Planetary Radar Astronomy with Ground-Based Astrophysical Assets

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Thematic Area: Radio, Millimeter, and Submillimeter Observations from the Ground

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Abstract: Planetary radar is a unique method for studying solid bodies in the Solar System and arguably the most powerful method for post-discovery physical and dynamical characterization of near-Earth objects. Motivated primarily by the George E. Brown, Jr. Near-Earth Object Survey Act and the National Near-Earth Object Preparedness Strategy and Action Plan, we argue planetary radar plays a critical and unique role in the tracking and characterization of near-Earth objects, where all facilities used for planetary radar are astrophysical or deep-space communication assets. With the construction of a dedicated planetary radar facility (or facilities) unlikely, it is imperative that the single-dish radio telescopes with radar transmitters currently in use: Arecibo Observatory and the Goldstone Solar System Radar (part of the Deep Space Network), along with the Green Bank Telescope, often used in conjunction with the transmitting telescopes, remain viable. Access to these facilities for planetary radar must be sustained, if not expanded considerably, to keep pace with the expected near-Earth object discovery rates of future surveys like the Large Synoptic Survey Telescope and a space-based infrared observatory like NEOCam. Satisfying federal mandates requires continued and expanded support of planetary radar programs and the facilities that host planetary radar capabilities. Any breakdown of the planetary radar programs using single-dish astrophysical assets would be detrimental to planetary defense and small-body exploration on the timescale of the decadal survey.

Background: Several science white papers were submitted on planetary radar observations and ground-based characterization of small bodies in the Solar System (Campbell et al., 2019; Lovell et al., 2019; Margot et al., 2019; Milam et al., 2019; Taylor et al., 2019a). Here, we concentrate on access to the facilities used for planetary radar studies of small bodies, specifically the near-Earth objects (NEOs) that make up roughly 90% of the telescope time used by planetary radar.

The motivation for a healthy planetary radar program stems from planetary defense. The *George E. Brown, Jr. Near-Earth Object Survey Act*, which became part of the National Astronautics and Space Administration (NASA) Authorization Act of 2005,[1] tasked NASA to detect, track, catalog, and characterize 90% of all NEAs larger than 140 meters by 2020. While this 2020 goal is unattainable, it drives the efforts of future surveys like the National Science Foundation's (NSF) Large Synoptic Survey Telescope (LSST) and possible future NASA missions like NEOCam, a space-based infrared observatory dedicated to the detection and characterization of small bodies. As described in the National Research Council study *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*[2], 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 astronomy community at large has shown support for science operations of single-dish radio telescopes with planetary radar capabilities, namely Arecibo Observatory, as evidenced by resolutions from the American Astronomical Society (AAS)[3] and the Division for Planetary Sciences of the AAS.[4] Furthermore, the Small Bodies Assessment Group has consistently stated[5] that planetary radar systems and the astrophysical assets that host them constitute critical national assets for both planetary astronomy and planetary defense.

Planetary astronomy of small bodies is not solely the responsibility of NASA. In June 2018, the *National Near-Earth Object Preparedness Strategy and Action Plan*,[6] 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*[7], from the National Academies of Sciences, Engineering, and Medicine finds the

[1] https://www.gpo.gov/fdsys/pkg/PLAW-109publ155/pdf/PLAW-109publ155.pdf
[2] https://www.nap.edu/openbook.php?record_id=12842&page=R1
[3] https://aas.org/governance/society-resolutions#arecibo
[4] https://www.naic.edu/~pradar/AreciboResolution.pdf
[5] https://www.lpi.usra.edu/sbag/findings/
[6] https://www.whitehouse.gov/wp-content/uploads/2018/06/National-Near-Earth-Object-Preparedness-Strategy-and-Action-Plan-23-pages-1MB.pdf
[7] https://www.nap.edu/catalog/25476/finding-hazardous-asteroids-using-infrared-and-visible-wavelength-telescopes

most effective means of attaining the "completeness and size requirements given in the George E. Brown, Jr. Near-Earth Object Survey Act … in a timely fashion" is with a space-based infrared survey telescope. It also describes planetary radar as a post-discovery technique capable of providing the "best attainable size from remote observations," complementing infrared and optical observatories by leveraging the use of existing astrophysical and deep-space communication 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 been used to detect more than 800 NEAs[8] or 3 to 4% of the known NEA population. In the next decade, LSST and NEOCam are expected to come online, where it is suggested LSST could detect ~15,000 asteroids larger than 140 meters,[9] about 60% of those predicted to exist, during ten years of operation, and, similarly, NEOCam could detect and characterize close to 100,000 NEOs, including ~67% of those larger than 140 meters.[10] With an acceleration in the discovery rate expected over the next decade, there will be even more radar targets available. ***The current planetary radar program 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 have focused on NEAs, observations of other solar system bodies (Campbell et al., 2019; Margot et al., 2019), and even interstellar visitors,[11] are a natural byproduct of sustaining (and expanding or upgrading) the planetary radar programs that focus on small bodies.

