Astro2020 APC White Paper

GBT Planetary Radar System

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Ground Based Project

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Executive Summary:

A transmission radar capability for the 100 m Robert C. Byrd Green Bank Telescope (GBT) located at the Green Bank Observatory (GBO) would be an excellent complementary system to existing planetary radars at the Arecibo and Goldstone Observatories, meeting growing community need for mono- and bi-static radar observations. The GBT site provides good natural shielding and is protected from radio frequency interference (RFI) inside the National Radio Quiet Zone (NRQZ). The telescope is fully steerable, giving full access to 85% of the celestial sphere from the site and tracking capabilities. Here, we discuss the technical considerations and scientific applications for a Ka-Band transmitter (35 GHz). This high-frequency option will provide high spatial resolution on targets, complementing existing lower frequency systems. Ka-Band is the most technically challenging of the possible systems compatible with GBT. We highlight the value and tractibity of a Ka-Band system because all lower-frequency systems could be implemented at a lower cost and with fewer scheduling constraints. This paper complements the concurrent APC white paper by J. Lazio et al., “Linking the Solar System and Extrasolar Planetary Systems with Planetary Radar: An Infrastructure Activity” and the concurrent APC white paper by P. Taylor et al, “Planetary Radar Astronomy with Ground-Based Astrophysical Assets”.

1 Key Science Goals and Objectives

1.1 Asteroids

Planetary radar systems are the primary means for tracking and studying near earth objects (NEOs) and near earth asteroids (NEAs). An advanced radar, such as a Ka-Band transmitter can only further our understanding of these objects and help us to better track their courses [12]. A Ka-Band radar will give finer resolution imaging for smaller objects. In the era of the Large Synoptic Survey Telescope (LSST) many NEOs will be discovered and the rapid response and sky coverage provided by the GBT will be greatly beneficial. Radar is also much more cost effective than space based missions to asteroids. It provides the necessary information required for tracking, shape modeling, and orbital path. For more information please see the Astro2020 scientific white paper, “Planetary Radar Astronomy with Ground-Based Astrophysical Assets” by P. Taylor et al. [12].

1.2 Planetary Surface Studies

Radar plays a crucial role in the mapping of planetary surfaces. Radar allows us to see beneath the surface of what is visible to optical telescopes. For more information see the Astro2020 science white paper, “Radar Astronomy for Planetary Surface Studies” by B. Campbell et al. [1].

1.3 Planetary Structure and Spin

Planetary radar is an inexpensive and powerful way to monitor the planets. Tracking planetary spin states is one of the most important tools in determining interior structure of a planet [7]. For more information see Astro2020 science white paper “Structure of terrestrial planets and ocean worlds” by J. Margot et al. [7].

1.4 Comets

Radar reveals comets' size, spin rate, and surface features on the nucleus as well as the coma grains at about the 0.1 λ scale. This radar would probe a new size regime of coma particles between the micron scale of visible light scattering and the cm-scale of existing S-Band and X-Band radars. For this application, far less power is required. For more information see the Astro2020 science white papers "Ground-based Observations of Small Solar System Bodies: Probing Our Local Debris Disk" by A. Lovell et al. [6].

1.5 Space Situational Awareness Tracking

A Ka-Band radar of even medium power would be highly valuable for the tracking of geostationary and lower orbit GPS satellites. Adding a target illumination signal will expand the GBT capabilities allowing it to participate in Space Situational Awareness (e.g. space "junk"), imaging, and tracking [9]. The GBT's tracking potential has already been demonstrated through a series of observations of known objects conducted in collaboration with AGI in December 2015. With the increasing number of objects in Earth's orbit, this technology would allow for accurate tracking of satellites, micro-meteorites, "space junk", etc.

2 Technology Overview

2.1 Existing Planetary Radar Systems

Within the US there are only 2 transmitting sites: Arecibo Observatory (AO) in Puerto Rico and the Goldstone Solar System Radar (GSSR) in California (Table 2.1.1) [2].

