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Cross-Disciplinary Deep Space Radar Needs Study

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Executive Summary

The purpose of this study is to explore and analyze common needs from key stakeholders as initial examination of whether a coordinated development of future deep space radar facilities should be further explored. The key stakeholders come from multiple government agencies, including the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF). This study should not be interpreted as a reflection of, or insight into, any future decisions to be made by the stakeholder community. This study identified significant gaps between the deep space radar capabilities desired by the stakeholders and the capabilities provided by today's facilities. The mission areas that could benefit from a new national radar capability include planetary defense, planetary science, atmospheric science, ionospheric science, geospace science, and cislunar space situational awareness (SSA). In addition to the active radar capabilities, the passive, receive-only capabilities of a future radar facility could also have value to the astronomy community. From the stakeholder inputs at several Technical Interchange Meetings (TIMs), planetary defense and cislunar SSA were selected as the two core mission areas that would drive further technical analyses.

In addition to assessing today's facilities, the study reviewed the ability of potential planned facilities to meet stakeholder needs. A high-power radar on the Green Bank Telescope (GBT+HPTx), when paired with the large collecting area of the next generation Very Large Array (ngVLA), could potentially provide the capabilities desired by several stakeholders, but would not meet all stakeholder needs. This study developed a range of notional reference architectures that meet some, but not all, of the stakeholder needs by taking into account the desired frequency bands, sensitivities, fraction of facility time needed, and other factors. Table 1 shows a summary of existing, and potential planned facilities and their expected performance to meet core missions' threshold and objective needs, as well as notional reference architectures. The rough order of magnitude (ROM) costs for these notional architectures range from the hundreds of millions of dollars to over three billion dollars, depending on the sensitivity and capability delivered. This study did not reassess costs for current and planned facilities, for which cost estimates are already available.

Table 1. Performance of Current, Potential Planned, and Notional Radar Architectures Relative to Mission Needs

Transmit Facility*	Receive Facility*	Planetary Defense: Detect 100m NEA at 5e7 km	Planetary Defense: Detect 50m NEA at 5e7 km	Cislunar SSA: Detect 1m metal sphere at Earth-Moon L2 distance	Cislunar SSA: Detect 0.2m metal sphere at Earth-Moon L2 distance	Cost Estimate (BY23$M)
Goldstone DSS-14		No	No	Yes	No	
Goldstone	GBT	No	No	Yes	Yes	
Goldstone	VLA	No	No	Yes	Yes	
GBT+HPTx **	VLBA	No	No	Yes	Yes	
GBT+HPTx **	VLA	No	No	Yes	Yes	
GBT+HPTx **	ngVLA	Yes	No	Yes	Yes	
11 notional transmitters	9 notional receivers	No	No	Yes	No	**$500**
36 notional transmitters	21 notional receivers	No	No	Yes	Yes	**$1,300**
25 notional transmitters	ngVLA***	Yes	No	Yes	Yes	**$800**
60 notional transmitters	37 notional receivers	Yes	No	Yes	Yes	**$2,200**
51 notional transmitters	ngVLA***	Yes	Yes	Yes	Yes	**$1,600**
95 notional transmitters	59 notional receivers	Yes	Yes	Yes	Yes	**$3,300**

**Bistatic arrays of 18-meter transmit and receive antennas, 50 kW transmitter power at X-band per antenna*
***Potential planned facility*
****Does not include ngVLA construction cost*

The conclusion of this study is that feasible technical solutions exist to fully capture threshold and objective needs for planetary defense with a large array of transmitters and receivers at X-band. Such an array would envelop the cislunar needs and meet many, but not all, of the planetary science needs. To fully capture planetary science, atmospheric science, ionospheric science, and geospace science needs would necessitate the addition of radar transmit frequencies beyond X-band, which is noted but not costed in the reference architecture of this study.

While a feasible technical solution exists for a national deep space radar facility that could serve the needs of multiple stakeholder communities, additional analysis is required to determine the programmatic feasibility of such a national facility given that NASA does not develop ground-based facilities of its own, NSF's scope does not include development of planetary defense or cislunar SSA facilities, and all potentially interested agencies have their own competing priorities and processes. The high cost of a national facility that meets the objective needs of all stakeholders is likely beyond the ability of any one stakeholder to fund. A new national deep space radar facility would require close coordination and collaboration among all stakeholders in terms of work breakdown responsibilities, cost sharing, budgetary cycles, as well as buy-in, prioritization, and scheduling within each stakeholder community. Nevertheless, the results of this study provide a starting point for the development of a broader collaborative framework.

Contents

Figures

Tables

1. Introduction

1.1 Overview

Radar is an important tool with many applications, utilized throughout a variety of government and scientific communities. The loss of the Arecibo Observatory's (AO) 305-meter antenna and planetary radar in 2020 has left a significant gap in today's deep space radar capabilities. NASA's Planetary Defense Coordination Office (PDCO) uses radar to characterize Near-Earth objects (NEOs) – asteroids and comets – that may be considered an impact hazard to Earth. NEOs must first be discovered by optical or infrared (IR) telescopic sky surveys, but once discovered and when they are within radar-detectable distance, deep space radar is a powerful tool for studying their properties. Radar can yield range and velocity information of objects of interest, improve orbital propagation prediction, shed clues on composition, and determine size and surface characteristics. It can perform very precise measurements and provide a better understanding of an object's shape and various morphological features (i.e., concavities, large craters, boulders, etc.). This capability also helps characterize objects in the cislunar environment. As robotic and human exploration of the Moon increases, there is a higher need to keep track of all cislunar activity. Electro-optical (EO) sensors are limited by solar/lunar exclusion zones and passive RF only works when the target is transmitting a signal; radar can aid in looking for and maintaining situational awareness of spacecraft during these circumstances.

Radar provides significant and unique capabilities for scientific communities. For example, planetary radar has been used to study Mercury, Venus, the Moon, Mars, and Saturn's largest moon, Titan. The destination of *Psyche* and other spacecraft missions to small bodies were first characterized by radar. Earth-based planetary radar observations of the Moon can penetrate below the lunar surface, which may provide additional support for lander missions. Current radar facilities cannot keep up with the increasing demand for these types of observations. The Goldstone Solar System Radar on NASA's Deep Space Network (DSN) is the only facility in the U.S. that can make some of these observations, but Goldstone's primary responsibility for spacecraft communications significantly limits the available time for the deep space radar community.

The 2010 National Academies "Defending Planet Earth" [1] report notes that radar surveys should attempt to detect as many 30- to 50- meter diameter objects as possible, but that this search should not be allowed to interfere with the survey for larger objects. The report recommends that NASA and the NSF support a program of radar observations of NEOs at a facility like Arecibo and support Goldstone for orbit determination and the characterization of physical properties. Published after the loss of Arecibo's deep space radar capability, the National Academies 2022 Planetary Science and Astrobiology decadal survey [2] encouraged NASA and NSF to work together to support a plan for ground-based planetary radar equal to or exceeding the capabilities of Arecibo. The National Preparedness Strategy & Action Plan for Near-Earth-Object Hazards and Planetary Defense [3] recommends exploring opportunities in existing and planned telescope programs to improve the detection, tracking, and characterization of NEOs. This study serves as a response to these studies and other decadal surveys to support a plan in reviewing current radar infrastructure and determine how best to meet the community's needs.

1.2 Study Objectives

The key objective of this study is to determine a comprehensive list of common needs from key government stakeholders for deep space radar capabilities. These key stakeholders come from NASA, NSF, and potentially other Government organizations. The study aims to identify gaps in radar capabilities across these organizations and generate core mission needs from a multi-agency stakeholder perspective. The study also assesses the capabilities of current and potential planned facilities that could meet these core needs. To address any gaps, the study provides notional ground-based deep space radar architectural solutions.

This study is intended to provide reference architectures that would improve upon the capabilities of Arecibo, not just to replace it, and to inform a response to the Planetary Science and Astrobiology decadal survey [2] recommendations. It generates a comprehensive context for next generation cislunar, planetary science, and planetary defense radar capabilities, synthesized with inputs from Government stakeholders and informed by subject matter experts (SMEs) across the federally funded research and development center (FFRDC) and university-affiliated research center (UARC) communities.

1.3 Study Flowchart

This study was facilitated by the Aerospace team following the analytical process shown in Figure 1. From the stakeholder inputs at TIMs, the team analyzed potential mission areas and selected two core missions (planetary defense and cislunar SSA) that would drive the facility design for further technical analyses. Two supporting missions, planetary science and atmospheric/ionospheric/geospace science did not drive the design but informed additional potential parameters to be considered. The Aerospace team also conducted several trade studies, performed link budget analyses, and met with various SMEs to further define potential reference architectures. These key steps and their results are discussed in the rest of this report.

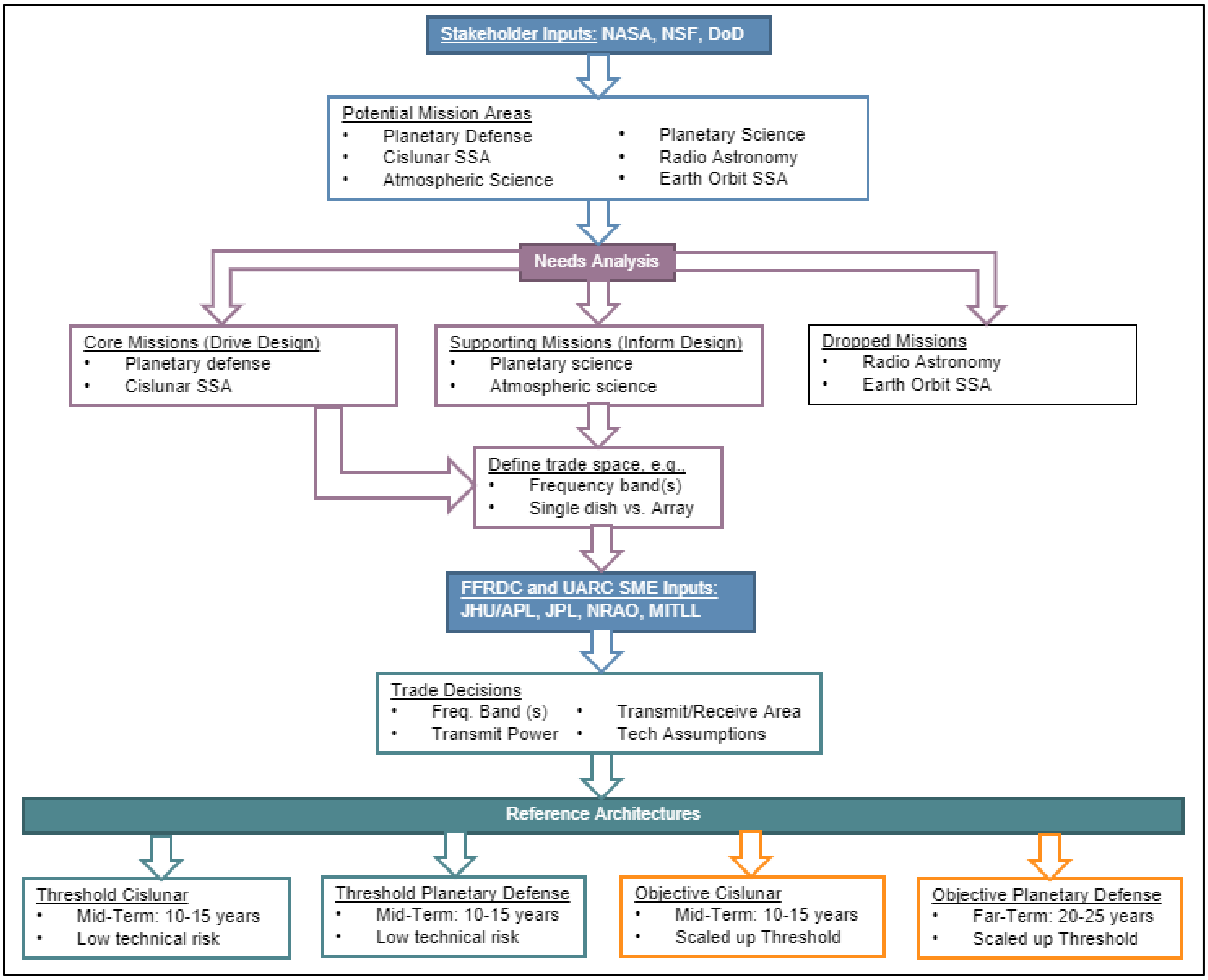

Figure 1. Study flowchart.

1.4 Study Organization

The Aerospace Corporation is a nonprofit corporation that operates a FFRDC for the United States Space Force and provides support across the U.S. Government space enterprise. FFRDCs support government science, engineering and technology development and do not compete with industry or manufacture products, thus eliminating conflict of interest. FFRDCs operate as strategic partners with their sponsoring government agencies to ensure the highest levels of objectivity and technical excellence.

