed that this parabolic stacked antenna configuration was capable of operating at frequencies that partially operate within CBSP antenna operating frequencies as well as the directional SDT antenna frequency range. For NMT Q / Ka and X / Ka frequency functionality, the large Cassegrain antenna provided the X band frequency, the medium Cassegrain antenna provided K and Ka band frequencies, and the small splash plate antenna provided the Q band frequency. As shown in Figure 48, the large Cassegrain antenna, medium Cassegrain antenna and small splash plate antenna are stacked in front of one another to provide C, X, Ku, K, Ka and Q band capabilities that the NMT Q / Ka, NMT X / Ka, directional SDT antenna variants operate within as well as a portion of frequencies that the CBSP antenna variants operate within.



(a)

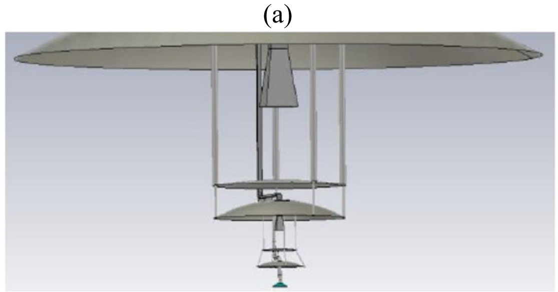

(b)

Figure 48 Dual Cassegrain with Splash Plate Parabolic Stacked Antenna (a) Side view (b) Top view [103]

The overall antenna size of the dual Cassegrain with splash plate parabolic stacked antenna was 36.8% smaller than the currently fielded NMT Q / Ka antenna. Utilizing a similar pedestal as the NMT Q / Ka antenna would allow the currently fielded antenna to be replaced with the tri-band parabolic stacked antenna with ease. The physical parameters for the tri-band parabolic stacked antenna is shown in Table 22 and in Table 23.

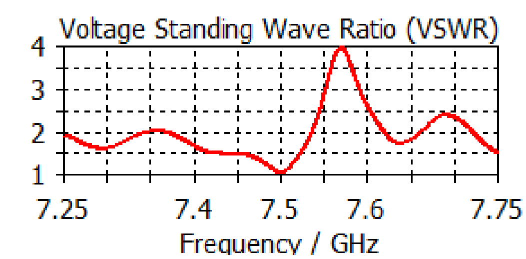
Table 22 Large and Medium Cassegrain Antenna Physical Parameters

Cassegrain Antenna Physical Description	Short Name	Large Cassegrain Antenna Values	Medium Cassegrain Antenna Values
Primary reflector diameter	Dp	962.6 mm	240.6 mm
Primary reflector focal length	Fp	442.8 mm	108.9 mm
Secondary reflector diameter	Ds	240.6 mm	59.18 mm
Secondary reflector focal length	Fs	221.4 mm	54.44 mm
Horn aperture to focal point offset	Sf	0 m	0 m
Waveguide length	Lg	39.97 mm	9.829 mm
Flare length	Lf	106.0 mm	26.07 mm
Aperture height	Ha	46.00 mm	11.31 mm
Aperture width	Wa	60.00 mm	14.75 mm
Waveguide height	Hg	15.69 mm	3.858 mm
Waveguide width	Wg	31.38 mm	7.716 mm

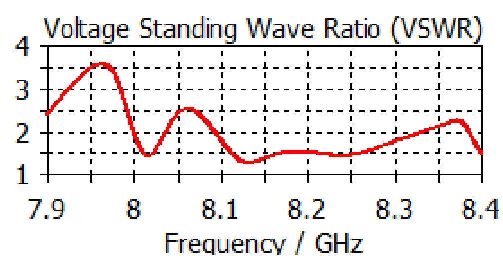
Table 23 Small Splash Plate Antenna Physical Parameters

Splash Plate Antenna Physical Description	Short Name	Small Splash Plate Antenna Values (m)
Dish diameter	D	8.63E-02
Focal depth	F	4.88E-02
Feed offset from focal point	S	2.65E-03
Waveguide diameter	Dg	5.00E-03
Waveguide length	Lg	1.50E-02
Length of tuning roller	Ltr	5.12E-03
Diameter of tuning roller	Dtr	1.85E-03
Radius of dielectric lens	Rdl	1.60E-02
Offset of dielectric lens	Sdl	1.52E-02
Height of dielectric lens	Hdl	5.50E-03
Diameter of reflecting plane	Drp	2.70E-02
Diameter of spherical cap	Dsc	6.00E-03
Height of spherical cap	Hsc	7.49E-04
Inset / extension of dielectric into waveguide	Sd	5.50E-03

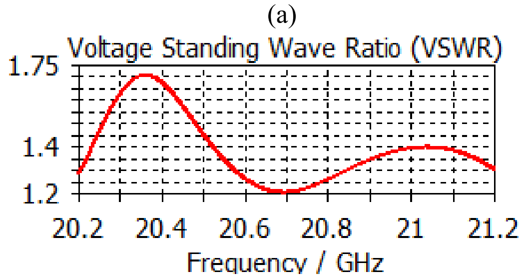
The Cassegrain antennas and the splash plate antenna combined provided the same RF band capabilities that the NMT Q / Ka and NMT X / Ka antennas operate within. VSWR values were assessed for frequencies within the X, K, Ka and Q bands. When no power is reflected from the antenna, the VSWR value would be 1. For antenna design, the VSWR values are kept as low as possible. The tri-band parabolic stacked antenna had VSWR values greater than 2:1 for frequencies between 7.54 GHz through 7.71 GHz where the maximum VSWR value was 3.5:1 within the X band frequency range. The X band frequency range also had VSWR values greater than 2:1 within the frequency range of 7.9 GHz through 8.07 GHz along with frequencies 8.36 GHz through 8.38 GHz. The K band frequency range had a maximum VSWR values of 1.73:1. The Ka band frequency range had VSWR values greater than 2:1 between frequencies 30.1 GHz and 30.35 GHz with the highest VSWR value being 2.4:1. The Q band frequency range had a few ranges of frequencies that exceeded the VSWR value of 2:1 which included frequencies 44.8 GHz to 45.5 GHz with the highest VSWR value being 2.28:1. The VSWR values with relationships to the NMT Q / Ka and NMT X / Ka antenna variant frequencies are shown in Figure 49.



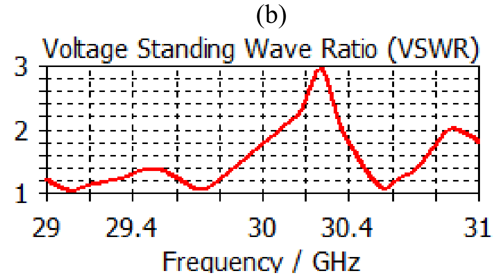
(a)



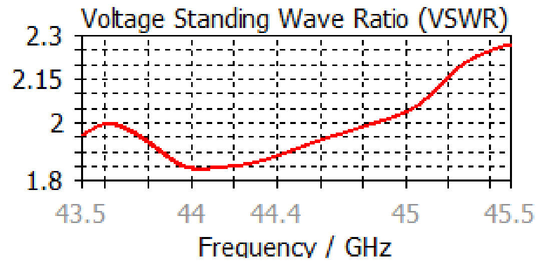
(b)



(c)



(d)



(e)

Figure 49 VSWR of the Dual Cassegrain and Splash Plate Parabolic Stacked Antenna. (a) X band (7.25 GHz - 7.75 GHz). (b) X band (7.9 GHz - 8.4 GHz). (c) K band (20.2 GHz to 21.2 GHz). (d) Ka band (29 GHz - 31 GHz). (e) Q band (43.5 GHz – 45.5 GHz) [103]

The dual Cassegrain and splash plate antenna had gain values of up to 34.6 dB for operating frequencies related to the NMT Q / Ka and NMT X / Ka variant antennas. The X band which operated within the large Cassegrain antenna had gain values of 34.4 dB at the center frequency of 7.5 GHz and 34.6 dB at the center frequency of 8.15 GHz. The angular width (3 dB) was measured at 2.5 degrees at the center frequency of 7.5 GHz and 2.6 degrees at the center frequency of 8.15 GHz. The X band frequency simulated had side lobe level values of -14.1 dB at a center frequency of 7.5 GHz and a side lobe level value of -26.2 dB for a center frequency of 8.15 GHz. The K band center frequency of 20.7 had a gain of 29.4 dB with a side lobe level -1.1 dB and an angular width (3 dB) of 39.9 degrees which operated within the medium Cassegrain antenna. The medium Cassegrain antenna had a 34.4 dB gain value when simulated using the Ka band center frequency 30 GHz. The medium Cassegrain antenna had an angular width (3 dB) of 2.4 degrees with a side lobe level of -13.2 GHz utilizing the 30 GHz center frequency. The small splash plate antenna had a 26.3 dB gain at Q band center frequency 44.5 GHz. This small splash plate antenna depicted a side lobe level of -12.5 dB with an angular width (3 dB) of 4.3 degrees. The radiation patterns for the dual Cassegrain and splash plate parabolic stacked antenna is shown in Figure 50.

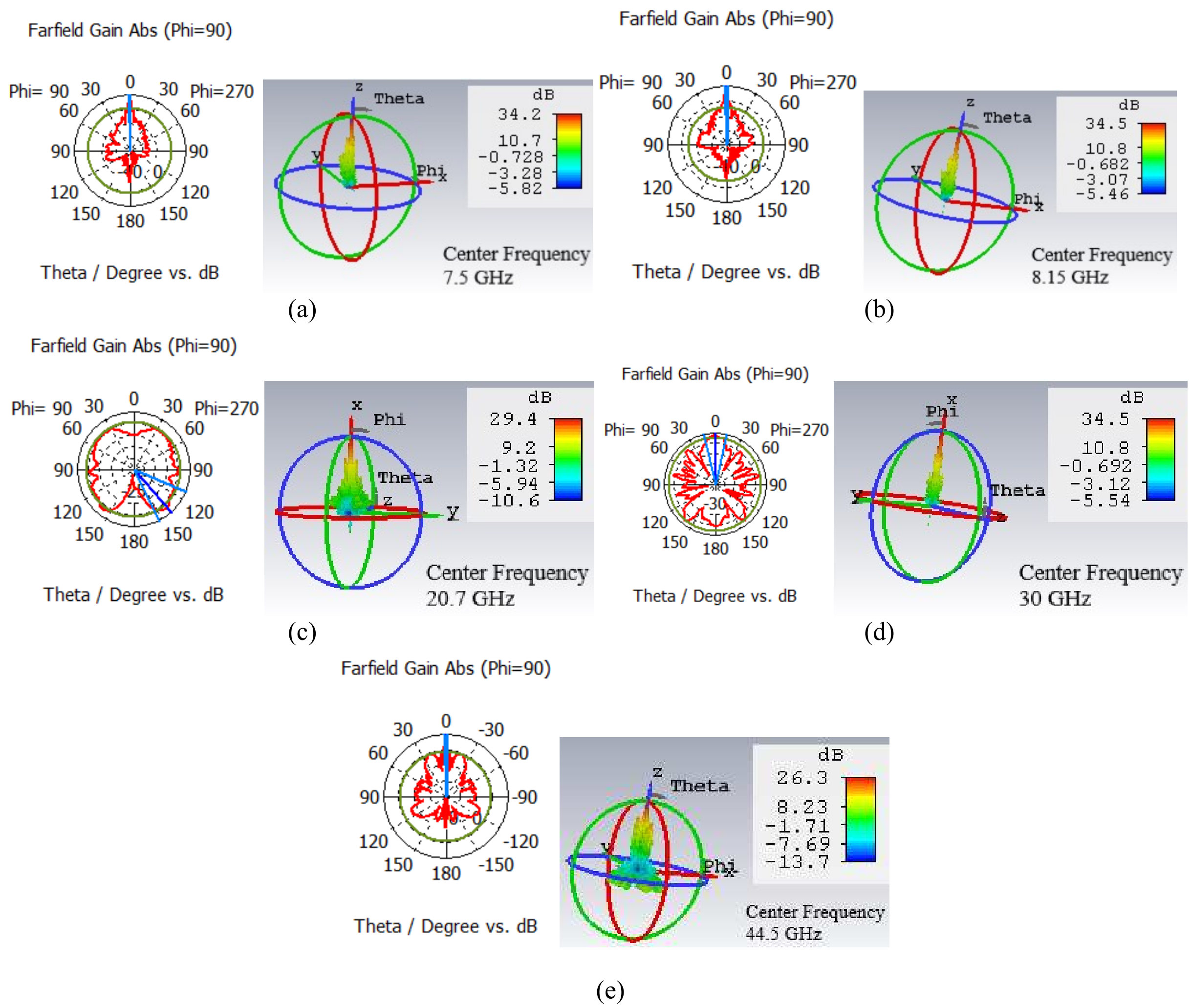


Figure 50 Radiation pattern of the Dual Cassegrain and Splash Plate Parabolic Stacked Antenna. (a) X band (7.5 GHz). (b) X band (8.15 GHz). (c) K band (20.7 GHz). (d) Ka band (30 GHz). (e) Q band (44.5 GHz) [103]

The dual Cassegrain and splash plate parabolic stacked antenna was capable of operating within some of the CBSP operating frequencies for SATCOM communications and the SDT operating frequencies for LoS communications. The C band frequency range of 5.85 GHz to 6.425 GHz had VSWR values that peaked to 3.4:1. Frequencies 5.92 GHz to 6.425 GHz had VSWR values less than 2.4:1. The Ku band frequency range of 10.95 GHz to 12.175 GHz had VSWR values equal and less than 2.6:1. The Ku band frequency range of 13.75 GHz to 14.5 GHz had VSWR values equal and less than 2.65. The LoS Ku band frequency range of 14.4 to 15.35 GHz has VSWR values equal and less than 2.8:1. This antenna was not capable of operating within the L band frequency range of .95 GHz to 2.05 GHz and the lower C band frequency range of 3.7 GHz to 4.2 GHz. The VSWR values for the capable frequencies are shown in Figure 51 (a)-(d).

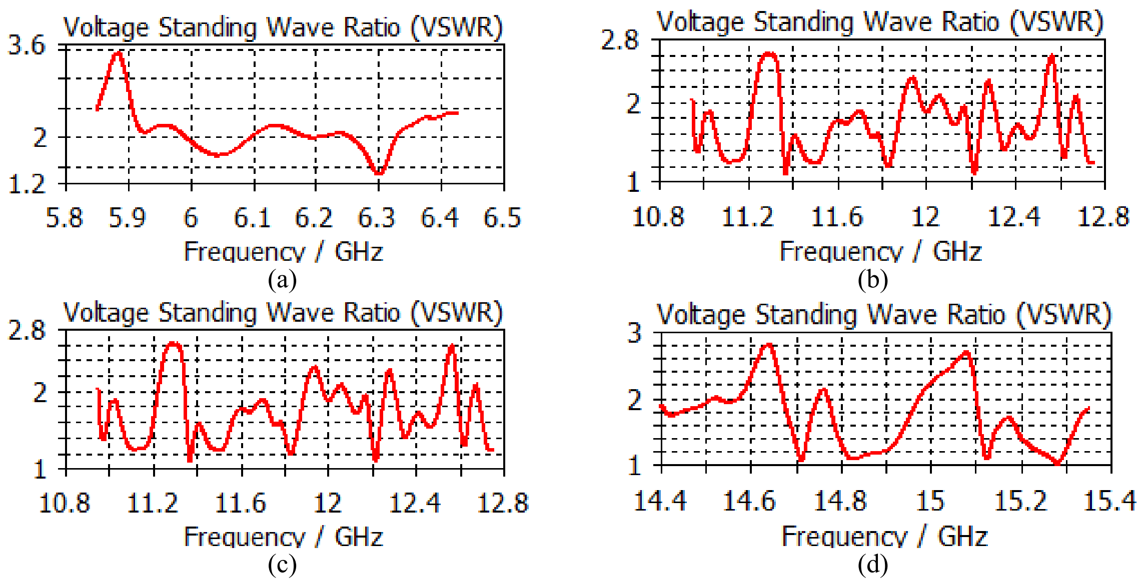


Figure 51 VSWR of the dual Cassegrain and splash plate parabolic stacked antenna. (a) C band (5.85 GHz to 6.425 GHz). (b) Ku band (10.95 GHz to 12.75 GHz). (c) Ku band (13.75 GHz to 14.5 GHz). (d) Ku band (14.4 GHz to 15.35 GHz)

Radiation patterns, gain, side lobe levels, and angular width (3 dB) were captured using the frequencies that the CBSP antenna and directional SDT antennas are capable of operating within with the exception of the L band frequency range .95 GHz to 2.05 GHz and the lower C band frequency range of 3.7 GHz to 4.2 GHz. The C band center frequency of 6.14 GHz was simulated to obtain a gain of 31.8 dB, side lobe level of -13.1 dB and an angular width (3 dB) of 2.9 degrees. The Ku band center frequency of 11.9 GHz produced a gain of 34.5 dB, side lobe level of -12.5 dB and an angular width (3 dB) of 2.5 degrees. The Ku band center frequency of 14.1 GHz was also simulated to obtain a gain value of 33.2 dB, side lobe level of -18.5 dB and an angular width (3 dB) of 2.9 degrees. The LoS Ku band center frequency of 14.875 achieved a gain value of 34.6 dB, side lobe level of -19.9 dB and an angular width (3 dB) of 2.7 degrees. Radiation patterns for the frequencies tested that were capable of performing at limited CBSP antenna operating frequencies and SDT directional antenna frequencies for the dual Cassegrain parabolic stacked antenna are shown in Figure 52 (a)-(d).

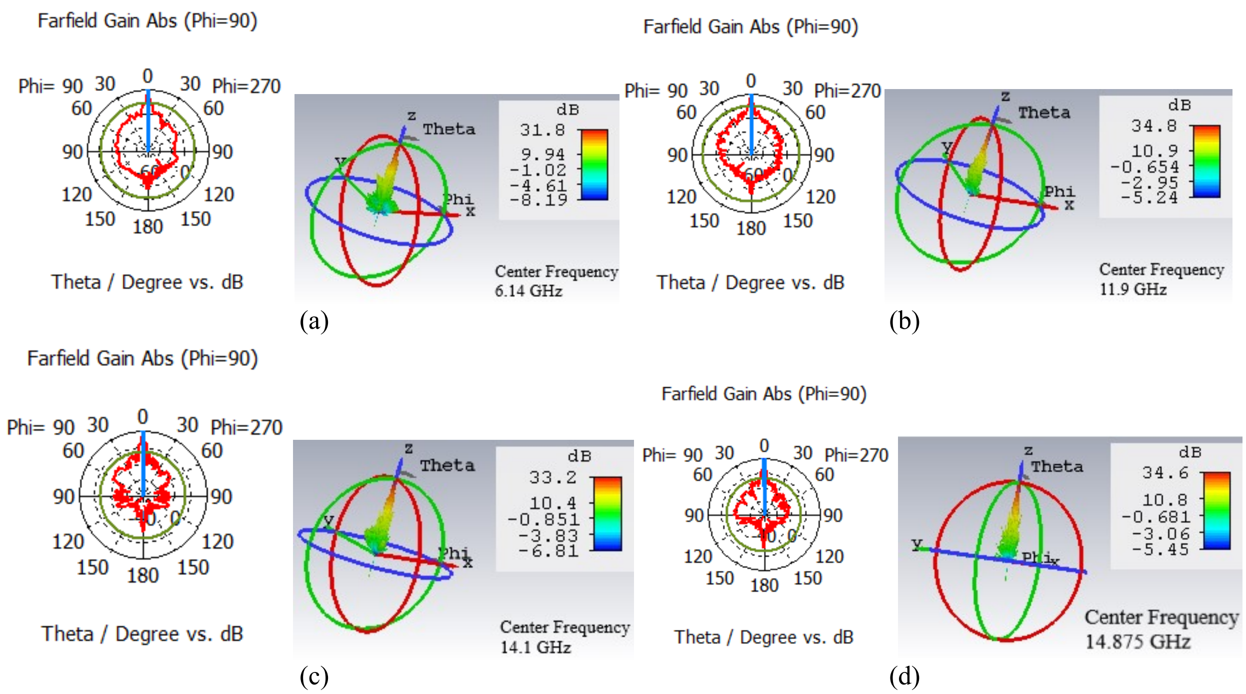
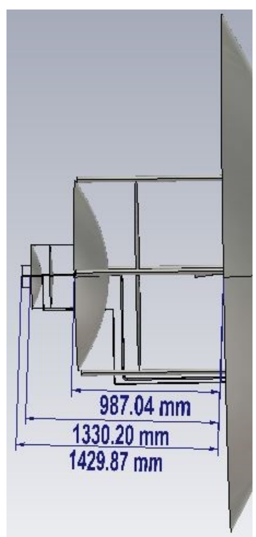


Figure 52 Radiation pattern of the dual Cassegrain and splash plate parabolic stacked antenna. (a) C band (6.14 GHz). (b) Ku band (11.9 GHz). (c) Ku band (14.1 GHz). (d) Ku band (14.875 GHz)

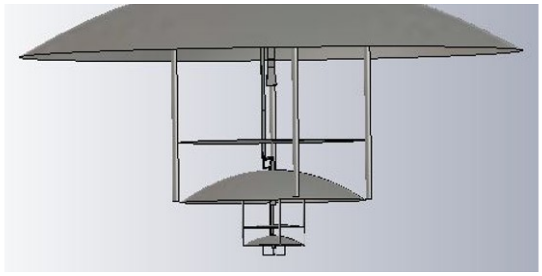
The dual Cassegrain with splash plate parabolic stacked antenna has the ability to meet the RF band needs for consolidating the NMT Q / Ka, X / Ka and directional SDT antenna variants. Consolidating three variants of antennas reduces the amount of space required along with providing additional capability to smaller shipboard platforms that do not have the space to allow multiple antenna variants to be placed topside. The parabolic stacked antenna methodology used in this configuration combined two Cassegrain antennas and one splash plate antenna on a single pedestal to provide X, K, Ka and Q band frequency capabilities along with limited CBSP antenna and SDT antenna frequency capabilities operating within the C and Ku band.