Transmitting Locations	Frequency [GHz]	Bandwidth [MHz]	Power [MW]	Receiving Location
Arecibo, PR	2.38	20	1.0 (CW)	AO, GBT, VLA, LRO, VLBA
(300 m)	0.43	0.6	2.5 (pulsed)	AO, GBT
Goldstone, CA DSS-14 (70 m)	8.56	50	0.5 (CW)	GSSR, GBT, AO, VLA,10 VLBA sites
DSS-13 (34 m)	7.19	80	0.08 (CW)	GSSR DSS-28, GBT, AO

Table 2.1.1: Current US planetary radar systems and the telescopes that are used as receiving stations, primarily for NEA observations but also for other planetary studies. The Table is a minor adaptation of Table 6.1 of the US National Academies 2015 reports a strategy for active remote sensing amid increasing demand for radio spectrum. N.B. Close asteroid observations require bistatic operation. Very Large Array (VLA) in Socorro, NM, Lunar Reconnaissance Orbiter (LRO), lunar orbit, Very Long Baseline Array (VLBA), Deep Sky Station (DSS).

Existing transmitter sites are excellent for observing, but also have a number of limitations including sky coverage, time accessibility, and maximum usable frequency [9]. The GBT is able to accommodate all these issues with its excellent sky coverage, dynamic scheduling system, and large frequency range.

There are other radar systems outside the US, but due to their location and the Earth's rotation, there is only limited mutual visibility [4]. Observations between Goldstone and Canberra in theory are able to be used bistatically, but such observations have never been done.

2.2 Radar Technical Specifications

A high-powered Ka-Band (35 GHz) transmitter is feasible and should be installed on the GBT. GBO would build a radar transmitter and receiver package consisting of low-noise receivers and a ~500 kW pulsed transmitter, along with the ancillary modulator, monitor, control electronics and air conditioning units.

The work will consist of integrating a transmitter package, a quasi-optical beam waveguide, a modulator / demodulator system, and receivers designed and built by the GBO into the GBT-based system (Figure 2.2.1).

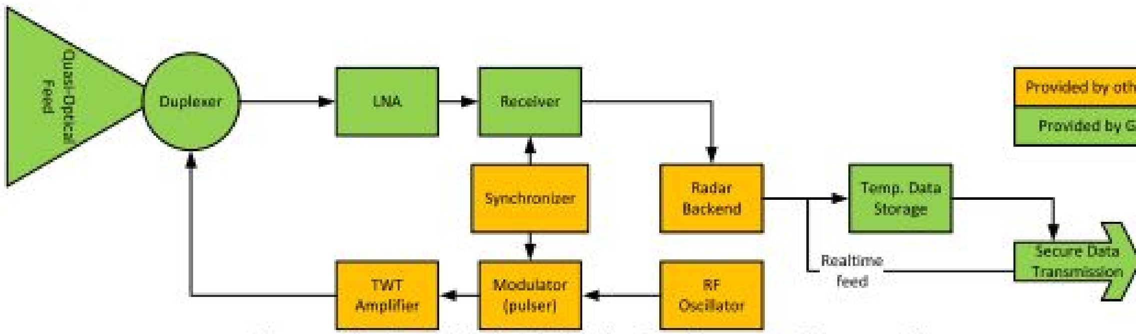

Figure 2.2.1 Simplified GBT Radar Configuration (Proposed)

This radar would conform to the parameters listed in Section 2.4.

2.3 Antenna

The JPL Agile receiver backend is already integrated into the GBT's system. The backend would need to be configured to use the already existing transmitter setting. Beyond that the Telescope Operators would need to be trained on the control of the transmitter using the same system used currently to control the backend [4].

