White Paper on the Future of Radar Astronomy at Arecibo

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With spacecraft missions providing more and more detailed information about solar system bodies, the opportunities for Earth based telescopes to make truly significant contributions to our knowledge of the solar system are becoming increasingly limited. Where Earth based telescopes can still work on the cusp of discovery are studies requiring a sampling frequency and/or duration that spacecraft observations cannot meet and those necessitating a large sample of objects. Examples are the study of trans-Neptunian bodies – Kuiper Belt Objects – where spacecraft have not yet ventured (the New Horizons mission will reach Pluto in 2015) and the number of bodies is large, the study of asteroids and comets where, again, the objects are numerous are diverse, long term monitoring studies building on the (usually) higher resolution spacecraft observations made over a relatively short time interval, and studies that require precise measurements over extended periods such as the perihelion precession of objects in eccentric orbit about the Sun to study General Relativity (GR) effects.

Observations with the Arecibo radar systems have made very significant contributions since 1964 to our knowledge of the Moon and terrestrial planets, Jovian and Saturnian satellites, and smaller bodies in the inner solar system. With the large increase in sensitivity achieved via the 1990s upgrading of the Arecibo telescope and radar system, the pace of new discoveries over the past ten years significantly quickened. The question is “what are the predictable substantial investigations that justify the continued use and support of the radar system over the next ten years?” We use the term “predictable” because several of the significant results over the past ten years (e.g. the interior structure of Mercury) were not predicted in the justification for the 1990s upgrading of the radar system.

Solar system research areas to which Arecibo will be able to make unique contributions of the next ten years are:

1. Near Earth Asteroid (NEA) astrometry and characterization
2. Comet nucleus and coma imaging
3. Tests of general relativity and measurements of solar oblateness from NEA astrometry
4. Internal structure of Mercury and Venus, and atmosphere-surface interactions for Venus from precise spin vector measurements using radar speckle displacement
5. Monitoring surface activity on Venus, surface properties of the Moon and surface geology on Mars

Near Earth Objects: Recent Science papers have highlighted the Arecibo radar system’s capabilities in the area of Near Earth Object (NEO) astrometry and characterization (e.g. Margot et al, 2002; Chesley et al, 2003; Ostro et al, 2006; Taylor et al, 2007). High precision astrometry led to the verification of the Yarkovsky and YORP effects related to the effect of solar radiation on the orbits and spin states of small NEOs and providing a mechanism for perturbing the orbits of small main belt asteroids so that they ultimately cross that of the Earth (Chesley et al, 2003). Earth based radar is currently the only method available to resolve NEOs, to image large numbers of them at decameter resolution and to obtain detailed shape models (Ostro et al, 2006; Taylor et al, 2007). In the case of binary NEOs, about 16% of the population, radar data reveals fascinating dynamical and evolutionary processes and provides information on masses, densities, material strength, and formation mechanisms (Margot et al, 2002, Ostro et al, 2006). The ongoing discovery and characterization of binary systems, of which 60% have been discovered with radar, combined with the verification of the YORP effect, has led to a completely new understanding of the evolution of binary NEOs (Pravec and Harris, 2007). The complex dynamics and evolution of these systems as seen in the 1999 KW4 system (Ostro et al., 2006; Scheeres et al., 2006; Scheeres 2007) would have been impossible to detect (much less study) without radar imaging. Radar reflectivity and polarization ratios reveal important differences in macroscopic surface properties across NEO taxonomic classes (Benner et al, submitted). Precision radar astrometry can identify those NEOs that are a potential hazard to Earth (Giorgini et al, 2002) as the recent discussion about the potentially hazardous asteroid (PHA) Apophis has demonstrated.

The advent about 10 years ago of organized searches for NEOs as a result of the Congressional mandate to find 90% of all NEOs larger than 1 km by 2008 led to a tremendous increase in the discovery rate. The new “mandate” to find by 2020, 90% of the approximately 100,000 NEOs with diameters greater than 140 m (i.e. those bodies that could cause significant statewide or ocean margin damage if they collide with Earth) will lead to a massive increase in the discovery rate of NEOs (see “Near-Earth Object Survey and Deflection Analysis of Alternatives”, NASA Report to Congress, March 2007). Approximately 20% of NEOs larger than 140 m, the ones that approach within 0.05 AU of Earth, are characterized as PHAs. The first element of the wide field optical search system Pan-STARRS is about to begin observations and larger Pan-STARRS systems are planned. An even larger wide field system, the Large Synoptic Survey Telescope (LSST) is in the advanced design stage and space based systems are being considered.

