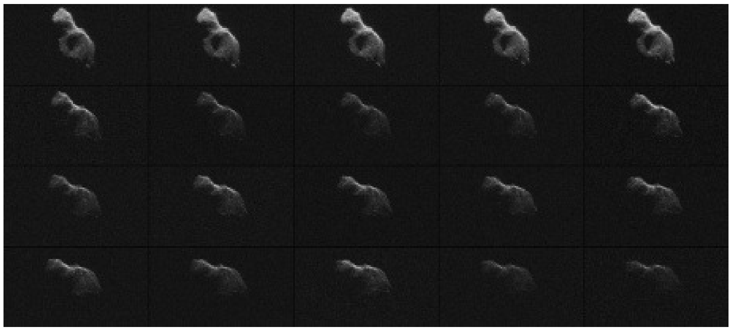
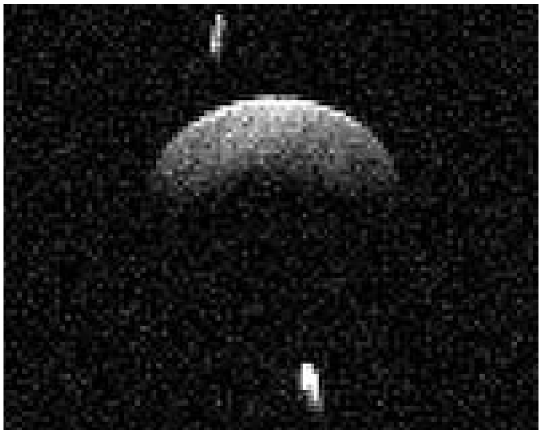
Solar System Radar Astronomy at Arecibo

Observations with Arecibo radar systems have made ***unique and critical*** contributions to our knowledge of the **Moon, terrestrial planets, satellites, asteroids and comets**. Radar astrometry can improve orbit characterization and predictions, assisting with planning and executing spacecraft rendezvous, analysis of non-gravitational effects on the orbits, testing of General Relativity predictions, measuring solar oblateness, and assessing impact hazards. As the ***most sensitive S-band planetary radar and highest resolution available of any radar for asteroid, lunar, and planetary studies***, the Arecibo Observatory offers the opportunity to monitor objects over long periods of time to monitor small changes, either in orbits or surfaces.

Radar imaging enables determination of object shapes, estimation of spin pole positions, ***discovery of satellites*** or contact binaries, and characterization of surface and near-surface processes and properties. Right: Radar delay-Doppler images of asteroid 2014 HQ124. Credit: Marina Brozovic and Joseph Jao, JPL/ Caltech/ NASA/ USRA/ Arecibo Observatory/ NSF.



The Arecibo planetary radar system offers extremely high resolution views, which, for some objects, ***rivals that of spacecraft imaging. Ground-based radar is available for a much wider sample of objects, can respond to new discoveries much more rapidly, and for a tiny fraction of the cost.*** Long time baselines for monitoring solar system objects are essential for improving orbit predictions, assessing non-gravitational effects such as Yarkovsky and YORP, estimating solar oblateness or precession due to general relativity, investigating surface-atmosphere interactions, or geologic changes on the surfaces.



The majority of **Binary NEOs**, which comprise about 15-16% of the near-Earth population, have been discovered with radar. The ***only known triple-asteroid systems have been discovered by radar***. Radar observations of binary asteroids constrain masses, densities, and material properties as well as verification of the YORP effect.

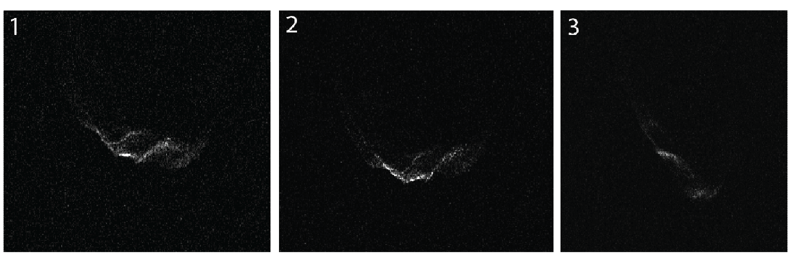
Left: 2001 SN263 delay-Doppler radar image revealing triple nature of the system. Time delay increases from bottom to top, and Doppler shift increases from left to right. Photo courtesy Arecibo Observatory.

Radar astrometry observations of NEOs are critical in ***assessment of impact hazards***. Once a potentially hazardous object is discovered, Arecibo radar can reduce the difficulty and cost of mitigation efforts by determining the object's size, shape, mass, spin state, and orbit, and revealing any orbiting companions.