4.5 Triple Cassegrain Parabolic Stacked Antenna

The triple Cassegrain parabolic stacked antenna is another configuration to support the consolidation of the NMT Q / Ka, NMT X / Ka and directional SDT variant antennas. The parabolic stacked antenna described features the directional capability of the CDL LoS antenna only whereas the omni directional antenna feature would be best suited for a separate antenna that can radiate in all directions equally [104]. The LoS operational feature lies within the Ku band frequency range of 14.4 GHz – 15.35 GHz. This is an additional capability where this parabolic stacked antenna can be used for both SATCOM and LoS operations. This configuration uses three Cassegrain parabolic antennas stacked in front of one another to operate at the LoS and SATCOM frequency bands. The side view and top view of the triple Cassegrain parabolic stacked antenna is shown in Figure 53.



(a)



(b)

Figure 53 Triple Cassegrain Parabolic Stacked Antenna. (a) Side view. (b) Top view [104]

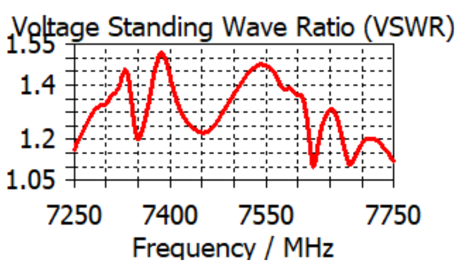
The triple Cassegrain parabolic stacked antenna had a large Cassegrain antenna with a 1.9m parabolic dish, a medium Cassegrain antenna with a 480mm parabolic dish, and a small Cassegrain antenna with a 125.7 mm parabolic dish. Each antenna was stacked in front of one another with the feed being routed through the back side of each parabolic antenna to the rear of the large Cassegrain antenna. Antenna Magus software was used to model the individual Cassegrain antennas for CST Microwave Studio simulation and the physical parameters of the triple Cassegrain parabolic stacked antenna is shown in Table 24.

Table 24 Triple Cassegrain Parabolic Stacked Antenna Physical Parameters

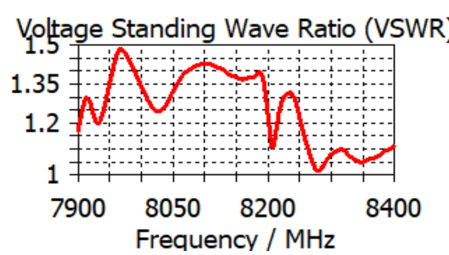
Triple Cassegrain Parabolic Stacked Antenna Physical Description	Short Name	Large Cassegrain Antenna Values	Medium Cassegrain Antenna Values	Small Cassegrain Antenna Values
Primary reflector diameter	Dp	1.9 m	480 mm	125.7 mm
Primary reflector focal length	Fp	609.8 mm	165.7 mm	42.86 mm
Secondary reflector diameter	Ds	480.0 mm	125.7 mm	37.59 mm
Secondary reflector focal length	Fs	304.9 mm	82.84 mm	21.43 mm
Horn aperture to focal point offset	Sf	0 m	0 m	0 m
Waveguide length	Lg	39.97 mm	14.48 mm	6.662 mm
Flare length	Lf	88.00 mm	31.88 mm	14.67 mm
Aperture height	Ha	38.67 mm	14.01 mm	6.444 mm
Aperture width	Wa	49.33 mm	17.87 mm	8.222 mm

Waveguide height	Hg	15.69 mm	5.684 mm	2.615 mm
Waveguide width	Wg	31.38 mm	11.37 mm	5.230 mm

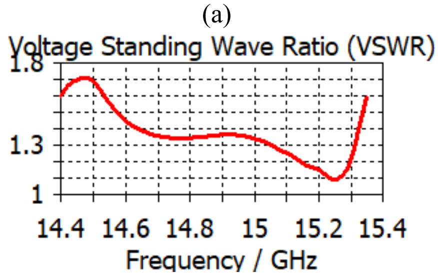
The VSWR values for the triple Cassegrain parabolic stacked antenna resulted in VSWR values of up to 2.58:1. The large Cassegrain antenna at X band frequency range of 7.25 GHz to 7.75 GHz had VSWR values reaching up to 1.52:1. The large Cassegrain antenna at the X band frequency range of 7.9 GHz to 8.4 GHz had VSWR values up to 1.48:1. The large Cassegrain antenna at the Ku band which provides the LoS capability had VSWR values of up to 1.55:1 which spanned the frequencies of 14.4 GHz to 15.35 GHz. VSWR values of up to 1.54:1 were obtained for the medium Cassegrain antenna at the K band frequency range of 20.2 GHz to 21.2 GHz. The medium Cassegrain antenna at the Ka band frequency range of 29 GHz to 31 GHz had VSWR values of up to 2.58:1. The small Cassegrain antenna at the Q band frequency range of 43.5 GHz to 45.5 GHz had VSWR values up to 2:1. The VSWR values for the triple Cassegrain parabolic stacked antenna capable of operating at frequencies that the NMT Q / Ka, NMT X / Ka and directional SDT antenna variants are show in Figure 54 (a)-(f).



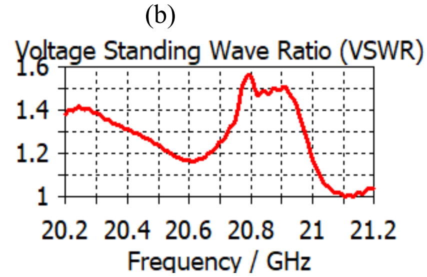
(a)



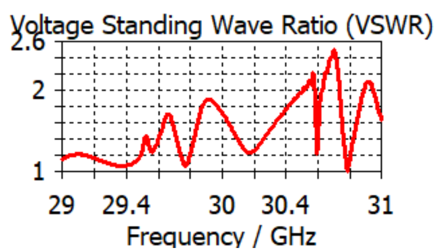
(b)



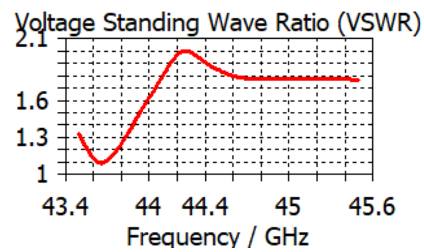
(c)



(d)



(e)



(f)

Figure 54 VSWR of Triple Cassegrain Parabolic Stacked Antenna. (a) X band (7.25 GHz – 7.75 GHz). (b) X band (7.9 GHz – 8.4 GHz). (c) Ku band (14.4 GHz – 15.35 GHz). (d) K band (20.2 GHz – 21.2 GHz). (e) Ka band (29 GHz to 31 GHz). (f) Q band (33 GHz – 50 GHz). [104]

Radiation patterns, gain, side lobe levels and angular width (3 dB) values were obtained by simulating the triple Cassegrain parabolic stacked antenna through CST microwave studio for frequencies associated with the NMT Q / Ka, NMT X /Ka and directional SDT antenna variants. Frequency bands X, Ku, K, Ka and Q were successfully captured for the triple Cassegrain parabolic stacked antenna. The large Cassegrain antenna at X band center frequency of 7.5 GHz was used to depict a gain of 40.6 dB, an angular width (3 dB) of 0.8 degrees and side lobe level of -28 dB. The large Cassegrain antenna at X band center frequency 8.15 GHz produced results of 41.5 dB of gain, angular width (3 dB) of 0.7 degrees and side lobe level of -22.9 dB. The large Cassegrain antenna at Ku band center frequency of 14.875 GHz operated at 40.1 dB of gain, angular width (3 dB) of 0.6 degrees and a side lobe level of -22.6 dB. The medium Cassegrain antenna at K band center frequency of 20.7 GHz was simulated to produce values of 37.4 dB of gain, angular width (3 dB) of 1.8 degrees and side lobe level of -14.5 dB. The medium Cassegrain antenna at Ka band center frequency of 30 GHz produced results of 40.3 dB of gain, angular width (3 dB) of 0.9 degrees and side lobe level of -28.2 dB. The small Cassegrain antenna at Q band center frequency of 44.5 GHz resulted in the gain value of 32.5 dB. This Q band center frequency produced an angular width (3 dB) of 3.4 degrees and side lobe level of -13.1 dB. Radiation patterns, gain values, and side lobe levels for these frequencies are shown in Figure 55 (a)-(f).

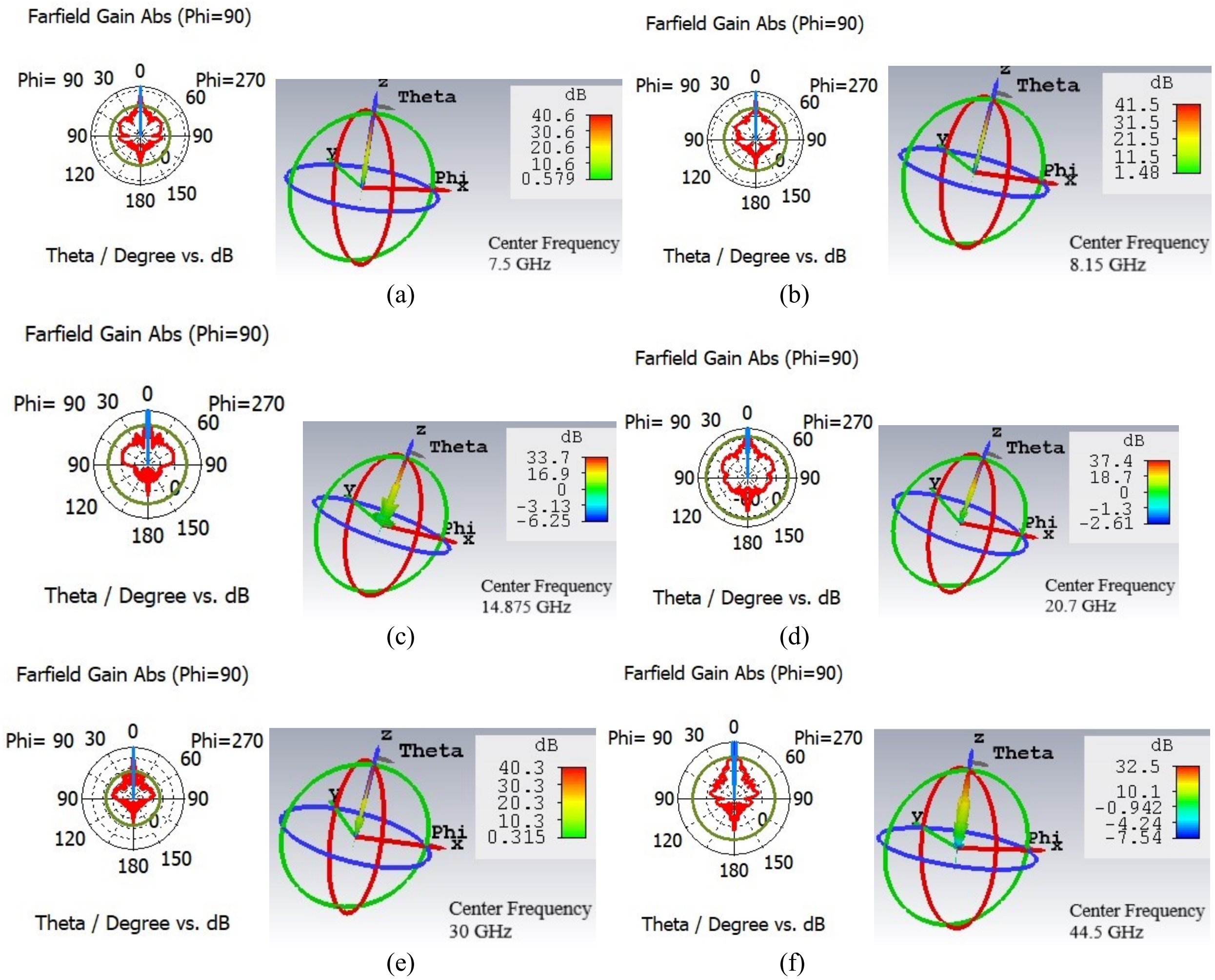


Figure 55 Radiation Patterns of Triple Cassegrain Parabolic Stacked Antenna. (a) X band (7.5 GHz). (b) X band (8.15 GHz). (c) Ku band (14.875 GHz). (d) K band (20.7 GHz). (e) Ka band (30 GHz). (f) Q band (44.5 GHz). [104]

The triple Cassegrain parabolic stacked antenna is capable of operating at SATCOM and LoS frequency bands. These frequencies include X, Ku, K, Ka and Q bands that current SATCOM and LoS antennas operate within. This configuration includes three Cassegrain antennas stacked in front of one another and is smaller than the currently fielded NMT X / Ka antenna. The larger Cassegrain antenna was capable of operating within the X band, the medium Cassegrain antenna was capable of operating within the Ku, K and Ka bands, and the small Cassegrain antenna was capable of operating within the Q band frequency range.

The triple Cassegrain antenna had additional capabilities of operating within certain frequencies that the CBSP antenna variants provided with the exception of the L band (0.95 GHz – 2.05 GHz) frequency range and the C band (3.7 GHz to 4.2 GHz) frequency range. This parabolic stacked antenna configuration also had overlapping operating frequency capabilities between the large, medium and small Cassegrain antennas. The large Cassegrain antenna was capable of operating within the C band frequency range of 5.85 GHz to 6.425 GHz with a maximum VSWR value of 1.81:1, gain of 38.3 dB, angular width (3 dB) of 1.1 degrees and a side lobe level of -15.1 db. Figure 56 depicts the large Cassegrain C band VSWR and radiation details of the triple Cassegrain parabolic stacked antenna configuration.

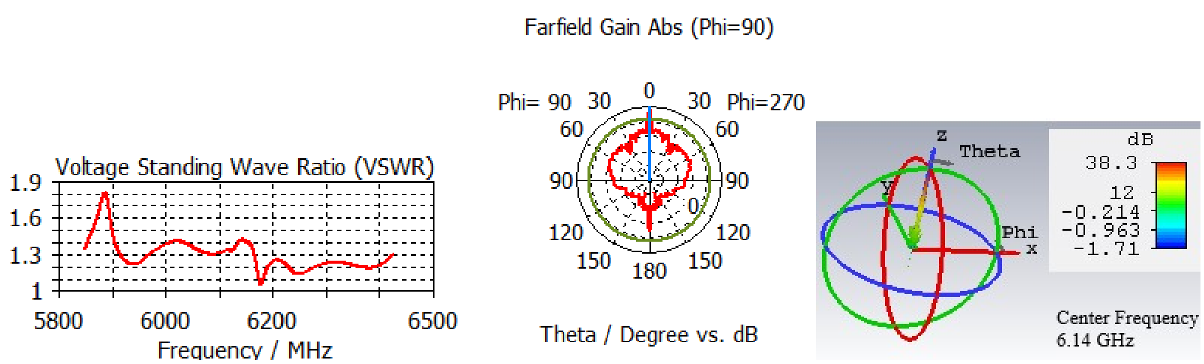


Figure 56 Large Cassegrain C Band VSWR and Radiation Details of the Triple Cassegrain Parabolic Stacked Antenna Configuration

The large Cassegrain antenna was capable of operating within the Ku band frequency range of 10.95 GHz to 12.75 GHz with a maximum VSWR value of 1.68:1, gain of 43.5 dB, angular width (3 dB) of 0.4 degrees and a side lobe level of -29.8 db. This CBSP operating frequency is used for receiving communication capabilities. Figure 57 depicts the large Cassegrain Ku band VSWR and radiation details of the triple Cassegrain parabolic stacked antenna configuration.

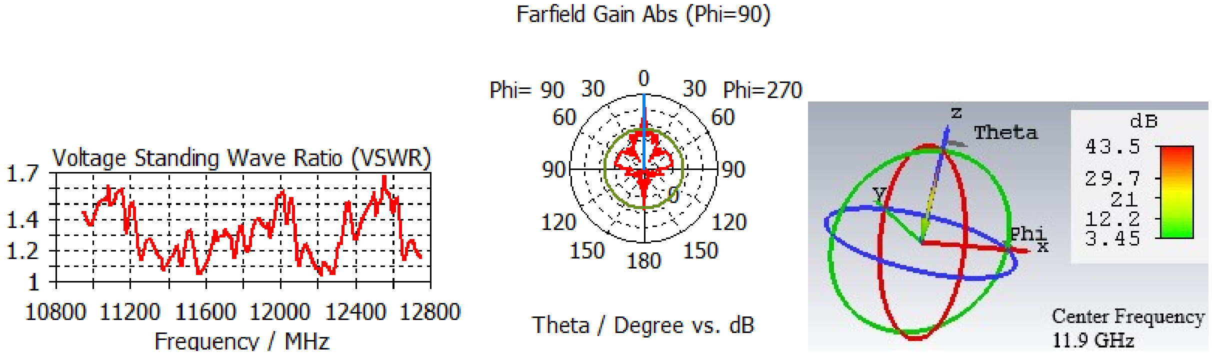
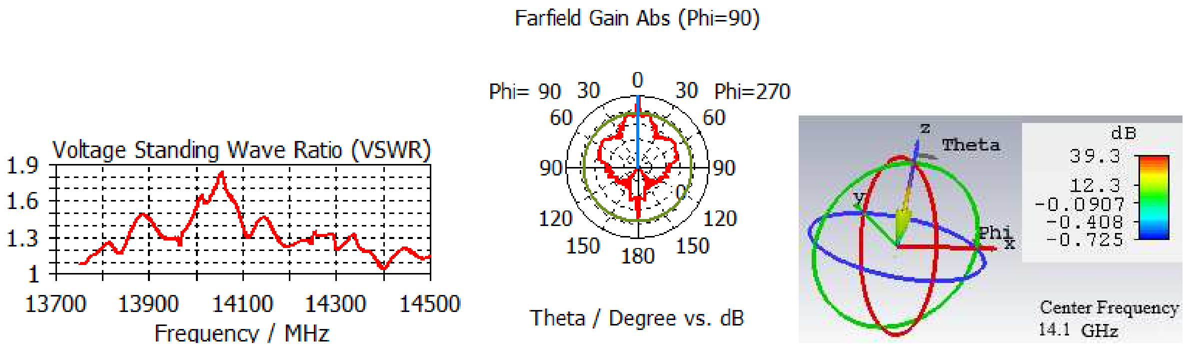
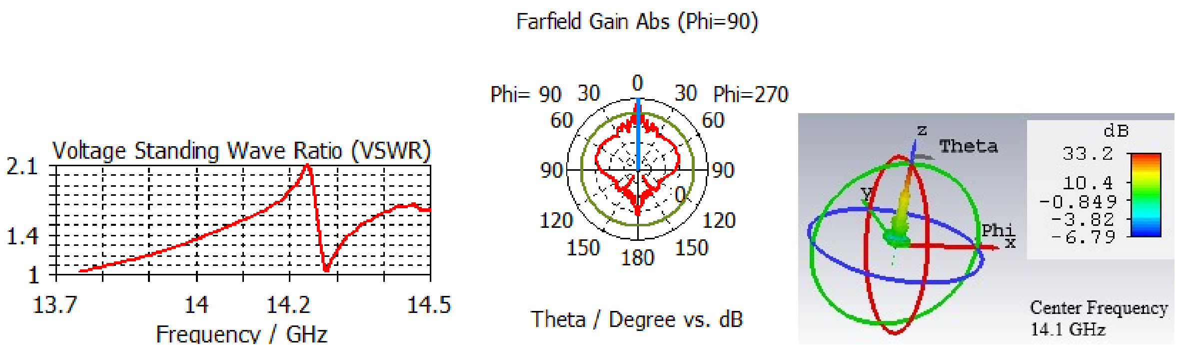


Figure 57 Large Cassegrain Ku band VSWR and Radiation Details of the Triple Cassegrain Parabolic Stacked Antenna Configuration

The large Cassegrain and medium Cassegrain antenna was capable of operating at the Ku band frequency 13.75 GHz to 14.5 GHz. Figure 58(a) displays results for the large Cassegrain antenna where the peak VSWR value was 1.84:1, 39.3 dB of gain, side lobe level of -22.7 dB and an angular width (3 dB) of 0.5 degrees. Figure 58(b) depicts the results for the medium Cassegrain antenna where the peak VSWR value was 2.1:1, 33.2 dB of gain, side lobe level of -13.7 dB and an angular width (3 dB) of 2.5 degrees. The large Cassegrain antenna provided slightly lower VSWR results and higher gain then the medium Cassegrain antenna. The larger Cassegrain antenna is recommended to be used primarily with the medium Cassegrain antenna being used as a backup.



