THE ARECIBO OBSERVATORY PLANETARY RADAR SYSTEM. P. A. Taylor[1], M. C. Nolan[2], E. G. Rivera-Valentín[1], J. E. Richardson[1], L. A. Rodriguez-Ford[1], L. F. Zambrano-Marin[1], E. S. Howell[2], and J. T. Schmelz[1]; [1]Arecibo Observatory, Universities Space Research Association, HC 3 Box 53995, Arecibo, PR 00612 (*ptaylor@naic.edu*); [2]Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Blvd., Tucson, AZ 85721.

Introduction: The William E. Gordon telescope at Arecibo Observatory in Puerto Rico is the largest and most sensitive single-dish radio telescope and the most active and powerful planetary radar facility in the world. Since opening in 1963, Arecibo has made significant scientific contributions in the fields of planetary science, radio astronomy, and space and atmospheric sciences. Arecibo is a facility of the National Science Foundation (NSF) operated under cooperative agreement with SRI International along with Universities Space Research Association and Universidad Metropolitana, part of the Ana G. Méndez University System. The planetary radar program and radar infrastructure maintenance at Arecibo are currently funded via grants from the NASA Near-Earth Object Observations program.

The 305-m William E. Gordon telescope has studied objects in the Solar System since its construction in the 1960s. The initial 430-MHz transmitter was used to unambiguously determine the rotation periods of the planets Mercury and Venus, refine the value of the astronomical unit, and to obtain some of the first images of the surface of Venus. A joint NSF and NASA-funded upgrade in the 1970s included the installation of a 450 kW, S-band (2.38 GHz) transmitter. Over the next 15 years, this system detected tens of near-Earth and main-belt asteroids (NEAs and MBAs) and several comets, imaged the surface of Venus at 2-km resolution, discovered the anomalous reflection properties of icy surfaces at radio wavelengths, and mapped the ice deposits at the poles of Mercury. In the 1990s, a second NSF and NASA-funded upgrade increased the sensitivity of the radar system by a factor of ten to twenty depending on declination. Observations with this system have provided characterization and astrometric measurements of dozens of NEAs per year, confirmed the existence of binary and triple NEAs, verified the existence of the Yarkovsky effect and contributed to the verification of the YORP effect (both effects due to solar radiation), obtained the first non-spacecraft images of cometary nuclei, imaged a number of main-belt asteroids, discovered hydrocarbon lakes on the surface of Titan, imaged the rings of Saturn, and obtained multi-polarization imagery of the Moon and terrestrial planets.

Technical Capabilities: Its 1 MW transmitter, nearly 20-acre collecting area, and gain of 2×10^6 make the Arecibo planetary radar the world's most powerful instrument for post-discovery characterization and orbital refinement of near-Earth objects and the study of Solar System objects at radio wavelengths. The unmatched sensitivity of Arecibo allows for detection of any potentially hazardous asteroid (PHA; absolute magnitude $H < 22$) that comes within $\sim$0.05 AU of Earth ($\sim$20 lunar distances) and most any asteroid larger than $\sim$10 meters ($H < 27$) within $\sim$0.015 AU ($\sim$6 lunar distances) in the Arecibo declination window (0° to +38°), as well as objects as far away as Saturn.

In terms of near-Earth objects, Arecibo observations are critical for identifying those objects that may be on a collision course with Earth in addition to providing detailed physical characterization of the objects themselves in terms of size, shape, spin, and surface-property (reflectivity, polarization, geologic features and sometimes composition and density) information. In fact, radar investigations of near-Earth objects are roughly equivalent, in their science content, to spacecraft flyby missions, but at a cost orders of magnitude less. Range-Doppler radar measurements provide line-of-sight positional astrometry, orthogonal and complementary to optical plane-of-sky astrometry, with precision as fine as $\sim$10 m in range and $\sim$1 mm/s in velocity with a fractional precision 100 to 1000 times finer than that of typical optical measurements. These unique capabilities of radar are critically important as we work towards the 2005 congressional mandate of detecting and characterizing 90% of NEAs down to 140 m in diameter.

Current Research: The majority of telescope hours dedicated to planetary radar observations in recent years have concentrated on near-Earth asteroids with the remainder dedicated to monitoring the Moon, the surface of Venus, comets, main-belt asteroids, and the Galilean satellites of Jupiter. Currently Mars and Saturn are too far south to view from Arecibo, but will return in a few years. Observations of planets, planetary satellites, comets, main-belt asteroids, and near-Earth asteroids are proposed on a semesterly basis and peer-reviewed prior to time allocation. A significant fraction of NEAs are observed as targets of opportunity during other scheduled tracks, as individual urgent proposals, or as part of monthly survey nights to observe "whatever is up" during a typically 8-hour track near new moon. Nearly half of the asteroids detected in 2015 were on their discovery apparition and observed in one of these modes. Among these, Arecibo actively responds to NASA requests for observations of PHAs and those asteroids specifically of interest for possible future robotic

