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GROUND-BASED RADAR OBSERVATIONS OF POTENTIALLY HAZARDOUS ASTEROIDS

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Extended Abstract—

Ground-based radar is a powerful technique for post-discovery dynamical and physical characterization of near-Earth asteroids (NEAs) and for spacecraft mission support. The most active radar facilities in the world are the 305-m William E. Gordon telescope at the Arecibo Observatory in Puerto Rico (USA) and the 70-m DSS-14 telescope, part of the Deep Space Network, at the Goldstone Solar System Radar complex in the Mojave Desert of California (USA). Together, these facilities have averaged 87 NEA detections per year since 2012 when support from the National Aeronautics and Space Administration (NASA) for radar at both facilities increased significantly. While the fixed Arecibo reflector is more sensitive due to its sheer size, Goldstone is more maneuverable and capable of finer range and frequency resolution, making the facilities quite complementary. Figures 1 and 2 show the NEA observation statistics for Arecibo and Goldstone since 1998, along with the number of potentially hazardous asteroids (PHAs) observed.

Radar observations are critical for identifying objects that may present a hazard to Earth. Radar provides ultraprecise astrometric measurements of the line-of-sight distance to and velocity of a target, which are orthogonal to optical plane-of-sky astrometry. Line-of-sight distances and velocities can be determined as finely as tens of meters and millimeters per second, respectively, or, equivalently, with a fractional precision of about one part in ten million, and often in as little as minutes of observation. Combining radar and optical astrometry at the same epoch provides the complete six-dimensional position/velocity state vector of the target, reducing orbital-element uncertainties by orders of magnitude and routinely preventing newly discovered objects from being lost and requiring rediscovery in the future. Over multiple apparitions, radar astrometry greatly aids elucidation of the subtle Yarkovsky orbital drift of asteroids, the largest source of uncertainty for long-term trajectory prediction, and can yield mass estimates.

Radar also provides detailed physical characterizations of asteroids in terms of size, shape, spin, and surface properties (reflectivity, polarization, geologic features and sometimes composition and density) as signal strength allows. In fact, radar-imaging campaigns with resolution as fine as 7.5 meters with Arecibo and 3.75 meters with Goldstone are roughly equivalent in their science content to space flyby missions, but cost orders of magnitude less and can be accomplished for orders of magnitude more targets. Such a campaign and subsequent physical characterization has proven invaluable for the planning of the OSIRIS-REx sample-return mission to PHA 101955 Bennu and will inform and benefit any future impact mitigation efforts. Furthermore, radar is very efficient at unambiguously identifying multiple-asteroid systems that make up ~15% of the NEA population larger than 150 m in diameter. Characterization of

multiple-asteroid systems provides insight into the bulk densities, implied porosities, and internal structures of asteroids, knowledge that is otherwise difficult to obtain with other ground-based assets.

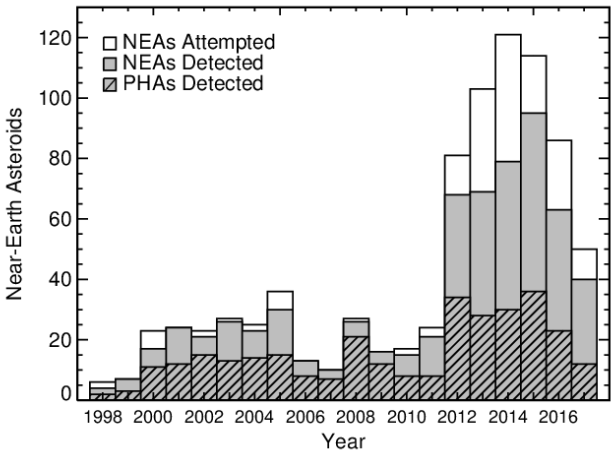

Figure 1. Near-Earth asteroid (NEA) and potentially hazardous asteroid (PHA) detections by Arecibo since 1998. Detections per year have more than tripled since 2012 when the Arecibo radar program became fully supported by NASA.

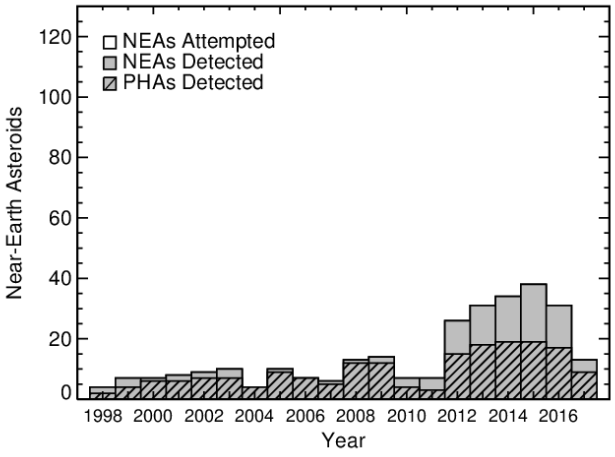

Figure 2. Near-Earth asteroid (NEA) and potentially hazardous asteroid (PHA) detections by Goldstone since 1998. Goldstone detections have similarly increased by a factor of three since 2012 with increased support from NASA.

Here, we will specifically look at radar characterization of potentially hazardous asteroids. To date, 311 PHAs have been detected with ground-based radar systems; nearly half of all radar-detected asteroids (664) are PHAs. In fact, PHAs, in addition to human accessible targets (see abstract by A.K. Virkki *et al.*), are actively prioritized for radar characterization. We will summarize radar observations of the PHA population and highlight recent observations from Arecibo and Goldstone, including asteroid 2014 JO25, shown in Figure 3, observed in April as it flew by Earth at a distance roughly five times further away than the Moon.

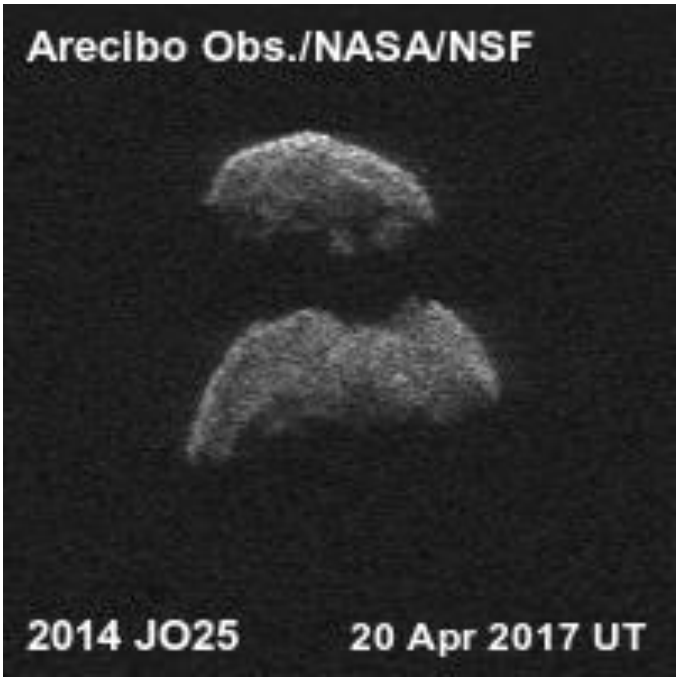

Figure 3. Arecibo flyby-quality radar image of potentially hazardous asteroid 2014 JO25 with resolution of 7.5 m per pixel. Radar revealed this PHA is about 1 km in its longest dimension and rotates every 4.5 hours. Such a double-lobed shape is common among near-Earth asteroids.

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