Planetary Radar Astronomy with Ground-Based Astrophysical Assets

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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 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, upgrades to the facilities that host the planetary radar systems, and adequate communication between Congress and all relevant agencies that manage the facilities and the planetary radar programs. Continued research into improved radar transmitter technology and the use of phased array radars on interplanetary distance scales is warranted. 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: Planetary radar astronomy has a rich history beginning with measurements of the rotation rates of Mercury (Pettengill and Dyce, 1965) and Venus (Dyce et al., 1967). Early astrophysical accomplishments include refinement of the astronomical unit (e.g., Ash et al., 1967) and direct evidence of the perihelion advance of Mercury due to General Relativity (Shapiro et al., 1972). In the decades since, ground-based planetary radar has provided a number of insights about the Solar System: finding evidence for water ice in the permanently shadowed regions of Mercury (Harmon and Slade, 1992), which was confirmed by MESSENGER (Chabot et al., 2013; Lawrence et al., 2013); elucidating Mercury has a molten core (Margot et al., 2007); piercing through the thick venusian atmosphere to map its surface (e.g., Campbell and Burns, 1980); revealing terrain buried under the lunar and martian regoliths (e.g., Campbell et al., 1997; Harmon et al., 1999); evaluating landing sites on Mars (e.g., Tyler et al., 1976; Putzig et al., 2017); noting specular reflections from Titan (Campbell et al., 2003) consistent with the hydrocarbon lakes found by Cassini (Stofan et al., 2007); and detecting the solid nuclei of comets through their optically thick comae (e.g., Harmon et al., 1989).

Planetary radar astronomy of asteroids has been especially fruitful with more than 800 near-Earth asteroid (NEA) detections over time.[1] Science highlights include unambiguous discovery and detection of more than 50 binary- and multiple-asteroid systems (e.g., Margot et al., 2015); estimates of the spin and shape distributions of NEAs (Taylor et al., 2012); and the first evidence of YORP spin-up (Taylor et al., 2007) and Yarkovsky orbital drift (Chesley et al., 2003), known as a significant source of uncertainty in long-term, impact probability determination. Continued monitoring of NEAs with low perihelia will place stringent constraints on the solar quadrupole moment (J_2) and the β parameter of General Relativity (Verma et al., 2017). Furthermore, characterization of the NEA population hints at how our Solar System formed and evolved over time and reveals clues to understanding protoplanetary debris disks in extrasolar systems. 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), and *DESTINY*$^+$ to activated asteroid 3200 Phaethon (Taylor et al., 2019). Radar also provides ground-truth size measurements for infrared observatories such as NEOWISE 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.***

Synergy between ground-based optical and radar observations leads to improved knowledge of an asteroid's dynamical and physical properties. NEAs are typically discovered via wide-field optical surveys, which provide plane-of-sky astrometry as well as size and rotation period estimates; radar provides 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 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[2]).

With increasing signal strength, radar provides range astrometry with fractional precision of

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[1] https://echo.jpl.nasa.gov/asteroids/PDS.asteroid.radar.history.html

[2] https://trs.jpl.nasa.gov/bitstream/handle/2014/45703/16-3971_A1b.pdf

order one part in ten million (e.g., less than 1 km in range for a body millions or tens of millions of km from Earth), constraints on reflectivity, composition, taxonomic class (e.g., Benner et al., 2008), 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-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 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. ***Thus, 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.***