Radar imaging of **Near Earth Objects (NEOs)** at decameter resolution are critical for shape determination, which constrains collisional and compositional evolution of these objects. Furthermore, radar monitoring over multiple days can place critical constraints on asteroid pole positions, helping to remove ambiguities that plague interpretation of optical and infrared lightcurve observations. Range-Doppler radar measurements complement optical observations by providing line-of-sight positional astrometry with precision as fine as 10 m in range and 1 mm/s in velocity, with a fractional precision 100 to 1000 times finer than that of typical optical measurements. Radar data increase the average interval of predictability by up to 370 years and can provide warnings of impact during the initial discovery period, whereas two widely separated observations are needed in optical-only orbits. Radar data can also quickly eliminate collision false alarms caused by optical-only data and assist in spacecraft target selection.

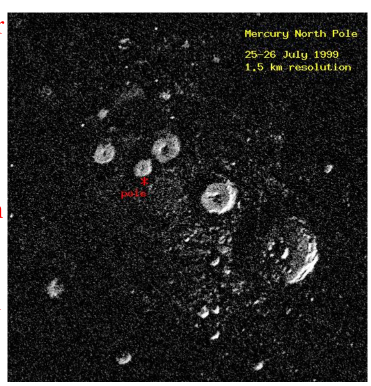
Planetary Radar has made numerous other contributions, including

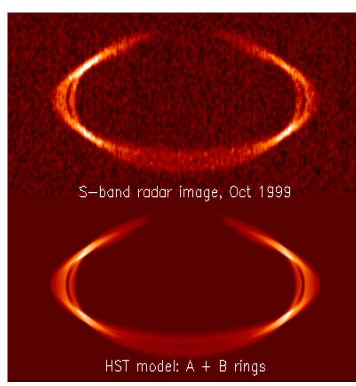
Comet nucleus and coma particle swarm characterization.
Tests of general relativity and measurements of Solar oblateness from NEOs.
Rotation and Precession Rates of Planets and minor bodies.
Ice on the Moon, Mercury, and outer solar system satellites.
The only probe of the surface of Venus under its opaque atmosphere.
Probing subsurface lava flows on the Moon at extremely high resolution.
Probing the subsurface of Mars.
Studies of outer planet icy satellites.
Unique Investigations of Saturn's Rings.



Three views of comet 209P/LINEAR. Several features are visible on the comet, perhaps ridges or cliffs. This is only the fifth comet nucleus imaged by Arecibo in the last 16 years, and the most detailed. Credit: Arecibo Observatory/NASA/Ellen Howell, Patrick Taylor

Right: Arecibo radar image of the north polar region of Mercury. The resolution is 1.5 km and the image measures 450 km on a side. The bright features are thought to be ice deposits on permanently shadowed crater floors.





Left: A delay-Doppler image of Saturn's rings at a frequency of 2380 MHz (12.6 cm) compared to a reprojected model constructed from optical HST images. Time delay increases from bottom to top, and Doppler shift increases from left to right. The effective spatial resolution is 2000 km by 15000 km.

Introduction

Observations with Arecibo radar systems have made unique and critical contributions to our knowledge of the Moon, terrestrial planets, satellites, and small bodies in the solar system. Regular radar astrometry can improve orbit characterization and predictions, assisting with planning and executing spacecraft rendezvous, analysis of non-gravitational effects on the orbits, testing of General Relativity predictions, measuring solar oblateness, and assessing impact hazards. Characterization of solar system bodies with radar probes the sub-surface in ways that complement observations and passive techniques employed at several other wavelengths. Radar imaging enables determination of object shapes, estimation of spin pole positions, discovery of satellites or contact binaries, and characterization of surface and near-surface processes and properties. The Arecibo system, with additional support from NASA, and also in conjunction with other radio facilities in bistatic, interferometric, or radar speckle experiments, offers extremely high resolution views which for some objects rivals that of spacecraft imaging.