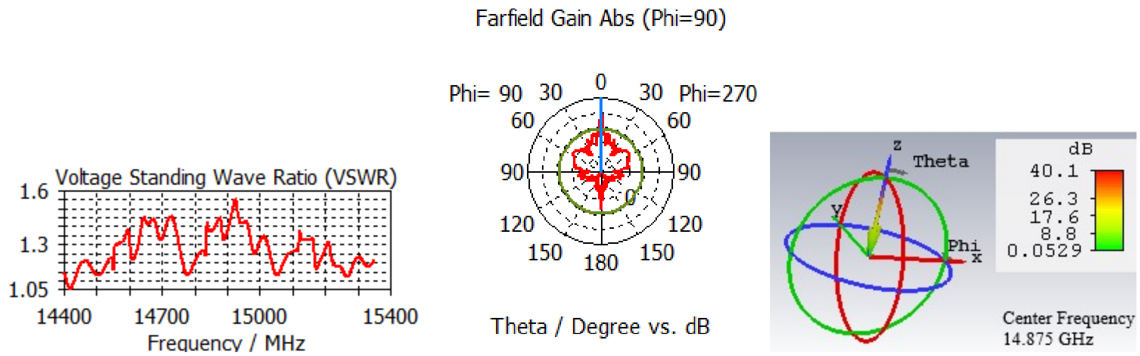
(a)



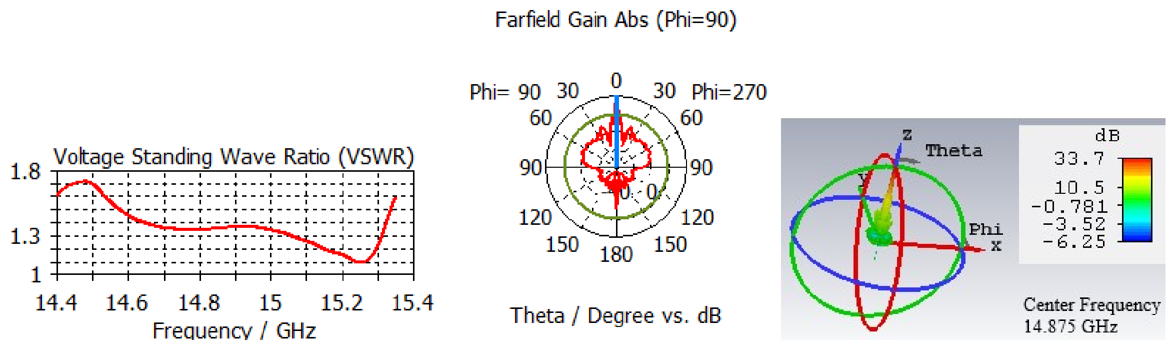
(b)

Figure 58 Ku band 13.75 GHz to 14.5 GHz VSWR and Radiation Details of the Triple Cassegrain Parabolic Stacked Antenna Configuration Comparison. (a) Large Cassegrain Antenna Results. (b) Medium Cassegrain Antenna Results

The large Cassegrain and medium Cassegrain antenna was capable of operating at the Ku band frequency 14.4 GHz to 15.35 GHz. Figure 59(a) displays results for the large Cassegrain antenna where the peak VSWR value was 1.55:1, 40.1 dB of gain, side lobe level of -22.6 dB and an angular width (3 dB) of 0.6 degrees. Figure 59(b) depicts the results for the medium Cassegrain antenna where the peak VSWR value was 1.81:1, 33.7 dB of gain, side lobe level of -14.3 dB and an angular width (3 dB) of 2.4 degrees. The large Cassegrain antenna provided slightly lower VSWR results and higher gain then the medium Cassegrain antenna. The larger Cassegrain antenna is recommended to be used primarily with the medium Cassegrain antenna being used as a backup.



(a)



(b)

Figure 59 Ku band 14.4 GHz to 15.4 GHz VSWR and Radiation Details of the Triple Cassegrain Parabolic Stacked Antenna Configuration Comparison. (a) Large Cassegrain Antenna Results. (b) Medium Cassegrain Antenna Results.

The medium Cassegrain and small Cassegrain antenna was capable of operating at the Ka band frequency 29 GHz to 31 GHz. Figure 60(a) displays results for the medium Cassegrain antenna where the peak VSWR value was 2.58:1, 40.3 dB of gain, side lobe level of -28.2dB and an angular width (3 dB) of 0.9 degrees. Figure 60(b) depicts the results for the small Cassegrain antenna where the peak VSWR value was 2.15:1, 28.2 dB of gain, side lobe level of -12.9 dB and an angular width (3 dB) of 4.4 degrees. The medium Cassegrain antenna provided slightly higher VSWR results and higher gain then the small Cassegrain antenna. The medium Cassegrain antenna is recommended to be used primarily due to the high gain value with the small Cassegrain antenna being used as a backup.

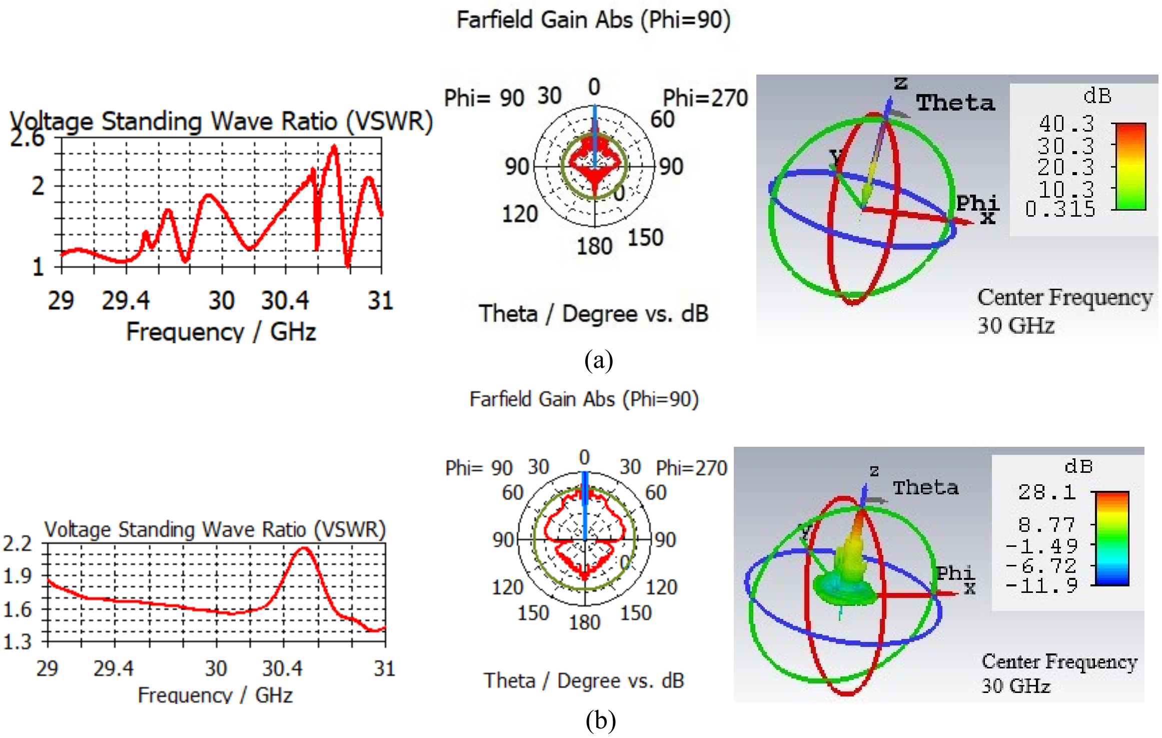
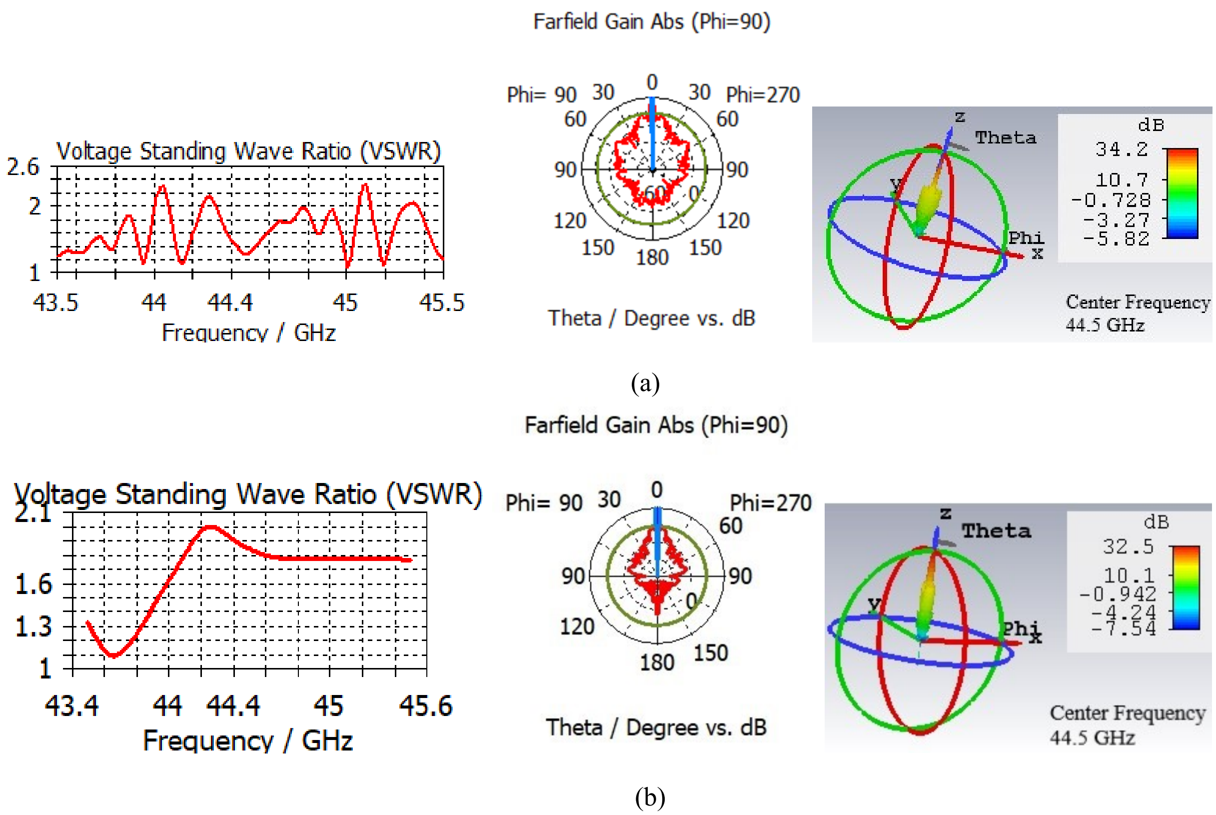


Figure 60 Ka band 29 GHz to 31 GHz VSWR and Radiation Details of the Triple Cassegrain Parabolic Stacked Antenna Configuration Comparison. (a) Medium Cassegrain Antenna Results. (b) Small Cassegrain Antenna Results

The medium Cassegrain and small Cassegrain antenna was capable of operating at the Q band frequency 43.5 GHz to 45.5 GHz. Figure 61(a) displays results for the medium Cassegrain antenna where the peak VSWR value was 2.35:1, 34.2 dB of gain, side lobe level of -16.4 dB and an angular width (3 dB) of 3.4 degrees. Figure 61(b) depicts the results for the small Cassegrain antenna where the peak VSWR value was 2:1, 32.5 dB of gain, side lobe level of -13.1 dB and an angular width (3 dB) of 3.4 degrees. The medium Cassegrain antenna provided slightly higher VSWR results and higher gain then the small Cassegrain antenna. The medium Cassegrain antenna is recommended to be used primarily due to the high gain value with the small Cassegrain antenna being used as a backup.



(a)

(b)

Figure 61 Q band 43.5 GHz to 44.5 GHz VSWR and Radiation Details of the Triple Cassegrain Parabolic Stacked Antenna Configuration Comparison. (a) Medium Cassegrain Antenna Results. (b) Small Cassegrain Antenna Results

The triple Cassegrain parabolic stacked antenna is capable of operating within C, X, Ku, K, Ka and Q band frequencies. Operational capabilities include functioning within frequencies that the NMT Q / Ka, NMT X / Ka and directional SDT antenna variants currently provide. Operating frequencies that CBSP antenna variants provide are limited with the triple Cassegrain parabolic stacked antenna configuration. Certain frequencies were capable of operating at a particular sized antenna along with the next sized antenna stacked in front of it. This capability provides redundancy with potential failover options for overall operational availability.

4.6 Dual Splash Plate Parabolic Stacked Antenna Assessment

To achieve multiband frequency capabilities, parabolic antenna stacking allows multiple antennas to exist on a single pedestal. Reducing the amount of shipboard topside antennas assist with decreasing the weight, space and power multiple platforms consume as well as promoting system life cycle cost savings. Simulation testing was performed using CST Microwave Studio with the assistance of Antenna Magus software. A dual splash plate parabolic stacked antenna is capable of operating at frequencies within the L, C, Ku, K, Ka, X and Q bands. This parabolic stacked antenna can consolidate CBSP FLV, CBSP ULV, NMT Q / Ka, NMT X / Ka, and directional SDT antennas. The dual splash plate parabolic stacked antenna consists of a large splash plate antenna which has a 2.248m diameter dish with an 810mm diameter reflecting plane (drp) and smaller splash plate antenna that is comprised of a secondary 810mm diameter dish with a 149mm drp. The dual splash plate parabolic stacked antenna model is shown in Figure 62.

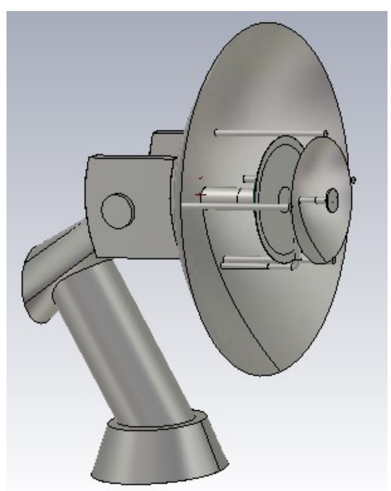
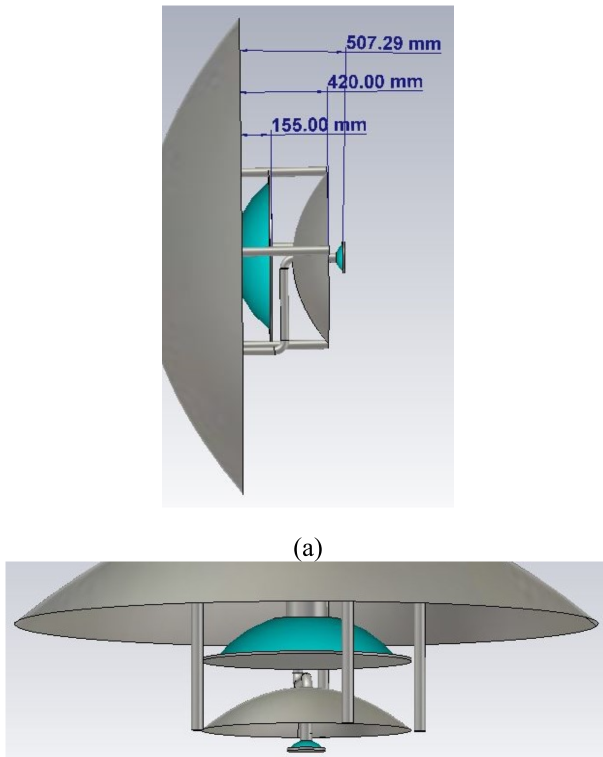


Figure 62 Dual Splash Plate Parabolic Stacked Antenna [105]

The larger splash plate antenna is capable of operating at frequency bands L, C, Ku and X. The smaller splash plate antenna is capable of operating at frequency bands X, Ku, K, Ka and Q.

The dual splash plate parabolic stacked antenna features capabilities of the CBSP, NMT and directional SDT antenna variants. The smaller splash plate antenna is mounted in front of the larger splash plate antenna. The smaller splash plate antenna's wave guide would be routed around the larger splash plate antenna's drp and through the larger splash plate antenna's parabolic dish. A side view of the dual splash plate parabolic stacked antenna model is shown in Figure 63.



(a)

(b)

Figure 63 Side View of the Dual Splash Plate Parabolic Stacked Antenna. (a) Side View. (b) Top View [105]

The smaller splash plate antenna is mounted in front of the larger splash plate antenna. The larger splash plate antenna had a diameter of 2.248 m for the primary parabolic dish. The drp of the larger splash plate antenna had a diameter of 810 mm. To reduce the amount of physical interference of the smaller splash plate antenna, the smaller splash plate antenna was designed to have a primary parabolic dish of the same value as the drp of the larger splash plate antenna. The smaller splash plate antenna had a diameter of 810 mm for the primary parabolic dish. The drp of the smaller splash plate antenna had a diameter of 149 mm. The physical dimensions for the dual splash plate parabolic stacked antenna are described in Table 25.

Table 25 Physical Dimensions of the Dual Splash Plate Parabolic Stacked Antenna

Splash Plate Antenna Physical Description	Short Name	Large Splash Plate Antenna Values (m)	Small Splash Plate Antenna Values (m)
Dish diameter	D	2.25E+00	8.10E-01
Focal depth	F	6.75E-01	2.48E-01
Feed offset from focal point	S	7.33E-02	0.0135
Waveguide diameter	Dg	1.38E-01	2.54E-02
Waveguide length	Lg	4.15E-01	7.63E-02
Length of tuning roller	Ltr	1.42E-01	2.61E-02
Diameter of tuning roller	Dtr	5.11E-02	9.41E-03
Radius of dielectric lens	Rdl	4.42E-01	8.14E-02
Offset of dielectric lens	Sdl	4.22E-01	7.76E-02
Height of dielectric lens	Hdl	1.52E-01	2.80E-02
Diameter of reflecting plane	Drp	8.10E-01	1.49E-01
Diameter of spherical cap	Dsc	1.66E-01	3.05E-02
Height of spherical cap	Hsc	2.07E-02	3.82E-03
Inset / extension of dielectric into waveguide	Sd	1.52E-01	2.80E-02

The 2.248m diameter dish with an 810mm drp and the secondary 810mm diameter dish with a 149mm drp were simulated to observe the radiation pattern as well as identify VSWR, gain, side lobe and angular width (3 dB) values. CST Microwave Studio simulation software was used to assess the frequency ranges that these antennas were capable of operating in. The frequency bands that were used for testing included L, C, X, Ku, K, Ka, and Q bands. The frequency bands tested reflect the operational capabilities of the CBSP FLV / ULV, NMT Q / Ka, NMT X / Ka, and directional SDT antenna variants. The (T) denotes the transmitting frequency while the (R)

denotes the receiving frequency. The (T) and (R) side by side represents that both transmitting and receiving frequencies are operated within that range. There were instances where both the larger and the smaller antenna were able to operate at a particular frequency range. The smaller antenna had conflicts with operating at low frequency ranges while the larger antenna had conflicts of operating at higher frequency ranges. The constraints for certain frequencies are shown in Table 26.

Table 26 Frequency to Parabolic Stacked Antenna Gain Relationship

	CBSP FLV (T)(R) 950 to 2050 GHz L Band	CBSP (R) 3.7 to 4.2 GHz C Band	CBSP (T) 5.85 to 6.425 GHz C Band	CBSP ULV & NMT (R) 7.25 to 7.75 GHz X Band	CBSP ULV & NMT (T) 7.9 to 8.4 GHz X Band	CBSP ULV (R) 10.95 to 12.75 GHz Ku Band	CBSP ULV & FLV (T) 13.75 to 14.5 GHz Ku Band	SDT (T)(R) 14.4 to 15.35 GHz Ku Band	NMT (R) 20.2 to 21.2 GHz K Band	CBSP ULV & NMT (R) 29 to 31 GHz Ka Band	NMT (T)(R) 43.5 to 45.5 GHz Q Band
Center Freq.	1.5 GHz	3.95 GHz	6.14 GHz	7.50 GHz	8.15 GHz	11.9 GHz	14.1 GHz	14.9 GHz	20.7 GHz	30 GHz	44.5 GHz
2248mm Dish 810mm DRP Gain	27.5 dB	25.8 dB	29.4 dB	24.6 dB	32 dB	36.2 dB	27.6 dB	32 dB			
VSWR	3.2:1	2.8:1	3:1	3.4:1	4.4:1	3.7:1	2.58:1	2.3:1			
810mm Dish 149mm DRP Gain				34 dB	34.2 dB	33.5 dB	31.5 dB	27.1 dB	34.1 dB	35.8 dB	41.6 dB
VSWR				4.5:1	1.75:1	3.1:1	2.05:1	2.25:1	2.9:1	3.6:1	2.05:1

=N/A

=Recommended antenna to use based on VSWR Values

VSWR values and radiation patterns were recorded amongst the 2.248m diameter dish antenna with an 810mm drp and the secondary 810mm diameter dish antenna with a 149mm drp. The simulation outputs were recorded to provide which antenna will operate more efficiently utilizing the L, C, X, Ku, K, Ka, and Q frequency bands. This parabolic stacked antenna would provide a method of consolidating the CBSP FLV, CBSP ULV, NMT X / Ka, NMT Q / Ka and directional SDT antennas to a singular platform solution.

The 2.248m diameter dish with an 810mm drp was simulated using the L Band frequency range 950 MHz to 2050 MHz shown in Figure 64. There were instances where frequencies within the L Band range exceeded the targeted VSWR value 2:1. The center frequency (1500 MHz) performed well with having a value less than 2:1. Frequencies between 1275 MHz and 1405 MHz had VSWR values greater than 4:1, while frequencies after that range spanning to 2050 MHz stayed below the VSWR value of 4:1. Frequencies between the 1405 MHz and 2050 MHz range stayed around the VSWR value of 2:1 mark with a few deviations of +/- 1. The radiation pattern depicts a main lobe magnitude of 27.5 db with an angular width (3 dB) of 5.4 degrees and a side lobe level of -10.0 dB. The secondary splash plate antenna was unable to meet the capability of supporting L band frequencies of 950 to 2050 MHz.