The Aerospace team includes members bringing a wide range of experience and subject matter expertise to the study. The Aerospace team includes experts in radar systems, spectrum management, cost analysis, astronomy, and atmospheric/ionospheric science. The team utilized FFRDC access to a wide range of agencies to facilitate the discussions of common needs for deep space radar facilities across multiple government agencies and met with additional SMEs with stakes in deep space radar capabilities.

2. Needs, Goals, and Objectives

The study stakeholders met throughout multiple briefs and TIMs to identify the needs, goals, and objectives of each agency. The study team identified the primary set of missions based on stakeholder needs for a deep space radar capability and interest in exploring the coordinated development of a future multi-use facility. Six total mission areas were considered that cover the gamut of potential users of a deep space radar facility, for both a transmit and receive capability.

Planetary Defense – According to NASA, the planetary defense mission is "used to encompass all the capabilities needed to detect the possibility and warn of potential asteroid or comet impacts with Earth, and then either prevent them or mitigate their possible effects." Planetary defense involves (1) finding and tracking, (2) characterization, and (3) mitigation. The mission role of a deep space radar system for planetary defense is in the characterization of NEOs to "determine their orbit trajectory, size, shape, mass, composition, rotational dynamics and other parameters." [4]

Cislunar SSA – The cislunar mission involves the tracking and characterization of objects beyond Geostationary Orbit (GEO) out to the Earth-Moon Lagrange Point 2 (L2) distance. SSA is one of the tools that will enable Space Traffic Management (STM) approaches in the cislunar environment. The primary method of tracking cislunar objects is via optical telescopes. However, there is a period of approximately 2-5 days each month (24 – 60 days each year) when the Sun is in the field of view of the telescope making optical observations difficult or impossible within this Sun exclusion zone. These 2-5 days of observations each month in the solar exclusion zone is a gap that radar observations can fill. In addition, there may be benefits to supplementing optical observations with radar measurements even when the Sun-Earth-Moon geometries allow optical measurements.

Planetary Science – According to a National Academy of Sciences report, current planetary science activities are focused "around three observational modes: (1) astrometry based on precision distance and radial velocity measurements, (2) imaging based on measuring echo power as a function of position on the surface of a solar system body, and (3) speckle interferometry, which can be used to make very precise measurements of the rotation vectors of Mercury, Venus and, perhaps, the icy Galilean satellites of Jupiter and estimates of the spin state direction of near-Earth asteroids.… [Additionally], Radar's sensitivity to centimeter-scale and larger surface roughness, its ability to penetrate dry surfaces, and its unique ability to detect water ice has kept it relevant to investigations of the Moon and terrestrial planets as well." [5]

Atmospheric Science – The atmospheric, geospace, and ionospheric science mission is also being considered as a possible user of a new multi-use facility. The Arecibo Observatory's Incoherent Scatter Radar (ISR) was used to profile the ionosphere giving range-resolved observations of electron concentrations, temperatures, ion compositions, and other important parameters. A future facility should have at least a 45-degree field of view to allow observations parallel and perpendicular to the Earth's magnetic field. The atmospheric science mission requires only a fractional share of a facility, making it potentially compatible with the multi-use concept, but the comparatively low frequencies used for this ionospheric research would require a different transmitter/receiver than the planetary science mission. Follow-on analysis will be needed to determine if a multi-use facility concept could incorporate the atmospheric and ionospheric mission needs.

Radio Astronomy – The 2021 National Academies "Pathways to Discovery in Astronomy and Astrophysics for the 2020s" report [6] found that the radio astronomy capabilities lost with Arecibo could be partially replaced with the Jansky Very Large Array (VLA) and the Green Bank Telescope (GBT). In the ngVLA era there may not be any significant capability gaps to fill, so while a multi-use radar facility may be able to serve a radio astronomy purpose, there may be no need to design the facility specifically to meet the needs of the radio astronomy community.

Earth Orbit Space Situational Awareness (SSA) – The Earth Orbit SSA mission involves the tracking and characterizing of non-natural objects from Low Earth Orbit (LEO) to GEO. Existing or planned systems fulfil this mission need. The gap in capability is for orbital debris in the 1 mm to 5 mm diameter sizes [7]. Because of the small size of these objects, a high frequency radar such as Ka-band would be needed. Additionally, a system designed to include orbital debris would need to track many of these small objects moving at high-speed relative to the ground radar and receiver. Adding the capability to track millimeter-sized objects moving at high angular velocities to a deep space radar facility would increase the complexity and cost of a resulting system beyond what is needed to satisfy this study's primary missions of planetary defense and cislunar SSA. Therefore, even though a gap exists for characterizing the 1-5 mm orbital debris environment, it was deemed incompatible with the stakeholders' needs for a deep space radar and was excluded from further consideration.

Of the six mission areas described, this study initially narrowed the scope down to two core missions (planetary defense and cislunar SSA) and two supporting missions (planetary science and atmospheric/ionospheric science).

2.1 Core Missions

The 2010 National Academies report "Defending Planet Earth" [1] found that ground-based radar is an important component of the program to identify NEO threats and recommended increasing the use of existing radar facilities. Since that report, the loss of Arecibo's planetary radar decreased existing radar capability and capacity. New capabilities, beyond what Goldstone provides today and what Arecibo formerly provided, are needed to meet the mission needs. Therefore, this study has identified planetary defense as one of the core missions.

The Cislunar Security National Technical Vision [8] notes that there is expected to be an increase in activity at the Moon and in cislunar space, which necessitates increasing the national capabilities for situational awareness in the cislunar domain. The purpose of this cislunar SSA is to identify norm violations, enable space traffic management, enhance safety, and avoid hazards. Although the Cislunar Security National Technical Vision does not specify the sensitivity and capacity that a ground-based radar would need to provide, it does make clear that capability gaps exist, and cislunar SSA is therefore one of the mission drivers for this study. The cislunar SSA needs do not represent any one stakeholder's requirements but instead are meant to present a reasonable and technologically achievable summary of the capabilities that could be expected of a deep space radar facility.

2.2 Supporting Missions

The National Academies 2022 Planetary Science and Astrobiology decadal survey [2] notes the importance of ground-based radar facilities to characterize near-Earth asteroids (NEAs), solar system planets and moons, and other topics of scientific interest. The report recommends that NASA and NSF work together to meet the needs of the planetary science community, and to include capabilities to map the Venusian surface, replacing those lost with Arecibo (because the Goldstone Solar System Radar X-band facility is too high frequency to penetrate the Venusian atmosphere). Given the gap between the mission needs and capabilities of today's facilities, this study includes planetary science as a supporting mission driver for a future deep space radar facility. However, for the purposes of this study, the planetary science mission was not considered a core mission, so the notional facility designs did not support trades that favored planetary science at the expense of the planetary defense and cislunar SSA missions.

A workshop sponsored by the NSF's Division of Atmospheric and Geospace Sciences and held in 2021 [9] identified the driving science that could inform investment in one or more new ISR facilities. Discussion with subject matter experts, review of reports, and research of other open sources of information led to the decision to include atmospheric, ionospheric, and geospace science among the supporting missions that could potentially be met by a new multi-use facility. The atmospheric/ionospheric science mission that Arecibo previously supported can only be carried out at much lower frequencies than the other core mission areas; therefore, meeting those needs would entail additional transmitters and receivers, and possibly entirely different antennas than would be needed for the planetary defense, planetary science, and cislunar missions.

A summary of the identified missions and stakeholder's core and supporting needs for deep space radar can be found below in Table 2.

Table 2. Deep Space Radar Synthesized Stakeholder Needs

Missions	Detection Sensitivity Threshold and Objective	Spatial Resolution	Frequency Constrains	Schedule Considerations	Facility Usage (time)
Planetary Defense	T: Detect 100 m NEA at 50 million km O: Detect 50 m NEA at 50 million km	5 m resolution at 8 million km	Proven success with S-band (2.4 GHz) and X-band (8.5 GHz)	Schedule within a day or two of apparition	10%-20% of facility time needed: • Assume several hours per NEA to be imaged • Assume hundreds of NEAs to be observed per year
Cislunar SSA	T: Detect 1 m metal sphere at Earth-Moon L2 distance O: Detect 0.2 m metal sphere at Earth-Moon L2 distance	N/A	S-band and higher frequencies	Generally easy to schedule well in advance	10%-20% of facility time needed: • Tens of minutes of continuous observations per day • 2-5 days per ~4-week period
Planetary Science	T: Radar echo spectra of Titan at opposition with OC SNR of 600 O: Detect 100 km asteroid at 5 AU	Same as Planetary Defense	< 8 GHz might be preferred	Generally easy to schedule well in advance	10% + of facility time
Atmospheric & Ionospheric Science	• Measure the complete altitude profile of the diurnal plasma line • Measure thermal plasma oscillations in the ionosphere	150 m vertical resolution	Current ISRs operate in the VHF and UHF frequency bands	Generally easy to schedule well in advance	10% + of facility time
Receive-only mission	10% + of facility time				

2.2.1 Needs Overlaps

This study found areas of overlap between several of the core and supporting missions. None of these missions rely on exclusive, continuous use of a deep space radar facility, potentially allowing multiple missions to share time on a multi-use facility.

The frequency constraints on the planetary defense, planetary science, and cislunar SSA missions have some overlap, though as will be discussed in Section 3.4, there is a trade to be made between moving to higher frequencies to improve antenna gain and moving to lower frequencies to capture more of the planetary science desired capabilities.

In terms of sensitivity, there is overlap between the planetary science and planetary defense missions in the types of objects that would be observed. We expect that a facility that could meet the planetary defense mission needs, which would be more capable than the Goldstone or Arecibo planetary radars, would also cover a significant portion of the planetary science mission needs. With some important caveats noted in the following sections of this report, a facility that could meet the planetary defense mission needs would also have the sensitivity to carry out the cislunar SSA mission needs. However, a deep space radar sized to serve the cislunar SSA mission would not have the sensitivity to meet the planetary defense mission needs. Therefore, for the purposes of this study, we have produced notional facility designs and costs that are focused on the planetary defense and cislunar SSA missions.

Table 3. Deep Space Radar Needs Overlap

Mission Area	Facility Sized for Planetary Defense (X-band)	Facility Sized for Cislunar SSA (X-band)
Planetary Defense	Covered by design	Expect shortfall
Cislunar SSA	Expect overage	Covered by design
Planetary Science	• Satisfy most planetary bodies lacking thick atmospheres • Needs C-band or lower for most planetary bodies with significant atmospheres (Venus, Titan)	• Satisfy some planetary bodies lacking thick atmospheres • Resolution and sensitivity constraints
Atmospheric, Ionospheric, & Geospace Science	No overlap unless additional Tx are considered	• No overlap unless additional Tx are considered • Possible sensitivity limitations for mission

2.3 Needs as Drivers of Architecture Design

The mission needs described above were used to drive the design of notional radar facility architectures. This study focused on designing the notional architectures to meet the planetary defense detection and imaging missions, and the cislunar detection mission. As shown below, the primary driver for the facility architecture design is the planetary defense detection mission (range and size). The ability of the notional facilities to meet other stakeholder needs, such as planetary science, will be discussed in later sections of this report, and the calculations used to estimate the performance of the notional facilities defined in this study can be found in Appendix B.

2.3.1 Planetary Defense Detection and Imaging Missions

The planetary defense mission needs identified in this study fall into two categories: detection and imaging. The threshold performance values are to detect a 100-meter NEA at a distance of 50 million km (approximately 1/3 the distance between the Earth and Sun, and the approximate distance at which it is considered a NEO) and to image a NEA with 5-meter resolution at a distance of 8 million km (approximate distance at which it is considered a Potentially Hazardous Object (PHO)).

The following approximate calculations show that the NEA detection mission is more challenging, from a facility design perspective, than the imaging mission. The main factor that makes the planetary defense mission much more challenging than the cislunar SSA mission is the far greater distance to the target for the NEA mission. Therefore, the detection mission was used to size the number, size, power, and other parameters of the notional facilities proposed in this study. Appendix B includes details on the more exact calculations that went into the notional facility designs described elsewhere in the report.