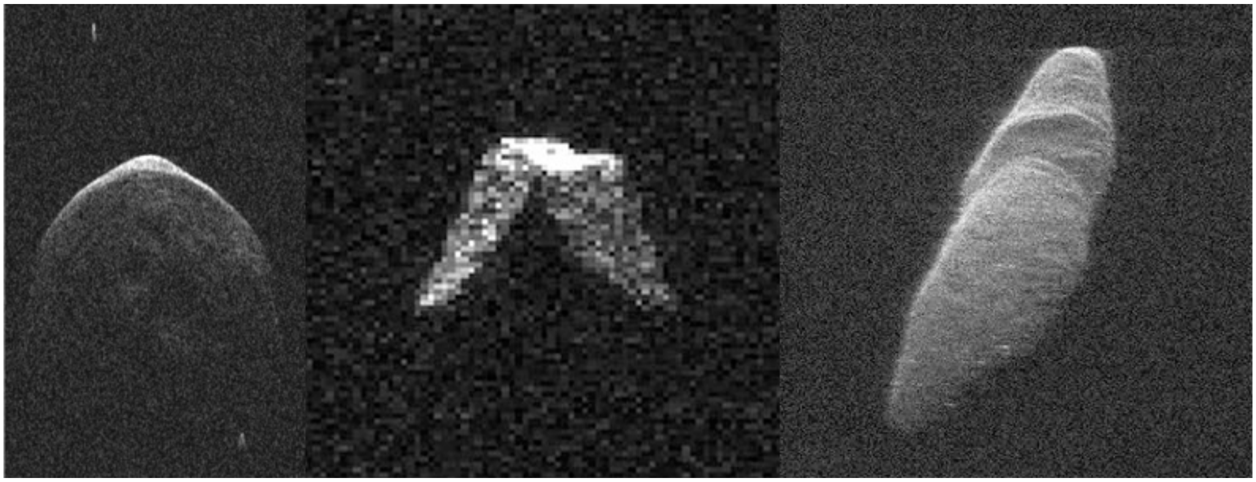

Figure 1. Radar images of (*left*) triple-asteroid 3122 Florence from Arecibo, (*center*) 2017 BQ6 from Goldstone, and (*right*) (163899) 2003 SD220 from Goldstone/Green Bank. Range from the observer increases downward at 7.5 m, 3.75 m, and 3.75 m per pixel, respectively. Florence has two moons at the 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.

The majority of planetary radar observations utilize ground-based facilities, the primary function of which is either radio astronomy or deep-space communication. The key facilities for planetary radar are the NSF's 305-meter Arecibo 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,[3] 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

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[3] Deep Space Network sites in Australia have limited planetary radar capabilities, notably the 70-meter DSS-43.

approaching targets or when increased frequency resolution is needed). ***In all cases, these are shared-use facilities such that their status in the astronomy and astrophysics community has a direct effect on the health of planetary astronomy and planetary defense.***

Motivation: Here, we concentrate on planetary radar of small bodies, specifically the NEAs that make up roughly 90% of the telescope time used by planetary radar. Observations of other solar system bodies, and even interstellar visitors,[4] are a natural byproduct of sustaining (and expanding or upgrading) the planetary radar programs that focus on small bodies. 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 NASA Authorization Act of 2005,[5] tasked NASA with detecting 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 NSF's 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. 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, as described in the National Research Council study by Shapiro et al. (2010).[6] Furthermore, the Small Bodies Assessment Group has consistently stated[7] that planetary radar systems and the astrophysical assets that host them constitute critical national assets for both planetary astronomy and planetary defense. The astronomical community at large has shown support for science operations of single-dish radio telescopes, namely Arecibo Observatory, as evidenced by resolutions from the American Astronomical Society (AAS)[8] and the Division for Planetary Sciences of the AAS.[9]

Planetary astronomy of small bodies, though, is not solely the responsibility of NASA. In June 2018, the National Near-Earth Object Preparedness Strategy and Action Plan,[10] 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 (NEO) 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."

Because NEA discoveries and radar detections of NEAs have followed similar tracks (Fig. 2), a significant increase in the number of radar observations is expected in the coming decade. In the late 1990s, dedicated all-sky, optical surveys came online coinciding with the last major upgrade to the sensitivity of the Arecibo telescope and its radar system, which allowed radar to

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[4] Recovery from Hurricane Maria prevented Arecibo radar observations of 1I/'Oumuamua in October 2017.