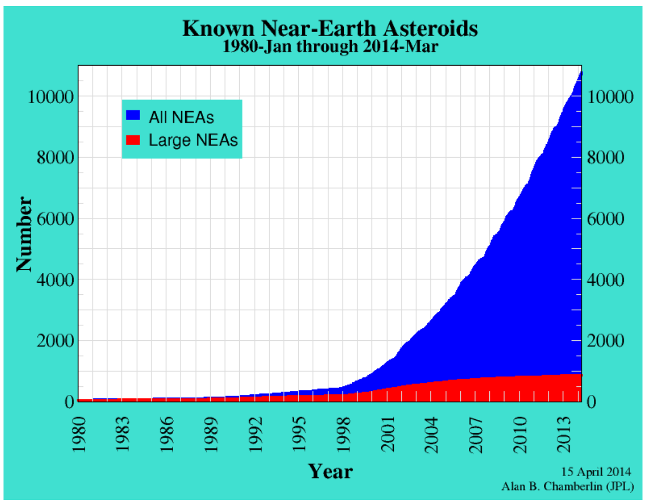
As a result of concerted observational efforts since the 1990s sensitivity upgrade, and funding from NASA for near-Earth object studies, the Arecibo radar systems have made unique discoveries in the investigation of numerous asteroids, several comets, planetary surfaces, rings, and satellites. As the most sensitive S-band planetary radar and highest resolution available of any radar for asteroid, lunar, and planetary studies, the Arecibo Observatory offers the opportunity to monitor objects over long periods of time to monitor small changes, either in orbital elements or surface properties. Long time baselines for monitoring solar system objects are essential for improving orbit predictions, assessing non-gravitational effects such as Yarkovsky and YORP, estimating solar oblateness or precession due to general relativity, investigating surface-atmosphere interactions, or geologic changes on the surfaces. Students (undergraduates and graduates) are actively trained in using the facility for planetary science, and a number of PhD dissertations have been based on Arecibo Radar projects (Fang & Margot, 2012; Fang et al., 2011; Naidu & Margot, 2014; Naidu et al. 2013).

Near Earth Object (NEO) astrometry has advanced tremendously as a result of the sensitivity of Arecibo radar, in combination with concerted surveys that have discovered a wealth of new small bodies and increased the variety and sizes of targets that can be investigated ((Benner et al., 2006, 2002; Brozović et al., 2011; Brozovic et al., 2010; Busch et al., 2011; Magri et al., 2011, 2007b; Nolan et al., 2013; Ostro et al., 2000, 2004, 2003; Shepard et al., 2006) Radar astrometry observations of NEOs are a critical component of the assessment of impact hazards, and also nicely complement astrometry obtained in other parts of the electromagnetic spectrum. High precision astrometry has enabled verification of the Yarkovsky and YORP effects, and will be an important element of predicting potential future Earth orbit crossings for hazard assessment. Yarkovsky and YORP effects are non-gravitational perturbations to small body orbits and spin states, resulting from asymmetric absorption and re-emission of solar radiation. (Chesley, 2006; Chesley et al., 2003; Farnocchia and Chesley, 2014; Farnocchia et al., 2013; Nugent et al., 2012; Shor et al., 2012; Taylor et al., 2007; Vokrouhlický et al., 2005, 2000)

Precision radar astrometry can identify, and more importantly rule out, potential Earth impact hazards (Benner et al., 2002; Giorgini et al., 2008; Ostro et al., 2007; Yeomans et al., 2009) by making dramatic improvements over optical astrometry and permitting orbital predictions much further into the future. A high-profile example was the case of potentially hazardous asteroid

(PHA) Apophis (Chesley, 2006; Farnocchia et al., 2013; Giorgini et al., 2008; Shor et al., 2012; Vinogradova et al., 2008).

Congressionally mandated NEO searches to find objects larger than 1km by 2008 have led to dramatic increases in the discovery rate for this population. The new target threshold for NASA's NEO program is to discover 90% of objects with diameters greater than 140m – those which could cause significant city- or state-wide damage to land or ocean margins. The figure below shows the number of known near-Earth asteroids, now over 11000, with this number expected to continue increasing as Pan-STARRS and the Large Synoptic Survey Telescope (LSST) contribute more sensitivity to the search. Around 1500 known objects already meet the criteria for potentially hazardous asteroids (PHAs), and with additional discoveries the diagnosis of direct threat to Earth will require increasing attention, only answerable with precision astrometry. The vastly superior astrometry technique is provided by only two ground-based radar systems: Arecibo and Goldstone, operating at different frequencies and relative sensitivities (Desmars et al., 2013; Ostro et al., 2007, 1991; Yeomans et al., 1987).



NEO characterization. Ground-based radar resolution can rival that of imaging during a spacecraft encounter, but is available for a much wider sample of objects, can respond to new discoveries much more rapidly, and for a tiny fraction of the cost. Imaging observations at decameter resolution are critical for shape determination (Benner et al., 2002, 1999; Brozovic et al., 2010; Harris et al., 2009; Hestroffer et al., 2002; Hudson et al., 2000; Kaasalainen and Viikinkoski, 2012; Magri et al., 2007b; Nolan et al., 2013; Ostro et al., 2004, 2002, 2000, 1999, 1990a, 1990b, 1988, 2005), which is an important constraint for collisional and compositional evolution of these objects. Furthermore, radar monitoring over multiple days can place critical constraints on asteroid pole positions, helping to remove ambiguities inherent in the interpretation of optical and infrared lightcurve observations. Radar astrometry observations of NEOs are a critical component of the assessment of impact hazards, and also nicely complement astrometry obtained in other parts of the electromagnetic spectrum (Magri et al., 2011; Mueller et al., 2002; Nolan et al., 2013). Even for objects that have been observed in previous close passes to Earth, due to differences in viewing geometry and distances, new and surprising results from radar campaigns, including new satellite discoveries, are still common.