The signal-to-noise ratio (SNR) of a radar observation is given by

$$SNR = \frac{P_t\ G_t\ G_r\ \lambda^2\ \sigma}{(4\pi)^3\ R^4\ kT_{sys}} \frac{\sqrt{\tau}}{\sqrt{B}}$$

Where P_t is the transmitted power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the wavelength of the transmission, σ is the radar cross section of the target, R is the distance to the target, k is the Boltzmann constant, T_{sys} is the system temperature of the receiving system, τ is the integration time, and B is the bandwidth of the radar echo [10]. The radar cross section of the target can be given by

$$\sigma = \frac{\sigma_0 \pi D^2}{4}$$

Where σ_0 is the radar albedo of the target and D is the diameter of the target [10]. The Bandwidth of the radar echo is given by

$$B = \frac{4\pi D}{\lambda P} \cos\phi$$

Where P is the rotation period of the target and ϕ is the angle between the spin vector and the plane of the sky [10]. Holding the terms describing the radar facility constant and examining just those terms specific to the target, the SNR is proportional to

$$SNR \propto \frac{\sigma_0 D^2}{R^4\ \sqrt{B}} \propto \frac{\sigma_0 D^{1.5} \sqrt{P}}{R^4}$$

As can be seen from this SNR proportionality, it is harder to achieve sufficient SNR for a 100-meter object at a distance of 50 million km than it is for a 5-meter object at a distance of 8 million km. Virkki et al. [11] give several examples of Arecibo images of NEAs with 7.5 m resolution at distances comparable to 8 million km. Slade et al. [12] report that the Goldstone Solar System Radar (GSSR) could produce range resolutions as fine as 3.75 meters. However, as shown in this report and in Lazio et al. (2021) [13], neither GSSR nor Arecibo is/was capable of detecting a 100-meter NEA at a distance of 50 million km.

Assuming that a future facility has a license from the National Telecommunications and Information Administration (NTIA) to use a broad enough bandwidth and assuming that the rotation rate and orientation of the NEA is compatible with high resolution delay-Doppler mapping, the notional facility design would be driven by the planetary defense detection mission more than by the imaging mission.

2.3.2 Planetary Defense Detection and Cislunar Detection

In addition to the primary planetary defense mission, the cislunar SSA mission also drives the notional facility design. Although the TIMs carried out for this study did not settle on the exact needs of the various stakeholders, there was agreement that the summary presented in Table 2 (threshold of 1 meter object and objective of 0.2 meter object, at Earth-Moon L2 distance) were close enough for the purpose of determining the feasibility of a jointly sponsored facility. The following approximate calculations will show that the NEA detection mission is much more stressing than the cislunar detection mission, meaning that precise cislunar needs are not critical, from a facility design perspective, for the purpose of a joint-facility feasibility study.

The proportionality in the previous section shows that the most dominant factor in the SNR of a radar detection is the distance to the object, followed by the size of the object. In the signal-to-noise ratio proportionality shown in Section 2.3.1, the SNR is proportional to the NEA diameter to the 1.5 power and inversely proportional to the NEA distance to the 4^{th} power. The distance to the Earth-Moon L2 Point is, very roughly, 100 times closer than the 50 million km distance used in the planetary defense calculation. The object sizes for the cislunar mission are, again very roughly, 100 times smaller than the object sizes in the planetary defense mission. Therefore, the cislunar mission needs are generally easier to satisfy than the planetary defense mission needs. As shown in Section 3, a radar facility that just meets the planetary defense threshold need exceeds the minimum cislunar SSA target size for detectability by a factor of 30. One important exception to this is when the line of sight from the radar facility to the cislunar object intersects with, or is close to, the Moon. Pointing close to the Moon, such that power from the beam is re-radiated to the receiver from a reflection off the Moon's surface, results in an increase in the system temperature by approximately a factor of 10 [14], increasing the difficulty of the cislunar mission. However, even with a factor of 10 increase in the system temperature for the cislunar mission, the planetary defense mission remains the more difficult of the two to satisfy. In the figures and calculations in this study, we assume the target is well-separated from the Moon in angular distance unless noted otherwise.

3. Facilities Study

This study includes an evaluation of the ability of current and potential planned facilities to meet the needs, goals, and objectives of the stakeholders. To the extent that these facilities do not meet the threshold or objective goals, we identify high-level reference architectures that can provide the desired capabilities.

3.1 Current Facilities

The most sensitive facility carrying out deep space radar transmissions today is the 70-meter Goldstone Solar System Radar DSS-14, which is part of NASA's Deep Space Network (DSN). There are other deep space radar transmit facilities, such as Goldstone 34-meter DSS-13 and the DSN facilities near Canberra, Australia, but they are significantly less sensitive than DSS-14 and therefore are not evaluated in detail as part of this study. The current deep space radar receive facilities evaluated in this study are DSS-14, the 10-element Very Long Baseline Array (VLBA), the 27-element Very Large Array (VLA), and the Green Bank Telescope (GBT).

3.1.1 Current Facilities Fact Sheet

The GSSR DSS-14 (Figure 2), located near Barstow, California, is part of the NASA's DSN. The GSSR consists of a 500 kW X-band transmitter on a 70 m antenna. The primary mission of the DSN is communications with interplanetary spacecraft but some time is allocated to solar system radar. Other parameters used to model the GSSR (antenna gain, transmit-to-receive switch time, system temperature, aperture efficiency, etc.) are described in the 2019 Goldstone Solar System Radar Learning Manual [15]. The GSSR can be used for monostatic observations or used as a transmitter to another receive facility, such as the GBT, for bistatic observations. The sensitivity of the GSSR when paired with the GBT is improved by a factor of 2.3 when compared with GSSR monostatic observations.

Figure 2. GSSR DSS-14.

(Courtesy of NASA/JPL-Caltech)

The VLBA (Figure 3), operated by the National Radio Astronomy Observatory (NRAO), consists of 10 antennas located as far west as Hawaii and as far east as the Virgin Islands. Each identical 25 m antenna has receivers covering the spectrum from 300 MHz to 100 GHz. There are no radar transmitters on the VLBA, so while the VLBA can be used as the receive facility for bistatic observations it cannot be used for monostatic radar observations. Time on the VLBA is roughly evenly split between "open skies" (competitively solicited) science observations and dedicated observations for the U.S. Naval Observatory. Additional information used to model the performance of the VLBA is available through the NRAO website.

Figure 3. One of ten VLBA 25-meter antennae.

(Courtesy of NRAO/AUI/NSF)

The VLA (Figure 4), operated by NRAO, consists of 27 antennas located on the Plains of San Agustin in New Mexico. Each identical 25-meter antenna has receivers covering the spectrum from 74 MHz to 50 GHz. There are no radar transmitters on the VLA, so while the VLA can be used as the receive facility for bistatic observations it cannot be used for monostatic radar observations.

Figure 4. VLA.

(Aerospace photo)

The GBT (Figure 5), part of the National Science Foundation's Green Bank Observatory, is a 100 m antenna located in the National Radio Quiet Zone and the West Virginia Radio Astronomy Zone. It is used today for passive observations, including as the receive facility for bistatic radar observations with another transmit facility, such as the GSSR. While there is no transmit capability currently on the GBT, experiments were previously made with a 700 W Ku-band transmitter. The GBT covers a non-contiguous frequency range from 290 MHz to 116 GHz.

Figure 5. GBT.

(Aerospace photo)

3.2 Potential Planned Facilities

The Green Bank Observatory, National Radio Astronomy Observatory, and Raytheon Intelligence & Space have demonstrated a 700 W prototype transmitter and are in the early phase of designing a high-power planetary radar system for the GBT for which NRAO plans to propose for funding. For the purposes of this study, we assume that a GBT high-power radar transmitter could be characterized as follows: 100-meter aperture, proposed conceptual 500 kW transmitter at Ku-band (13.7 GHz), 64% aperture efficiency, and a 21 K system temperature. This study shows the potential of such a high-power radar on the GBT (GBT+HPTx), when paired with the VLBA, the VLA or the next generation Very Large Array (ngVLA), to meet the planetary defense and cislunar mission needs. However, there also needs to be a full assessment of the impacts to the highly sensitive receive capability of the GBT of installing a high power transmit capability on the antenna.

The ngVLA is a potential successor to the current Jansky Very Large Array and VLBA. The ngVLA was defined as a high priority new ground-based observatory in the 2021 National Academies Astronomy and Astrophysics decadal survey [6]. The ngVLA has completed its technical conceptual design review and antenna design review and has funding to complete an antenna prototype. This study's evaluation of its capabilities as a radar receive facility are based on the available design documentation. For the purposes of this study, we assume that the ngVLA radar receive array could be characterized as follows: 214 apertures, each 18 m in diameter, 64% aperture efficiency, and a 21 K system temperature.

3.3 Evaluation of Current and Potential Planned Relative to Needs

The performance of combinations of current and potential planned transmit and receive facilities, relative to the planetary defense and cislunar mission detection needs, is shown in Table 4. For each pair of facilities, the minimum detectable object size is determined as a function of distance, using the approach described in Appendix B, and the result is compared with the threshold and objective detection values for the cislunar and planetary defense missions.

Table 4. Performance of Current and Potential Planned Radar Facilities Relative to Mission Needs

Transmit Facility	Receive Facility	Planetary Defense		Cislunar SSA	
		Detect 100m NEA at 5e7 km	Detect 50m NEA at 5e7 km	Detect 1m metal sphere at Earth-Moon L2 distance	Detect 0.2m metal sphere at Earth-Moon L2 distance
Goldstone DSS-14		No	No	Yes	No
		(610 m)		(0.25 m)	
Goldstone	GBT	No	No	Yes	Yes
		(430 m)		(0.17 m)	
Goldstone	VLA	No	No	Yes	Yes
		(350 m)		(0.14 m)	
GBT+HPTx *	VLBA	No	No	Yes	Yes
		(340 m)		(0.11 m)	
GBT+HPTx *	VLA	No	No	Yes	Yes
		(210 m)		(0.07 m)	
GBT+HPTx *	ngVLA*	Yes	No	Yes	Yes
		(100 m)		(0.03 m)	

** Potential planned facility*
Values in parentheses show the minimum object size that could be detected with the transmit/receive pairings at 50 million km and 450,000 km.

The general approach to evaluating the performance of each pair of transmit and receive facilities was to assess the SNR as a function of object size and distance. The calculations include assumptions about the target, including size, distance, and albedo. We assume radar albedos of 0.2 and 0.5 for the planetary defense and cislunar targets, respectively. The calculations include assumptions about the potential planned transmit and receive facilities, including the number of apertures, the aperture size, transmit power, frequency range, antenna efficiency, system temperature, and an estimate of the integration time. Appendix B includes additional details to account for atmospheric losses and other modifications to the simplified SNR equations presented in Section 2.3.1.

As shown in Table 4, today's facilities have the capability to meet the threshold and objective of the cislunar detection mission. However, each of these facilities already have other demands on the facility time (communications, science observations, planetary defense, etc.), so there may not be sufficient capacity to meet the SSA needs. A dedicated deep space radar facility would likely be able to meet the capacity needs of the cislunar SSA community and other stakeholders, as shown in Table 2.

None of today's facilities have the capability to meet the planetary defense mission needs, even at the threshold level of performance. However, a potential future pairing of a high-power radar transmitter on the GBT (GBT+HPTx) with the large collecting area of the ngVLA would just meet the threshold needs for the planetary defense mission, within the uncertainties of the performance of these potential facilities. The planetary defense mission stakeholders would need to work with NSF and NRAO to determine whether it would be possible to secure enough time on the GBT and ngVLA to meet the planetary defense capacity needs. None of the potential planned facilities meet the planetary defense objective capability, though notional facility architectures that can do so are described in Section 3.4.

Figures 6-11 show a detailed comparison of the performance of each of the transmit and receive combinations summarized in Table 4.