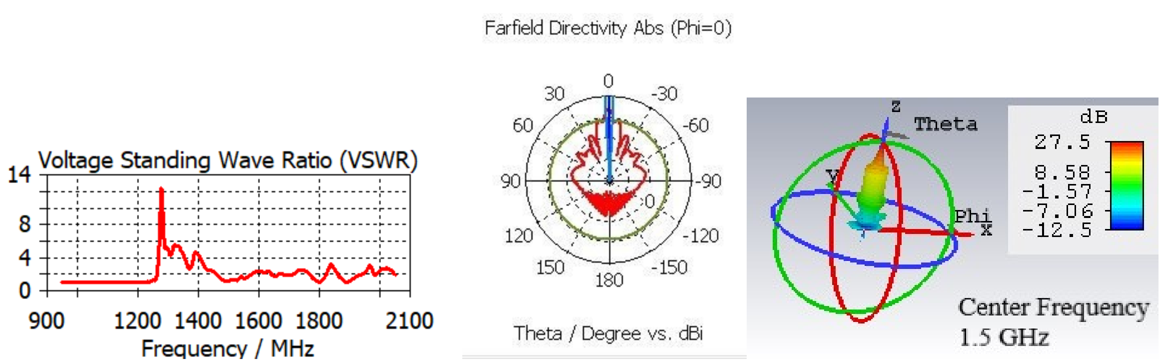


Figure 64 2.248m Splash Plate VSWR and Radiation Pattern for the L band Frequency 950 MHz to 2050 MHz

The 2.248m diameter dish with an 810mm drp was simulated using the C Band frequency range 3700 MHz to 4200 MHz as shown in Figure 65. There were a few instances where frequencies within the C Band range exceeded the targeted VSWR value 2:1. Frequencies 3725 MHz to 3780 MHz had VSWR values ranging from 2.1:1 to 2.8:1, and frequencies 4050 MHz to 4060 MHz had VSWR values ranging from 2.1:1 to 2.6:1. The center frequency (3950 MHz) performed well with having a value less than 2:1. The radiation pattern depicts a main lobe magnitude of 25.8 db with an angular width (3 dB) of 1.9 degrees and a side lobe level of -4.9 dB. The secondary splash plate antenna was unable to meet the capability of supporting C band frequencies of 3700 MHz to 4200 MHz.

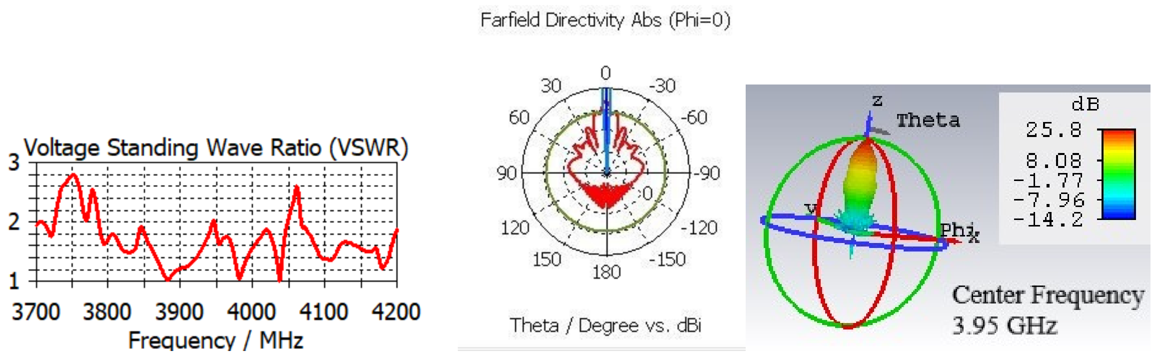


Figure 65 2.248m Splash Plate VSWR and Radiation Pattern for the C band Frequency 3700 MHz to 4200 MHz

The 2.248m diameter dish with an 810mm drp was simulated using the C Band frequency range 5850 MHz to 6425 MHz shown in Figure 66. There were a few instances where frequencies within the C Band range exceeded the targeted VSWR value 2:1. Frequencies 5850 MHz to 5860 MHz had VSWR values ranging from 2.35:1 to 2.1:1, and frequencies 5875 MHz to 5885 MHz had VSWR values ranging from 2.35:1 to 2.1:1 as well. Frequencies 5970 MHz and 5980 MHz had VSWR values from 2.3:1 to 2.1:1. Frequencies 6075 MHz to 6100 had VSWR values ranging from 2.1:1 to 2.42:1. Frequencies 6125 MHz to 6150 MHz had VSWR values ranging from 2.1:1 to 2.39:1. Frequencies 6310 MHz to 6360 MHz had VSWR values between 2.1:1 and 2.8:1. Frequencies 6390 MHz to 6425 MHz had VSWR values between 2.1:1 and 3:1. The center frequency (6140 MHz) performed well with having a value less than 2:1. The radiation pattern depicts a main lobe magnitude of 29.4 dB with an angular width (3 dB) of 0.8 degrees and a side lobe level of -2.1 dB. The secondary splash plate antenna was unable to meet the capability of supporting C band frequencies of 5850 MHz to 6425 MHz.

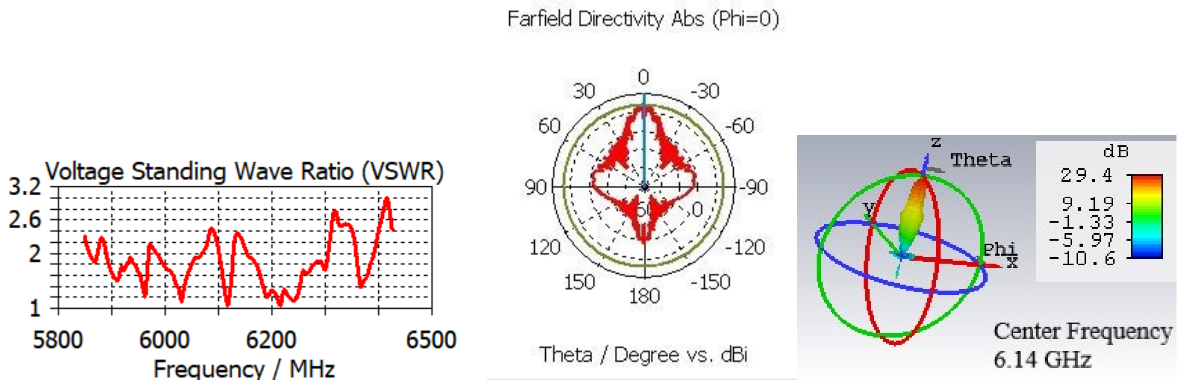
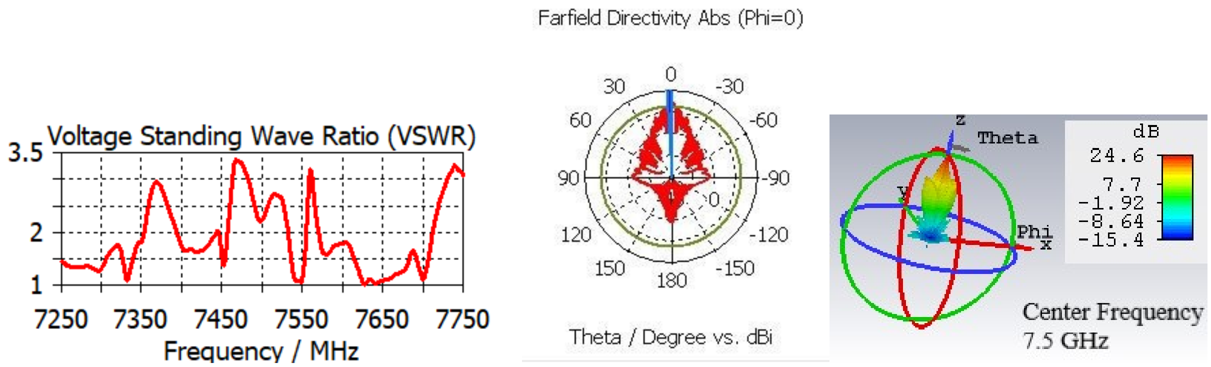


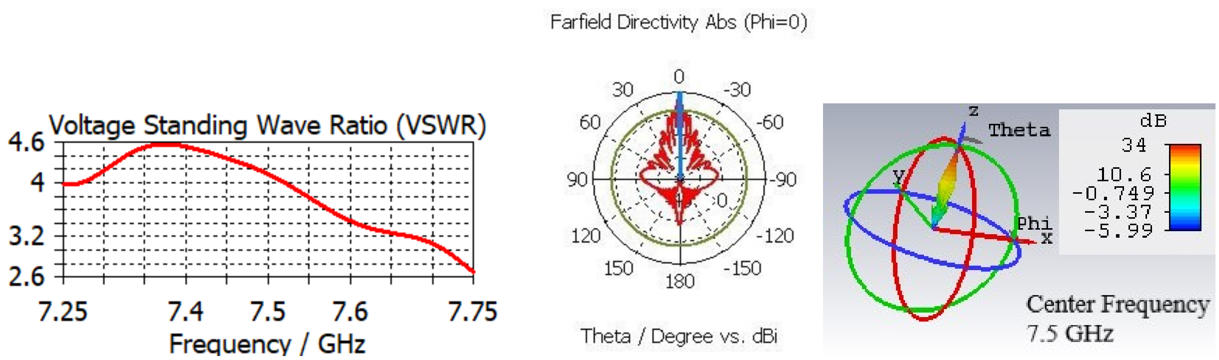
Figure 66 2.248m Splash Plate VSWR and Radiation Pattern for the C band Frequency 5850 MHz to 6425 MHz

The 2.248m diameter dish with an 810mm drp and the secondary 810mm diameter dish with a 149mm drp was simulated using the X Band frequency range 7250 MHz to 7750 MHz as shown in Figure 67. There were a few instances where frequencies within the C Band range exceeded the targeted VSWR value 2:1. Frequencies 7355 MHz to 7390 MHz had VSWR values ranging from 2.1:1 to 2.9:1. Frequencies 7460 MHz to 7540 MHz had VSWR values between 2.1:1 and 3.4:1. Frequencies 7555 MHz to 7570 MHz had VSWR values ranging from 2.1:1 to 3.3:1. Frequencies 7725 MHz to 7750 MHz had VSWR values from 2.1:1 to 3:1. The center frequency (7500 MHz) performed well with having a value slightly greater than 2:1. The radiation pattern depicts a main lobe magnitude of 24.6 dB with an angular width (3 dB) of 2.7 degrees and a side lobe level of -3.3 dB. The secondary splash plate antenna having an 810mm diameter dish with an 149mm drp was able to operate at X band frequencies of 7250 to 7750 MHz, but had

VSWR values much greater than 2:1. VSWR values ranged from 4.5:1 to 2.5:1 and had a main lobe magnitude of 34 dB. Due to the overall VSWR values, the larger 2.248m diameter dish with an 810 drp is recommended for primary use.



(a)



(b)

Figure 67 Splash Plate VSWR and Radiation Pattern for the X band Frequency 7250 MHz to 7750 MHz. (a) Large Splash Plate Results. (b) Small Splash Plate Results

The 2.248m diameter dish with an 810mm drp and the secondary 810mm diameter dish with a 149mm drp was simulated using the X Band frequency range 7900 MHz to 8400 MHz as shown in Figure 68. There were a few instances where frequencies within the X Band range exceeded the targeted VSWR value 2:1. Frequencies 8055 MHz through 8100 MHz had VSWR values ranging from 2.1:1 to 2.6:1. Frequencies 8140 MHz through 8145 MHz had VSWR values ranging from 2.1:1 to 2.3:1. Frequencies 8160 MHz to 8165 MHz had VSWR values ranging from 2.1:1 to 2.2:1. Frequencies 8170 MHz to 8205 MHz had VSWR values of 2.1:1 to 4.4:1.

Frequencies 8210 MHz to 8225 MHz had VSWR values ranging from 2.1:1 to 3.1:1. Frequencies 8340 MHz to 8375 MHz had VSWR values ranging from 2.1:1 to 2.4:1. The center frequency (8150 MHz) met the benchmark of a VSWR value of 2:1. The radiation pattern depicts a main lobe magnitude of 32 db with an angular width (3 dB) of 1.1 degrees and a side lobe level of -5.8 dB. The secondary splash plate antenna having an 810mm diameter dish with a 149mm drp was able to operate more efficiently at X band frequencies of 7900 to 8400 MHz, and had VSWR values less than 2:1. VSWR values ranged from 1.75:1 to 1.18:1 and had a main lobe magnitude of 34.2 dB. The smaller antenna also had an angular width (3 dB) of 2.9 degrees with a side lobe level of -12.4 dB. Due to the overall VSWR values, the smaller diameter dish of 810mm with a 149 drp is recommended for primary use.

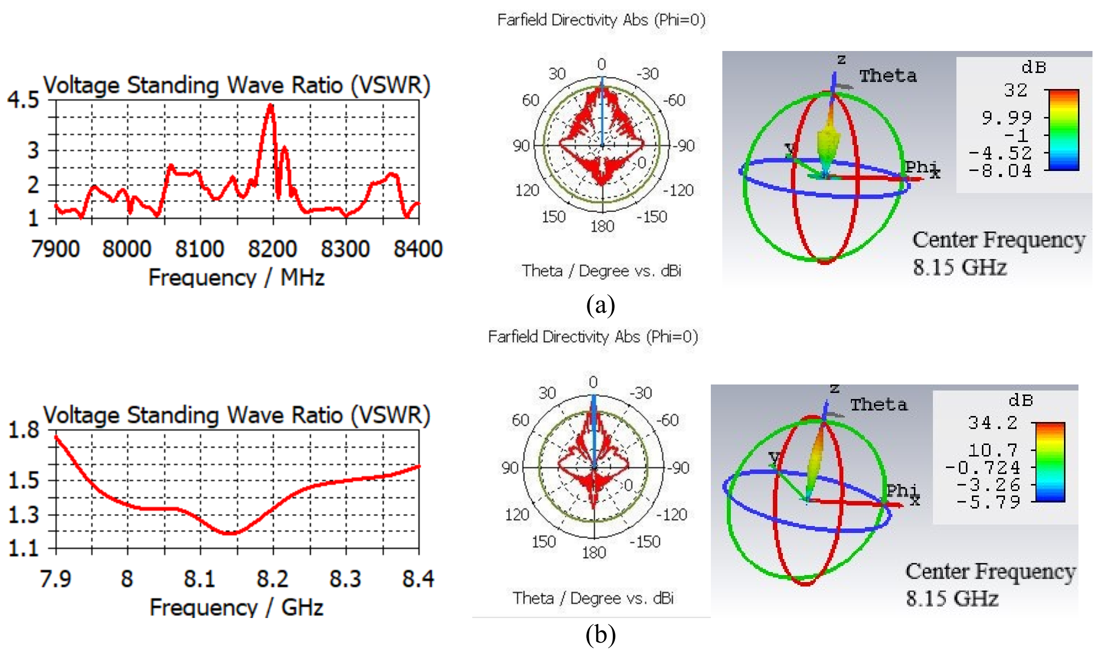


Figure 68 Splash Plate VSWR and Radiation Pattern for the X band Frequency 7900 MHz to 8400 MHz. (a) Large Splash Plate Results. (b) Small Splash Plate Results.

The 2.248m diameter dish with an 810mm drp and the secondary 810mm diameter dish with a 149mm drp was simulated using the Ku Band frequency range 10.95 GHz to 12.75 GHz as shown in Figure 69. There were a few instances where frequencies within the Ku Band range exceeded the targeted VSWR value 2:1 for the 2.248m diameter antenna. Frequencies 11 GHz to 11.03 GHz had VSWR values ranging from 2.1:1 to 2.7:1. Frequencies 11.3 GHz to 11.32 GHz had VSWR values of 2.1:1 to 2.15:1. Frequencies 11.63 GHz to 11.65 had VSWR values of 2.1:1 to 2.65:1. Frequencies 11.95 GHz to 11.96 GHz had VSWR values from 2.1:1 to 2.2:1. Frequencies 12.03 GHz to 12.04 GHz had VSWR values from 2.1:1 to 2.2:1 as well. Frequencies 12.25 GHz to 12.26 GHz had VSWR values from 2.1:1 to 2.2:1. Frequencies 12.29 GHz to 12.33 GHz had VSWR values ranging from 2.1:1 to 2.5:1. The center frequency (11.9 GHz) met the benchmark of a VSWR value of 2:1. The radiation pattern depicts a main lobe magnitude of 36.2 dB with an angular width (3 dB) of 1.6 degrees and a side lobe level of -6.3 dB. The secondary splash plate antenna having an 810mm diameter dish with a 149mm drp was able to operate at the Ku band frequencies of 10.95 GHz to 12.75 GHz with a few frequencies exceeding the VSWR value of 2:1 benchmark. Frequencies 10.95 GHz to 11.36 GHz had VSWR values ranging from 2.1:1 to 3.15:1. Frequencies 12.3 GHz to 12.75 GHz had VSWR values ranging from 2.1:1 to 2.3:1. The center frequency (11.9 GHz) met the benchmark of a VSWR value of 2:1. VSWR values ranged from 3.1:1 to 1.2:1 and had a main lobe magnitude of 33.5 dB. The smaller antenna also had an angular width (3 dB) of 2.2 degrees with a side lobe level of -13.7 dB. Due to the overall VSWR values, both of these antennas are acceptable to use for this frequency range.

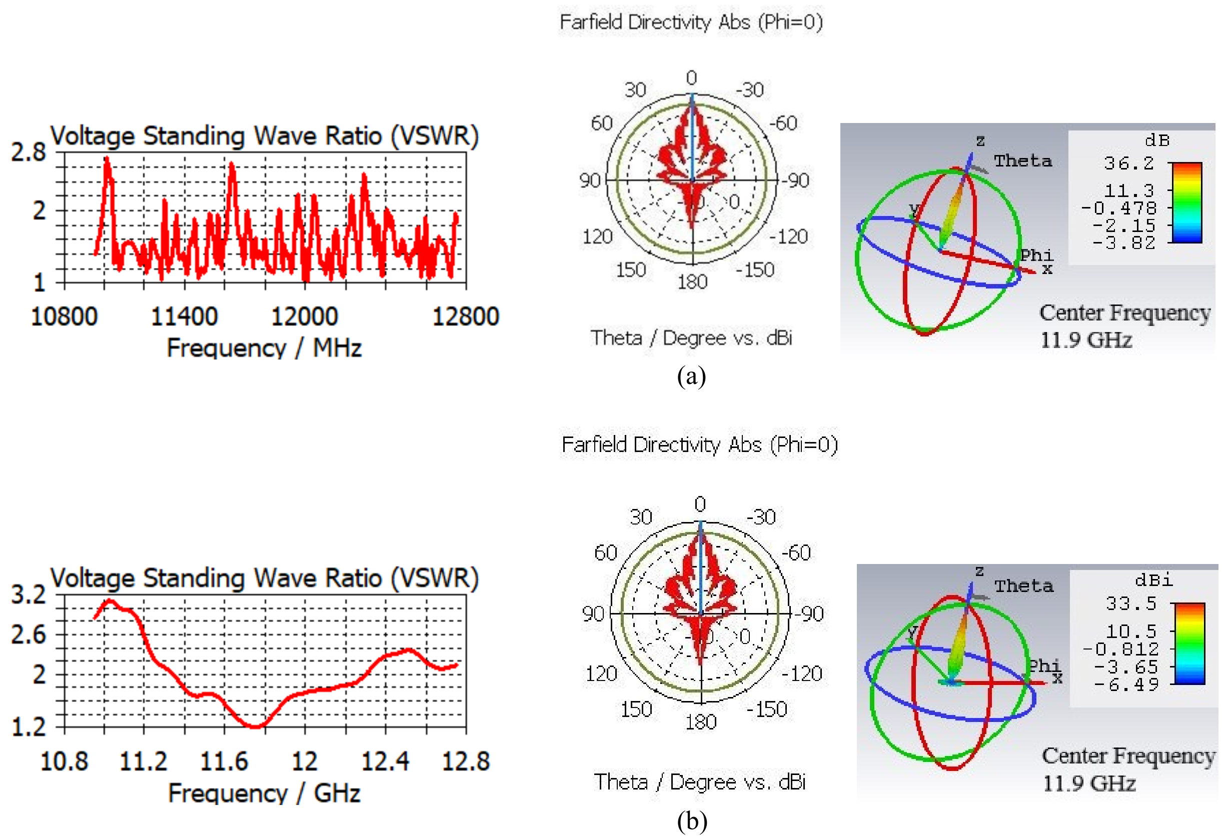


Figure 69 Splash Plate VSWR and Radiation Pattern for the Ku band Frequency 10.95 GHz to 12.75 GHz. (a) Large Splash Plate Results. (b) Small Splash Plate Results

The 2.248m diameter dish with an 810mm drp and the secondary 810mm diameter dish with a 149mm drp were simulated using the Ku band frequency range 13.7 GHz to 14.5 GHz as shown in Figure 70. There were a few instances where frequencies within the Ku band range exceeded the targeted VSWR value 2:1 with the 2.248m diameter antenna. The center frequency (14.1 GHz) met the benchmark of a VSWR value of 2:1. Frequencies 13.7 GHz to 13.76 GHz had VSWR values of 2.3:1 to 2.1:1. Frequencies 13.81 GHz to 13.82 GHz had VSWR values ranging from 2.01:1 to 2.02:1. Frequencies 14 GHz to 14.03 GHz had VSWR values from 2.1:1 to 2.5:1. Frequencies 14.8 GHz to 14.9 GHz had VSWR values ranging from 2.1:1 to 2.25:1. Frequencies 14.23 GHz to 14.25 GHz had VSWR values ranging from 2.01:1 to 2.02:1. Frequencies 14.33

GHz to 14.35 GHz had VSWR values 2.1:1 to 2.5:1. The radiation pattern depicts a main lobe magnitude of 27.6 dB with an angular width (3 dB) of 0.7 degrees and a side lobe level of -7.7 dB. The secondary splash plate antenna having an 810mm diameter dish with a149mm drp was able to operate slightly more efficiently at Ku band frequencies of 13.7 GHz to 14.5 GHz. This antenna had VSWR values less than 2:1 with an instance of going up slightly above 2:1 between the frequencies 14.275 GHz to 14.3 GHz and 14.42 GHz to 14.45 GHz. The main lobe magnitude was 31.5 dB. The smaller antenna also had an angular width (3 dB) of 4.4 degrees with a side lobe level of -3.9 dB. Due to the overall VSWR values, both of these antennas are acceptable for use; however the smaller antenna has consistent lower VSWR values at the lower end of the RF spectrum tested.