Once a potentially hazardous object is discovered, its physical structure must be characterized to inform impact mitigation strategies (Belton et al., 2004; Yeomans et al., 2009). In addition to the scientific interest, characterization of a wide sample of objects, hazardous or not, informs the statistics of what a newly-discovered object is likely to be like in structure and composition. Asteroids may be a single coherent monolith, a contact binary or "rubble pile" which is a looser association of numerous smaller objects, and can be round or elongated, spin rapidly or slowly, and be single or multiple systems. Composition of asteroids is informed by classification schemes, which depend on either optical or infrared spectroscopy. Radar imaging offers complementary information, including shape, spin, and physical structure (Benner et al., 2008, 1997; Magri et al., 2001). With repeated observations and surveys over a long period of time, the characteristics of a wide population of asteroid, including very small objects that may be difficult to detect optically, can be achieved (Benner et al., 1997; Campbell, 1991; Harris et al., 2009; Magri et al., 2007a; Ockert-Bell et al., 2008; Palmer et al., 2011; Shepard et al., 2010, 2008a, 2008b). With good statistics on the characteristics and orbits of objects, with high-resolution radar imaging of targets with close approaches to Earth, the best-informed decisions can be made, both for impact mitigation if necessary, and for spacecraft target selection (Brozovic et al., 2009; Ostro et al., 2004, 2004). NEO missions may be of interest for robotic and human exploration, for scientific investigation, hazard mitigation, and mineral resources.

The majority of **Binary NEOs**, which comprise about 15-16% of the near-Earth population, have been discovered with radar. Radar observations of binary asteroids constrain masses, densities, and material properties (Brozović et al., 2011; Brozovic et al., 2010; Magri et al., 2011; Margot et al., 2002; Ostro et al., 2006; Shepard et al., 2006). Such constraints and discoveries have revolutionized understanding of the formation and evolution of binary NEOs. Studies of systems such as 1999 KW4, which exhibit complex dynamics and fascinating evolution (Harris et al., 2009; Ostro et al., 2006) are uniquely enabled by radar imaging.

Comet nucleus and coma characterization. Much of the case outlined above applies also to larger main-belt asteroids which were the likely parent population of the NEOs, and can easily extend to the study of comets. Comets can be studied by radar both as solid-nucleus targets and as particle swarms as the sublimation of ices releases dust into an escaping exosphere. Since comets tend to be lower density (Andert et al., 2013; Campbell et al., 1989; J. K. Harmon et al., 2011) and activity can drive splitting or multiple fragmentation events, radar is critical to assess the size and shape of fragments for split comets. The increased activity after fragmentation events renders a bright coma that often masks the nucleus from study at other wavelengths (Harmon et al., 1999; Howell et al., 2007; Nolan et al., 2006a, 2006b).

During the perihelion passage of split comet 73/P-Schwassmann-Wachmann 3 in May/June, 2006 the Arecibo radar provided delay-Doppler images of the B and C components of comet 73P/Schwassmann-Wachmann 3 and the large particle dust coma of component B (Nolan et al., 2006a). Large dark particles in a cometary coma are difficult to detect with other techniques, but the distribution and velocity of such particles contribute strongly to the radar echo when present. Cometary nuclei and comae, whether known to be split or not, can be probed effectively with

Arecibo radar when comets approach within 0.1 AU of Earth while visible in the appropriate range of declinations for Arecibo to observe. Comets, like asteroids, can be characterized with high resolution imaging when approaching closer than ~0.05 AU. As for asteroids, radar observations of comets are a very important complement to spacecraft observations and ground-based observations at other wavelengths (Andert et al., 2013; Belton et al., 2013; Bird et al., 2000; Campbell et al., 1989; Gim et al., 2012; John K. Harmon et al., 2011a; Moehlmann and Kuehrt, 1991; Sekanina, 1988; Shapiro, 1991).