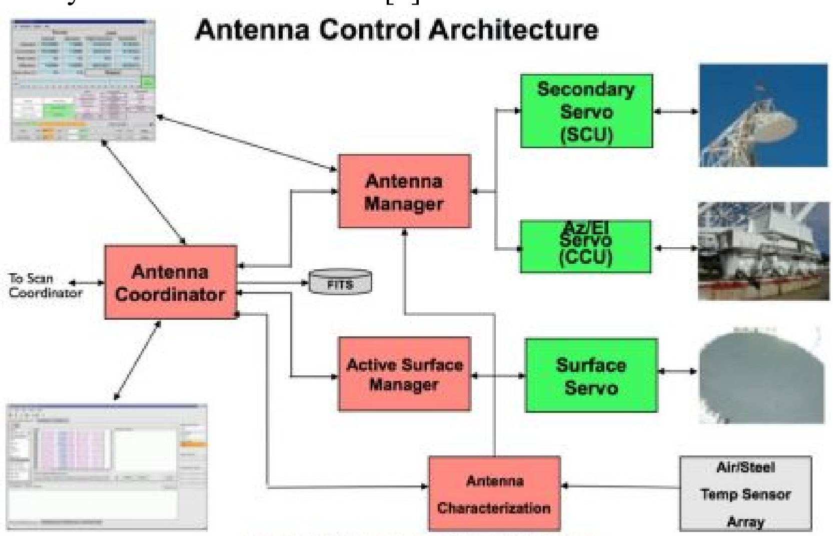

Figure 2.3.1 GBT Antenna Control System block diagram

Upgrades to infrastructure, power, and cooling systems would need to be taken into account and many options are already available to mitigate these potential issues. Additional weight added to the tipping structure of the GBT, mostly due to the cooling system can be easily mitigated. There are multiple options that can be used for this and the best option would be determined once all the final aspects were decided upon.

2.4 Transmitter

The transmitter will meet the following requirements:

- Center Frequency (GHz): 35
- Maximum Bandwidth (GHz): 4
- Modulation: Continuous Wave (CW), Linear Frequency Modulation (LFM), Bi-Phased Code (BPC)
- Beamwidth (amin): 0.29
- Antenna Gain (dB): 87.8
- Transmitter Power (kW): 500
- Typical Pulse Width (μs): 100
- Duty Cycle: ≥ 20%
- Power Source: Traveling Wave Tubes (TWT) (4 @ 250 kW each)

Currently there are no existing transmitter tubes that can transmit such a high power at Ka-Band. They would need to be developed (further discussed in Section 3.1). There are however existing Ka-Band tubes that produce a much lower level of power. While this option is not the preferred method, it can also be employed and is discussed in more detail in Section 2.8.

The transmitter assembly will consist of:

- Power supply
- Controls
- Cooling System
- TWT protection system

In the current model we would use the traveling wave tubes over the standard klystrons. They are much lighter and easier to cool. They are also what is being used at the Millimeter Wave Telescope (MMW).

Klystrons are about 50% efficient and the TWTs that we are proposing are probably about 55% efficient. Overall, to transmit 500 kW of power, we need to input 1 MW of power into the system. We would need 4 tubes of 250 kW per tube to generate about 1 MW of total power and transmit 500 kW of power. Combining the TWTs together can also cause efficiency loss. The typical life for a TWT is about 2,000 operating hours and they may be rebuilt twice for a full lifespan of 6,000 hours [9]. The proposed system would consist of 6 tubes:

- 4 being used
- 1 spare
- 1 being rebuilt at the factory

For cooling, several air cooling units will be installed near the transmitter [3]. These units would be the heaviest components added to the tipping structure and would require mitigation of weight elsewhere. Many options are already available to accommodate this.

2.5 Quasi-Optical Beam Waveguide

GBO will design and build the quasi-optical beam waveguide isolator/circulator assembly needed to match the transmit power to the antenna.

The transmitted signal from the horn is redirected and refocused by two mirrors in a clamshell configuration. Two mirrors are used to eliminate cross-polarization products of one mirror generated from the amplitude of the necessary off-axis configuration of the mirror. The second mirror launches the signal into the isolator/circulator assembly, configured with wire grid polarization filters and a polarization rotator [8].

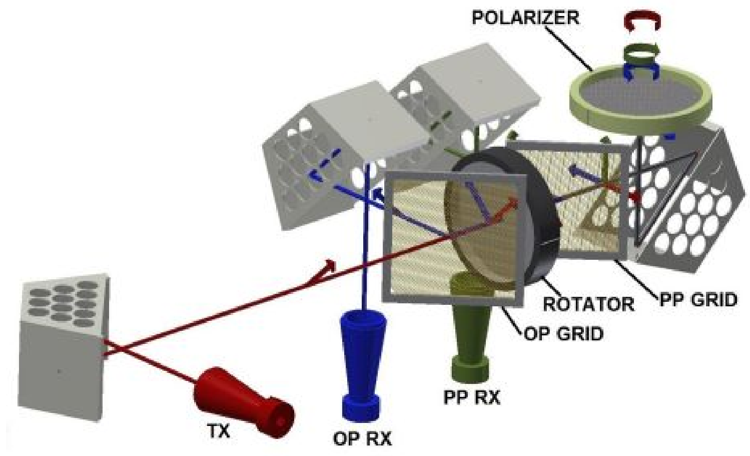

Figure 2.5.1 Quasi-optical beam waveguide isolator/circulator assembly for 1 tube. Transmit path and polarization are in red, receive paths and polarizations for Preferred Polarization (PP) are in green, and receive paths and polarizations for Opposite Polarization (OP) are in blue.