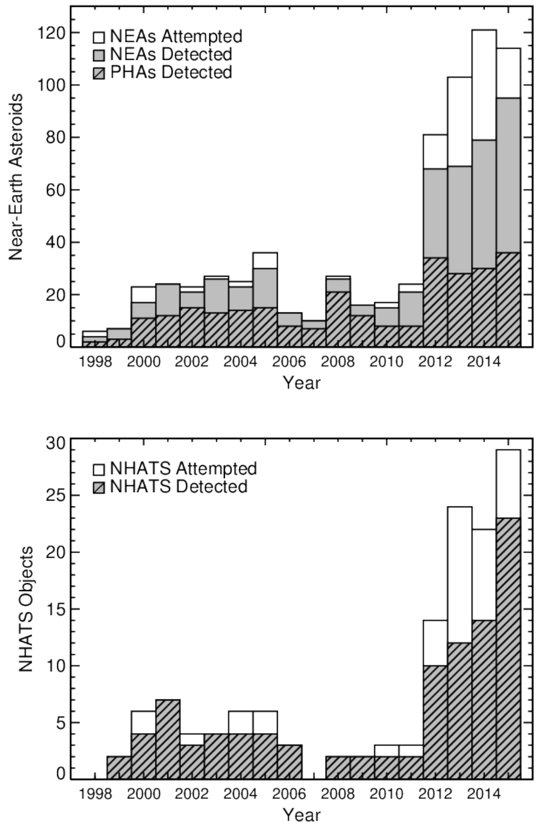

Figure 1: Detections per year of near-Earth asteroids (top) and the subsets of potentially hazardous asteroids (top) and NHATS objects (bottom). The number of detections has grown substantially under NASA support. A detection rate of ∼100 objects per year is sustainable and could possibly increase.

or crewed missions, referred to as "NHATS compliant" by the NASA Near Earth Object Program Office.

Since the second upgrade in the mid-1990s, Arecibo has detected over 500 near-Earth asteroids, almost half of which are designated as potentially hazardous and more than 1 in 6 are NHATS compliant. Figure 1 shows the number of NEA observations attempted and successfully completed since 1998. After the planetary radar program became fully NASA funded in late 2010, asteroid observations drastically increased by more than a factor of 3. In fact, 2015 included a record number of detections in all categories: 95 NEAs, 36 PHAs, and 23 NHATS objects.

Broader Impacts: The unique capabilities of radar to provide ultra-precise astrometry and fine spatial resolution of Solar System bodies impacts the astronomical community, its ground- and space-based astronomical assets, and humanity as a whole. Radar astrometry complements optical astrometry and routinely extends our ability to accurately predict the trajectories of asteroids for decades or centuries into the future, often preventing newly discovered objects from being lost. Radar, often in conjunction with other radio telescopes such as Goldstone, the Green Bank Telescope and elements of the Very Long Baseline Array, is the only ground-based technique capable of characterizing a large number of near-Earth objects in detail, providing insight into the population as a whole and revealing that the population is heterogeneous in terms of size, shape, spin, and surface properties. Additionally, compared to visible or infrared studies, radar allows for direct measurement of object sizes without assumption of albedo or thermal properties. Radar-based size and shape information acts as a calibrator for infrared observations by the WISE and Spitzer spacecraft, which typically assume spherical shapes to estimate sizes and albedos. Radar also provides direct determination of densities for those objects that are binary (or multiple) systems, a property notoriously difficult to measure accurately by other means. Such level of characterization of the population, in addition to specific bodies, is critical to hazard assessment and mitigation, necessary for understanding dynamical and collisional evolution in the Solar System, and invaluable in planning for spacecraft missions.

Radar reconnaissance has played an important role in reducing risk incurred by spacecraft missions by simplifying navigation and predicting the gravitational and surface environments the spacecraft will encounter. Arecibo has contributed to the planning and execution of missions such as the Hayabusa mission to (25143) Itokawa, the upcoming OSIRIS-REx mission to (101955) Bennu, the Marco Polo-R, Asteroid Impact & Deflection Assessment (AIDA), and Psyche mission concepts, the Deep Impact extended mission (EPOXI) to comet 103P/Hartley, and in characterizing the surface conditions of proposed landing sites on Mars. Arecibo also aided in the recovery of the SOHO satellite and came to the assistance of the Lunar Reconnaissance Orbiter (LRO) when its onboard radar transmitter failed. Subsequent bistatic Arecibo transmissions to the Moon received by LRO allowed for the first non-zero phase angle observations of the lunar surface.

Acknowledgments: The Arecibo Observatory is operated by SRI International under a cooperative agreement with the National Science Foundation (AST-1100968) and in alliance with Ana G. Méndez-Universidad Metropolitana and the Universities Space Research Association. The Arecibo Planetary Radar Program is supported by the National Aeronautics and Space Administration under Grant Nos. NNX12AF24G and NNX13AQ46G issued through the Near-Earth Object Observations program.