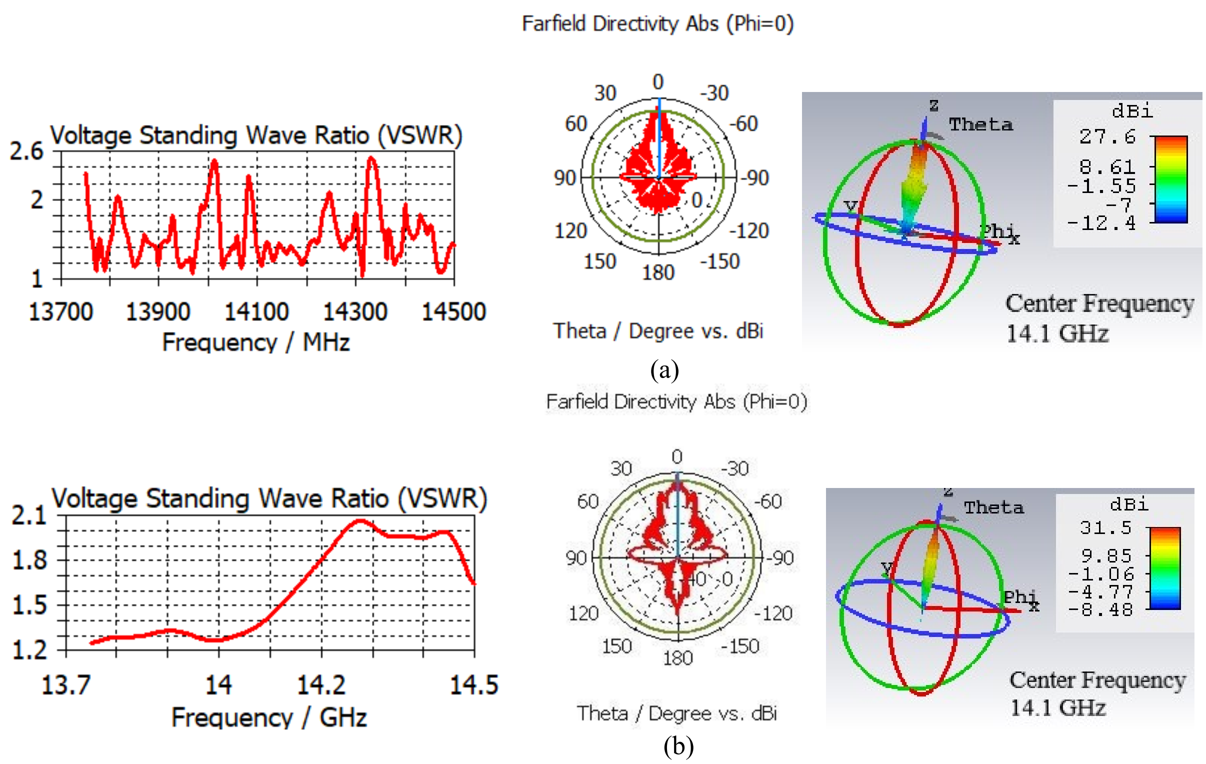
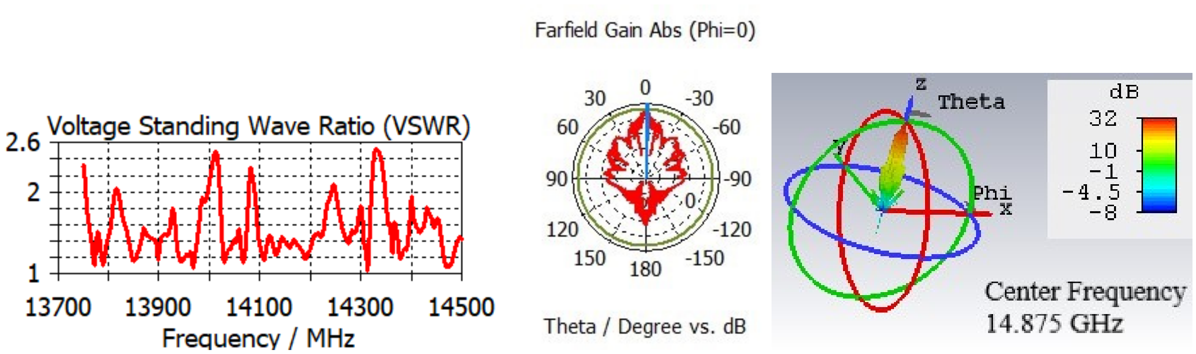
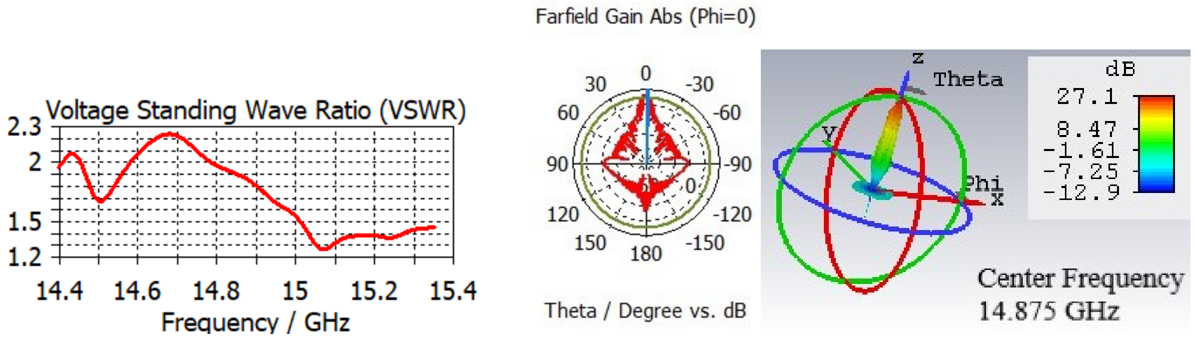


Figure 70 Splash Plate VSWR and Radiation Pattern for the Ku band Frequency 13.7 GHz to 14.5 GHz. (a) Large Splash Plate Results. (b) Small Splash Plate Results

The 2.248m diameter dish with an 810mm drp and the secondary 810mm diameter dish with a 149mm drp were simulated using the Ku band frequency range 14.4 GHz to 15.35 GHz as shown in Figure 71. This frequency range is for LoS operations. There were a few instances where frequencies within the Ku band range exceeded the targeted VSWR value 2:1 with the 2.248m diameter antenna and the 810mm diameter splash plate antenna. The center frequency (14.875 GHz) had VSWR value of less than 2:1 on both splash plate antennas. On the larger 2.248m splash plate antenna VSWR values showed a spike slightly over 2:1 within frequencies 14.65 GHz to 14.68 GHz. This spike reached to a VSWR value of approximately 2.3:1. On the smaller 810mm splash plate antenna VSWR values showed a spike slightly over 2:1 as well within frequencies 14.41 GHz to 14.45 GHz and 14.58 GHz to 14.79 GHz. The largest spike reached a VSWR value of 2.25:1 which was within the 14.58 GHz to 14.79 GHz range. The rest of the frequencies within the 14.4 GHz to 15.35 GHz range stayed below the VSWR value of 2:1. The 2.248m splash plate antenna had a radiation pattern that depicts a 32 dB gain with an angular width (3 dB) of 0.9 degrees and a side lobe level of -1.1 dB. The secondary 810mm splash plate antenna had a radiation pattern that depicts a 27.1 dB gain with an angular width (3 dB) of 1.3 degrees and a side lobe level of -3.3 dB. Due to the overall VSWR values, both of these antennas are acceptable for use; however the larger antenna had a higher gain value of 32.1 dB vice the smaller antenna having a gain value of 27.1 dB.



(a)



(b)

Figure 71 Splash Plate VSWR and Radiation Pattern for the Ku band Frequency 14.4 GHz to 15.35 GHz. (a) Large Splash Plate Results. (b) Small Splash Plate Results

The 810mm diameter dish with a 149mm drp was simulated using the K band frequency range 20.2 GHz to 21.2 GHz as shown in Figure 72. There were instances where frequencies within the K band range exceeded the targeted VSWR value 2:1. The center frequency (20.7 GHz) performed well with having a value less than 2:1. Frequencies between 20.2 GHz and 20.45 GHz had VSWR values greater than 2:1. Specifically, frequencies 20.2 GHz to 20.475 GHz had VSWR values ranging from 2.1:1 to 2.9:1. Frequencies 20.55 GHz to 20.65 GHz had VSWR values from 2.1:1 to 2.2:1. The radiation pattern depicts a main lobe magnitude of 34.1 dB with an angular width (3 dB) of 3.4 degrees and a side lobe level of -5.5 dB. The large 2.248m splash plate antenna was unable to meet the capability of supporting K band frequencies of 20.2 GHz to 21.2 GHz.

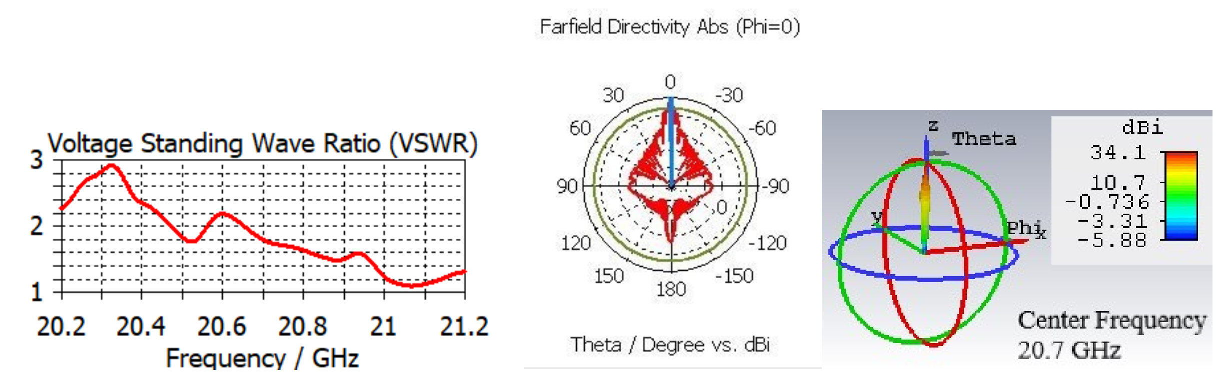


Figure 72 810mm Splash Plate VSWR and Radiation Pattern for the K band Frequency 20.2 GHz to 21.2 GHz

The 810mm diameter dish with a 149mm drp was simulated using the Ka band frequency range 29 GHz to 31 GHz as shown in Figure 73. There were instances where frequencies within the Ka band range exceeded the targeted VSWR value 2:1. The center frequency (30 GHz) performed well with having a value less than 2:1. Frequencies between 30.61 GHz and 31 GHz had VSWR values greater than 2:1 ranging from 2.1:1 to 2.6:1. The radiation pattern depicts a main lobe magnitude of 35.8 dB with an angular width (3 dB) of 0.8 degrees and a side lobe level of -4.7 dB. The large 2.248m splash plate antenna was unable to meet the capability of supporting Ka band frequencies of 29 GHz to 31 GHz.

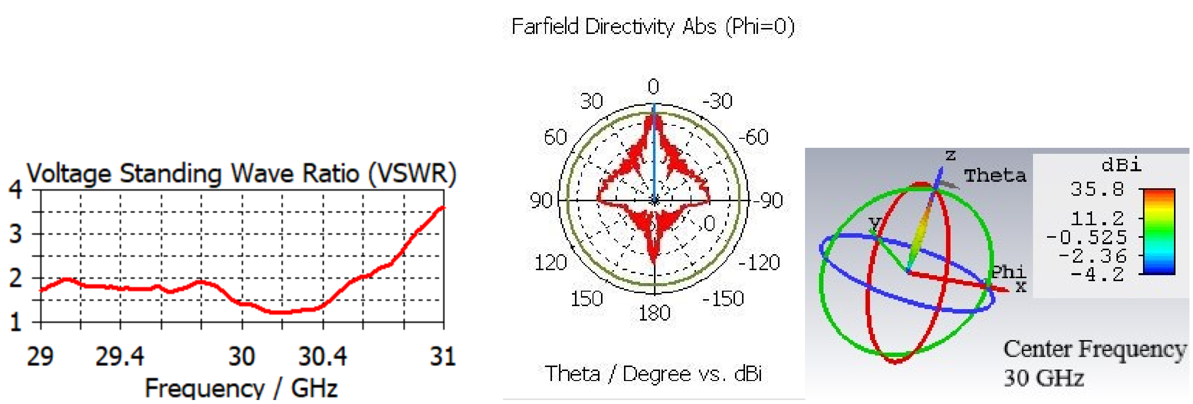


Figure 73 810mm Splash Plate VSWR and Radiation Pattern for the Ka band Frequency 29 GHz to 31 GHz

The 810mm diameter dish with a 149mm drp was simulated using the Q band frequency range 43.5 GHz to 45.5 GHz as shown in Figure 74. There were instances where frequencies within the Q band range slightly exceeded the targeted VSWR value 2:1. The maximum VSWR that was reached had a value of 2.05:1. The radiation pattern depicts a main lobe magnitude of 41.6 dB with an angular width (3 dB) of 0.6 degrees and a side lobe level of -5.2 dB. The large 2.248m splash plate antenna was unable to meet the capability of supporting Q band frequencies of 43.5 GHz to 45.5 GHz.

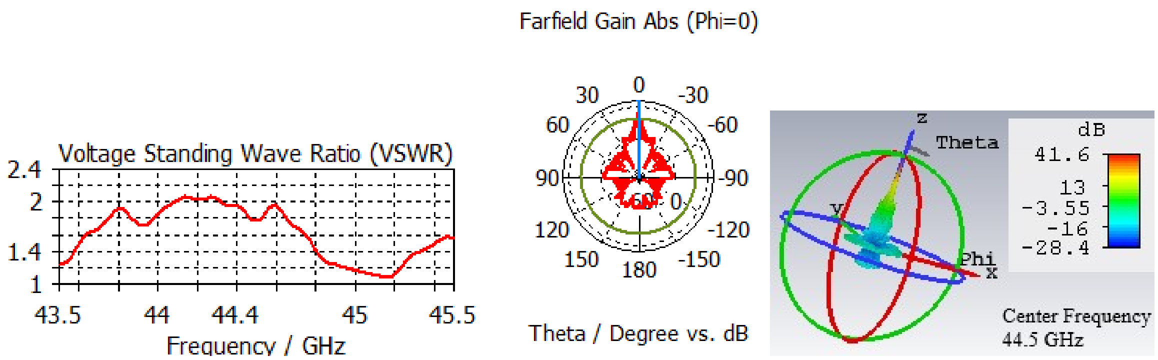


Figure 74 810mm Splash Plate VSWR and Radiation Pattern for the Q band Frequency 43.5 GHz to 45.5 GHz

Antenna Magus and CST Microwave Studio is a useful tool for antenna engineering efforts. Putting constraints into the software would provide results of VSWR, gain, side lobe, angular width (3 dB) values, radiation patterns and physical attributes of the antenna intended for design. The splash plate antenna example demonstrated utilizing the parabolic stacked antenna method for multiple frequency capabilities. Limitations were shown with the splash plate antenna where certain frequencies required a different dish size in order to effectively operate. Antenna Magus and CST Microwave Studio provides support to SE personnel / antenna engineers to determine feasible antenna options for design considerations such as parabolic antenna stacking. The dual splash plate parabolic stacked antenna is capable of operating at frequencies of all variants of NMT and CBSP antennas [105]. This parabolic stacked antenna is also capable of supporting Ku band directional LoS operations that the SDT antenna provides as well.

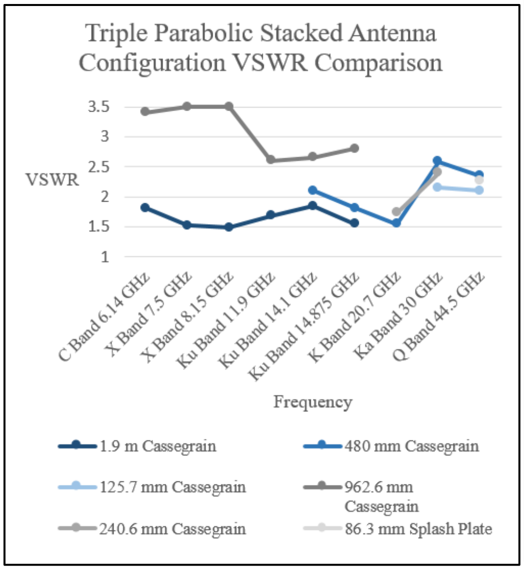
4.7 Parabolic Stacked Antenna Configuration Comparison

The six parabolic stacked antenna configurations showed tradeoffs between one another. Table 27 depicts the results for parabolic stacked antenna configurations utilizing three antennas while Table 28 displays the results for parabolic stacked antenna configurations utilizing two antennas. The gray areas indicated frequencies that were unable to provide efficient values using CST Microwave Studio software for a particular parabolic stacked antenna configuration. Each parabolic stacked antenna configuration were capable of operating at NMT Q / Ka, NMT X / Ka and directional SDT antenna variant frequency bands. The dual splash plate parabolic stacked antenna described in Section 4.6 was capable of supporting CBSP ULV and CBSP FLV operating frequencies in addition to the NMT Q / Ka, NMT X / Ka and directional SDT antenna variant operating frequency bands.

Parabolic antenna stacking utilizing three antennas proved that multiple antennas are capable of being stacked in front of one another as long as the a blockage area exists with the reflecting dish, and as long as there is a smaller capable antenna that can operate at a particular frequency. Table 27 and Figure 75 depicted results for the triple Cassegrain parabolic stacked antenna as well as the dual Cassegrain with splash plate configuration. The triple Cassegrain configuration had a maximum diameter of 1.9m which is 22% smaller than the large NMT X / Ka antenna variant which had a diameter of 2.44m. The triple Cassegrain parabolic stacked antenna showed VSWR values which ranged from 1.48:1 to 2.58:1 and gain values ranging from 28.2 dB to 43.5 dB. This parabolic stacking configuration had redundant operating frequency capabilities which would be used as a failover option to improve overall operational availability. The dual Cassegrain with splash plate parabolic stacked antenna had a maximum diameter of 962.6mm which is 36.8% smaller than the small NMT X / Ka antenna variant that had a diameter of 1.52m. The dual Cassegrain with splash plate configuration provided VSWR values which ranged from 1.73:1 to 3.5:1 and gain values ranging from 26.3 dB to 34.8 dB.

Table 27 Parabolic Stacked Antenna Configurations with Three Antennas

	Triple Cassegrain Parabolic Stacked Antenna			Dual Cassegrain with Splash Plate Parabolic Stacked Antenna		
Primary Dish Size	1.9m			962.6mm		
Secondary Dish Size		480mm			240.6mm	
Third Dish Size			125.7mm			86.3mm
Gain L Band (Center Freq. 1.5 GHz)						
Max. VSWR L Band (.95 GHz to 2.05 GHz)						
Gain C Band (Center Freq. 3.95 GHz)						
Max. VSWR C Band (3.7 GHz to 4.2 GHz)						
Gain C Band (Center Freq. 6.14 GHz)	38.3 dB			31.81 dB		
Max. VSWR C Band (5.85 GHz to 6.425 GHz)	1.81:1			3.4:1		
Gain X Band (Center Freq. 7.5 GHz)	40.6 dB			34.4 dB		
Max. VSWR X Band (7.25 GHz to 7.75 GHz)	1.52:1			3.5:1		
Gain X Band (Center Freq. 8.15 GHz)	41.5 dB			34.6 dB		
Max. VSWR X Band (7.9 GHz to 8.4 GHz)	1.48:1			3.5:1		
Gain Ku Band (Center Freq. 11.9 GHz)	43.5 dB			34.8 dB		
Max. VSWR Ku Band (10.95 GHz to 12.75 GHz)	1.68:1			2.6:1		
Gain Ku Band (Center Freq. 14.1 GHz)	39.3 dB	33.2 dB		33.2 dB		
Max. VSWR Ku Band (13.75 GHz to 14.5 GHz)	1.84:1	2.1:1		2.65:1		
Gain Ku Band (Center Freq. 14.875 GHz)	40.1 dB	33.7 dB		34.6 dB		
Max. VSWR Ku Band (14.4 to 15.35 GHz)	1.55:1	1.81:1		2.8:1		
Gain K Band (Center Freq. 20.7 GHz)		37.4 dB			29.4 dB	
Max. VSWR K Band (20.2 GHz to 21.2 GHz)		1.54:1			1.73:1	
Gain Ka Band (Center Freq. 30 GHz)		40.3 dB	28.2 dB		34.4 dB	
Max. VSWR Ka Band (29 GHz to 31 GHz)		2.58:1	2.15:1		2.4:1	
Gain Q Band (Center Freq. 44.5 GHz)		34.2 dB	32.5 dB			26.3 dB
Max. VSWR Q Band (43.5 GHz to 45.5 GHz)		2.35:1	2:1			2.26:1



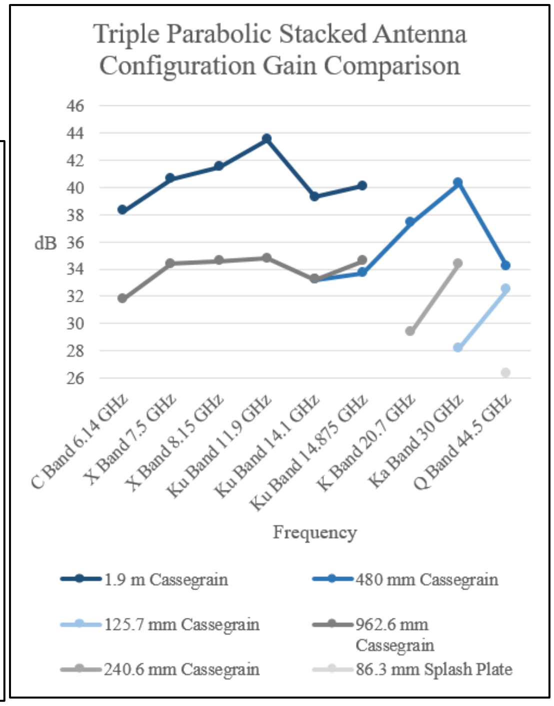


Figure 75 Triple Parabolic Stacked Antenna Configuration Comparison

Dual antenna configurations using parabolic antenna stacking methods proved to have multi-band capabilities to support C, X, Ku, K, Ka and Q band frequencies. Table 28 and Figure 76 displays the results for three parabolic stacked antenna configurations to include the Gregorian with splash plate parabolic stacked antenna, the Cassegrain with Gregorian parabolic stacked antenna and the dual Gregorian parabolic stacked antenna. The Gregorian with splash plate parabolic stacked antenna was similar in size to the NMT Q / Ka antenna, had VSWR values which ranged from 1.51:1 to 1.85:1 and gain values ranging from 34.6 dB to 41.8 dB. The Cassegrain and Gregorian parabolic stacked antenna had the same main dish size of 1.5 m for the larger antenna as well as the main dish size of 325.9 mm for the smaller antenna compared to the Gregorian and splash plate parabolic stacked antenna configuration. The Cassegrain and Gregorian parabolic stacked antenna had VSWR values which ranged from 1.34:1 to 2.21:1 and gain values ranging from 33.4 dB to 40.1 dB. The dual Gregorian parabolic stacked antenna had a maximum diameter of 1.921m which is 22% smaller than the NMT X / Ka antenna variant which had a diameter of 2.44m. The dual Gregorian parabolic stacked antenna had VSWR values which ranged from 1.45:1 to 1.68:1 and gain values ranging from 36.1 dB to 42.5 dB.