The wire grid polarization filters have closely spaced, parallel wires running in one direction. Signals polarized perpendicular to the direction of the wires pass through the grid, while signals polarized parallel to the wires are reflected. The first wire grid polarization filter encountered by the transmit signal, the opposite polarization (OP) filter, has the wires set perpendicular to the transmit polarization to pass the transmit signal and the plane of the wires is set at a 45° angle to the axis of propagation, which reflects the returning OP signal to the OP receiver feed horn.

After passing through the OP grid the transmit signal passes through the polarization rotator, a gyromagnetic Faraday device. It consists of a ferrite material in a magnetic field collinear with the direction of propagation. In this state, ferromagnetic resonance affects the propagation of the two counter-rotating circular components of the polarization differently, slowing one but not the other. The combination of ferrite thickness and magnetic field strength act on the linear polarization and rotate the polarization through a specific angle. With finite loss in the ferrite material and the associated undesired heating of the material, a higher strength magnetic field allowing for a thinner ferrite is desired. The rotator is a non-reciprocal device; the rotation effect occurs in the same angular direction as seen from one port of the rotator regardless of the direction of propagation through the rotator. For the purposes of this particular isolator/circulator, the rotation will be 45° and it rotates the transmit signal polarization so it is parallel to the surface of the GBT turret.

After the rotator, the transmit signal passes through the preferred polarization (PP) wire grid filter. The wires in this filter are oriented perpendicular to the surface of the GBT turret and the plane of wires is oriented at 45° to the axis of propagation to reflect the returned PP signal to the PP receiver feed horn.

From the PP wire grid filter the signal is redirected and refocused by a second clamshell mirror pair through a circular polarizer. This polarizer is made up of parallel conducting plates arranged similarly to an open Venetian blind, followed by parallel strips of dielectric material similarly spaced and arranged perpendicular to the conducting plates. The polarizer is positioned with the conductive plates and dielectric strips both oriented 45° to the linear polarization of the transmit signal; this results in equal, orthogonal components of the transmit signal oriented perpendicular and parallel to the conductive plates. The component perpendicular to the conductive plates passes through the polarizer with a free space wavelength; the parallel component passes through with a wavelength equal to a TE_{10} (transverse electric) mode in a rectangular waveguide of width equal to the separation between the plates. The depth of the conductive plates is adjusted for a differential phase shift of 90° between the orthogonal components, which results in a circularly polarized output. This effect is not particularly broadband; the addition of dielectric strips perpendicular to the conductive plates improves the desired response over a wider bandwidth. Unlike the rotator, this device is reciprocal and also converts circularly polarized signals to perpendicular, linear polarization.

As a result of refocusing by the second clamshell mirror pair through the circular polarizer, the transmit signal is launched into the telescope optics identically in appearance to a circularly polarized signal emitted from a feed horn at the focus. The signal travels to, and is reflected by a target, or targets, of interest.

A low-noise monopulse receiver system will be developed as well. This receiver will be optimized for the lowest possible noise over 4 GHz bandwidth.

2.6 Modulator/Demodulator System

A modulator / demodulator system capable of modulating the signal with a LFM chirp, or a pseudo-random, BPC. Chirped or coded waveforms allows for increased radar range, which allows for better, more precise measurements. A CW waveform will also be capable of being generated.

2.7 Data Processing

Since the backend will most likely be the existing radar backend, post processing of the observations will be similar to how they are done now, with some Green Bank personnel already capable of reducing the data.

2.8 Existing Transmitter Technology

Currently, a system has already been designed for the GBT using low power Ka-Band TWTs that already exist. The system can support 1 to 2 VTA-5701C CC TWTs from Communication and Power Industries (CPI) or a similar company, which are coupled cavity traveling wave tubes. This would produce only 60 kW of power. However more could be added to increase the amount of power. This system would include 5 tubes:

- 2 in use
- 2 spares
- 1 being reconstructed at the manufacturer [9]

The calculations for this are to be found in Section 2.9. The costing for this system is also included in Section 6.2.

