GROUND-BASED RADAR OBSERVATIONS: ENABLING THE FUTURE OF SMALL-BODY SCIENCE, PLANETARY DEFENSE, AND SOLAR SYSTEM EXPLORATION. P. A. Taylor[1], L. A. M. Benner[2], E. G. Rivera-Valentín[1], A. Virkki[1], M. W. Busch[3], and M. C. Nolan[4], [1]Arecibo Observatory, Universities Space Research Association, Arecibo, PR 00612; [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; [3]SETI Institute, Mountain View, CA 94043; [4]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

State of the Art: The S-band (2.38 GHz, 12.6 cm; 1 MW output power) planetary radar system on the 305-m William E. Gordon telescope at Arecibo Observatory is the most sensitive planetary radar system in the world, a factor of ~15 more sensitive than the X-band Goldstone Solar System Radar (8.56 GHz, 3.5 cm; 450 kW) on the 70-m DSS-14 antenna. The unmatched sensitivity and 7.5-m minimum range resolution of Arecibo make it the premiere instrument for ultra-precise astrometric measurements and detailed physical characterization of near-Earth objects (NEOs), though its field of view is limited to declinations between +0 and +38 degrees. While less sensitive, the flexibility of the fully steerable Goldstone system, along with its finer frequency resolution and 3.75-m minimum range resolution, complements Arecibo by detecting NEOs at southern (above -35 degrees) and high northern declinations and over longer windows of visibility. Together, Arecibo and Goldstone typically detect more than 100 NEOs each year and play a vital role in the tracking and characterization of potentially hazardous objects (PHOs) for planetary defense purposes and NHATS (Near-Earth Object Human Spaceflight Accessible Targets Study) compliant objects for future spacecraft mission planning. Overall, ~660 NEOs have been detected with radar, about 4.3% of the population. Additionally, in the last two years, the C-band (7.16 GHz, 4.2 cm; 80 kW) system on the 34-m DSS-13 antenna at Goldstone and the S-band (2.11 GHz, 13 cm; 100 kW) system on the 70-m DSS-43 antenna in Canberra, Australia have detected several asteroids, though their relative sensitivities compared to Arecibo and DSS-14 have limited their utility. The 100-m Green Bank Telescope and elements of the Very Long Baseline Array are regularly utilized as radar receivers for Arecibo and Goldstone, while the 64-m Parkes telescope receives for DSS-43.

Radar Capabilities: Range-Doppler radar measurements provide line-of-sight positional astrometry, orthogonal and complementary to optical plane-of-sky astrometry, with precision as fine as ~10 m in range and ~1 mm/s in velocity with a fractional precision of one part in 10^7, which is 100 to 1000 times finer than that of typical optical measurements. Radar astrometry routinely extends the ability to accurately predict the trajectories of asteroids for decades or centuries into the future, often preventing newly discovered objects from being lost and requiring optical re-discovery. Two-dimensional range-Doppler images that resolve the target spatially along the line of sight and in frequency (velocity) space reveal its basic shape and surface features that may be inverted to provide a three-dimensional shape model and complete spin-state description. Further, range-Doppler images unambiguously reveal binary and triple asteroid systems, which provide estimates of the mass, density, and internal structure of the bodies. The demonstrated correlation between radar polarization ratio and asteroid spectral type, in addition to the unique radar-reflection properties of metals, allows for the interpretation of asteroid composition.

Planetary Defense: Ground-based radar observations enable accurate projection of trajectories into the future, including measurement of the subtle Yarkovsky drift, while constraining the physical properties of potential impactors. This combination of knowledge will allow for well-informed planning of impact mitigation strategies. Potential impact hazards are best managed with a long lead time as the utility of different deflection techniques improves with the amount of warning time given. Although to date, impact mitigation technologies have not been tested, potential technology demonstrations require ground-based radar observations to confirm mission success, including the proposed ESA/NASA Asteroid Impact Mission/Double Asteroid Redirect Test kinetic impactor demonstration and the enhanced gravity tractor demonstration by the NASA Asteroid Robotic Redirect Mission.

Solar System Exploration: Ground-based radar observations inform mission planning by constraining the target's trajectory, size, shape, mass, spin state, composition, potential satellites, and gravitational and surface environments. Such detailed characterizations of a large number of objects cannot be obtained by other ground-based techniques. In fact, nearly all missions to asteroids have had their targets first characterized by radar. Arecibo and Goldstone have contributed to the mission planning for a number of successful (and proposed) spacecraft from NASA, ESA, JAXA, and CNSA (China) over the last 30 years.

Vision: *Observing cadence:* All current radar-enabled telescopes share observing time with other sciences and/or deep-space communication; there is no dedicated radar installation for the study of NEOs. Currently, less than 30% of radar-detectable asteroids are actually detected with Arecibo and Goldstone, partly due to scheduling constraints. The number of discoveries and, hence, the number of radar-detectable NEOs, will only increase with the advent of Large Synoptic Survey Telescope. Keeping up with the rate of discovery will require more observing time on existing radar telescopes, improved automation of observing, and streamlining of data-reduction and data-analysis pipelines. Truly keeping up with the rate of discovery will require dedicated radar facilities unconstrained by time sharing with other disciplines. With more radar observations come more physical characterizations that will benefit planetary defense, mission planning, and resource identification.

Additional radar stations: An 80-kW, C-band transmitter on the 34-m antenna in Canberra would be more sensitive than the current S-band system on DSS-43. A radar system on the 100-m Green Bank Telescope, especially at Ka band (30 GHz, 1 cm), would be more sensitive than the DSS-14 system at Goldstone and complement the existing S-, C-, and X-band systems. However, a more arid location for such high frequencies is preferred, *e.g.*, 100-m telescope(s) at Goldstone or the Atacama desert. By 2050, Arecibo and Goldstone will be ~85 years old and the Green Bank Telescope will be 50 years old; new facilities must be considered in the coming decades.

Hardware upgrades: Upgrading the Arecibo system to a higher frequency would allow for finer resolution down a few meters in range (matching DSS-14), which combined with its unmatched sensitivity would improve the ability to characterize small NEOs and the surfaces of larger NEOs. Observing more NEOs would benefit from increased sensitivity or being able to “see” further into space with radar. This can be accomplished at existing sites by increasing the transmitted power: doubling the output power results in “seeing” 20% further and increasing the number of radar-detectable NEOs by a similar amount.

New technologies: Preliminary work on the use of solid-state amplifiers as radar transmitters is promising and could replace expensive, highly specialized klystrons with “off-the-shelf” technology. The long-term future of ground-based planetary radar may lie in phased arrays at higher frequencies, *e.g.*, Ka band (30 GHz, 1.0 cm) and higher, that could provide dedicated high-power, high-resolution stations for tracking and characterizing NEOs.

Summary: As noted in the Vision and Voyages planetary science decadal survey, ground-based radar observations play a unique and vital role in planetary science and will continue to be instrumental in understanding the nature of the Solar System, supporting planetary defense capabilities, and informing spacecraft mission planning. Therefore, a healthy ground-based radar infrastructure is required to enable the goals and objectives of planetary science, as prioritized by the decadal survey, for the foreseeable future.

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