Ground-Based Radar for Planetary Science and Planetary Defense

A White Paper Submitted to the Planetary Science and Astrobiology Decadal Survey (2023-2032) Committee

Left: The Goldstone Solar System Radar 70-m DSS-14 telescope in California; *Center*: The Arecibo Observatory 305-m William E. Gordon Telescope in Puerto Rico; *Right*: The Green Bank Observatory 100-m Green Bank Telescope in West Virginia. *Image Credits*: Hal Janzen, Israel Cabrera, and NRAO.

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Co-Signers: Full List of Endorsements

This white paper has broad support from more than 50 members of the planetary science community, including graduate students to senior scientists from public and private institutions, profit and non-profit organizations, and NASA centers; ground- and space-based observers from across the electromagnetic spectrum; current and former SBAG chairs and steering committee members; former (and future) DPS chairs and current and former DPS Committee members; spacecraft mission PIs; and scientists working with Rubin Observatory (LSST) and NEOSM.

Executive Summary: Planetary radar is a unique method for studying solid bodies in the Solar System and arguably the most powerful method for post-discovery, remote physical and dynamical characterization of near-Earth objects. Radar plays a critical role in planetary science and planetary defense, where all facilities equipped for planetary radar are shared-use assets. With dedicated planetary radar facilities unlikely on the decadal timescale, it is imperative that the shared-use, single-dish radio telescopes utilized for planetary radar remain viable through the next decade. This includes transmitters at Arecibo Observatory and the Goldstone Solar System Radar, along with the Green Bank Telescope, which is often used as a receiver in conjunction with the transmitting telescopes. The near-Earth object discovery rate will accelerate with the advent of the Vera C. Rubin Observatory and the Near-Earth Object Surveillance Mission. To satisfy federal mandates for tracking and characterizing the known near-Earth object population, we recommend that: (1) single-dish radio telescopes are adequately funded, (2) investments are made in planetary radar programs to keep pace with discovery rates, (3) transmitter technology is improved and facility upgrades are studied, and (4) the multidisciplinary use of time-shared facilities is given complete consideration in future decision making. ***Any breakdown of the planetary radar programs using single-dish radio telescopes would be detrimental to planetary defense and small-body science and exploration on the timescale of the decadal survey.***

Motivation: Several science white papers describe the important role of radar in planetary science (Virkki et al.; Rivera-Valentín et al.; Haynes et al.; Margot et al.) as well as planetary defense (Mainzer et al.; Adamo et al.). Here, we concentrate on planetary radar studies of small bodies, specifically the near-Earth objects (NEOs) that make up roughly 90% of the telescope time used for planetary radar. NEOs include near-Earth asteroids (NEAs), the dominant population both in number and observations, and near-Earth comets.

The motivation for healthy national planetary radar programs stems from planetary defense, small-body science, and mission support. Planetary defense is a key applied program in the National Aeronautics and Space Administration (NASA) Science Mission Directorate's strategy for science excellence [1] through "leading efforts to detect, track, and characterize" NEOs via the Planetary Defense Coordination Office (PDCO). In fact, the *George E. Brown, Jr. Near-Earth Object Survey Act*, which became part of the NASA Authorization Act of 2005 [2], tasked NASA to detect, track, catalog, and characterize 90% of all NEAs larger than 140 meters by the end of 2020. While this 2020 goal is unattainable, its premise drives the efforts of surveys that will shape our understanding of small bodies in the Solar System over the next decade, including the National Science Foundation's (NSF) Vera C. Rubin Observatory (formerly the Large Synoptic Survey Telescope), designed in part to inventory the Solar System, and NASA's Near-Earth Object Surveillance Mission (NEOSM), a space-based infrared observatory dedicated to the detection and characterization of small bodies. As described in the National Research Council report *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies* [3], in addition to optical and infrared observations, ***radar plays a "unique role" in achieving the tracking and characterization goals of the George E. Brown Act***.

The Planetary Science Subcommittee of the NASA Advisory Council (now the Planetary Science Advisory Committee) acknowledged the role of Arecibo Observatory in planetary defense, encouraging NASA to work with NSF to "preserve the nation's science and security interests and provide for the stability and productivity of this critical national asset" [4a]. NASA's response included a letter [4b] to NSF in which then NASA Planetary Science Division Director and current ***NASA Chief Scientist James L. Green recognized Arecibo Observatory as a "particularly important asset for NASA's NEO tracking and characterization efforts, which are mandated by law. Continuing radar operation is valuable to the mission of NASA's Planetary Defense Coordination Office."*** The astronomy community at large has shown support for science operations of single-dish radio telescopes with planetary radar capabilities, especially Arecibo, through a statement from the American Astronomical Society (AAS) [5] and two unanimous resolutions of the Division for Planetary Sciences of the AAS [6]. The Small Bodies Assessment Group has consistently stated [7] that planetary radar programs and the facilities that host them constitute critical national assets for both planetary science and planetary defense.