Tests of general relativity and measurements of Solar oblateness from NEO astrometry: Radar astrometry can make accurate constraints on the perihelion advance of near-Earth objects with eccentric trajectories that reach deep inside the gravitational well of the Sun, providing a direct dynamical measurement of solar oblateness for comparison to helioseismology results. These measurements are ongoing and it is critical to continue them for 10-15 years to get firm results on solar physics. Similar observations can reduce uncertainties in the Eddington parameter beta of General Relativity (Margot and Giorgini, 2010; Pitjeva, 2005).

Moon and Terrestrial Planets

Radar observations of larger planets and satellites provide unique contributions to the study of these bodies as well. Ground-based radar provided some of the first suggestions of ice at the poles of the moon and Mercury (Harmon, 2004; Harmon and Slade, 1992; Harmon et al., 2001; John K. Harmon et al., 2011b; Neumann et al., 2013; Slade et al., 2004), and offers a unique means of probing below the regolith for assessing the geologic activity history of the Moon, Venus, and Mars. Lunar radar observations require different stations to transmit and receive signals because of short delays, and radar speckle observations, which probe interference patterns resulting from scattering as the object rotates, require multiple receiving stations (generally an antenna array such as the VLA or VLBA). Polarimetric observations supplement assessment of surface scattering by being sensitive to the smoothness of the material on wavelength scales. These techniques have been applied to asteroids, planets, and satellites with many interesting results. Much of the power of these results is in continued monitoring, so the Arecibo radar facility is a critical part of that capability for the future.

Mercury exhibits fascinating dynamics, influenced by tidal interactions as well as General Relativity. Radar speckle constraints on the instantaneous spin of Mercury can probe librations on different timescales (Margot, 2012; Margot, 2009; Margot et al., 2007; Peale, 2005; Peale et al., 2014, 2009, 2008) and inform predictions about core-mantle angular momentum exchange. As with many planetary observations, such an investigation of Mercury's interior dynamics may inform models for similar processes on Earth.

Venus: The thick atmosphere of Venus precludes the study of its surface at visible or near-IR wavelengths, and its proximity to Earth during inferior conjunction makes it accessible for monitoring with radar. Measurements of the instantaneous spin of Venus can be made via radar speckle displacement measurements, enabling monitoring of atmospheric angular momentum sensitive to changes at the 1% level. Atmosphere and interior interactions can both influence the spin and orientation of Venus, and radar monitoring the instantaneous spin of the planet constrains atmospheric torques as well as the planet's moment of inertia (Margot et al., 2012b).

The difficulties of studying Venus have limited our ability to assess the current level of activity on one of the youngest surfaces in the solar system. Radar monitoring can assess surface changes that might be due to active surface processes, and will be particularly effective due to the recent availability of the upgraded VLA system to make ~1km resolution surface radar images.

Moon: Bistatic Arecibo (transmit)-Green Bank Telescope (receive) radar observations provide very high (~20m) resolution radar imaging of the moon, probing the regolith to study volcanic, tectonic, and impact processes on the moon. Ground-based radar studies of the moon complement visible-wavelength imaging from the ground and from lunar orbit, enable detailed study of areas of interest, and can be used to identify target sites for spacecraft imaging or landing. Radar enabled the mapping of the dark regions of the lunar poles in a search for ice (Stacy, et al. 1997). For additional perspective and to probe different subsurface depths, imaging of the moon can be done at 12.6cm as well as 70cm, and with all four Stokes polarization parameters (Campbell and Campbell, 2006; Campbell, 2012, 1997; Campbell et al., 2014, 2010, 2009, 2006).

Mars: Though at somewhat lower resolution, radar observations can also probe the immediate subsurface of Mars, offering unique investigations of volcanic processes as well as ice deposits. Mars is of great interest due to the availability of high-resolution orbital imagery which can inform and complement ground- and space-based radar of the red planet. Frequent oppositions of Mars and the accessibility of ecliptic targets to the Arecibo system make Mars a productive target for radar investigations (Harmon et al., 2012).

Saturn, Rings, and Icy Satellites: The increased sensitivity of the S-band radar system at Arecibo provided enough transmitter power to reach Saturn and its satellites. Radar observations of Saturn's rings at different viewing angles probe the distribution of particles, sizes, and polarization properties, and complement recent observations from the Cassini spacecraft (Nicholson et al., 2005). In addition, the Arecibo system can detect several of Saturn's satellites, including hazy Titan and its distinctive potentially lake-dotted surface (Black et al., 2011; Campbell et al., 2003). Since outer planet satellites may present tremendous surprises, such as plumes of outgassing from Enceladus, and spacecraft missions may only be able to adapt somewhat to new discoveries, ground-based radar observations are a critical supplement to satellite investigations (Black et al., 2007; Goldstein and Morris, 1975; Pettengill, 1978).

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