[5] https://www.gpo.gov/fdsys/pkg/PLAW-109publ155/pdf/PLAW-109publ155.pdf

[6] https://www.nap.edu/openbook.php?record_id=12842&page=R1

[7] https://www.lpi.usra.edu/sbag/findings/

[8] https://aas.org/governance/society-resolutions#arecibo

[9] https://www.naic.edu/~pradar/AreciboResolution.pdf

[10] https://www.whitehouse.gov/wp-content/uploads/2018/06/National-Near-Earth-Object-Preparedness-Strategy-and-Action-Plan-23-pages-1MB.pdf

detect 3 to 4% of the known NEA population. Another acceleration in the discovery rate occurred after 2010 when the output of next-generation optical surveys like the Catalina Sky Survey increased significantly and the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) came online (now joined by the Asteroid Terrestrial-impact Last Alert System or ATLAS program). Over both discovery inflections, radar has been able to keep pace. In the next decade, LSST and NEOCam are expected come online. It is suggested LSST could detect ~15,000 asteroids larger than 140 meters,[11] about 60% of those predicted to exist, during ten years of operation. Similarly, NEOCam could detect and characterize close to 100,000 NEOs, including ~67% of those larger than 140 meters.[12] Currently, Arecibo and Goldstone detect less than 30% of available targets (Naidu et al., 2016). With another acceleration in the discovery rate expected over the next decade, there will be even more radar targets available. ***With LSST and NEOCam on the horizon, the current planetary radar programs will not be able to keep up with the upcoming abundance of radar targets.***

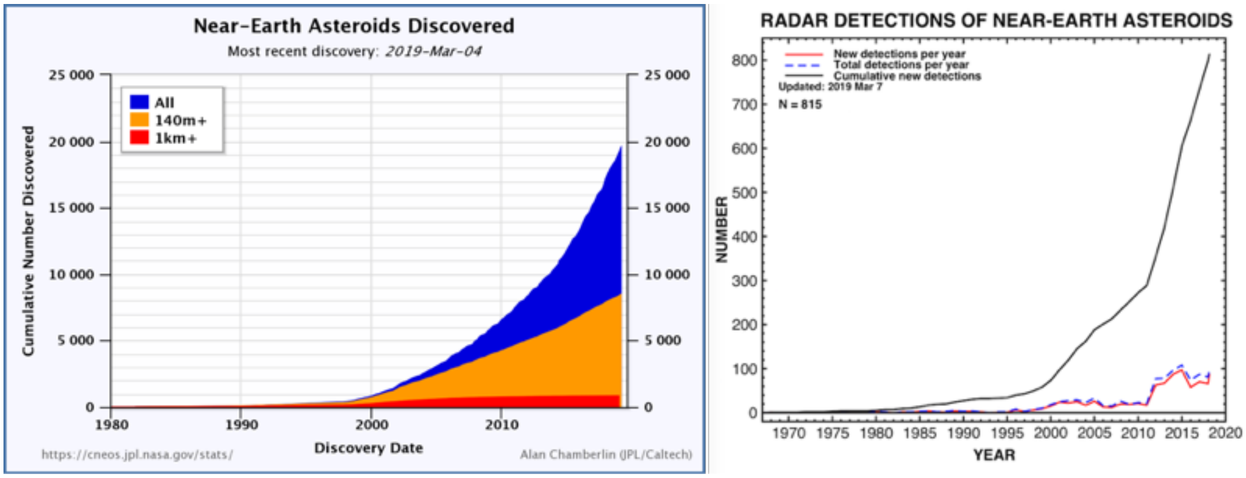

Figure 2. *Left:* NEA discoveries have increased rapidly over the last 20 years to more than 8000 larger than 140 meters (Figure from https://cneos.jpl.nasa.gov). *Right:* Over 800 NEAs have been detected with radar, about 4% of the population (Figure updated from Naidu et al., 2016). The discovery rate is expected to accelerate as new assets come online and requires growth of the radar community to supply a similar level of tracking and characterization.