As suggested above, planetary science of small bodies and planetary defense are not solely the responsibility of NASA. In June 2018, the *National Near-Earth Object Preparedness Strategy and Action Plan* [8], a report by the Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects of the National Science & Technology Council (NSTC) was published to "improve our Nation's preparedness to address the hazard of near-Earth object impacts over the next 10 years." As part of this strategy, the NSTC advised that the "United States should lead in establishing a coordinated global approach for tracking and characterizing NEO impact threats." To do so, ***a short-term action (<2 years) tasked NASA, NSF, and the United States Air Force to "identify existing and planned telescope programs to improve detection and tracking by enhancing the volume and quality of current data streams, including from optical, infrared, and radar facilities."*** This leads to the long-term action (5 to 10 years) to "inform investments in telescope programs and technology improvements to improve completeness and speed of NEO detection, tracking, and characterization."

The June 2019 report, *Finding Hazardous Asteroids Using Infrared and Optical Wavelength Telescopes* [9], from the National Academies of Sciences, Engineering, and Medicine advocates for a space-based infrared survey telescope (i.e., NEOSM) to complete the requirements of the George E. Brown, Jr. Act in a timely fashion. After NEOs are discovered, it describes planetary radar as a technique capable of "providing … positional and characterization measurements," including the "best attainable size from remote observations," complementing infrared and optical observatories by leveraging the use of existing assets with known maintenance costs. As such, ***the combination of radar, infrared, and optical assets is "critical for a full understanding of the [Earth] impact hazard."***

Radar has detected more than 950 NEAs [10] or 4% of the known NEA population. Currently, radar observations are obtained of only ~30% of possible targets (Naidu et al., 2016). In the next decade, the Rubin Observatory and NEOSM will come online. It is expected Rubin Observatory will detect ~15,000 asteroids larger than 140 meters [11], about 60% of those predicted to exist, during ten years of operation. Similarly, NEOSM will detect hundreds of thousands of NEOs, including ~76% of those larger than 140 meters in its five-year nominal survey (Sonnett et al., 2020). With an acceleration in the discovery rate of NEOs over the next decade, there will be even more radar targets in need of tracking and characterization. ***The current planetary radar programs will not be able to keep up with the upcoming abundance of radar targets and will require expansion to meet the tracking and characterization goals of the George E. Brown Act.*** While we focus on NEOs (along with Virkki et al.), characterization of other Solar System bodies (see Rivera-Valentín et al.; Margot et al.) and interstellar visitors [12] are natural byproducts of supporting the planetary radar programs that focus on small bodies.

Key Capabilities: Today, NEOs are typically discovered via wide-field optical surveys, which provide plane-of-sky astrometry as well as size estimates based on brightness. Post discovery, radar provides complementary line-of-sight astrometry and detailed physical characterization. The combination of line-of-sight velocity and distance astrometry from radar, with fractional precision as fine as 1 part in 100 million, with contemporaneous optical plane-of-sky astrometry fully determines the six-dimensional position and velocity state vector of the target. Radar astrometry often prevents newly discovered objects from being lost and requiring re-discovery, while routinely reducing uncertainties on orbital elements by five orders of magnitude. In terms of planetary defense, this capability extends the timescale of Earth-encounter predictability by a factor of 5 (to 400 years on average) and greatly improves impact probability estimates, while increasing impact warning time an average of 4 years compared to optical-only datasets (Ostro & Giorgini, 2004; Giorgini et al., 2009, [13]). Furthermore, non-gravitational accelerations on NEO orbits, significant sources of uncertainty for long-term trajectory prediction, are constrained more stringently by multi-apparition radar astrometry than by optical data alone. ***The most important (and common) outcome of obtaining radar astrometry is ruling out future impacts, e.g., (99942) Apophis, which is of supremely high value, as it lessens the urgency and burden of contingency planning, eliminates the enormous associated costs of fast-reacting mitigation and/or evacuation measures, and reduces societal anxiety.***