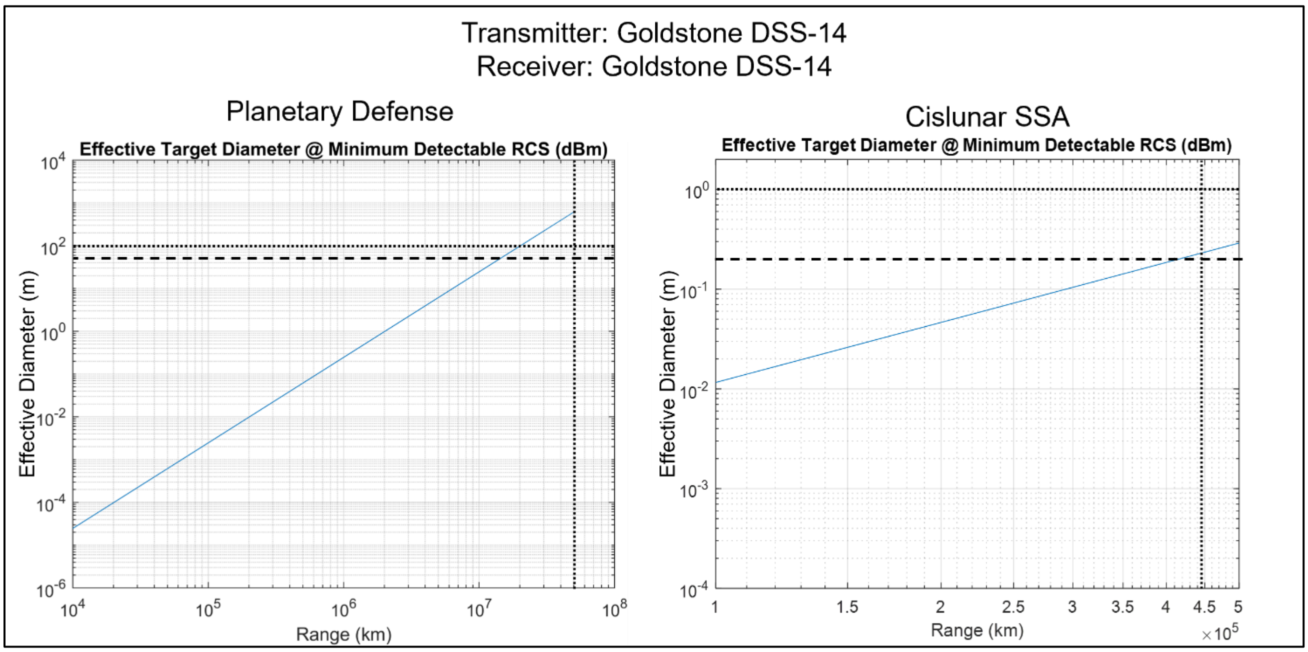

Figure 6. Performance of monostatic observations with the GSSR.

(Left) Minimum NEA size detectable by the GSSR as a function of target distance. The vertical dotted line is drawn at a distance of 50 million km. The horizontal dotted line shows the threshold target size of 100 m and the dashed horizontal line shows the objective target size of 50 m. (Right) Minimum cislunar target size detectable by the GSSR as a function of distance. The vertical dotted line is drawn at the Earth-Moon L2 distance. The horizontal dotted line shows the threshold target size of 1 m and the dashed horizontal line shows the objective target size of 0.2 m.

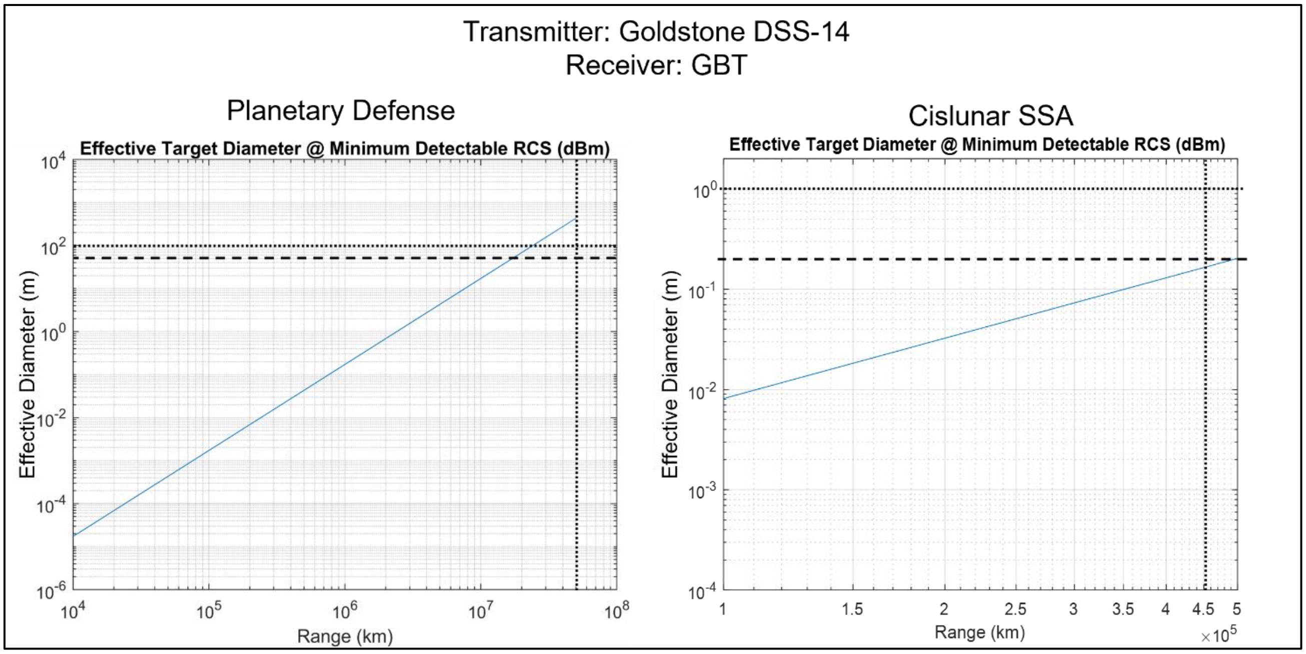

Figure 7. Performance of GSSR transmitting to the GBT.

(Left) Minimum NEA size detectable by the GSSR-to-GBT as a function of target distance. The vertical dotted line is drawn at a distance of 50 million km. The horizontal dotted line shows the threshold target size of 100 m and the dashed horizontal line shows the objective target size of 50 m. (Right) Minimum cislunar target size detectable by the GSSR-to-GBT as a function of distance. The vertical dotted line is drawn at the Earth-Moon L2 distance. The horizontal dotted line shows the threshold target size of 1 m and the dashed horizontal line shows the objective target size of 0.2 m.

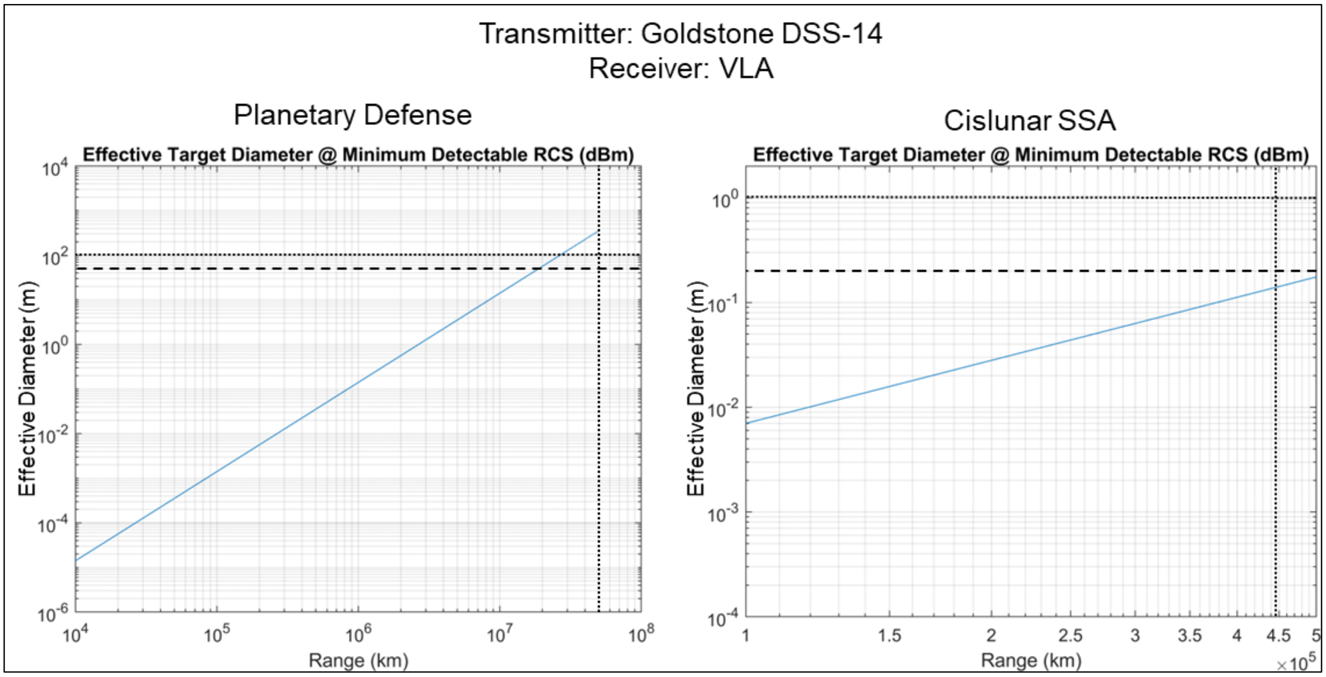

Figure 8. Performance of GSSR transmitting to the VLA.

(Left) Minimum NEA size detectable by the GSSR-to-VLA as a function of target distance. The vertical dotted line is drawn at a distance of 50 million km. The horizontal dotted line shows the threshold target size of 100 m and the dashed horizontal line shows the objective target size of 50 m. (Right) Minimum cislunar target size detectable by the GSSR-to-VLA as a function of distance. The vertical dotted line is drawn at the Earth-Moon L2 distance. The horizontal dotted line shows the threshold target size of 1 m and the dashed horizontal line shows the objective target size of 0.2 m.

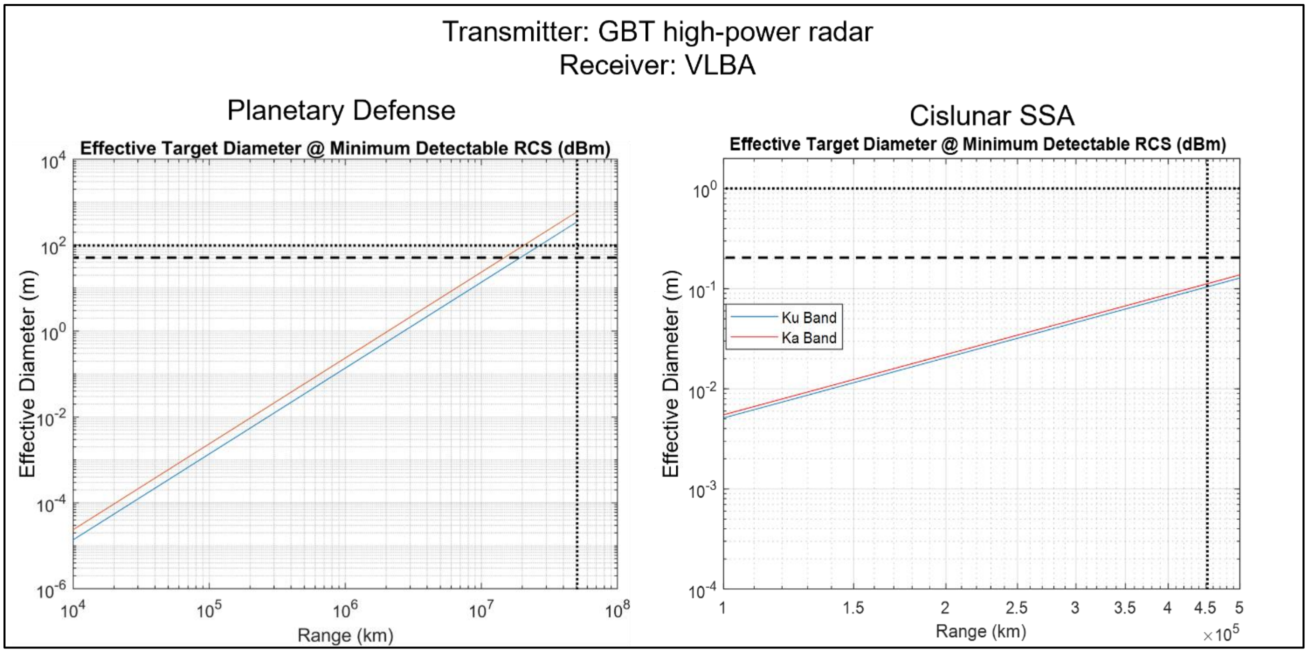

Figure 9. Performance of GBT+HPTx transmitting to the VLBA.

(Left) Minimum NEA size detectable by the potential GBT+HPTx-to-VLBA as a function of target distance. The vertical dotted line is drawn at a distance of 50 million km. The horizontal dotted line shows the threshold target size of 100 m and the dashed horizontal line shows the objective target size of 50 m. (Right) Minimum cislunar target size detectable by the potential GBT+HPTx-to-VLBA as a function of distance. The vertical dotted line is drawn the Earth-Moon L2 distance. The horizontal dotted line shows the threshold target size of 1 m and the dashed horizontal line shows the objective target size of 0.2 m. In both panels, the performance of a Ku-band implementation of the GBT high-power radar transmitter is shown in blue and the performance of a Ka-band implementation of the GBT high-power radar transmitter is shown in orange.