Key Capabilities: Today, NEAs are typically discovered via wide-field optical surveys, which provide plane-of-sky astrometry as well as infer sizes and estimate rotation periods. Post discovery, radar provides complementary line-of-sight astrometry and detailed physical characterization. The combination of ultra-precise, radar line-of-sight astrometry with contemporaneous optical plane-of-sky astrometry fully determines the six-dimensional position and velocity state vector of the target and greatly constrains its orbit, more so than optical astrometry alone. ***Radar observations often prevent newly discovered objects from being lost, reduce uncertainties on orbital elements by orders of magnitude, and, on average, extend the timescale of Earth-encounter predictability by a factor of five, greatly improving impact probabilities compared to optical-only datasets*** (Ostro & Giorgini, 2004; Giorgini et al., 2009[12]).

With increasing signal strength, radar provides range astrometry with fractional precision of order one part in ten million (i.e., less than 1 km in range for a body millions or tens of millions of km from Earth), constraints on reflectivity, composition, taxonomic class, surface density, and surface roughness, a direct measurement of size, a shape estimate, evidence of surface geology, and, in the case of multiple-asteroid systems or Yarkovsky orbital-drift measurements, the bulk density. Radar images (Fig. 1) 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 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 NEAs and carries a modest cost for information that can warn of, and possibly mitigate, an Earth impact.***

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[8] https://echo.jpl.nasa.gov/asteroids/index.html
[9] https://cneos.jpl.nasa.gov/doc/JPL_Pub_16-11_LSST_NEO.pdf
[10] https://neocam.ipac.caltech.edu/page/mission
[11] Recovery from Hurricane Maria prevented Arecibo radar observations of 1I/'Oumuamua in October 2017.
[12] https://trs.jpl.nasa.gov/bitstream/handle/2014/45703/16-3971_A1b.pdf

While stellar occultations can provide size and shape estimates of asteroids, this task is exceedingly difficult at the sub-km scale of NEAs as the shadow spot size is of order the asteroid diameter. And though adaptive optics images of asteroid 66391 (1999 KW4)[13] unambiguously revealed its binary companion, this technology cannot yet yield the resolution or volume of observations that radar can over the same range of asteroid diameters.

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 101955 Bennu (Nolan et al., 2013), among other past missions, as well as to future missions such as the first planetary defense technology demonstration *DART* to binary asteroid 65803 Didymos (Cheng et al., 2018), *Psyche* to metal-rich 16 Psyche (Shepard et al., 2017), *DESTINY*$^{+}$ to activated asteroid 3200 Phaethon (Taylor et al., 2019b), and *Janus*,[14] a finalist for NASA's Small Innovative Missions for Planetary Exploration (SIMPLEx) call, to two binary near-Earth asteroids previously characterized by radar. Radar also provides ground-truth size measurements for infrared observatories such as NEOWISE (and a NEOCam-like mission on the timescale of the decadal survey) that infer asteroid sizes to determine the NEA size-frequency distribution. ***Radar reconnaissance of NEAs will play a crucial role in future robotic and crewed missions, both for scientific and impact mitigation purposes.***

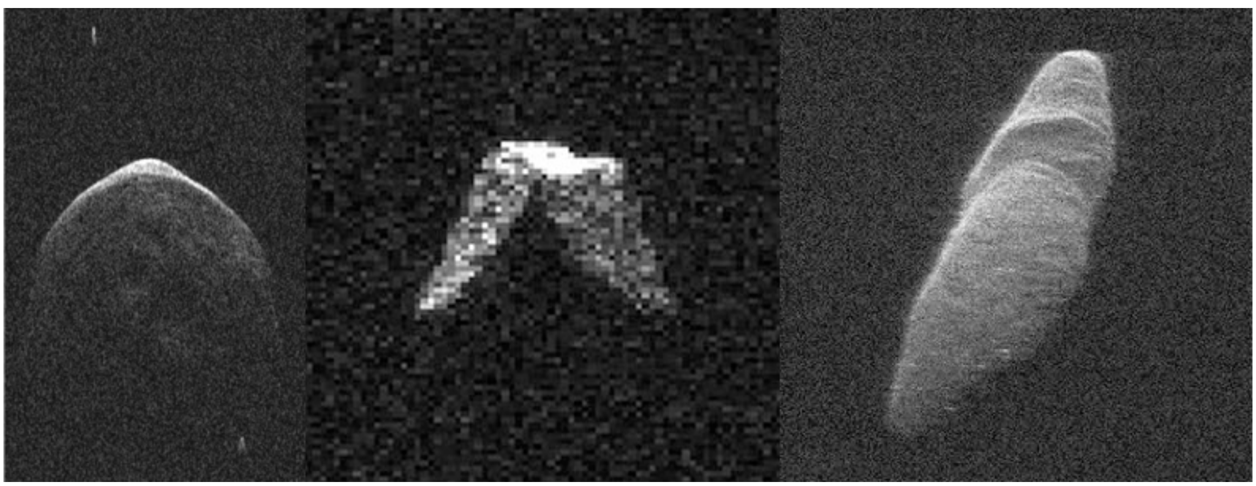

Figure 1. Radar images of (*left*) triple-asteroid 3122 Florence from Arecibo, (*center*) 2017 BQ6 from Goldstone, and (*right*) (163899) 2003 SD220 from Goldstone/Green Bank. Range from the observer increases downward at 7.5 m, 3.75 m, and 3.75 m per pixel, respectively. Florence has two moons at the top-left and bottom-right of the image; 2017 BQ6 is strikingly angular and faceted; 2003 SD220 is highly elongated and rotates in ~12 days. High-resolution radar images reveal a level of detail comparable to a spacecraft flyby at a fraction of the cost.