With increasing echo strength, radar provides distance astrometry (precise to less than 1 km for a body several million km from Earth); constraints on reflectivity, composition, taxonomic class, near-surface density and roughness, and rotation state; direct evidence for satellites; a direct measurement of size; a shape estimate; evidence of surface geology; and, in the case of multiple-body systems, estimates of the system mass and bulk density. In particular, radar has discovered >70% of all known NEA satellites, identifying asteroid companions when observing circumstances did not allow other techniques to do so. These properties are of great interest both to planetary science for understanding the small-body population (see Virkki et al.) and planetary defense for estimating impact effects and informing if and when mitigation is necessary and how to do so (see Mainzer et al.; Abell et al.). Impact energy scales as density × $(\text{diameter})^3$ × $(\text{velocity})^2$ and radar can constrain all three parameters through mass and volume estimates from binary systems, sizes from resolved imaging, and relative velocity from precise astrometry. As such, radar played an important role in the International Asteroid Warning Network global planetary defense exercises for NEAs 2012 TC4 (Reddy et al., 2019) and (66391) Moshup [14]. Radar images with resolution as fine as 7.5 m per pixel with Arecibo and 1.875 m per pixel with Goldstone reveal a level of detail and science content comparable to a spacecraft flyby. In this sense, it is possible to characterize orders of magnitude more objects with radar at orders of magnitude less cost than dedicated spacecraft missions. ***Radar is arguably the most powerful method of post-discovery physical and dynamical characterization of the NEO population and carries a modest cost for information that can warn of, and possibly be used to mitigate, an Earth impact.***

In the context of robotic exploration, radar has provided invaluable information to asteroid sample-return missions *Hayabusa* to (25143) Itokawa (Ostro et al., 2004, 2005) and *OSIRIS-REx* to primitive asteroid (101955) Bennu (Nolan et al., 2013) as well as to future missions such as the planetary defense technology demonstration *DART* to binary asteroid (65803) Didymos (Naidu et al., 2020), *Psyche* to metal-rich (16) Psyche (Shepard et al., 2017), *DESTINY+* to activated asteroid (3200) Phaethon (Taylor et al., 2019), and the *Janus* concept to two binary NEAs (Benner et al., 2012; Naidu et al., 2018). Radar also provides ground-truth size measurements for infrared observatories such as Spitzer, AKARI, NEOWISE, and the future NEOSM that infer asteroid sizes to determine the NEA size-frequency distribution. In a sense, radar acts as a calibrator for sizes inferred by other methods and will do so for NEOSM. ***Radar reconnaissance of NEOs will play a significant role in preparing, supporting, and enhancing future robotic and crewed missions, both for scientific and impact-mitigation purposes.*** This includes constraining the orbit, spin state, and surface evolution of (99942) Apophis during its extremely close flyby of Earth in 2029, perhaps a once-per-millenium event (see Binzel et al.).

Facilities: Large apertures and powerful transmitters are required for ground-based planetary radar to overcome the inverse $(\text{distance})^4$ dependence of the strength of radar echoes. Therefore, the majority of planetary radar observations utilize the largest single-dish assets in the nation, the primary functions of which are radio astronomy or deep-space communication. The key facilities for planetary radar are the NSF's 305-meter Arecibo Observatory in Puerto Rico (whose planetary radar program is funded by NASA) and NASA's Goldstone Solar System Radar, which uses the 70-meter DSS-14 and 34-meter DSS-13 antennas of the Deep Space Network, in California. Typically, less than 10% of available telescope time is used for planetary radar at either facility. While Arecibo is nominally some 15 times more sensitive than DSS-14 (Naidu et al., 2016), its field of view is limited to ~33% of the sky, meaning fully steerable telescopes (~80%) are complementary to the sensitivity of Arecibo and can provide finer range resolutions at higher transmitter frequencies. Note, though, NEOs often traverse a range of declinations during Earth flybys with >90% of NEOs in the northern hemisphere visible from Arecibo at some time. The 70-m DSS-43 antenna and two 34-m antennas in Canberra, Australia have also seen proof-of-concept use for NEAs (Benson et al., 2017) with limited output power. Other astrophysics assets utilized as receivers for radar observations include the fully steerable, 100-meter Green Bank Telescope (GBT), which is exploring adding its own transmitter [15], elements of the Very Long

Baseline Array, the Karl G. Jansky Very Large Array, and other elements of the Deep Space Network. The GBT, as a receiver, is the most-utilized facility for radar observations after Arecibo and Goldstone as its size and antenna efficiency allow for increased sensitivity compared to Goldstone receiving its own (monostatic) echoes and the optimal sensitivity when receiving from Arecibo when a bistatic configuration is warranted. ***The primary facilities used for planetary radar are shared-use, single-dish radio telescopes, making planetary radar beholden to the health of the nation's single-dish radio telescopes within the astrophysics and deep-space communication communities.***