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. As such, planetary radar astronomy and its contributions to planetary defense are completely beholden to the health of the nation's single-dish radio telescopes. 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. ***We must preserve the currently available facilities and nurture the possibilities for sustaining and expanding planetary radar capabilities.***

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[11] https://cneos.jpl.nasa.gov/doc/JPL_Pub_16-11_LSST_NEO.pdf

[12] https://neocam.ipac.caltech.edu/page/mission

Recommendations:

1. **Single-dish radio telescopes must remain part of the national science portfolio as crucial elements in our planetary defense strategy.** Not only do single-dish radio telescopes have tremendous sensitivity and provide complementary science to other telescopes and arrays across the astrophysical spectrum, they are currently the only facilities hosting planetary radar systems in support of planetary defense. 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[13] and will drop to \$2 million from NSF by 2023[14] and Green Bank Observatory's operating budget has reduced to 60% and may drop to as little as 30%[15]). Full community input must be considered when deciding future funding directions.
2. **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 <u>do not fully meet</u> 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. Continued and expanded access to Arecibo, Goldstone, and the GBT are necessary to accomplish these missions.
3. **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. Improving Arecibo's sensitivity requires an increase in frequency (2.38 GHz to ~5 GHz; 7.5 m to ~4 m resolution); Goldstone requires additional transmitters to double its output power. GBT could house transmitters up to ~30 GHz, though the power of current 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 2 increase in sensitivity or output power translates to a 20% further "reach" into space (70% increase in search volume). Scientific advancement will be driven by improvements in transmitter technology. Further research on phased array radars with interplanetary reach, akin to KaBOOM and KARNAC (Geldzahler et al., 2017), is also encouraged.
4. **Cross-division and cross-agency coordination are required among all relevant NSF and NASA divisions to improve our nation's preparedness to address Earth impact hazards.** 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 astronomy and planetary defense purposes. Such coordination would also ensure that Congress is properly informed on the use of ground-based facilities for planetary defense.

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[13] https://www.nsf.gov/od/oia/OIABudget/NSFBudget/FY2013_BudgetRequestToCongress.pdf

[14] https://www.nsf.gov/pubs/2017/nsf17538/nsf17538.pdf

[15] https://greenbankobservatory.org/science/partners/nsf-open-skies/

References

Ash, M.E., et al., Astronomical Constants and Planetary Ephemerides Deduced from Radar and Optical Observations, Astronomical Journal 72, 338-350, 1967.

Benner, L.A.M., et al., Near-Earth Asteroid Surface Roughness Depends on Composition Class, Icarus 198, 294-304, 2008.

Campbell, B.A., et al., Regolith Composition and Structure in the Lunar Maria: Results of Long-Wavelength Radar, Journal of Geophysical Research 102, 19307-19320, 1997.

Campbell, D.B., and B.A. Burns, Earth-Based Radar Imagery of Venus, Journal of Geophysical Research Space Physics 85, 8271-8281, 1980.

Campbell, D.B., et al., Radar Evidence for Liquid Surfaces on Titan, Science 302, 431-434, 2003.

Chabot, N.L., et al., Craters Hosting Radar-Bright Deposits in Mercury's North Polar Region: Areas of Persistent Shadow Determined from MESSENGER Images, Journal of Geophysical Research: Planets 118, 26-36, 2013.

Cheng, A.F., et al., AIDA DART Asteroid Deflection Test: Planetary Defense and Science Objectives, Planetary & Space Science 157, 104-115, 2018

Chesley, S.R., et al. Direct Detection of the Yarkovsky Effect by Radar Ranging to 6489 Golevka, Science 302, 1739-1742, 2003.

Dyce, R.B., et al., Radar Determination of the Rotations of Mercury and Venus, Astronomical Journal 72, 351-359, 1967.