Facilities: Large apertures and powerful transmitters are required for ground-based planetary radar to overcome the distance to the fourth power 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 function of which are either radio astronomy or deep-space communication. The key facilities for planetary radar are the NSF's 305-meter Arecibo

[13] https://www.eso.org/public/usa/news/eso1910/

[14] https://www.lpi.usra.edu/sbag/meetings/jun2019/presentations/Hartzell.pdf

Observatory in Puerto Rico and NASA's Goldstone Solar System Radar, which uses the 70-meter DSS-14 and 34-meter DSS-13 elements of the Deep Space Network,[15] in California. Typically, less than 10% of available telescope time is used for planetary radar at either facility. While Arecibo is some 15 times more sensitive than DSS-14 (Naidu et al., 2016), its field of view is limited, meaning fully steerable telescopes are complementary to the sensitivity of Arecibo. Other astrophysics assets utilized as receivers for radar experiments include the fully steerable, 100-meter Green Bank Telescope (GBT), elements of the Very Long Baseline Array, the 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 allows for increased sensitivity compared to Goldstone receiving its own (monostatic) echoes and minimal reduction in sensitivity when receiving from Arecibo if a bistatic configuration is warranted (i.e., very close approaching targets or when increased frequency resolution is needed). ***All facilities used for planetary radar are shared-use radio telescopes, making planetary radar completely beholden to the health of the nation's radio telescopes within the astronomy and astrophysics community.***

Needs: While funding for planetary radar and planetary defense in general has grown, NASA and its Planetary Defense Coordination Office cannot support dedicated ground-based facilities on their own. Radar characterization of NEOs, especially those potentially hazardous to Earth, necessitates timesharing on astrophysical and deep-space communication assets. The loss of access to Arecibo and/or the transmitters on the Goldstone 70- and 34-m telescopes either due to oversubscription for other uses or closure would cripple the field. ***Beyond planetary defense, single-dish radio 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, these facilities should not be constantly considered for divestment, mothballing, or closure.*** In fact, facilities used for radar have already suffered cuts (e.g., Arecibo's funding from NSF dropped to $8 million in 2012[16] and will drop to $2 million from NSF by 2023[17] and Green Bank Observatory's operating budget has reduced to 60% and may drop to as little as 30%[18]).

To adequately track and characterize a significant 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 LSST and a NEOCam-like mission necessitates a robust and enhanced national planetary radar program. Asteroid discovery surveys by themselves do not fully meet the federal mandates to track and characterize NEOs. Coordination with planetary radar assures the precise tracking of a substantial number of NEOs and provides the level of characterization needed to inform planetary defense strategies. With dedicated planetary radar facilities unlikely, continued and expanded access to Arecibo, Goldstone, and the GBT, especially if equipped with its own transmitter (Bonsall et al., 2019), are necessary to accomplish these mandates.

Existing radar facilities should consider hardware upgrades to improve tracking and characterization of NEOs. Studies on possible upgrades to the planetary radar systems at Arecibo and Goldstone should be reviewed, as should the feasibility of a transmitter on the GBT (Bonsall et al., 2019). For Arecibo, first, a project to re-align the 305-m reflecting surface in the

[15] Deep Space Network sites in Australia have limited planetary radar capabilities, notably the 70-meter DSS-43.
[16] https://www.nsf.gov/od/oia/OIABudget/NSFBudget/FY2013_BudgetRequestToCongress.pdf
[17] https://www.nsf.gov/pubs/2017/nsf17538/nsf17538.pdf
[18] https://greenbankobservatory.org/science/partners/nsf-open-skies/

wake of Hurricane Maria is required, which has initial funding[19] and will be undertaken in the next few years. Improving Arecibo's sensitivity further requires an increase in transmitter frequency (2.38 GHz to ~5 GHz; 7.5 m to ~4 m resolution), though it is not yet clear that such an upgrade is worth the cost and telescope downtime. Raising the output power at Goldstone requires improvements in transmitter technology to increase power density relative to size and weight of the equipment, possibly through the use of modular, solid-state components. GBT could house transmitters operating at up to ~30 GHz, though the power output of state-of-the-art transmitters decreases with increasing frequency, partly negating gains in sensitivity. The community should pursue improvements in transmitter technology to increase reliability and power output at higher frequencies to make upgrades worthwhile. A factor of two increase in sensitivity or output power translates to a 20% further "reach" into space (70% increase in observable volume). ***Scientific advancement will be driven by improvements in transmitter technology, but the health of the planetary radar community first and foremost relies on the health of the nation's shared-use, single-dish radio telescopes within the astronomy and astrophysics community.***

[19] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1838728

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