Needs: While NASA funding for planetary radar programs and planetary defense in general has grown, it is unlikely that NASA and the PDCO will support facilities for the sole purpose of planetary radar on the decadal timescale, even with a budget of $200M to $250M per year (see Mainzer et al.). Instead, *radar characterization of NEOs necessitates continued timesharing on astrophysical and deep-space communication assets*. Yet, in recent years, the Arecibo [16a] and Green Bank [16b] observatories were considered for divestment or closure by the NSF. At Arecibo, NSF funding is decreasing precipitously from $8.0M in 2017 to $2.0M in 2023 [17] (~67% to ~17% of the total budget) and is uncertain beyond then, while NSF funding for Green Bank Observatory has stabilized at ~$9M per year (~65%; M. Bloom, pers. comm.). The loss of access to Arecibo and/or the Goldstone 70- and 34-m telescopes due to oversubscription for other uses or closure would debilitate the radar community's efforts to support federally mandated tracking and characterization of NEOs for planetary defense. Beyond planetary defense, large single-dish telescopes have tremendous sensitivity and provide complementary science to other facilities across the astrophysical spectrum (e.g., Roshi et al., 2019; O'Neil et al., 2019). ***Therefore, single-dish radio telescopes should receive high priority for federal funding.***

To adequately track and characterize a significant and representative subset of NEOs over the next decade, an increase in radar observing time and/or radar facilities is required. The expected increase in NEO discoveries by the Rubin Observatory and NEOSM in the next decade necessitates robust and enhanced national planetary radar programs. *Asteroid discovery surveys by themselves do not fully meet the federal mandates to track and characterize NEOs.* Coordination with planetary radar ensures the precise tracking of a substantial number of NEOs and provides the level of characterization needed to inform planetary defense strategies. With new, dedicated planetary radar facilities unlikely on the decadal timescale, continued and expanded access to Arecibo, Goldstone, and the GBT (especially if the GBT is equipped with its own transmitter) is necessary to support these mandates. Commissioning of radar systems at the 70-m DSS-43 in Canberra and 70-m DSS-63 in Madrid, including 80 kW, C-band transmitters, could share some of the future observing load by covering southern declinations and expanding longitudinal coverage, respectively. Other avenues for expanded radar observations with existing and future assets are explored by Benner et al. (2015). *Having more than two radar facilities plus a robust stockpile of critical equipment would provide two-fault-tolerant redundancy, increased preparedness and resilience, plus more flexibility for scheduling at shared-use facilities, especially for urgent observations of possibly hazardous NEOs* (see Adamo et al.).

While next-generation planetary radar systems (see Lazio et al.; September deadline) will likely utilize phased-array systems, until such technology is matured and demonstrated over the next decade, ***maintenance of and upgrades to existing single-dish radio telescopes are required to ensure the continued participation of radar in the federally mandated tracking and characterization of NEOs***. We encourage studies on upgrades to the planetary radar systems at Arecibo and Goldstone, as well as the feasibility of a high-power, high-frequency transmitter on the GBT. Quantitatively, an order of magnitude increase in sensitivity or output power translates to a factor of 1.8 increase in "reach" into space or a factor of 5.6 increase in available volume. This would allow smaller objects to be detected farther from Earth, i.e., those discovered by the Rubin Observatory and NEOSM, as well as improve the scientific return from planetary-scale targets (see Rivera-Valentín et al.). Incremental increases in sensitivity may not be worth the cost and downtime; factors of several are likely required to justify major upgrades, such as shifting Arecibo from S to C band (2.38 GHz to ~5 GHz) or DSS-14 from X to Ka band (8.56 GHz to ~30 GHz). Continued progress on increasing power density, especially at higher frequencies, relative to size and weight of transmitters, possibly through the use of modular, solid-state components, is warranted. On smaller scales, improvements in transmitter reliability, retention of surface accuracy (gain), and maintenance of critical infrastructure (e.g., control systems, power generation) at planetary radar facilities are necessary investments. *Scientific advancement will be driven by improvements in transmitter technology, while the service of radar to planetary science and planetary defense over the next decade first and foremost relies on the health of the nation's shared-use, single-dish radio telescopes.*

Finally, *cross-division and cross-agency coordination is required among all relevant NSF and NASA divisions to improve our nation's ability to address Earth impact hazards as tasked by the national preparedness plan*. NSF's Division of Astronomical Sciences, which includes planetary astronomy, and NASA's Astrophysics Division coordinate their astronomy and astrophysics programs through the federal Astronomy and Astrophysics Advisory Committee (AAAC); however, NASA's Planetary Science Division (PSD) is not included. ***PSD must be included in the AAAC to coordinate the use of ground-based astrophysical assets for planetary science and planetary defense purposes.*** Such coordination would also ensure that Congress is properly informed of the use of ground-based facilities for planetary defense.

Statement on Diversity, Equity, and Inclusion

It is critical that the planetary science community fosters an interdisciplinary, diverse, equitable, inclusive, and accessible environment. We strongly encourage the decadal survey to closely consider the state of the profession and issues of diversity, equity, inclusion, and accessibility. Specific, actionable, and practical recommendations can be found in white papers submitted at the September deadline by Milazzo et al., Piatek et al., Rivera-Valentín et al., and Rathbun et al.

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