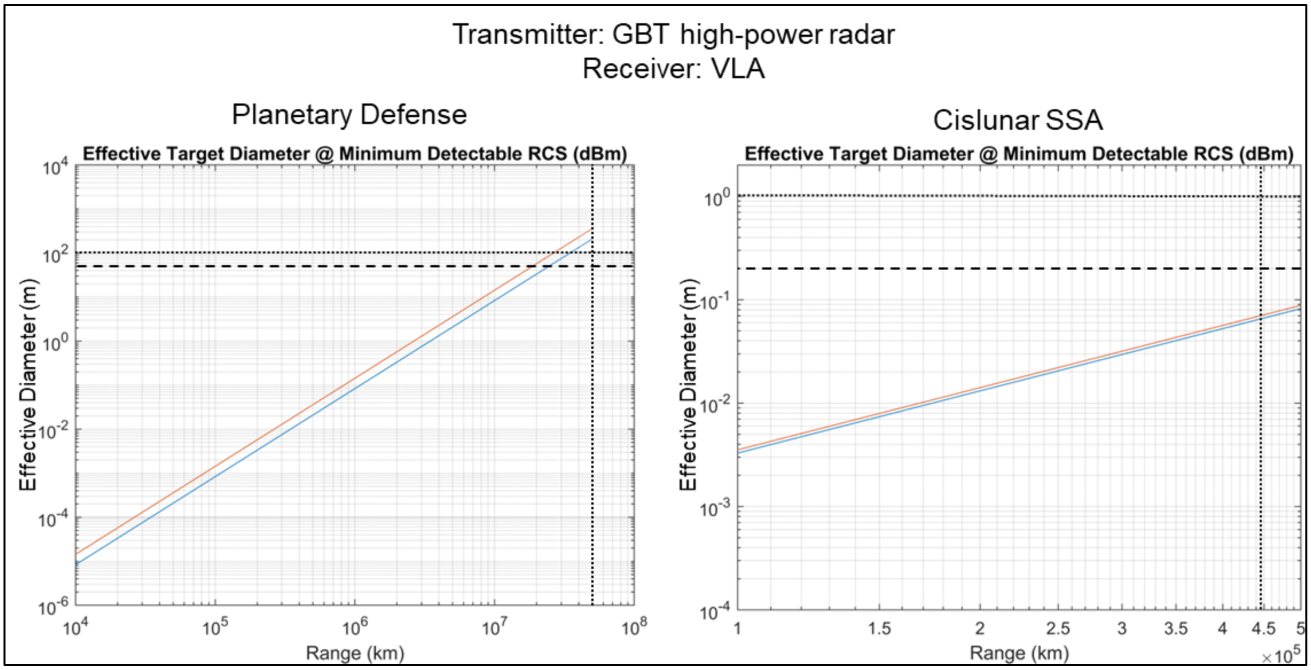

Figure 10. Performance of GBT+HPTx transmitting to the VLA.

(Left) Minimum NEA size detectable by the potential GBT+HPTx-to-VLA as a function of target distance. The vertical dotted line is drawn at a distance of 50 million km. The horizontal dotted line shows the threshold target size of 100 m and the dashed horizontal line shows the objective target size of 50 m. (Right) Minimum cislunar target size detectable by the potential GBT+HPTx-to-VLA as a function of distance. The vertical dotted line is drawn at the Earth-Moon L2 distance. The horizontal dotted line shows the threshold target size of 1 m and the dashed horizontal line shows the objective target size of 0.2 m. In both panels, the performance of a Ku-band implementation of the GBT high-power radar transmitter is shown in blue and the performance of a Ka-band implementation of the GBT high-power radar transmitter is shown in orange.

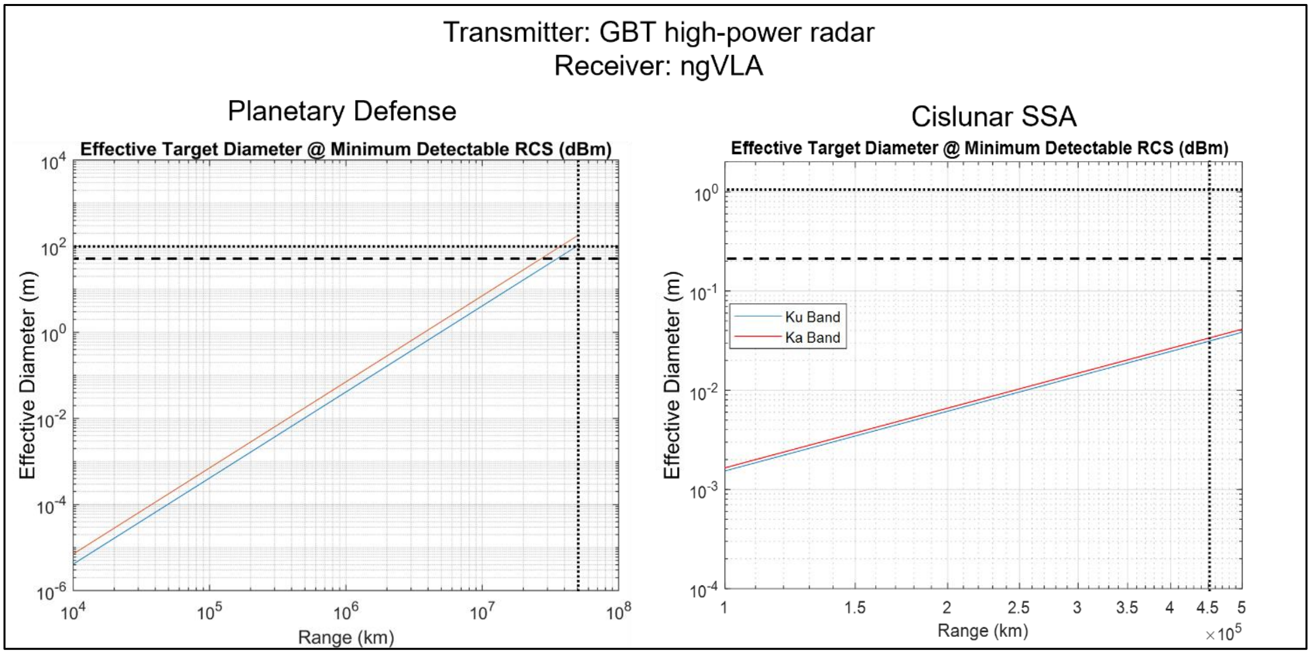

Figure 11. Performance of GBT+HPTx transmitting to the ngVLA.

(Left) Minimum NEA size detectable by the potential GBT+HPTx-to-ngVLA as a function of target distance. The vertical dotted line is drawn at a distance of 50 million km. The horizontal dotted line shows the threshold target size of 100 m and the dashed horizontal line shows the objective target size of 50 m. (Right) Minimum cislunar target size detectable by the potential GBT+HPTx-to-ngVLA as a function of distance. The vertical dotted line is drawn at the Earth-Moon L2 distance. The horizontal dotted line shows the threshold target size of 1 m and the dashed horizontal line shows the objective target size of 0.2 m. In both panels, the performance of a Ku-band implementation of the GBT high-power radar transmitter is shown in blue and the performance of a Ka-band implementation of the GBT high-power radar transmitter is shown in orange.

3.4 Evaluation of an Independent Facility

3.4.1 Design of an Independent Facility

In addition to calculating the performance of current or potential planned facilities relative to the mission needs, this study carried out a preliminary estimate of what new radar facility architectures could meet the cislunar and planetary defense missions. Although an optimization of the many factors that feed into radar facility architecture design is outside the scope of this study, we nevertheless considered several trades in order to produce a reasonable, though entirely notional, facility architectures. These notional facility architectures are an attempt to strike a balance between performance (in terms of satisfying the mission needs), cost, and risk.

One trade assessed was between a monostatic and bistatic facility design. Monostatic facilities, by using the same antenna(s) for both transmit and receive, have the potential to reduce the number of antennas required. However, monostatic facilities must switch between the transmit and receive functions, and that switching time sets a limit on how close a radar target can be before the round-trip light travel time is less than the transmit/receive switch time. The switching time for the Goldstone Solar System Radar is greater than 1 second, precluding radar observations of objects significantly closer than the Moon [14]. The notional facilities discussed in this study employ bistatic observations, based on a decision to provide better performance of cislunar (and closer) space.

A second trade assessed was between a large single dish design and arrays of smaller dishes. Although the cislunar missions can be carried out with a large single dish, the sensitivity requirements for the planetary defense mission and the implausibility of making a single aperture significantly larger than the GBT or Arecibo drive the design to a distributed array concept. Arrays provide graceful degradation, compared to single dish facilities, when an antenna, transmitter, or other key components fails. Furthermore, the lifecycle cost of arrays is lower than a single dish facility with equivalent performance [14]. A large distributed array can be used as multiple subarrays when the full sensitivity of a single large array isn't needed, allowing multiple missions to be carried out simultaneously. The power per transmitter is lower for an array, compared to a single dish system, making any required technology development less challenging. However, additional work will be needed to enable the coherent combination of the transmitted power for a ground-based planetary radar [16]. Generally, the ability to coherently combine the signals of a transmit array becomes more challenging as the separation between antennas increases, as the frequency of the transmission increases, and as the variability in the atmosphere and ionosphere increases. The notional facility architectures in this study use an array of transmitters and an array of receivers.

Another trade to consider is the size of the antennas. Sanchez Net et al. [16] showed that a ground-based planetary radar optimized for life-cycle cost will often employ 15 m or 18 m antennas. For this study, we selected 18 m antennas to take advantage of development work being done by NRAO for the 18 m ngVLA antennas.

A trade needed to be made on the frequency band of the observations. We expect that the planetary defense radar missions can generally be satisfied by a wide range of bands, since Arecibo operated at S-band, Goldstone operates at X-band, and the pilot radar demonstrated on the GBT operated at Ku-band. Antenna gains improve with increasing frequency, but atmospheric losses and the demands on the antenna surface accuracy also increase with increasing frequency. A portion of the planetary science mission can be carried out better at C-band or lower frequencies, for example observations of the surface of solar systems bodies with thick atmospheres, like Titan and Venus [17]. For this study, we selected X-band to take advantage of recent solid state power amplifier development [18], with the understanding that additional development at Ku-band led by NRAO (or others) might push the design to higher frequencies or that the needs of the planetary science community might push the design towards a lower frequency transmitter instead of (or in addition to) an X-band transmitter. In this study we assumed that the radar albedos of the target are relatively insensitive to frequency between S-band and Ku-band for both the planetary defense and cislunar targets. While there is a steep falloff in radar cross section for objects that are much smaller than the wavelength of the radar frequency, that is not especially relevant for the radio bands and objects that are the focus of this study. Finally, we needed to settle on a transmit power per antenna. Toshihaya et al. [18] demonstrated a 30 kW X-band solid state power amplifier. Using a higher power would reduce the number of transmitters needed but would increase the amount of technology development needed. As a compromise between technology risk and array size, we selected a 50 kW X-band transmitter for this study.

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In summary, the design space considered in this report were:

- Monostatic vs. Bistatic architecture (notional architectures in this study are bistatic)
- Large single dish antenna vs. Array of smaller antennas (notional architectures in this study are arrays)
- Size of “smaller” antennas (notional architectures in this study have 18 m antennas)
- Frequency band of radar transmitters (notional architectures in this study have X-band transmitters)
- Transmit power per antenna (notional architectures in this study have 50 kW transmitters)

Preliminary analysis showed that the total number of antennas in the array is slightly lower when a greater proportion of the overall antennas are transmitters than receivers, so the notional facilities shown in Table 5 reflect that trade. A full optimization of the trades discussed in this section is outside the scope of this study. The purpose of this study is to determine whether a deep space radar facility can meet the needs of multiple stakeholders, and if so, provide a rough estimate of what the design and cost of such a facility might be. Further study and optimization will be needed if the stakeholders decide to proceed with a new facility.

Putting together these design choices, Table 5 summarizes the number of transmitters and receivers that would be needed to meet the cislunar and planetary defense mission needs, either as completely new facilities or when paired with a representation of the ngVLA as a potential receive facility. The number of elements in the arrays shown in Table 5 (tens of elements for the cislunar mission, 100 or more elements for the planetary defense mission) are in broad agreement with the estimates of other notional deep space radar facilities [14, 16].