Table 28 Parabolic Stacked Antenna Configurations with Two Antennas

	Gregorian with Splash Plate Parabolic Stacked Antenna		Cassegrain with Gregorian Parabolic Stacked Antenna		Dual Gregorian Parabolic Stacked Antenna	
Primary Dish Size	1.5m		1.5m		1.921m	
Secondary Dish Size		325.9mm		325.9mm		480mm
Gain L Band (Center Freq. 1.5 GHz)						
Max. VSWR L Band (.95 GHz to 2.05 GHz)						
Gain C Band (Center Freq. 3.95 GHz)						
Max. VSWR C Band (3.7 GHz to 4.2 GHz)						
Gain C Band (Center Freq. 6.14 GHz)	35.69 dB		36 dB		38.4 dB	
Max. VSWR C Band (5.85 GHz to 6.425 GHz)	1.59:1		1.58:1		1.55:1	
Gain X Band (Center Freq. 7.5 GHz)	37.2 dB		36.65 dB		40 dB	
Max. VSWR X Band (7.25 GHz to 7.75 GHz)	1.63:1		1.49:1		1.5:1	
Gain X Band (Center Freq. 8.15 GHz)	39.8 dB		39.2 dB		41.5 dB	
Max. VSWR X Band (7.9 GHz to 8.4 GHz)	1.62:1		1.53:1		1.49:1	
Gain Ku Band (Center Freq. 11.9 GHz)	40.99 dB		40.9 dB		42.4 dB	
Max. VSWR Ku Band (10.95 GHz to 12.75 GHz)	1.61:1		1.86:1		1.55:1	
Gain Ku Band (Center Freq. 14.1 GHz)	41.6 dB		39.3 dB		42.4 dB	
Max. VSWR Ku Band (13.75 GHz to 14.5 GHz)	1.64:1		2.09:1		1.46:1	
Gain Ku Band (Center Freq. 14.875 GHz)	41.8 dB		40.1 dB		42.3 dB	
Max. VSWR Ku Band (14.4 to 15.35 GHz)	1.53:1		2.21:1		1.58:1	
Gain K Band (Center Freq. 20.7 GHz)		34.7 dB		33.4 dB		36.1 dB
Max. VSWR K Band (20.2 GHz to 21.2 GHz)		1.51:1		1.34:1		1.48:1
Gain Ka Band (Center Freq. 30 GHz)		35.2 dB		36.8 dB		40.8 dB
Max. VSWR Ka Band (29 GHz to 31 GHz)		1.85:1		1.55:1		1.45:1
Gain Q Band (Center Freq. 44.5 GHz)		34.6 dB		39.1 dB		42.5 dB
Max. VSWR Q Band (43.5 GHz to 45.5 GHz)		1.79:1		2.1:1		1.68:1

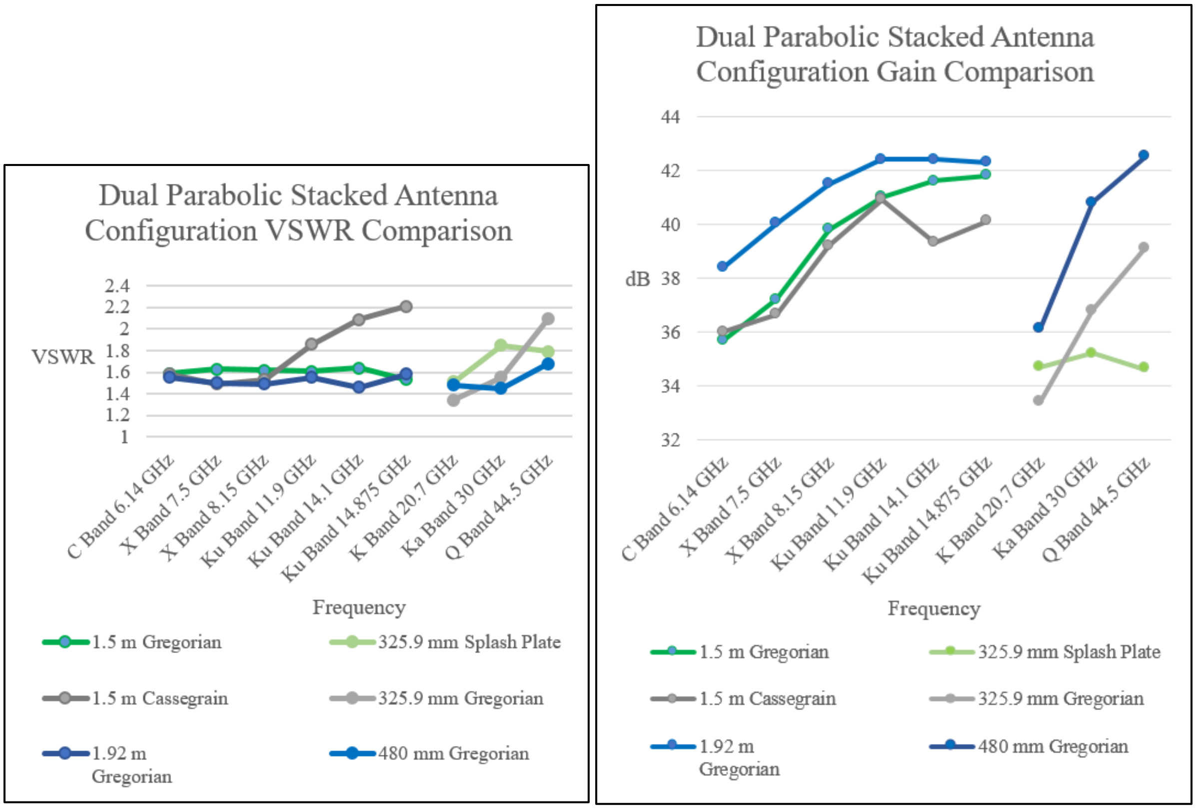


Figure 76 Dual Parabolic Stacked Antenna Configuration Comparison

The dual splash plate parabolic stacked antenna was capable of operating at all frequency bands that the CBSP FLV, CBSP ULV, NMT Q / Ka, NMT X / Ka, and SDT antennas operate within as shown in Section 4.6. The maximum VSWR of the L Band frequency range of .95 GHz to 2.05 GHz was around 3.2:1 except for the frequency range of 1.25 GHz to 1.41 GHz where a VSWR value spike of 12:1 was observed in Figure 64 in Section 4.6. The dual splash plate parabolic stacked antenna had maximum VSWR values ranging from 1.75:1 to 4.5:1 excluding the frequency range of 1.25 GHz to 1.41 GHz. This antenna configuration had antenna gain values of 24.6 dB to 41.6 dB. This parabolic stacking configuration had redundant operating frequency capabilities which would be used as a failover option to improve overall operational availability.

To operate within frequency bands L, C, X, Ku, K, Ka, and Q for SATCOM and LoS operations, the dual splash plate parabolic stacked antenna is recommended as described in Section 4.6. Comparing the dual splash plate parabolic stacked antenna with the other configurations demonstrated that the dual splash plate parabolic stacked antenna had more frequency band capabilities. The dual splash plate parabolic stacked antenna had both SATCOM and LoS capabilities. These capabilities included frequencies that the CBSP FLV, CBSP ULV, NMT Q / Ka, NMT X / Ka, and LoS directional antennas operate within. The triple cassegrain parabolic stacked antenna should be considered for X, K, Ka, and Q band operations when antenna failover options are desired due to multiple antennas are able to operate within similar sets of frequency bands. The Gregorian with splash plate antenna configuration is similar in diameter size of the NMT Q / Ka antenna and is capable of operating within NMT Q / Ka, NMT X / Ka and directional SDT antenna variants. The Cassegrain with Gregorian parabolic stacked antenna had the same main dish and sub-reflector diameter as the Gregorian with splash plate antenna, but had higher VSWR values with certain frequency bands. The dual Gregorian parabolic stacked antenna configuration provides slightly higher gain values than the smaller Gregorian with splash plate antenna parabolic stacked antenna configuration while operating within the same set of frequencies. If a smaller alternative that can operate at C, X, Ku, K, Ka and Q bands is required, the dual Cassegrain with splash plate parabolic stacked antenna can provide these SATCOM and LoS capabilities.

4.8 Technology Maturation and Risk Reduction

The TMRR phase determines what technologies are needed to be integrated into the system along with reducing risk associated with engineering, life cycle costs and other technical aspects. This phase would entail expanding on the ICD by adding details to it to create a Capability

Development Document (CDD). The CDD specifies operational requirements and describes meeting the capability needs. Development Key Performance Parameters (KPP) and Key System Attributes (KSA) are listed to determine acceptable values when considering cost and schedule constraints. KPPs are capabilities that the system has that meets the operational needs. KSAs are attributes considered most critical or essential for an effective capability but not selected as KPPs [106]. KPPs and KSAs do not necessarily have to associate with each other, but KPPs are higher with respect to prioritization. The TMRR phase would introduce designs, adjust cost estimates based on system life cycle information, assess system production, and develop system baselines.

Various artifacts are produced and updated during this phase such as Test and Evaluation Master Plans, System Engineering plans, program protection plans, requirements documents, information support plans and safety documentation. The test and evaluation master plan would provide overarching guidance on how the integrated product team will conduct testing activities. Various testing activities would be identified throughout the system's life cycle including tests associated with hardware, software, simulation, development, pre-production, post-production, pre-installation, and post-installation. The Systems Engineering Plan (SEP) would document high level guidance for engineering execution and control. The SEP would include requirements, resourcing needs, technical configuration management, technical review concepts, and integration strategies. Guidance for managing technical requirements would be identified in the SEP where a central repository would be identified with traceability methods. Technical resources for the development and fielding of the parabolic stacked antenna would include an engineering, development, logistic and management team. These teams would be decomposed to lower level teams such as engineering integration, risk management, software development, hardware development, financial management, configuration management and so on. Various teams would be considered an integrated product team which would strive to deliver the parabolic stacked antenna system to the war fighter. Program protection plans would provide information assurance and cyber security details with respect to unclassified or classified information. This document identifies sensitive information to the technology being developed to ensure appropriate security measures are being practiced during the system's life cycle. Cost analyses, ongoing risk and safety assessments are activities performed during the TMRR. Cost analyses would be based off of historical information and estimates acquired from SMEs. Risk management is practiced to reduce overall program risk that has potential impacts to cost, schedule and technical parameters. Safety assessments would entail human factors with respect to the environment and usability of the system. Safety assessments would factor into risk management to reduce or eliminate areas of safety concerns.

The Preliminary Design Review (PDR) solidifies the system baseline with respect to system operation. This review ensures the system's design is meeting the requirements with hardware and software baselines. Cost, schedule, performance, and risk review is also incorporated within the PDR. The Integrated Baseline Review (IBR) involves the integrated product team along with other support needed such as contractors. A mutual understanding of the scope of work and responsibilities between all parties are established to ensure product development effectiveness is met with the intent of delivering a product. As in each review, management criteria such as cost, schedule, performance, and risks are reviewed. Reducing overall program risk along with maturing the system design are key points within the TMRR. Concluding activities within the TMRR phase would meet the criteria for reaching Milestone B.

Risk management is essential to identify, analyze, prioritize and map, resolve, and monitor risks. These risk management activities is an iterative process where identifying new risks will occur throughout the life cycle of the system. Risks have been identified and has been listed below with their corresponding mitigation.

Risk 1: If antenna stress testing simulation is not performed, then the physical antenna prototype may be damaged during shock and vibe testing.

Mitigation: Use stress testing simulators such as solid works to determine the strength of the antenna, and adjust mounting hardware as needed. When a prototype is created, place the prototype parabolic stacked antenna on a motion table to stress test which shipboard pitch and roll criteria.

Risk 2: If antenna radiation with respect to human interaction and surroundings is not identified, then injuries could occur while being exposed to RF radiation.

Mitigation: Identify and implement Hazards of Electromagnetic Radiation to Ordnance (HERO) and Hazards of Electromagnetic Radiation to Personnel (HERP) standards.

Risk 3: If antenna radiation with respect to other electronic devices is not assessed, then there could be interference with SATCOM communication links.

Mitigation: Identify surrounding electronic devices to the parabolic stacked antenna and simulate antenna radiation patterns to speculate potential interference.

Risk 4: If a RF signal switch mechanism or multiband feed is not chosen or developed, then particular RF signal bands may be limited.

Mitigation: Investigate if commercial off the shelf RF signal / wave guide switch or multiband feed solutions are available or develop a RF signal / wave guide switch or multiband feed to accommodate L, C, K, Ka, Ku, X, and Q bands.

Risk 5: If antenna amplifier locations are not identified, then certain RF bands may not be accessible.

Mitigation: Research previous consolidated antenna amplifier locations such as the Ka band amplifiers and Q band amplifiers that are mounted on the backside of the NMT antenna to propose potential amplifier mounting locations to account for L, C, K, Ka, Ku, X, and Q bands.

Risk 6: If wave guide transmission distances are not assessed, then there will be RF signal loss.

Mitigation: Research maximum wave guide transmission distance values and determine wave guide locations and installation procedures to prevent RF signal loss.

Risk 7: If the weight of the antenna is not measured, then the platform may not be able to support the parabolic stacked antenna.

Mitigation: Choose appropriate materials, estimate weight values, identify platform strength by perform modal testing on the platform.

Risk 8: If Agile / lean methods are not implemented for antenna system simulation testing and software development, then costs and time may increase due to rework.

Mitigation: Obtain concurrence from stakeholders to work in an Agile methodology (e.g. SAFe) to deliver faster simulation results and software increments in effort to obtain feedback early to reduce costly change requests.

Risk 9: If collaboration amongst system stakeholders are not practiced, then system design and development may contain issues.

Mitigation: Assign an overall governing structure to enforce system stakeholder collaboration while budgeting for system stakeholder support.

Risk 10: If budget for the parabolic stacked antenna replacement / consolidation is not identified, sustainment costs for existing fielded SATCOM and LoS antennas will increase due to systems being end of life.

Mitigation: Work with system stakeholders to gain concurrence on a budget to replace / consolidate existing fielded SATCOM and LoS antennas with parabolic stacked antennas.

Risk 11: If radome space is not considered with antenna maintainability features, repairing and replacing parts on the parabolic stacked antenna may be arduous.

Mitigation: Design the parabolic stacked antenna radome to fit within the existing antenna footprint (antenna being replaced) with enough space for personnel to enter and repair the parabolic stacked antenna.

Risk 12: If a physical prototype is not developed, verification of simulation results can not be complete.

Mitigation: Fabricate a prototype antenna to test parabolic antenna stacking methodology

Risk 13: If antenna material is not identified and tested, durability of the antenna over 22 years will remain uncertain.

Mitigation: Obtain historical material data of the NMT antenna and incident reports to assess antenna material durability on a shipboard platform.

Risks would be measured by its' likelihood of occurring and the consequence of impact. These risks would be managed by analyzing, prioritizing, mapping, resolving, and monitoring. Ideally these risks would be mitigated by having the current likelihood and consequence values decreasing. Risks are considered low currently due to the parabolic stacked antenna effort being within the early stages of the system lifecycle. As new risks are identified they would have to be mapped on the risk matrix shown in Figure 77 to assist with prioritizing.

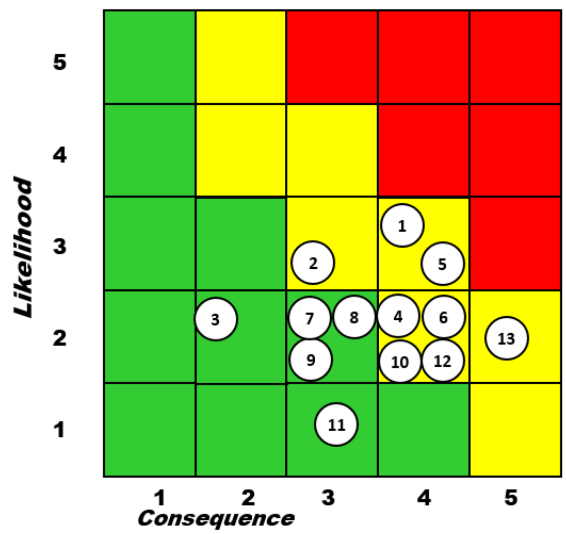


Figure 77 Risk Matrix

Risks can be identified in various aspects to designing a parabolic stacked antenna system. The parabolic stacked antenna risks shown within this dissertation at the current time are relatively mid to low. These risks would either increase or decrease in severity once funding, schedule and resources are agreed upon with Navy stakeholders. These risks provide parabolic stacked antenna development considerations for follow on work. Tradeoffs may introduce themselves when two or more concepts are feasible. One concept may have a more definitive way forward in regards to producing a system while the other concept may involve unknown variables that would include high risk investments to move forward with design and development. Stakeholders would have to agree with certain tradeoffs and risk when selecting a risk mitigation concept. A high risk concept may yield negative results if certain factors are not considered. Agreement to sever a high risk concept at a certain point would be essential to cut losses and move towards a contingency plan. Agreeing on a budget threshold or schedule threshold to abandon a particular effort is necessary to stay within cost and schedule milestone boundaries. Further research on a particular concept may be applicable to produce additional details on a high risk system being developed. SMEs would provide information relating to concept feasibility. Some criterion may not be within reach with certain risk mitigation concepts which would pose high uncertainty. Risk management is recommended to be practiced during the early phases throughout the late phases of the parabolic stacked antenna system's life cycle.

5. Mid to Late Phase System Engineering

The Engineering & Manufacturing Development phase begins after Milestone B. The goal of this phase is to complete the development of a system or increment of capability, complete full system integration, develop affordable and executable manufacturing processes, complete system fabrication, and test and evaluate the system before proceeding into the Production and Deployment Phase [107]. Developing the parabolic stacked antenna system would include developing a prototype of the parabolic stacked antenna along with integrated connections to various amplifiers, and communication groups. The communication groups would be located inside the shipboard platform and would transform RF signals into data services between the user and the distant end. Integration with the parabolic stacked antenna would involve connections between the SDT, CBSP, NMT, and GBS communication groups. A RF switching mechanism would be required to access various capabilities these communication groups provide. Integrating software would involve software engineering teams working with cybersecurity SMEs for the development of the software on the hardware platforms. The system integration and interoperability would have to be demonstrated in a test environment to verify operational aspects are meeting system requirement criteria.

Ensuring materiel availability with regards to logistics is included within the Engineering & Manufacturing Development phase. Determining Reliability, Availability and Maintainability (RAM) criteria assists with sustainability needs when fielding the parabolic stacked antenna system. Determining high failure rate components through testing and historical data would ensure an appropriate amount of spares are available for potential repair needs. Identifying Commercial Off the Shelf (COTS) and Government Off the Shelf (GOTS) parts assists with understanding the available stock that internal Government suppliers such as Navy Supply or commercial vendors may have to distribute. Designing the parabolic stacked antenna system for producibility would require coordination with contractor counterparts to meet fielding demands over a period of time / budget. A repeatable process to manufacture and test the parabolic antenna system would involve engineering teams creating a baseline process that is executed and refined for continuous process improvement. Protection of critical program information is another task that would require SME input for identification and control purposes. System supportability would be factored with determining personnel and logistic resources needed to maintain the parabolic antenna system. A CDR would entail assessing the design to ensure cost, schedule, and performance requirements are met to begin fabricating the system.