Geldzahler, B., et al., A Phased Array of Widely Separated Antennas for Space Communication and Planetary Radar, Advanced Maui Optical and Space Surveillance Technologies Conference, 2017.

Harmon, J.K., and M.A. Slade, Radar Mapping of Mercury - Full Disk Imagery and Polar Anomalies, Science 258, 640-643, 1992.

Harmon, J.K., et al., Radar Observations of Comet IRAS-Araki-Alcock 1983d, Astrophysical Journal 338, 1071-1093, 1989.

Harmon, J.K., R.E. Arvidson, E.A. Guinness, B.A. Campbell, and M.A. Slade, Mars Mapping with Delay-Doppler Radar, Journal of Geophysical Research 104, 14065-14090, 1999.

Lawrence, D.J., et al., Evidence for Water Ice Near Mercury's North Pole from MESSENGER Neutron Spectrometer Measurements, Science 339, 292, 2013.

Margot, J.L, et al., Large Longitude Libration of Mercury Reveals a Molten Core, Science 316, 710-714, 2007.

Margot, J.L., et al., Asteroid Systems: Binaries, Triples, and Pairs, in Asteroids IV, University of Arizona Press, 2015.

Naidu, S.P., et al., Capabilities of Earth-Based Radar Facilities for Near-Earth Asteroid Observations, Astronomical Journal 152, 99, 2016.

Nolan, M.C., et al., Shape Model and Surface Properties of the OSIRIS-REx Target Asteroid (101955) Bennu from Radar and Lightcurve Observations, Icarus 226, 629-640, 2013.

Ostro, S.J., and J.D. Giorgini, The Role of Radar in Predicting and Preventing Asteroid and Comet Collisions with Earth, in Mitigation of Hazardous Comets and Asteroids, Cambridge University Press, 2004.

Ostro, S.J., et al., Radar Observations of Asteroid 25143 Itokawa (1998 SF36), Meteoritics & Planetary Science 39, 407-424, 2004.

Ostro, S.J., et al., Radar Observations of Itokawa in 2004 and Improved Shape Estimation, Meteoritics & Planetary Science 40, 1563-1574, 2005.

Pettengill, G.H., and R.B. Dyce, A Radar Determination of the Rotation Rate of the Planet Mercury, Nature 206, 1485, 1965.

Putzig, N.E., et al., Radar-Derived Properties of the InSight Landing Site in Western Elysium Planitia on Mars, Space Science Reviews, 1-12, 2017.

Shapiro, I.I., et al., Mercury`s Perihelion Advance: Determination by Radar, Physical Review Letters 28, 1594-1597, 1972.

Shapiro, I.I., et al., Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies, The National Academies Press, 2010.

Shepard, M.K., et al., Radar Observations and Shape Model of Asteroid 16 Psyche, Icarus 281, 388-403, 2017.

Stofan, E.R., et al., The Lakes of Titan, Nature 445, 61-64, 2007.

Taylor, P.A., et al., Spin Rate of Near-Earth Asteroid 2000 PH5 Increasing due to the YORP Effect, Science 316, 274-277, 2007.

Taylor, P.A., et al., The Shape and Spin Distributions of Near-Earth Asteroids Observed with the Arecibo Radar System, Division for Planetary Sciences Conference, 302.07, 2012.

Taylor, P.A., et al., Arecibo Radar Observations of Near-Earth Asteroid (3200) Phaethon During the 2017 Apparition, Planetary & Space Science 167, 1-8, 2019.

Tyler, G. L., et al., Radar Characteristics of Viking 1 Landing Sites, Science 193, 812-815, 1976.

Verma, A.K., et al., Prospects of Dynamical Determination of General Relativity Parameter Beta and Solar Quadrupole Moment J2 with Asteroid Radar Astrometry, Astrophysical Journal 845, 166, 2017.