Table 5. Notional Facilities Designed to Meet Mission Needs

<table>
<tr><th rowspan="2">Transmit Facility*</th><th rowspan="2">Receive Facility*</th><th colspan="2">Planetary Defense</th><th colspan="2">Cislunar SSA</th></tr>
<tr><th>Detect 100m NEA at 5e7 km</th><th>Detect 50m NEA at 5e7 km</th><th>Detect 1m metal sphere at Earth-Moon L2 distance</th><th>Detect 0.2m metal sphere at Earth-Moon L2 distance</th></tr>
<tr><td rowspan="2">11 notional transmitters</td><td rowspan="2">9 notional receivers</td><td>No</td><td>No</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="2">(1100 m)</td><td colspan="2">(0.45 m)</td></tr>
<tr><td rowspan="2">36 notional transmitters</td><td rowspan="2">21 notional receivers</td><td>No</td><td>No</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">(220 m)</td><td colspan="2">(0.09 m)</td></tr>
<tr><td rowspan="2">25 notional transmitters</td><td rowspan="2">ngVLA</td><td>Yes</td><td>No</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">(100 m)</td><td colspan="2">(0.04 m)</td></tr>
<tr><td rowspan="2">60 notional transmitters</td><td rowspan="2">37 notional receivers</td><td>Yes</td><td>No</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">(100 m)</td><td colspan="2">(0.04 m)</td></tr>
<tr><td rowspan="2">51 notional transmitters</td><td rowspan="2">ngVLA</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">(50 m)</td><td colspan="2">(0.02 m)</td></tr>
<tr><td rowspan="2">95 notional transmitters</td><td rowspan="2">59 notional receivers</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">(50 m)</td><td colspan="2">(0.02 m)</td></tr>
</table>

** Bistatic arrays of 18 m transmit and receive antennas, 50 kW transmitted power at X-band per antenna. Values in parentheses show the minimum object size that could be detected with the transmit/receive pairings at 5e7 km and 450,000 km.*

3.4.2 Cost Estimate of an Independent Facility

A rough order of magnitude (ROM) cost estimate was developed for a deep space radar system to aid in determining affordability between multiple architectures. Six scenarios, listed below, with varying antenna quantities were estimated, which meet cislunar and planetary defense threshold and objective needs.

- Assume ngVLA receive assets are leveraged
  - 25 TX are needed (meets Planetary Defense Threshold, PD TH)
  - 51 TX are needed (meets Planetary Defense Objective, PD Obj)
- Cislunar
  - Threshold (TH) – 9 RX and 11 TX
  - Objective (Obj) – 21 RX and 36 TX
- Planetary Defense
  - Threshold (TH) – 37 RX and 60 TX
  - Objective (Obj) – 59 RX and 95 TX

The cost estimates were generated using a bottoms-up approach. As such, the hardware, software, facilities, and labor elements are the key inputs to the cost model. Likewise, the estimated costs are inextricably linked to the quantities of hardware and the key assumptions made. This methodology will describe each element of cost separately.

Hardware

The antenna estimates assume 18 m diameter dish antennas of varying quantities per scenario. Receive and transmit antennas were estimated using the same methods for the antenna, core electronics, and foundation/infrastructure, but the transmit antennas also carry the additional cost of a transmitter.

Beginning with antenna costs, four data sources were utilized. Estimates include historical analogy data, anecdotal data, parametric estimates, and independent estimates of similar technology where the team leveraged the existing design and methods. Models include Aerospace's FIPA Analogy Model and Antenna Model. Cost improvement at 95% to account for learning and bulk buy benefits is applied to the antenna hardware.

The estimate assumes that a 50 kW X-band transmitter is used. There is greater uncertainty in the transmitter estimates, as the design is not yet established for a deep space radar; estimates are based on assumptions and other concepts' estimates. Four data points were used: GBT estimates included in Bonsall, et al. [19] were studied and informed the estimate; a cost scaled from this information was used; Diversified Technologies, Inc. (DTI) published TWT transmitter costs of $2-6M were utilized as well [20]; and lastly, an independent parametric transmitter cost was developed using the SEER-H tool.

Software, data, and the computing segment are estimated using a factor gleaned from historical data.

Facilities

The estimate includes the construction of two buildings. A site erection facility is needed to house antenna components during system deployment, and it's assumed it will be converted to a maintenance depot upon deployment completion. Secondly, an operations support facility is included as the primary operations location. Both buildings are estimated by analogy from historical data. Lastly, the team recognized that civil works costs such as parking and roads were to be included as well. These needs are not analogous to historical data, so the cost team assumed $2-3M dollars based on expert judgement and previous estimates.

Labor Elements and Other Direct Costs

Program management, systems engineering, integration and test (I&T) and commissioning were estimated using rule of thumb wrap factors.

Other direct costs, including shipping, travel, documentation, general and administrative (G&A), and contractor fee were also estimated using wrap factors gleaned from Aerospace's many years of experience supporting civil space and ground programs.

Summary of Costs Estimating Results

Probabilistic ranges of cost were generated for each scenario using Aerospace's FRISK tool [21]. FRISK employs an analytical (vice a Monte Carlo) cost risk approach to develop S-curves. Summary cost results are reported in Table 6 below at the 70th percentile to include contingency. Scenarios 1-6 are reported consecutively left to right. Antenna quantities are included for context, as they are the primary driver of cost.

Table 6. Summary of Cost Estimates

	PD TH ngVLA	PD Obj ngVLA	Cislunar TH	Cislunar Obj	PD TH	PD Obj
	BY23$M	BY23$M	BY23$M	BY23$M	BY23$M	BY23$M
Total with Contingency	$ 800	$1,600	$500	$1,300	$2,200	$3,300
Item	**Qty**	**Qty**	**Qty**	**Qty**	**Qty**	**Qty**
Receive Antennas	0	0	9	21	37	59
Transmit Antennas	25	51	11	36	60	95

Estimates for the two cases that use the ngVLA as the receive array do not include ngVLA construction costs.

These total costs include construction costs only; O&M costs are not included. The estimate is not phased; all costs are in BY23$M with no inflation included.

These results are specific to the scenarios as defined via antenna quantities. As these are build-up estimates, changes in the hardware quantities will affect the total cost results. Therefore, these costs should not be considered independent from the antenna counts they represent.

4. Other Considerations

4.1 Spectrum

The selection of radio spectrum to support the transmission capability of a deep space radar is a critical part of any future facility and will have ramifications related to antenna reflector size, compatibility with adjacent services, and the geographic location.

Radio frequency spectrum use is regulated using a roadmap of usage known in regulatory circles as a Table of Allocations. These allocations, developed under the International Telecommunication Union (ITU) Radio Regulations [22] by member nations, are then generally adopted by local regulators in a specific country. Within the United States, federal agencies are regulated by the National Telecommunications and Information Administration (NTIA) and the non-federal and private sector are regulated by the Federal Communications Commission (FCC). A future deep space radar would require application through the appropriate agency's spectrum management team and would need to operate within an appropriate existing allocation.

4.1.1 Special Considerations for New Frequency Allocations

The high power of a future deep space radar needed to meet the sensitivity needs of the stakeholders' mission creates regulatory challenges if proposed in a new allocation. New allocations often take four to eight years or more and require intensive study with all incumbent users to ensure no harmful interference.

The "roadmap" of spectrum usage in the U.S. is the U.S. Table of Allocations. The table is defined for users with Primary (or Co-Primary) use of a band segment, or for those secondary in priority to the primary users. The U.S. table is divided into Federal and Non-Federal Usage, with some bands being exclusive to Federal agencies, some shared and some exclusive to non-federal use. The U.S. tables are also modified by footnotes which convey restrictions and additional information pertinent to the frequency use.

Two allocation categories should be explored for operational missions of a deep space radar:

- Space Research (Active): space research service is defined as "A radiocommunication service in which spacecraft or other objects in space are used for scientific or technological research purposes." [22]
- Radiolocation: radiolocation service is defined as "A radiodetermination service for the purpose of radiolocation." [22] In laymen's terms, using a radar to locate objects.

The Table of Frequency Allocations is best explained by showing an example:

Table of Frequency Allocations		2483.5-3600 MHz (UHF/SHF)			Page 39
International Table			United States Table		FCC Rule Part(s)
Region 1 Table	Region 2 Table	Region 3 Table	Federal Table	Non-Federal Table	
3100-3300 RADIOLOCATION Earth exploration-satellite (active) Space research (active) 5.149 5.428			3100-3300 RADIOLOCATION G59 Earth exploration-satellite (active) Space research (active) US342	3100-3300 Earth exploration-satellite (active) Space research (active) Radiolocation US342	Private Land Mobile (90)
3300-3400 RADIOLOCATION 5.149 5.429 5.429A 5.429B 5.430	3300-3400 RADIOLOCATION Amateur Fixed Mobile 5.149 5.429C 5.429D	3300-3400 RADIOLOCATION Amateur 5.149 5.429 5.429E 5.429F	3300-3500 RADIOLOCATION US431B G2	3300-3450 US103 US342	

With careful examination of frequencies above 8500 MHz in the U.S. Table of Allocations, multiple bands are found that allow these services. However, with footnote restrictions or adjacent services for which the deep space radar transmissions could create interference, not all bands in the table would be suitable for deep space radar use.

If other services are co-primary in this band and a deep space radar could adversely affect their operation, that may make a particular band segment unattractive. For example, bands where satellites in space share spectrum with the deep space radar. The transmitted signal of a deep space radar has the potential to damage or degrade the space vehicle’s communications systems and should be avoided.

Another consideration when choosing a frequency band is the amount of contiguous bandwidth needed for a deep space radar mission. The contiguous bandwidth needed for the deep space radar missions depends on the frequency band(s) chosen and was not a focus of this study. However, the frequency allocations for some radar facilities are noted here as reference:

- Goldstone Solar System Radar (GSSR): Frequency assignment 8500 – 8620 MHz (120 MHz bandwidth)
- MIT Haystack: 9500 - 10500 MHz (1 GHz bandwidth)
- Arecibo used 2380 MHz, 430 MHz and 47 MHz

Future work would be needed to develop one or more optimized facility designs, taking into account spectrum management considerations. Additional details on the interpretation of ITU, NTIA, and FCC allocation tables may be found in Appendix C.

4.1.2 Power Limits and RF Safety Considerations

In some frequency bands, there are maximum produced power limits at the geostationary belt. Depending on the frequency band(s) chosen, a future deep space radar facility could have a decreased transmit power limit when oriented towards the GEO belt or could need to completely avoid transmissions in that direction.

Depending on where the system is located, fuel storage/dispensing (gas stations) and certain types of ordnance (weapons/explosives) can be negatively affected by RF. High power RF sources must also consider personnel safety. RF can affect personnel in a few ways; internal body heating can cause heat stroke and arcing from metallic objects can cause damaging burns to skin. Different frequencies affect the body differently.

4.1.3 Geographic Location Considerations

Many variables come together to choose an appropriate location. Interference to and from incumbents can cause degradation of the mission, and terrain can cause blockages to certain parts of the sky.

For the transmitting array, there should not be any incumbents that could be routinely interfered with by the deep space radar. This would result in power limits, limitations on time the system can transmit or calls to cease operations all together. For the receiver array, there shouldn't be any RF sources that could cause harmful interference routinely, which would result in lost data, missed targets, or false alarms. If the deep space radar is only allowed to operate during certain times of the day, huge portions of the sky could not be observed. General guidance for a future deep space radar facility is to choose a site with a low population density, that is distant from a DoD site that uses radar, and that has a favorable environment in terms of atmospheric attenuation (i.e., a high and dry site for radars at higher frequencies).

4.1.4 Transmission and Receiving Co-location

The main concern with transmitting and receiving in a relatively close area is the sheer amount of power the transmit array will produce. The side/back-lobes of the transmitting array can interfere and/or damage the receiver array. Interference can be mitigated by turning off the receiver when the transmitter is sending out signals or providing sufficient physical separation between the two arrays. If damage is a concern, the receiving array would need to sufficiently isolate the sensitive electronics while the transmitter is sending out signals, adding complexity to the receiving array design.

4.2 Additional Siting Considerations

With the loss of Arecibo's 305-meter antenna, there is no operating incoherent scatter radar (ISR) at low/mid latitudes in the American Sector, though there are ISRs in China and Japan. Additional analysis in a follow-on study would be needed to determine the range of acceptable locations of an ISR to meet the disparate needs of the atmospheric and ionospheric communities.

While there is no explicit siting requirement to satisfy the planetary defense mission, it is worth noting that NEAs are distributed across the sky and a single site located in either the northern or southern hemisphere will not be able to observe all of the objects of interest within a reasonably short period of weeks to months. While there could be some benefit to choosing a comparatively low latitude site within the United States to enable observations of a greater fraction of the sky, full coverage would require an additional facility of comparable capability in the southern hemisphere.

The cislunar mission needs collected for this study did not include an estimate of capacity, in terms of the number of objects to be observed or the fraction of the day over which observations would be needed. A single radar facility will only have access to the cislunar region for part of the day, so if nearly continuous coverage is desired then having multiple facilities over a range of longitudes would be needed to satisfy that desire.