Establishing a technical baseline from the approval of the CDR would entail configuration management for any changes that are made to the system baseline. Updates on costs, risks, development schedules, manufacturing, testing, coding, logistic plans, and other program documentation would lead up to the approval of the CDR. The Production Readiness Review (PRR) would occur near the end of the Engineering & Manufacturing Development phase in which Milestone C would be reached. The PRR would review all plans associated with production, quality management, logistics, requirements traceability and ensuring the system is ready for production. Contractor counterparts to assist with the production process would also provide input to the PRR in order to verify cost, schedule, and performance parameters are in line with projected efforts. LRIP can be approved during the PRR to begin producing an initial set of systems. The LRIP phase is considered to be within the Production and Deployment phase; however the decision can be made at Milestone C.

5.1 Design for Reliability, Availability, and Maintainability

Practicing early phase SE while coordinating with reliability engineers, availability designers, logisticians, and maintainability designers would account for various aspects of the system. Without practicing early phase SE, a bad design can produce a failing system. Obtaining RAM / operational availability requirements for a new SATCOM system would assist with design planning [108]. Maintenance issues would also promote system failure such as improper procedure, processes that are not standardized, user error, user competence and / or maintenance tool availability. Failing systems has the potential to cause injury, loss of life, rework to correct issues and expending unplanned funds and resources to resolve discrepancies. Calculating and capturing various delay times assist with computing the operational availability of the system as well as identifying areas for improvement.

$\bar{M}$ depicts mean active maintenance time which accounts for preventive and corrective maintenance. $\bar{M}ct$ corresponds to the mean time to repair on a corrective unscheduled basis. $\bar{M}pt$ is the mean time to repair on a preventive scheduled basis. **fpt** is the preventative maintenance rate as

$$\bar{\boldsymbol{M}} = \frac{(\lambda)\,(\bar{\boldsymbol{M}}\boldsymbol{ct}) + (\boldsymbol{fpt})(\bar{\boldsymbol{M}}\boldsymbol{pt})}{\boldsymbol{\lambda} + \mathbf{fpt}} \tag{22}$$

Total maintenance downtime MDT incorporates the active maintenance time involving preventing corrective and preventative maintenance along with total Logistics Delay Times LDT and total Administrative Delay Times ADT is combined as

$$\boldsymbol{MDT} = \bar{\boldsymbol{M}} + \boldsymbol{LDT} + \boldsymbol{ADT} \tag{23}$$

Total logistic delay times LDT correspond to the relationships between failure rate **λ,** corrective logistic delay times LDT_c , scheduled logistic delay times LDT_s , and preventative maintenance rates **fpt** as

$$\boldsymbol{LDT = \frac{(\lambda)\,(LDT_c)+(fpt)(LDT_s)}{\lambda+\mathrm{fpt}}} \tag{24}$$

Total administrative delay times ADT correspond to the relationships between failure rate **λ,** corrective administrative delay times ADT_c , scheduled administrative delay times ADT_s , and preventative maintenance rates **fpt** as

$$\boldsymbol{ADT = \frac{(\lambda)\,(ADT_c)+(fpt)(ADT_s)}{\lambda+\mathrm{fpt}}} \tag{25}$$

Mean Time Between Maintenance includes scheduled maintenance $MTBM_s$ and unscheduled maintenance $MTBM_u$ events as

$$\boldsymbol{MTBM = \frac{1}{\left(\frac{1}{MTBM_u}+\frac{1}{MTBM_s}\right)}} \tag{26}$$

Unscheduled corrective action $MTBM_u$ is in relation to the failure rate, which the scheduled $MTBM_s$ is in relation of the preventative maintenance rates **fpt**. The failure rate is calculated with the number of failures per hour. The MTBM is calculated as

$$\boldsymbol{MTBM_u = \frac{1}{\lambda}} \tag{27}$$

$$MTBM_s = \frac{1}{\mathrm{fpt}} \tag{28}$$

$$MTBM = \frac{1}{(\lambda + \mathrm{fpt})} \tag{29}$$

Operational Availability A_o is calculated by the relationship between MTBM and MDT as

$$A_o = \frac{MTBM}{(MTBM + MDT)} \tag{30}$$

Designing and planning for reliability prevents failures. Reliability is the probability of an item to perform a required function under stated conditions for a specified period of time, availability is a measure of the degree to which an item is in an operable state and can be committed at the start of a mission when the mission is called for at an unknown (random) point in time, and maintainability is the ability of an item to be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair [109]. Availability is the amount of time a system is in operational condition. Availability is the ratio of the system's uptime to downtime. Maintainability involves the ease of a system being maintained to operational status. The time it takes to repair an item and to perform preventive / corrective maintenance procedures are included within the maintainability criteria. RAM of a system are critical for overall operational availability. Operational availability of a system is essential for continuous operations without interruption.

5.2 Testing Process Analysis

Testing antenna systems prior to fielding identifies any potential issues and verifies equipment operation. Although manufacturers may test systems to a certain extent, integration testing may be limited due to interconnecting system availability that the manufacturer has access to. Antenna systems would go through a Pre-Installation Test and Check Off (PITCO) procedure prior to fielding the system. Performing a PITCO would ensure the system is operational prior to fielding within a live environment. Identifying issues prior to fielding reduces the chances of encountering problems once the antenna system is installed.

An Integration Definition for Process Modelling (IDEF0) is used to depict the testing process as shown in Figure 78. A scenario where antenna equipment is received from the manufacturer that requires PITCO prior to fielding is depicted within an IDEF0. Untested equipment would be received and stored in the warehouse until requested to be tested. Once the system is scheduled to be tested, the equipment is transported to the integration area where additional parts and pieces are added onto the system to simulate the environment on which it's fielded. The untested equipment is delivered to the lab to perform PITCO on the system. If failed parts are identified during PITCO, a request to cannibalize parts is made if spare parts are not available. Cannibalizing parts involve taking parts off of existing antenna systems received from the manufacturer to prevent logistical delays relating to spare part procurement. Once the antenna equipment is tested, the equipment is sent back to the integration area where the additional parts and pieces are removed from the system. The antenna system is sent back to the main warehouse to be prepped for shipping to the fielding site. Figure 78 PITCO Testing IDEF0 depicts the process of equipment being integrated and tested by key logistic, engineering, and SME personnel.

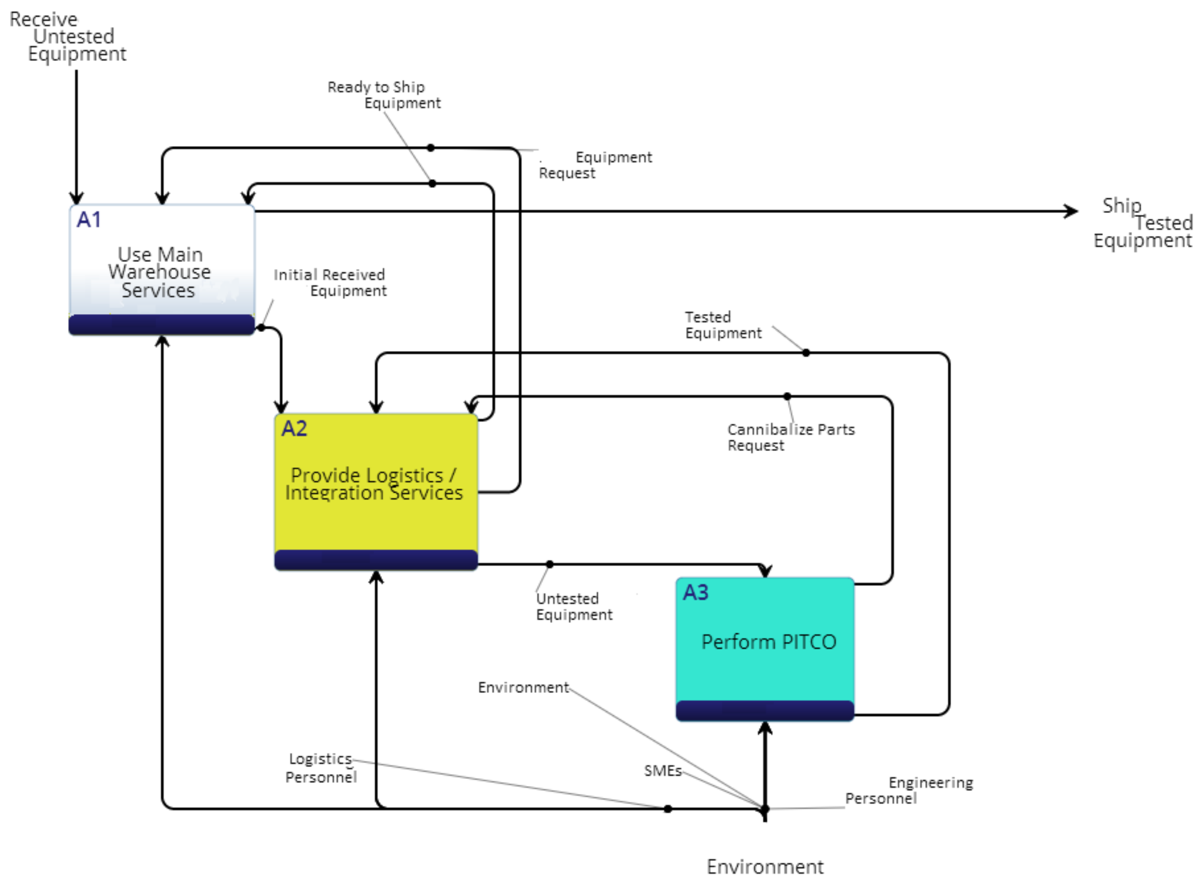


Figure 78 PITCO Testing IDEF0

SE simulation tools are useful to predict overall process times to ensure delivery schedules are met for fielding. Issues can also be identified such as bottlenecks in certain areas of the process where management intervention would take place to take corrective actions. ExtendSIM was used to simulate PITCO processing times. Known process areas, historical data and estimates were used to evaluate probable processing times in particular areas. The triangular distribution was used at various instances to list values for the minimum, most likely, and the maximum amount of time. These values would be picked randomly over numerous iterations to provide an average value to perform PITCO. The simulation involved three areas to include the main warehouse, integration staging area, and the PITCO lab. These areas had a variable amount of time where the antenna system would reside throughout the PITCO process. Inquiries on how long the process would take was fulfilled by simulation. Providing an estimated time to perform the task allowed for improved scheduling of fielding the antenna systems.

The untested equipment would be received at the main warehouse where an associated logistics delay time using the triangular distribution of 1 day being the minimum, 3 days being the maximum and 2 days being the most likely values that the untested antenna system would be at that location. The process continues where the untested antenna system would get integrated with various components in the integration staging area. Integrating the antenna system with components were needed to simulate the system within a life like environment. The triangular distribution for this part of the process would be 1 day for the minimum, 3 days being the maximum, and 2 days being the most likely values. The PITCO lab would receive the untested integrated antenna system to perform testing. PITCO times vary from 5 days being the minimum, 14 days being the maximum, and 8 days being the most likely values. There are instances where issues are encountered. The request for replacement parts or the request for cannibalizing an existing system is called for once the issue is isolated to a particular part or component. Historical data has found that a replacement part or component was required 10% of the time. Providing a part or cannibalizing an existing system typically takes 0.1 days at minimum, 0.3 days maximum, with 0.2 days being the most likely value. If there are no issues encountered during testing, the tested antenna system is sent back to the integration staging area where the components and parts added previously are removed. The minimum amount of time to process the equipment back to the main warehouse is 1 day. The maximum amount of time is 15 days where the most likely time is 5 days. A potential bottleneck is present here with the maximum amount of time being in this area constitutes to being 15 days. The main warehouse obtains the tested antenna system and has a minimum value of 1 day, maximum value of 5 days, and a most likely value of 3 days. The antenna system is prepped for shipping and sent to its fielded destination. Figure 79 Simulated PITCO Process depicts the ExtendSIM model to predict PITCO processing times.

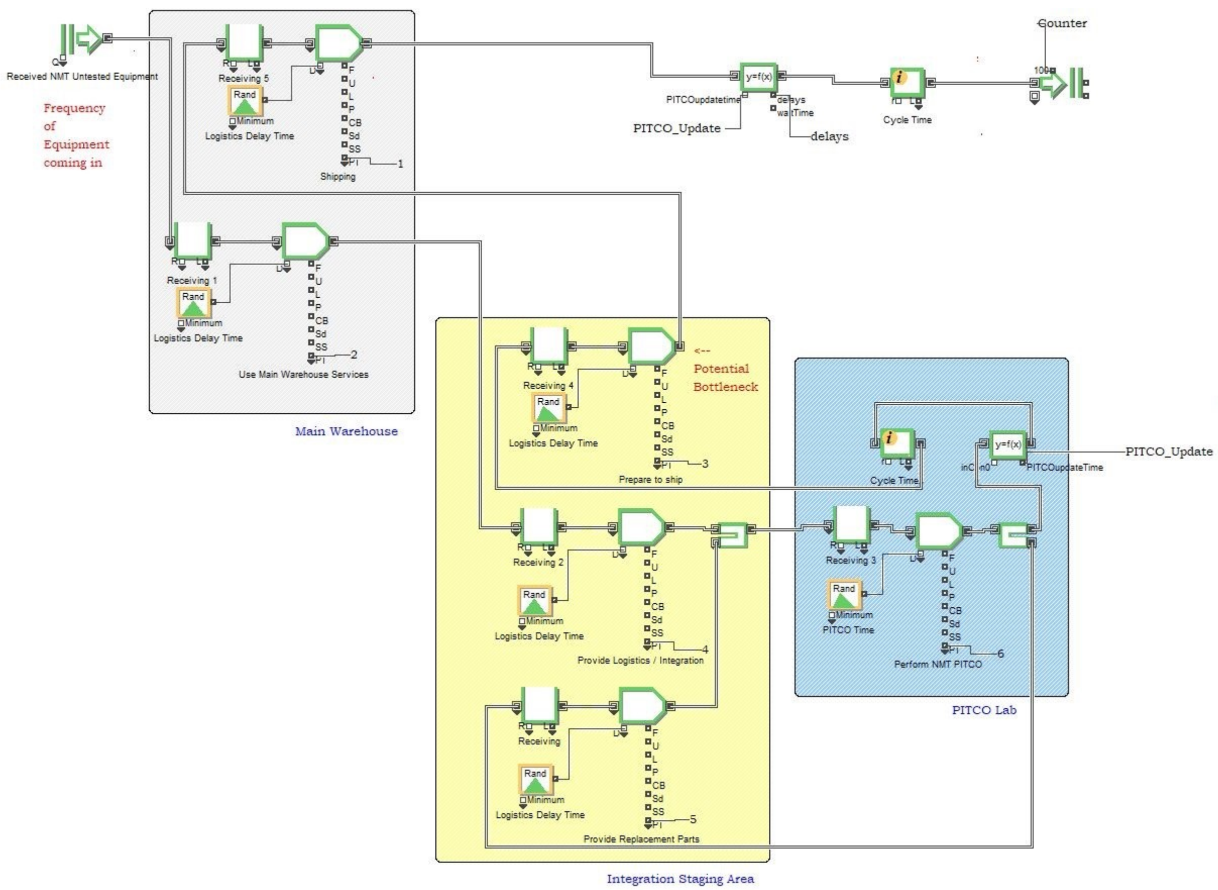


Figure 79 Simulated PITCO Process

Using the probability density function for triangular distribution allows minimum, maximum, and most likely values to be entered. These values can be used repeatedly during multiple iterations of the simulation. The probability density function of the triangular distribution is:

$$f(x|a,b,c) = \begin{cases} \frac{2(x-a)}{(b-a)(c-a)}; & a \leq x \leq c \\ \frac{2(b-x)}{(b-a)(b-c)}; & c \leq x \leq b \\ 0 \; ; & x < a, x > b \end{cases} \tag{31}$$

The triangular distribution provides upper and lower limitations on values decreasing the chances for any extreme values. The minimum value is denoted as *a*, the maximum value is denoted as *b*, and the most likely value is denoted as *c*. Figure 80 depicts the triangular distribution using these values.

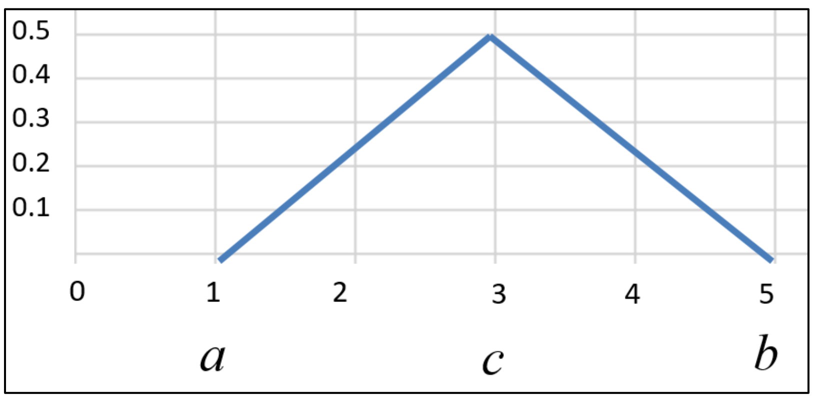


Figure 80 Probability Density Function for Triangular Distribution

This distribution starts at 0 with the minimum value of *a*, rises to the most likely value of *c,* then returns to 0 with the maximum value of *b*. This distribution provides a linear depiction of the minimum, maximum, and most likely values. The triangular distribution probability value at peak c is:

$$\frac{2}{(b-a)} \tag{32}$$

The average PITCO process was estimated at 25 days. ExtendSIM was able to simulate the process using triangular distributions at each process area. The PITCO lab had the SATCOM system for the most time performing the tests, while the integration area and the main warehouse added to the total estimated time to perform integration / logistic functions. 100 iterations were performed of this simulation and Figure 81 PITCO Process Average Delay Time Values displays the average processing times for the PITCO lab, integration area, main warehouse, and the overall cumulative value.

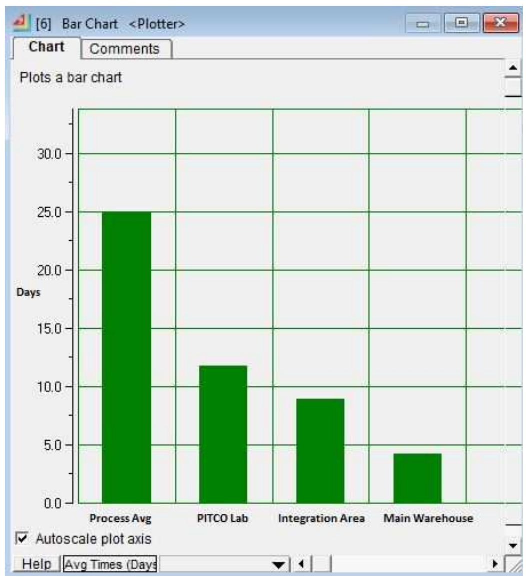


Figure 81 PITCO Process Average Delay Time Values

Utilizing ExtendSIM to simulate processing times for testing is a method to identify potential delays as well as providing an estimated length of time for scheduling purposes. Improvement efforts would be derived from this simulation data in order to reduce overall processing times. The process itself in its entirety would be adjusted to decrease time values or certain process areas would be analyzed to reduce or eliminate any delays. Using lean principles to reduce wasteful process steps and save on time and costs would result in a more efficient process. A bottleneck was identified at the integration staging area where the warehouse personnel was delayed at times from picking up the material to ship to the antenna's destination. A recommendation would include shipping and receiving directly from the integration staging area instead of shipping to the main warehouse. The main warehouse was a central point where the entire organization would ship and receive material. An exception to the organizational process via the organization process owner would be presented for a process improvement initiative depicting the amount of time and costs saved. In addition, having a spares repository in the PITCO lab would allow testers to quickly replace a part instead of manually retrieving the part from the remote integration staging area where the spares are kept. Figure 82 depicts the simulated PITCO process after lean improvements.