2.9 Calculations

Using the Radar Equation and comparing this to existing systems has allowed us to determine what would be the best option for the GBT. More power would make the system better, but would cause hindrances in other ways. Thus calculations were made to find the optimal middle ground.

The radar equation states:

$$SNR = \frac{P_t G (A_e A_{eff}) \sigma}{4\pi^2 R^4 k T_{sys} B}$$

[5]

Where SNR is signal to noise ratio, P_t is power transmitted, G is the antenna gain, A_e is the antenna area, A_{eff} is antenna efficiency, σ is radar cross section, R is the target-distance, T_{sys} is the system temperature, and B is the bandwidth.

Assuming $\sigma = 10\ m^2$ and an R = 1 LD (lunar distance = 3.8E5 m), we get the following powers (W) and Signal to Noise ratio (SNR) (dB) for Goldstone and Arecibo using their existing systems:

	AO (1 MW @ 2.4 GHz)	GSSR (500 kW @ 8.6 GHz)	GBT (500 kW @ 35 GHz)	GBT (60 kW @ 35 GHz)
Received Power:	4.13×10^{-18} W	8.8×10^{-20} W	1.07×10^{-17} W	1.28×10^{-18} W
Noise Power:	3.18×10^{-22} W	2.35×10^{-22} W	6.9×10^{-22} W	6.9×10^{-22} W
SNR:	41.14 dB	25.47 dB	41.90 dB	32.69 dB

Due to the GBT's diameter, aperture efficiency, and surface accuracy, a low-powered (60 kW) transmitter system at Ka-band is more sensitive than the current Goldstone system, while a high-powered system (500 kW) transmitter system would rival the current Arecibo system. As a fully steerable telescope with a significant fraction of open-skies time [11], a high-frequency transmitter system on the GBT is an attractive option that is complementary to the existing Arecibo and Goldstone planetary radars.

3 Technology Drivers

3.1 High-Powered Ka-Band Transmitting Tubes

Designing a higher power Ka-Band transmitter represents a significant challenge, but would be a great asset for planetary science. With the excellent sensitivity and efficiency of the GBT, developing a high powered Ka-Band transmitting tube would be advantageous and would take advantage of those attributes. We have determined that it should take about 4 years to develop a new tube of this power based on the time it takes to create upgrades to existing tubes. We are expecting about $3,000,000 for development, with each tube costing about $750,000 - $1,000,000 to purchase [5]. Operations at Ka-Band is affected by weather

4 Organization, Partnerships, and Current Status

Green Bank engineers have extensive experience in receiver design and construction, antenna integration, and tracking control systems. Transmitter design, radar pulse systems, and radar back end processing will be designed in collaboration with members of the radar community. The Green Bank concept development team has conducted numerous high-level discussions with equipment and system providers to research the various design and operating concept for the GBT radar. They have determined that the following areas would require external collaboration from the radar community:

- Transmit/receive synchronization system
- Transmitter design
- Pulse generation
- Radar backend processing

Many of these topics have already been researched with external sources for this proposal. Green Bank Observatory would also be looking into technology reuse wherever possible [10]. We are expecting to license or purchase the following major components:

- High Power Amplifier Tubes
- Signal Synthesis Modules
- Transmitter Assembly
- Commercial Cooling System

5 Schedule

5.1 Implementation Phases

We estimate about 4 years to get the system up and running, with an additional 1-2 years to create the additional backup transmitting tubes [5]. It should also be noted that the 4 years includes the time to develop the 250 kW TWT tubes [13]. There are 5 phases to complete this project:

Phase 1: Conceptual Design (6 months)

- Assemble GBO Radar Core Team
- Obtain Internal Funding for Conceptual Design Work
- Identify Major Technical and Cost Risks
- Conduct Feasibility Studies
- Draft Technical Proposal
- Conduct Conceptual Design Review
- Submit Technical Proposal to Stakeholders

Phase 2: Design Development (8 months from the start)

- Obtain Design Phase Approval
- Obtain Preliminary Funding
- Initiate Project Organizational Structure
    - GBO Project Team
    - External Partner/Consultant Relationships
    - Advisory Team
- Assemble Preliminary Technical Designs
- Prototype Design for High-Risk/Long Lead-Time Systems
- Prepare Detailed Implementation Plan
- Conduct Preliminary Design Review(s) (PDR)
- Submit Implementation Plan and PDR Results to National Science Foundation (NSF) and other Stakeholders