4.3 Programmatic

As discussed in Section 3.4 a single independent planetary radar facility could satisfy multiple mission needs across different organizations leading to a desire for interagency collaboration. However, it is important to consider and define the level of involvement of each agency as well as impediments and best practices prior to entering such agreements. Some of the impediments could include different agency goals and processes, as well as budget cycles for agencies with different congressional authorization and appropriation subcommittees, budget instability, and changes in policy direction from the administration and Congress [23]. For instance, NASA does not develop ground-based facilities of its own, NSF's potential future facilities in development do not have a mission requirement for planetary defense or cislunar SSA and are recommended on decade timescales, and all potentially interested agencies have their own competing priorities and processes.

Prior studies on interagency collaborations agree on a set of common key practices to help sustain agency collaborations as a whole: [24]

- Define and articulate a common outcome
- Establish mutually reinforcing or joint strategies
- Identify and address needs by leveraging resources
- Agree on roles and responsibilities
- Establish compatible policies, procedures, and other means to operate across agency boundaries
- Develop mechanisms to monitor, evaluate, and report on results
- Reinforce agency accountability for collaborative efforts through agency plans and reports
- Reinforce individual accountability for collaborative efforts through performance management systems.

Current Memorandums of Understanding (MOU) exist to advance space, Earth, biological, and physical sciences, as well as space exploration, scientific discovery, and security [25, 26]. Although these MOU have facilitated the shared use of facilities and technologies for radar observations, more formalized agreements are required to implement successful interagency collaborations.

For large projects, NSF and NASA rely on the decadal survey process to surface and validate high value facilities for funding consideration. A deep space radar facility especially designed to serve the planetary science and planetary defense community, would typically go through the next Planetary Science and Astrobiology decadal survey process, which will conclude in 2033. The ngVLA concept was already prioritized as part of the 2021 Astronomy and Astrophysics decadal survey [6].

For multiple government agencies to participate in the development of a deep space radar facility it would be important to have a clearly defined work breakdown structure with each agency responsible for specific work breakdown products. This would make each agency responsible for funding their responsible work products and would avoid mingling of funds, which could be problematic from a regulatory or policy standpoint. As an example, NSF and the Department of Energy Office of Science (DOE/SC) collaborated on the development of the Vera C. Rubin telescope. DOE/SC contributed the large camera for the telescope, with NSF providing the remainder of the telescope and facility.

Some government partners may choose to commit to paying for operational products, rather than participate in the construction of a deep space radar facility. Even though such partners may not participate in funding the construction of the facility, their endorsement and commitment to use the facility may be an important contribution to gaining sufficient political support for such an expensive construction project to be realized.

5. Findings and Conclusions

The key objective of this study is to determine a comprehensive list of common needs from government stakeholders for deep space radar capabilities. The findings of this study are briefly summarized in the following bullets and explained in greater detail below.

- There are significant gaps in the capabilities and capacities desired of a deep space radar facility by many mission stakeholders and the capabilities/capacities available today
- There is significant overlap in the capability gaps for at least some of the stakeholders, so there may be a common solution in a future deep space radar facility to meet those overlapping needs
- No single stakeholder expressed a need for full-time usage of a deep space radar, potentially enabling a multi-use facility to be shared amongst two or more stakeholders
- A notional facility dedicated to deep space radar observations and consisting of tens to 100+ antennas, each with 18 m apertures and using X-band transmitters or receivers, could meet a significant portion of today's unmet needs for the planetary defense, planetary science, and cislunar SSA missions at a cost of construction of roughly \$500M to \$3.3B
    - Other courses of action to be considered include optimizing use of facilities already in operations and directing development towards projects already in the design stage

There are areas of significant overlap in needs between the many missions and stakeholders considered in this study. A radar facility for the planetary defense mission could, if properly designed, also have the capability to satisfy cislunar SSA mission needs and a significant portion of the planetary science needs. However, such a facility might have limited ability to make significant contributions to the Earth Orbit SSA mission. In addition, the atmospheric/ionospheric mission requires a much lower frequency band than would be used for the core missions, so a multi-use facility would need additional transmitters, receivers, and possibly antennas to meet the atmospheric/ionospheric mission needs. In terms of capacity, this study has shown that it would be reasonable for the planetary defense, planetary science, and cislunar SSA missions to share time on a multi-use facility, with the caveat that there is still some uncertainty in the fractional facility time that would be desired by the cislunar SSA community.

This study assessed a range of trades to design notional facility architectures that meet the planetary defense and cislunar SSA core missions at the threshold and objective levels of desired sensitivity. For the purposes of this study, a full optimization is out of scope, but the notional facility architectures serve the purpose of enabling an order of magnitude cost estimate. Very roughly, we find that a facility with tens of transmit and receive antennas, each with 18 m apertures and with the transmit antennas equipped with 50 kW X-band transmitters, will meet the cislunar SSA sensitivity needs and could cost \$500M to \$1.3B to meet the threshold and objective sensitivity needs, respectively. A hundred or more such antennas would be needed to meet the planetary defense sensitivity needs and could cost \$2.2B to \$3.3B to meet the threshold and objective sensitivity needs, respectively. Alternatively (or in addition), the pairing of two potential planned facilities in the design phase, that being the GBT high-power radar facility (GBT+HPTx) as the transmitter with the ngVLA as the receiver, could satisfy the threshold planetary defense mission needs and exceed the cislunar SSA sensitivity needs.

Based on the assessments of mission needs, capabilities of today's facilities, the capabilities of potential planned facilities, and notional designs of independent facilities, there are several courses of action (COAs) to consider.

Continue use of today's facilities and do not build any new deep space radar capability – Following this COA would continue to provide some planetary science and planetary defense capability and would meet the sensitivity needs of the cislunar mission. Of the COAs considered here, this is the cheapest option. However, there would still be significant gaps between the planetary science and planetary defense mission needs and the delivered capability. Furthermore, radar is not the primary mission of Goldstone and there is not sufficient time available on the GSSR to satisfy fully the needs of any of the deep space radar stakeholders included in this study. Making the best use possible of today's facilities is the only near-term option identified in this study.

Direct development towards projects already in the design stage – This COA would include building a high-power radar transmitter on the GBT (GBT+HPTx), building the ngVLA, and securing sufficient time on both facilities to meet the needs of the deep space radar stakeholders. If enough time on GBT and ngVLA were available, then this option would provide sufficient sensitivity in the medium-term to carry out the planetary defense mission (at the threshold level of performance), a significant portion of the planetary science mission, as well as the cislunar SSA mission. The GBT high power radar would not satisfy the atmospheric, ionospheric, and geospace science missions. This option could be attractive if some funding from the deep space radar mission stakeholders were available to develop, construct, and operate the GBT and ngVLA, but there was not sufficient funding to construct an entirely separate deep space radar facility.

Build a dedicated, multi-use deep space radar facility – This COA would include building a new facility, likely an array of transmitters and receivers, dedicated to deep space radar missions. The array would likely have 100+ elements. Building such a facility would provide sufficient time to the deep space radar stakeholders to meet the identified mission needs and is the only option that meets the planetary defense objective need. However, this is likely to be the costliest option and the slowest to implement, making it a potential far-term solution.

6. Suggestions for Future Activities

In this report, we summarized the needs of multiple Government agencies and users and demonstrated that a feasible solution exists for a joint deep space radar capability that meets some combination of these needs. An independent facility that meets the most stressing objective needs of planetary defense would have on the order of one to two hundred antennas for transmit and receive and would likely have costs on the order of the ngVLA concept. Such an independent facility would be a large undertaking that would need the resources and support of multiple agencies and their associated user communities and would need to find budgetary windows that allow it to be slotted in with the funding and execution of other large infrastructure projects. Such an independent facility would likely need to wait until after ngVLA is realized. Note that while ngVLA has broad scientific community support and priority through the decadal survey process, it may still require the financial contributions of other government and international partners to be constructed as currently envisioned. With that in mind, the following are some thoughts on potential follow-ons to this study:

- Explore collaborative frameworks among stakeholders to determine if there is sufficient support for an independent facility versus collaborating on and potentially extending planned potential facilities and capabilities.
- Assess the need for siting additional radar facilities outside of U.S. territory to enable southern hemisphere coverage for planetary defense and continuous coverage for cislunar user communities. Identify and begin discussions with potential international partners, if appropriate.
- Assess radar technologies and potential technology investment programs that have the potential to provide capability and/or affordability advancements.
- Engage across the cislunar user community to provide more definition of cislunar SSA capability needs in order to refine the reference architecture and to determine the desirability to that stakeholder community of providing a cislunar deep space radar SSA capability.
- Conduct a cost-optimized study to determine if there is a reference architecture that can provide cost efficiencies over the feasible architecture presented in this study. Additionally, determine the extent to which cost drivers such as antenna and transmitter production unit costs and quantities can be controlled.
- Assess the planetary defense threshold and objective needs to determine their contribution to an overall planetary defense strategy. Determine the right balance of needs, effectiveness, and affordability.
- Assess the minimum radar capability needs to meet various planetary science goals and solicit feedback from the planetary science community to prioritize those goals.
- Create a reference development schedule which incorporates the realities of Federal budget cycle prioritizations.
- Develop and cost an approach to adding additional transmit frequencies into the reference architecture to more fully envelop the needs of the stakeholder community.
- More fully explore the spectrum implications of transmit power and frequency on site location and concept of operations.
- Assess the interplay between a high-power radar on GBT and the National Radio Quiet Zone
- Assess the ability of a joint facility to carry out multiple missions simultaneously, for example, breaking up the receive array into two subarrays to carry out a radar mission and a passive mission when the full sensitivity of the receive array is not needed for one mission.

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Appendix A. Acronym List

Acronym	Definition
AO	Arecibo Observatory
AU	Astronomical Unit
COA	Courses Of Action
DSN	Deep Space Network
EO	Electro-Optical
ESM	Electromagnetic Spectrum Management
FCC	Federal Communications Commission
FFRDC	Federally Funded Research and Development Center
G&A	General and Administrative
GBT	Green Bank Telescope
GBT+HPTx	High-power Radar on the GBT
GEO	Geostationary Orbit
GSSR	Goldstone Solar System Radar
I&T	Integration and Test
IR	Infrared
ISR	Incoherent Scatter Radar
ITU	International Telecommunications Union
L2	Lagrange Point 2
LEO	Low Earth Orbit
MOU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
NEA	Near-Earth Asteroid
NEO	Near-Earth Object
ngVLA	next generation Very Large Array
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
PDCO	Planetary Defense Coordination Office
PHO	Potentially Hazardous Object
RF	Radio Frequency
ROM	Rough Order of Magnitude
SME	Subject Matter Experts
SNR	Signal-to-Noise Ratio
SSA	Space Situational Awareness
STM	Space Traffic Management
TIM	Technical Interchange Meeting
UARC	University Affiliated Research Center
VLA	Very Large Array
VLBA	Very Long Baseline Array

Appendix B. Radar Link Budget

General approach

The link budget is a commonly used tool which allows simple computation of the available gains and losses to a signal used in communications and radar systems. It is used to calculate the physical effects of various design choices such that the system requirements can be properly evaluated. The link budget keeps a running tally of all gains and losses experienced by a system between the transmission of a signal, reflection off some object, and at the output of the receiver. Dominating the link budget equation are terms such as *path loss*, which is raised to the fourth power, *wavelength*, raised to the second power, and *antenna gain*, on both transmit and receive. The link budget is used to calculate the effective signal-to-noise ratio (SNR) and subsequent margin of the given transmission to be sensed by the receiver, with a goal of ensuring there is adequate signal for the available sensitivity of the system to understand the echo of the transmitted signal.

While the link budget calculates the forward problem, a radar designer is likely also interested in understanding the inverse problem – what SNR is required to achieve a given probability of detection and false alarm? For this, we utilize the Shnidman approach, whereby an estimate of the SNR is calculated given a desired probability of detection, probability of false alarm, number of non-coherently integrated pulses, and the Swerling case number. We then compare the achievable SNR from the link budget calculation with the required SNR from the Shnidman approach. The margin is the difference between the two.

Discussion of inputs and assumptions

Standard inputs to the link budget equation include transmit power, transmit gain, transmit losses, path loss, received power, receiver gain, and receiver losses. Typically, the user includes a desired radar cross-section (RCS) based on the objective target type and size. The system design parameters can be grouped into several categories. Those of the transmit system include properties such as transmit antenna size, peak transmit power, transmit frequency, antenna efficiency, number of transmit antennas, transmit phase coherency, and other miscellaneous transmit losses. Properties of the target include slant range (with considerations for atmospheric attenuation), RCS, and albedo, to characterize the re-radiated signal power from the target. And finally, properties of the receive system include receiver antenna size, receiver antenna efficiency, number of receivers, receiver phase coherency, and the system temperature of the receiver (including any cryo-cooled elements). Other miscellaneous losses include beam-shape loss, beamwidth factor, fluctuation loss, transmit line losses, mismatch loss (due to voltage standing wave ratio), scalloping loss, and other receiver losses. The coherent integration limit is found as the minimum time between atmospheric phase coherence limit and the master reference oscillator coherent integration limit.