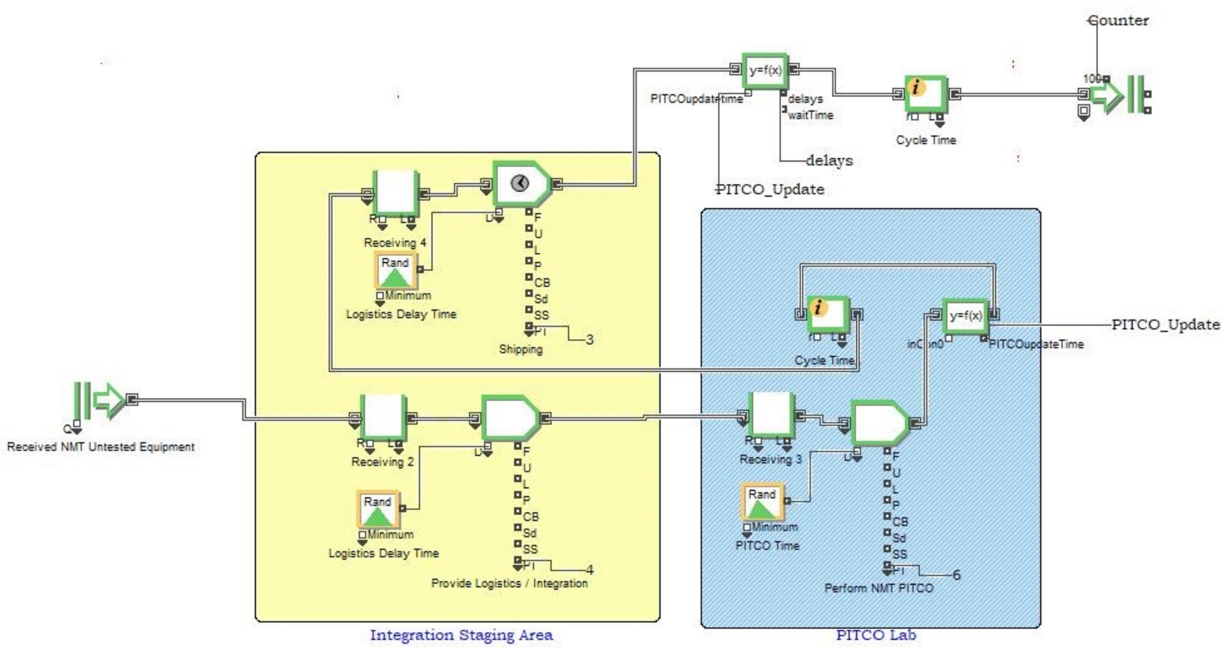


Figure 82 Simulated Lean PITCO Process

Upon performing lean practices on the known process, delay times can be reduced. The integration staging area would perform functions such as receiving, shipping, integration and other logistics services while the PITCO lab would perform PITCO as well as providing replacement parts as required. The minimum amount of days to receive, provide logistics support and integration in the integration staging area would be 1 day while the maximum amount of days would be 5 days. The most likely amount of days to perform these functions would be 3 days. The PITCO lab would perform PITCO and provide replacement parts with an estimated minimum value of 5 days, maximum value of 14 days, and most likely be able to complete these tasks within 8 days. Once testing is complete, the integration staging area would prepare and ship the antennas with a minimum value of 1 day, maximum value of 3 days, and most likely be able to complete the task within 2 days. 100 iterations of the simulation were performed and the results are shown in Figure 83 Lean PITCO Process Average Delay Time Values.

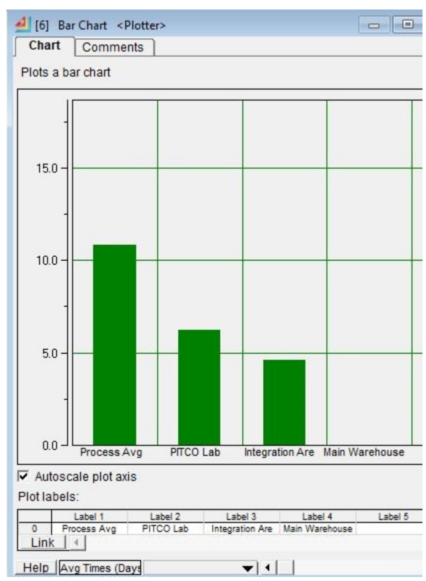


Figure 83 Lean PITCO Process Average Delay Time Values

Performing lean methodologies to known process areas can provide opportunities to reduce cycle times. The known PITCO process can be reduced from 25 days to 11 days by making a few adjustments to the process. These adjustments not only can reduce delay times for tasks but save on overall costs. These adjustments can be used as lessons learned for any upcoming projects or efforts that are similar in nature.

5.3 Production, Deployment, Operations and Support

The Production and Deployment phase consists of executing the LRIP as well as determining the readiness for FRP&D. Evaluations of the first line of systems would be performed to potentially improve the production process, quality of system and any other processes that reduces cost / schedule. The Production and Deployment phase begins after Milestone C. The product baseline is updated in this phase where any changes made on the system to correct issues or to enhance particular aspects of the system to support improved producibility, fielding, usability, and any other changes that are required. The test and evaluation plan would also be updated to include any testing related to the production and deployment phase. These tests would include PITCO and SOVT documents. PITCO would entail performing tests prior to the system being fielded. Performing PITCO would identify any issues with the system prior to the system being fielded. If this test was not performed, there would be a risk that a fielded system would have issues. The amount of rework to re-install a working system would me more than performing a PITCO prior to install. A SOVT would entail performing tests once the system is fielded which verifies operational functions the system would perform. Risk management would continue to be performed to identify any cost, schedule and technical risks that may be associated with production and deployment efforts. The life cycle sustainment plan would be updated to include new information on sustaining the system. Logistics support functions such as storage, personnel and other resources that have been uncovered or became more detailed would be documented within the life cycle sustainment plan. Any new or detailed maintenance support needs would also be documented within the life cycle sustainment plan or be referenced for access. The Systems Engineering Plan would be updated to include up to date production and deployment efforts and operation support functions. Standard operating procedure documents would be referenced to support the system to assist with maintenance and sustainment needs of the system. Ensuring any safety, environmental and health compliance documents are up to date is another activity within the production and deployment phase. The Full Rate Production Decision Review occurs to concur amongst stakeholders to go forward with manufacturing the large scale of parabolic stacked antenna systems. Assessing the LRIP of the systems with regards to lessons learned, manufacturing processes, potential defects, additional needed resources and an overview of production cost, schedule, and performance factors gives stakeholders confidence that full rate production of the parabolic antenna system can begin.

Operations and support has the system installed and is verified during the SOVT. Once the SOVT is completed, the system is handed over to the warfighter to maintain. Standard operating procedures along with training allows the warfighter to operate the system effectively. Training personnel initially as well as recurring training equips personnel with being able to operate, maintain, and troubleshoot the system without the need for external support. External support includes system help desk support for offsite and possible onsite support. Obtaining metrics for help desk trouble tickets provides insight on high failure items, defects, system issues or possible issues with training or operating procedures. Upgrades and modifications are included within this phase to enhance or fix any issue or any potential vulnerability. Software updates provide software bug fixes and information assurance vulnerability mitigations. Depending on the complexity of the modification to the system, the modification may or may not include assistance from SMEs. A low cost option for a not so complex modification entails providing the modification material / software to the user to perform themselves.

The system maintenance concept should include the entire system and not just a particular part of the system. Other areas are to consider are maintenance to other systems interoperating with the system. The system maintenance concept should be developed during the conceptual design phase which evolves from the definition of system operational requirements. Support concepts include:

Levels of Maintenance: This could include a basic level of maintenance where the actual user can perform themselves (i.e. inspect and perform weatherproofing procedures on connections to the antenna) as opposed to a professional performing more advanced maintenance activities (i.e. azimuth and elevation motor replacement).

Repair Policies: This would include establishing a baseline or agreement during the conceptual design process, which includes a repair strategy or policy that the customer / operator can adhere to (i.e. grease azimuth and elevation motors every 3 years).

Organizational Responsibilities: Responsibilities would be agreed upon via the repair policies where a user's responsibilities would need to be kept in order for them to maintain product warranty (i.e. Documentation of maintenance performed within 10 years need to be kept in order to provide antenna support during that time frame). Organizational Responsibilities may differ from the customer than the manufacturer of the system or component.

Maintenance support elements: Spares, man-power, etc. would be a part of maintenance support elements.

Effectiveness Requirements: This would include the availability of these items and the associated criteria for these resources. Factors will include the support capability associated with personnel, spares, demand rate, reliability, etc.

Environment: This would include shock, vibration, temperature and any other environmental factors that may have an effect on the system.

A system engineering model used to depict functional analysis is a Functional Flow Block Diagram (FFBD). A FFBD illustrates high level and lower level functions with traceability. The consolidated antenna development would include identifying the need, determining the requirements, design, testing, manufacturing, deploying, and operating / sustaining the system. The FFBD model is shown in Figure 84 to illustrate operation and maintenance activities involved in the consolidated antenna system's life cycle.

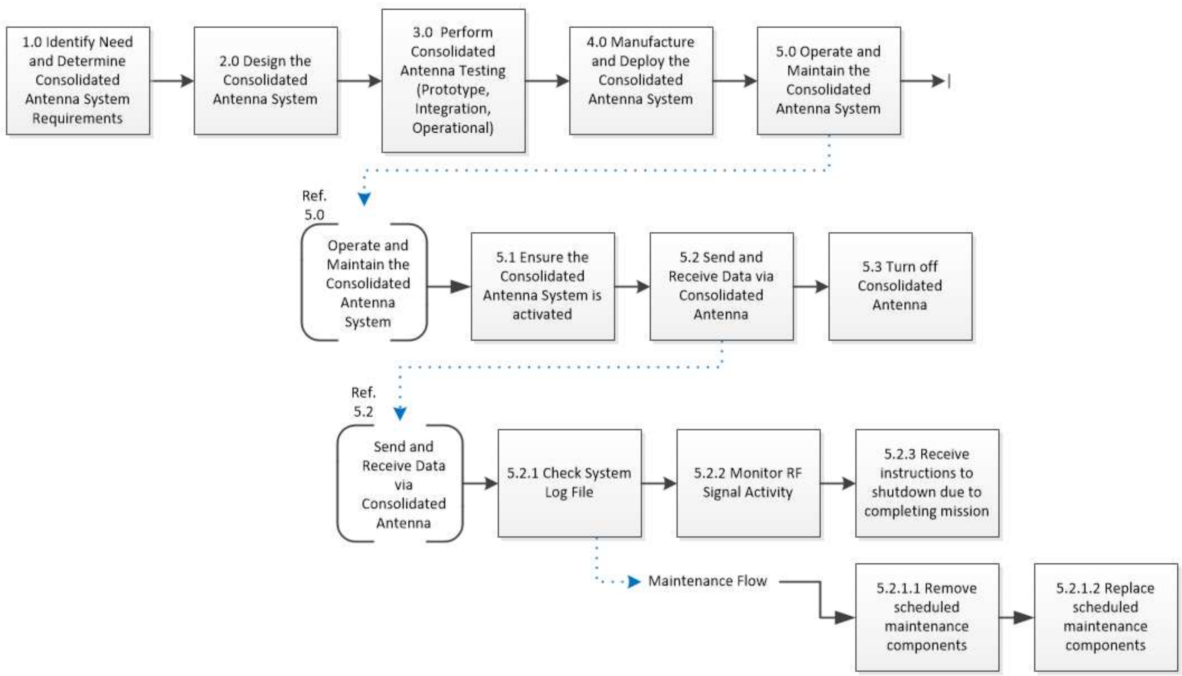


Figure 84 FFBD WRT System Operation and Maintenance

The FFBD example shows lower level activities associated with operating and maintaining a consolidated antenna system such as the parabolic stacked antenna. Basic operation functions are decomposed to lower level functions that link to maintenance actions. For this case a system log files reveals the need to remove / replace scheduled maintenance components. This high level FFBD assists with functional analysis of the overall system being developed.

Reliability deals with probability and statistical approach required when deriving reliability factors. Reliability is dependent on the design details. Input from SMEs are included to select particular components or sub systems. System designers, testers, manufacturers, installation team, product support team, users, maintainers, and other SMEs would be consulted to obtain RAM requirements. Maintainability requirements would be considered early on to address components to replace. Considering easy access for users is essential for repair or maintenance procedures. Repairing a parabolic stacked antenna would have to consider onsite repair procedures. A radome that houses a parabolic stacked antenna would limit the amount of space a user can use when repairing / maintaining the consolidated antenna. As shown in Figure 85, limited space to physically repair / maintain the antenna is observed.

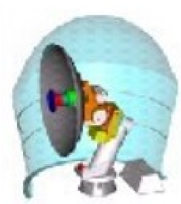


Figure 85 NMT Antenna in Radome Space [69]

Usability factors have to be addressed, such as performing repair / maintenance procedures. To perform repairs for the NMT antenna shown in Figure 85 for example, the antenna would have to be in a position where the user would be able to access certain components. Certain height and weight restrictions would be denoted for safety criteria in regards to being inside the radome with the antenna in place. Considerations for a user to get into and out of the radome to access the antenna is necessary in order to provide a cost effective repair / maintenance procedure.

Identifying critical items whose reliable operation is critical to the operation of the system. A critical item list would be identified for components and subsystems. Issues can be mitigated through the design process through design changes early within the system's life cycle. Identifying a single point of failures is essential to provide potential redundancy options. Reliability requirements defined early and determining if they are achievable is performed in the requirements definition phase. During functional analysis and allocation having a tradeoff study with an AoA can affect a choice by different reliability criteria. Design synthesis includes reviewing system and subsystem design, and maximizing redundancy with respect to tradeoffs with reliability, operational performance and system cost. Performing a Failure Mode, Effects & Criticality Analysis assists engineers to understand the system's failure modes with critical / single point of failures. Critical components would be monitored regularly to be inspected, repaired or replaced. Using de-rating factors such as the environment would account for the effects. The amount of time to put forth effort on performing RAM activities throughout the system's life cycle should be considered. Increasing design with more reliability details would increase schedule, but will prevent issues from surfacing later in the system's life cycle. Characterizing reliability criteria along with potential testing and data mining for historical data would increase the schedule as well, but have benefits in the long term. Adding additional components for redundancy may involve increasing the space and weight that the overall system encompasses.

The initial cost of a reliable system would cost more to develop, but would benefit during the sustainment phase of the system lifecycle by increasing the longevity of the system. Less reliable systems and components cost less initially but require more maintenance during the sustainment phase of the system's life cycle. Including reliability, availability, and maintainability criteria during the early phases of design would reduce overall life cycle costs by reducing rework, maintenance and sparing during the later stages of the system's life cycle.

6. Summary

Developing a consolidated antenna with multiband frequency capabilities can be achieved by performing SE activities and leveraging lessons learned from previous antenna consolidation efforts. Using parabolic antenna stacking methods consolidates multiple antenna capabilities onto a single pedestal. The NMT, CBSP and directional SDT antennas were assessed to determine RF capability requirements to design a single pedestal antenna to meet RF capabilities that the SATCOM and LoS antennas currently operate within. Prior consolidation efforts such as the NMT system was analyzed to determine life cycle costs throughout the DAS process. Cost estimates were determined by previous and projected budgets that were used for the NMT system to predict potential cost needs for developing a parabolic stacked antenna system. Agile and lean methodologies were proposed to reduce costs and delivery time frames. Use case scenarios were depicted to illustrate various operations that the parabolic stacked antenna would be capable of. Simulating processes demonstrates delay times especially with repeatable processes. Process simulation would identify potential improvement areas and predict delay times within each step of the process. A testing process was simulated to propose estimated delay times utilizing a triangular distribution probability set. The triangular distribution probability set included best, worst, and most likely time values based on historical process times at each step of the process. Lean methodologies were introduced to improve known process areas by reducing unneeded steps.

Following the DAS process provided an approach to develop a parabolic stacked antenna. Cassegrain, Gregorian and splash plate antennas were analyzed using the parabolic stacking method to determine the physical parameters and RF capabilities associated with each. A combination of the splash plate, Gregorian and Cassegrain antennas were also analyzed. The results showed that splash plate antennas using the parabolic stacking method required only two antennas to achieve RF capabilities that current NMT, CBSP and directional SDT antennas provide. The large X / Ka NMT and CBSP FLV variants have a parabolic dish diameter of 2.44m and 2.74m respectively. These two antennas provide limited RF coverage such as X, Ka bands for the large X / Ka NMT antenna and L, C, and Ku bands for the CBSP FLV variant. The parabolic stacked antenna using splash plate antennas is not only smaller (2.25m) than the large X / Ka NMT and CBSP FLV variants but also includes RF coverage that the other NMT and CBSP variants provide along with the directional RF capability of the SDT antenna. The dual splash plate parabolic stacked antenna is capable of operating at frequencies within the L, C, Ku, K, Ka, X and Q bands. The triple Cassegrain parabolic stacked antenna and dual cassegrain with splash plate parabolic stacked antenna proved that three antennas can be stacked in front of one another to meet operational requirements. Parabolic antenna stacking is possible when the reflecting dish produces a blockage area that another antenna could utilize to operate within to gain additional RF bands. The Gregorian with splash plate parabolic stacked antenna had a maximum dish size of 1.5m and was capable of operating within C, Ku, K, Ka, X and Q band frequency ranges. The Cassegrain and Gregorian parabolic stacked antenna had the same main dish size of 1.5m for the larger antenna as well as the main dish size of 325.9mm for the smaller antenna compared to the Gregorian and splash plate parabolic stacked antenna configuration. The Cassegrain and Gregorian parabolic stacked antenna had a higher VSWR value for select frequencies when compared to the Gregorian with splash plate parabolic stacked antenna. The dual Gregorian parabolic stacked antenna was larger and had a maximum dish size of 1.921m. The dual Gregorian parabolic stacked antenna was capable of the same frequency set and had slightly higher gain values. The triple Cassegrain parabolic stacked antenna and the dual splash plate parabolic stacked antenna were capable of operating at a particular sized antenna along with the next sized antenna stacked in front of it. This capability provides redundancy with potential failover options for overall operational availability.

Utilizing SE practices support decision making challenges that are encountered throughout the system life cycle. The Pugh matrix is recommended to be used with stakeholders to determine which design concept for the parabolic stacked antenna would be the best option to go forward with. Considering the design criteria, the parabolic stacked antenna option using dual splash plate antennas on a single pedestal was the best option to achieve L, C, X, Ku, K, Ka and Q band frequencies. A decision matrix could also be used for other areas where various options are present that need to be compared amongst different alternatives. This methodology provides a brief analysis of alternatives to facilitate decisions from stakeholders.

Developing a baseline schedule assists with future planning and manage stakeholder expectations. Considering the previous NMT system going through the DAS process, a similar timeline is followed for developing the parabolic stacked antenna to perform SE, MBSE, Agile and lean activities throughout the process. The Materiel Solution Analysis phase would last approximately 2 years, and the Technology Maturation and Risk Reduction phase would span across 2 years as well. The Engineering and Manufacturing development phase would span over 5 years using the DAS process incorporating Agile methodologies. The Production and Deployment phase would last for approximately 8 years where performing lean methodologies to known process areas while reducing planned procurement actions required for additional spares / antenna upgrades by procuring them in advance would assist with meeting this timeline. The Operations and Sustainment phase is planned to last 22 years which is similar to the Operations and Sustainment phase of the NMT system in which the service life of the parabolic antenna system is baselined against. The approximate life cycle costs for the NMT system was estimated to be

$2,646.4M. Reducing schedule for the Engineering & Manufacturing Development phase and the Production and Development phase by 3 years each would have a cost savings of $419.2M. Reducing these times would depict a baseline budget of $2,227.2M over 32 years for the parabolic stacked antenna system life cycle. Combining SDT, NMT, CBSP antenna platforms would reduce overall life cycle costs maintaining multiple systems. Additional cost savings would be realized from the Operations and Support phase for maintaining one antenna system as opposed to two. The approximate life cycle costs for the parabolic stacked antenna system was $2,227.2M over 32 years. Considering life cycle costs for two systems would amount to approximately $4,454.4M over 32 years. A life cycle cost savings of ~$2B over 32 years would be potentially realized by developing one consolidated system vice two individual systems.

Processing times is important to predict and incorporate delay times into schedule and to estimate the availability of the system. Simulating processing times identifies potential bottlenecks within the process that could be improved upon using lean methodologies. Using historical data for processing times and simulating processes using triangular distribution probability density functions creates estimated delay times to factor into schedule and system availability. A test process was simulated to determine delay times within each step of the process. These values can be used to determine the operational availability of a system when testing a replacement antenna is required. Testing the system produces delay times which would prompt the need to have spare systems and parts available if needed while considering the failure rate of the system itself. Capturing metrics on processing times along with metrics on help desk tickets during the Operations and Support phase of the life cycle will improve and maintain overall operational availability of the system.

This dissertation provided a consolidation approach using MBSE SysML models to identify interconnecting RF system criteria which revealed overlap of RF capabilities. This finding further stresses the longstanding need to reduce the amount of redundant antenna systems. Parabolic stacked antenna simulations of six different configurations identified tradeoffs amongst Cassegrain, Gregorian and splash plate antennas. Cost savings were realized by applying lean methodologies for practical efforts such as the PITCO process through simulating, assessing and improving PITCO process steps. Performing SE, MBSE, Agile and lean methodologies can assist with today's complex integrated systems. As technology advances, so does the complexity of systems. SE and MBSE modeling can help manage these complex systems by depicting interactions between integrated systems and also identify potential areas of concern through simulation. MBSE efforts should be used along with SE standard processes and Agile / lean methodologies to be able to achieve the most cost effective and timely solution.

6.1 Future Work

This research focuses on system engineering of a parabolic stacked antenna to minimize space taken from multiple antenna platforms performing similar functions, decrease overall life cycle costs and decrease time to develop this new capability. Combining multiple antennas upon a single pedestal using the parabolic stacked antenna methodology allows multiple RF bands to be accessed by a single antenna based platform. Performing simulation testing provides evidence that multiple RF bands on a single pedestal can be achieved. There are limitations for the parabolic stacked antenna simulation results where deviations would be realized when testing a prototype within an anechoic chamber. The prototype would have to be fabricated with particular materials that have slight variations with the material specifications. These slight variations provide a tolerance for RF fabricated components where simulations presented within this dissertation are set to a fixed value within the CST Microwave simulation software. Precision with fabricating the parabolic stacked antenna prototype would be needed to decrease measurement errors when comparing the simulation results to the physical prototype testing results. Avenues for continuing research of the system engineering of a parabolic stacked antenna include:

- Simulation of different types of parabolic stacked antenna configurations to provide alternatives to consolidate the NMT, CBSP, SDT and other variant antennas
- Continuing to capture simulation data to assess antenna problem areas with regards to frequency, VSWR, gain, side lobe levels, angular width (3 dB), interference and blockage
- Reducing design / development times and cost to produce a parabolic stacked antenna by detailing SE / Agile methodologies and possible alternative approaches
- Prototyping a physical parabolic stacked antenna to compare against simulation results
- Developing and determining the location of consolidated RF amplifiers and feeds to account for L, C, X, Ku, K, Ka and Q band frequencies
- Identifying additional risk areas and mitigating known risks for the design and development of a parabolic stacked antenna

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