Phase 3: Construction (2 years)

- Obtain Approval to Proceed to Construction Phase

- Secure Construction Funding
- Establish Design and Fabrication Contracts
- Procure Materials and Systems
- Start On-Site Construction and Fabrication
- Assemble and Test Radar Subsystems and Instruments On-Site
- Unit and Functional Testing
- Prepare for Commissioning and Operations
    - Develop Commissioning/Operations Plan
    - Assemble Operations Staff

Phase 4: Commissioning/Testing (4 months)

- Commission the Radar System and Instruments
- Train Operations Staff
- Evaluate System Performance
- Conduct End to End Testing
- Conduct Acceptance Reviews
- Transition to Preliminary Operations

Phase 5: Retirement (~10 - 15 years)

- Decommission the Radar System and Instruments
- Adjust operations to compensate for the reduced workload
- Disposal of equipment

5.2 Work Breakdown Structure

The tasks for the GBT radar system have been organized into a work breakdown structure (WBS; Figure 5.2) that will help determine the necessary work to complete from a project-based perspective with deliverables.

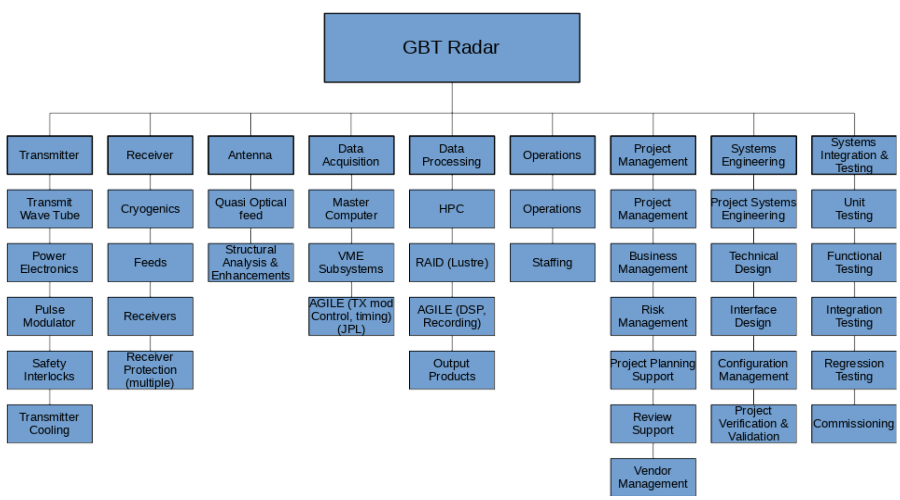

Figure 5.2: Work Breakdown Structure

5.3 Sessions and Maintenance

The anticipated GBO portfolio would include a manageable radar schedule shared with open-skies observing and other paid-time commitments. Since the GBT currently employs a dynamic scheduling system, it will be very easy to schedule observations as they come up or which may not be able to be planned far in advance.

Currently identified maintenance requirements suggest a two-week radar shutdown period will be required annually for activities such as preventative maintenance, cooling liquid replacement, full test of safety protections and interlocks, and inspection of the overall system [9]. In addition to annual maintenance, we plan to have one full day per month for radar maintenance that will occur on a pre-existing GBT maintenance day.

6 Cost Estimates

6.1 High Power Radar cost (500 kW)

The current rough order of magnitude cost estimate for the high powered (~500 Kw) version of the GBT Planetary Radar was composed in June 2019, by the GBO for the fiscal years 2021-2024:

High Powered Radar Costing	2021 (Development)	2022-2023 (Construction)	2024 (Commissioning)	Total
Total Estimated Costs:	**$4,500,00**	**$17,500,00**	**$2,000,000**	**$24,000,000**

6.2 Medium Power Radar cost (60 kW)

The current rough order of magnitude cost estimate for the medium powered (~60 kW) version of the GBT Planetary Radar was composed in June 2019, by the GBO for the fiscal years 2021-2024:

Medium Powered Radar Costing	2021 (Development)	2022-2023 (Construction)	2024 (Commissioning)	Total
Total Estimated Costs:	**$2,500,000**	**$13,500,000**	**$2,000,000**	**$18,000,000**

These costs are solely for the radar system itself, no costing for GBT infrastructure upgrades have been included at this time.

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