Equations

The standard form of the radar range equation, used to calculate the achievable SNR in a link budget, is given by

$$SNR = \frac{P_t \, \tau \, G_t \, G_r \, \lambda^2 \, \sigma}{(4\pi)^3 \, R^4 \, k \, T_{sys} \, L}$$

Where P_t is the peak transmitted power, τ is the pulse width, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the wavelength of the transmission, σ is the radar cross-section of the target, R is the distance to the target, k is the Boltzmann constant, T_{sys} is the system temperature of the receiving system, and L is a general loss factor.

The standard equation for the Shnidman approach to solving required SNR is given by

$$\eta = \sqrt{-0.8 * \ln\left(4 * P_{fa} * \left(1 - P_{fa}\right)\right)} + sign(P_d - 0.5) * \sqrt{-0.8 * \ln\left(4 * P_d * (1 - P_d)\right)}$$

$$K = \begin{cases} \infty, & Swerling\ Case\ 0\ or\ 5 \\ 1, & Swerling\ Case\ 1 \\ NCI, & Swerling\ Case\ 2 \\ 2, & Swerling\ Case\ 3 \\ 2 * NCI, & Swerling\ Case\ 4 \end{cases}$$

$$\alpha = \begin{cases} 0, & NCI \leq 40 \\ \frac{1}{4}, & NCI > 40 \end{cases}$$

$$SNR_0 = \eta * \left(\eta + 2 * \sqrt{\frac{NCI}{2} + \left(\alpha - \frac{1}{4}\right)}\right)$$

$$C_1 = \frac{\left((17.7006 * P_d - 18.4496) * P_d + 14.5339\right) * P_d - 3.525}{K}$$

$$C_2 = \frac{1}{K}\left(e^{27.31 * P_d - 25.14} + (P_d - 0.8) * \left(0.7 * \ln\left(\frac{10^{-5}}{P_{fa}}\right) + \frac{2 * NCI - 20}{80}\right)\right)$$

$$C_{dB} = \begin{cases} C_1, & 0.1 \leq P_d \leq 0.872 \\ C_1 + C_2, & 0.872 < P_d \leq 0.99 \end{cases}$$

$$C = 10^{\frac{C_{dB}}{10}}$$

$$SNR_{min} = 10 * \log\left(\frac{C * SNR_0}{NCI}\right)$$

Where P_{fa} is the probability of false alarm, P_d is the probability of detection, and NCI is the number of non-coherently integrated pulses. Swerling Case 2 was identified as the operant case for this simulation.

Appendix C. Application of Spectrum Allocation Tables

This appendix gives additional details on how to apply the ITU, NTIA, and FCC allocation tables to the choice of frequency band(s) for a future deep space radar facility.

Frequency Range	Frequency Allocation SRS (Active)	 Radiolocation	Relevant Footnotes of Interest	COMMENTS	Preliminary Suitability (Red Yellow Green)
8550 - 8650 MHz	X	X	G59, 5.468, 5.469, 5.469A	Co primary with EESS Active	
8650 - 9000 MHz		X	G59, US53	Secondary due to G59	
9000 - 9200 MHz		X	G2, 5.337, 5.473A G19	Shared with Aeronautical RadioNav	
9200 - 9300 MHz		X	G59, US110	Secondary. Primary user is Maritime Radionavigation	
9300 - 9500 MHz	X	X	G56 5.427, 5.474, 5.475A, 5.475B, US67, US71, US476A	DoD is primary, limited used by other agencies in support of experimentation and research	
9500 - 9800 MHz	X	X	5.476A	Shared with EESS (Active)	
9800 - 9900 MHz	X	X	5.478	Shared primary; secondary with EESS Active and SRS Active	
9900 MHz - 10 GHz		X	5.479	Perhaps close to 10GHz passiveTBD	
10 - 10.5 GHz		X	US108, G32, 5.479, US128	Fed Radiolocation shared with Amateur	
10.5 - 10.55 GHz		X	US59	Power restriction 40 Watts	
13.25 - 13.4 GHz	X		5.497	Shared with Aeronautical RadioNav	
13.4 - 13.75 GHz		X	G59	Power restriction 40 Watts	
13.75 - 14 GHz		X	G59, US356, US357, US337	Allocated to doppler nav aids 13.25-13.4 GHz. Shared with NF Fixed Satellite uplinks	
15.4 - 15.43 GHz		X	5.511E, US260	Shared with Aeronautical RadioNav	
15.43 - 15.63 GHz		X	5.511E, US260	Shared with Fixed Sat and Aeronautical RadioNav	
15.63 - 15.7 GHz		X	5.511E, US211, US260	Shared with Aeronautical RNAV; aeronautical mobile comms in this band; 5.511E might make this a showstopper	
15.7 - 16.6 GHz		X	G59		
16.6 - 17.1 GHz		X	G59	Shared with Space Research (deep space) uplinks	
17.1 - 17.2 GHz		X	G59, 5.512, 5.513		
17.2 - 17.3 GHz	X	X	G59	Shared with Space Rsh (Active) and EESS (Active)	
17.3 - 17.7 GHz		X	US259, G59, US402, G117	Shared with FCC Sat Comm Part 25	
24.05 - 24.25 GHz		X	G59	EESS-sat (Active) and too close to Passive	
24.65 - 24.75 GHz		X		Radiolocation- Satellite (uplink); shared with FCC Sat Comm Part 25	
33.4 - 34.2 GHz			US360, G34, G117	Shared with Space RSH (deep space)	
35.5 - 36.0 GHz	X		US360, G117	Shared with EESS Sat Active; adjacent to passive	
59.0 - 59.3 GHz		X	5.559	Shared with EESS Passive. Nonstarter	
59.3 - 64.0 GHz		X	5.559, 5.138, US353	Inter Satellite links and might still be close to Passive (TBD)	
76.0 - 81.0 GHz		X	5.560, US342	Shared with Radio Astronomy	
92.0 - 94.0 GHz		X	US161, US342	Shared with Radio Astronomy	
94.0 - 94.1 GHz	X	X	5.562, 5.562A	Shared with EESS (Active)	
94.1 - 95.0 GHz		X	US161, US342	Shared with Radio Astronomy	

The bands listed as "Green" in this preliminary assessment are located between 8550 – 9000 MHz, 9200 – 9300 MHz and 9500 – 10500 MHz. Some bands are limited to military systems per footnote G59 and G32. Therefore, agreement by DoD for use in these bands is required. The specific table entries and footnotes for those segments are shown below [27]:

8550 – 8650 MHz

8500-8550 RADIOLOCATION 5.468 5.469	8500-8550 RADIOLOCATION G59	8500-8550 Radiolocation	Private Land Mobile (90)
8550-8650 EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION SPACE RESEARCH (active) 5.468 5.469 5.469A	8550-8650 EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION G59 SPACE RESEARCH (active)	8550-8650 Earth exploration-satellite (active) Radiolocation Space research (active)	Page 46

8500 – 8550 MHz is allocated to radiolocation and may be suitable for some overlap on the higher end. Deep Space Network utilizes the 8450 – 8500 MHz band for communications, and there is a very low interference protection criterion. With the power output of a deep space radar, it will be difficult to stay below the limits close to the 8450 – 8500 MHz band.

G59: In the bands 902-928 MHz, 3100-3300 MHz, 3500-3650 MHz, 5250-5350 MHz, 8500-9000 MHz, 9200-9300 MHz, 13.4-14.0 GHz, 15.7-17.7 GHz and 24.05-24.25 GHz, all Federal non-military radiolocation shall be secondary to military radiolocation, except in the sub-band 15.7-16.2 GHz airport surface detection equipment (ASDE) is permitted on a co-equal basis subject to coordination with the military departments.

8650 – 9000 MHz

Table of Frequency Allocations			8.65-11.7 GHz (SHF)		Page 47
International Table			United States Table		FCC Rule Part(s)
Region 1 Table	Region 2 Table	Region 3 Table	Federal Table	Non-Federal Table	
8.65-8.75 RADIOLOCATION 5.468 5.469			8.65-9 RADIOLOCATION G59 US53	8.65-9 Radiolocation US53	Aviation (87) Private Land Mobile (90)
8.75-8.85 RADIOLOCATION AERONAUTICAL RADIONAVIGATION 5.470 5.471					
8.85-9 RADIOLOCATION MARITIME RADIONAVIGATION 5.472 5.473					
9-9.2 AERONAUTICAL RADIONAVIGATION 5.337 RADIOLOCATION 5.471 5.473A			9-9.2 AERONAUTICAL RADIONAVIGATION 5.337 RADIOLOCATION G2 5.473A G19	9-9.2 AERONAUTICAL RADIONAVIGATION 5.337 Radiolocation	

US53: In view of the fact that the band 13.25-13.4 GHz is allocated to doppler navigation aids, Federal and non-Federal airborne doppler radars in the aeronautical radionavigation service are permitted in the band 8750-8850 MHz only on the condition that they must accept any interference that may be experienced from stations in the radiolocation service in the band 8500-10000 MHz.

G59: In the bands 902-928 MHz, 3100-3300 MHz, 3500-3650 MHz, 5250-5350 MHz, 8500-9000 MHz, 9200-9300 MHz, 13.4-14.0 GHz, 15.7-17.7 GHz and 24.05-24.25 GHz, all Federal non-military radiolocation shall be secondary to military radiolocation, except in the sub-band 15.7-16.2 GHz airport surface detection equipment (ASDE) is permitted on a co-equal basis subject to coordination with the military departments.

9200 – 9300 MHz

9.2-9.3 EARTH EXPLORATION-SATELLITE (active) 5.474A 5.474B 5.474C RADIOLOCATION MARITIME RADIONAVIGATION 5.472 5.473 5.474 5.474D	9.2-9.3 MARITIME RADIONAVIGATION 5.472 Radiolocation US110 G59 5.474	9.2-9.3 MARITIME RADIONAVIGATION 5.472 Radiolocation US110 5.474	Maritime (80) Private Land Mobile (90)

US110: In the band 9200-9300 MHz, the use of the radiolocation service by non-Federal licensees may be authorized on the condition that harmful interference is not caused to the maritime radionavigation service or to the Federal radiolocation service.

Assessment must be undertaken to determine there would not be interference to the maritime radionavigation or federal radiolocation service.

Some alternative bands that may be appropriate are between 9500 MHz and 10500 MHz. Precautions to assess whether passive microwave measurement on weather satellites would be impacted need to be done.

9500 – 9800 MHz, 9800 – 9900 MHz, 9900 – 10000 MHz

9.5-9.8 EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION RADIONAVIGATION SPACE RESEARCH (active) 5.476A	9.5-9.8 EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION SPACE RESEARCH (active)	9.5-9.9 Earth exploration-satellite (active) Radiolocation Space research (active)	Private Land Mobile (90)
9.8-9.9 RADIOLOCATION Earth exploration-satellite (active) Fixed Space research (active) 5.477 5.478 5.478A 5.478B	9.8-9.9 RADIOLOCATION Earth exploration-satellite (active) Space research (active)		
9.9-10 EARTH EXPLORATION-SATELLITE (active) 5.474A 5.474B 5.474C RADIOLOCATION Fixed 5.474D 5.477 5.478 5.479	9.9-10 RADIOLOCATION 5.479	9.9-10 Radiolocation 5.479	

10000 - 10500 MHz

10-10.4 EARTH EXPLORATION-SATELLITE (active) 5.474A 5.474B 5.474C FIXED MOBILE RADIOLOCATION Amateur 5.474D 5.479	10-10.4 EARTH EXPLORATION-SATELLITE (active) 5.474A 5.474B 5.474C RADIOLOCATION Amateur 5.474D 5.479 5.480	10-10.4 EARTH EXPLORATION-SATELLITE (active) 5.474A 5.474B 5.474C FIXED MOBILE RADIOLOCATION Amateur 5.474D 5.479	10-10.5 RADIOLOCATION US108 G32 5.479 US128	10-10.45 Amateur Radiolocation US108 5.479 US128 NG50	Private Land Mobile (90) Amateur Radio (97)
10.4-10.45 FIXED MOBILE RADIOLOCATION Amateur	10.4-10.45 RADIOLOCATION Amateur 5.480	10.4-10.45 FIXED MOBILE RADIOLOCATION Amateur			
10.45-10.5 RADIOLOCATION Amateur Amateur-satellite 5.481				10.45-10.5 Amateur Amateur-satellite Radiolocation US108 US128 NG50	

G32: Except for weather radars on meteorological satellites in the band 9975-10025 MHz and for Federal survey operations (see footnote US108), Federal radiolocation in the band 10-10.5 GHz is limited to the military services.

Appendix D. Aerospace Team

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