Of the 20,000 PHAs expected to be discovered by 2020, the major question is “which ones pose a direct threat to Earth in the foreseeable future”. This question can only be answered by precision astrometry and by far the best astrometry is provided by the two Earth based radars, Arecibo and Goldstone. Once these objects are discovered, they must be studied to determine their physical structure, in order to determine what methods of mitigation might effective. For example, a “gravel pile” would need to be addressed differently than a “monolith”, a binary system differently from a single body. Optical spectroscopy can examine the composition, but not the shape or physical structure of these bodies. Only radar imaging can do this for the large number of objects needed to characterize the population. Radar imaging and astrometry provide near-spacecraft resolution imaging of small bodies, but are 4-6 orders of magnitude less expensive and 3 orders of magnitude less time consuming. They can therefore be applied to many more targets. This lets us study the population of near-Earth objects in order to choose the few targets that can be visited by spacecraft for higher-resolution study (Ostro et al, 2004).

Comets: During the perihelion passage of the comet 73/P-Schwassmann-Wachmann 3 in May/June, 2006 the Arecibo radar was used to obtain two dimensional delay-Doppler images of the nuclei of component B and C and the large particle coma of component B (Nolan et al, 2006). Schwassmann-Wachmann 3 broke up into several components during a previous perihelion passage. The images allow estimates of the size of the nuclei and the distribution, velocity and sizes of the coma particles responsible for the radar echo. Similar information can be obtained with the Arecibo radar for any comet approaching within 0.1 AU of Earth and in Arecibo declination range. For comets approaching closer than ~0.05 AU, high resolution imaging of the nucleus will be possible.

Tests of general relativity and measurements of Solar oblateness from NEO astrometry: Radar astrometric measurements of the perihelion advance of a dozen near-Earth objects with trajectories reaching deep inside the gravitational well of the Sun (i.e. objects in highly eccentric orbits with perihelion distances inside the orbit of Mercury) can provide a direct, purely dynamical, measurement of the oblateness of the Sun with <10% uncertainties, thereby testing the indirect helioseismological inferences. These measurements have been initiated and need to be continued over the next 10 to 15 years. These same measurements can also provide an order of magnitude reduction in uncertainties in the Eddington parameter beta of General Relativity.

Moon and Terrestrial Planets:

Mercury: Radar speckle displacement measurements of the instantaneous spin of Mercury can be obtained to 1 part in 10^5 and can reveal whether the planet exhibits a long-period (~12 years) libration in addition to the 88-day forced libration that has been detected recently (Margot et al, 2007). If due to core-mantle angular momentum interactions, measurement of the amplitude of the long-period libration will place constraints on the amount of core-mantle angular momentum exchange, perhaps allowing us to elucidate the physical coupling mechanism and to illuminate conditions at the Earth's core-mantle boundary.

Radar speckle displacement measurements of the spin orientation of Mercury have recently decreased previous uncertainties in pole orientation by 2-3 orders of magnitude and allowed the first experimental verification that the planet occupies a Cassini state (Margot et al, 2007). Because the spin axis may lag the instantaneous Cassini state location, a time history of the spin axis orientation may yield powerful constraints on energy dissipation due to solid-body tides and core-mantle interactions, as in the case of the Moon.

Venus: Radar speckle displacement measurements of the instantaneous spin of Venus can produce the first ever time history of atmospheric angular momentum changes (at the 1% level) and address fundamental questions related to atmospheric dynamics.

Radar speckle displacement measurements of the spin orientation of Venus obtained over a decade provide the only short-term hope of measuring the spin precession and the moment of inertia of the planet, a fundamental constraint on interior models.

“Is Venus still a tectonically active planet?” The answer is highly likely to be yes but, to date, no surface changes have been observed and there are no current plans for an imaging mission as a follow on to Magellan. Arecibo has the sensitivity to image Venus with a resolution of about 1 km during its close approaches to Earth. However, the current radar system has poor discrimination between echoes from the two hemispheres making the imagery difficult to interpret at a level that could unambiguously identify changes over time. The ongoing upgrading of the National Radio Astronomy Observatory’s Very Large Array (the EVLA) in New Mexico will result by 2012 in a bistatic radar system with Arecibo transmitting and the EVLA receiving the echo that can provide an imaging capability with ~ 1 km resolution for Venus.

Moon: The bistatic radar system with Arecibo transmitting and the Green Bank Telescope receiving the echo has the capability to image the near-side lunar surface with ~20 m resolution in all four Stokes polarization parameters (D. Campbell et al, 2006; B. Campbell et al, 2007). This capability is available to support lunar surface studies and verification of potential landing sites.

Mars: Radar has the unique capability to “see” below the immediate surface layer. Recent work by Harmon (2007) has demonstrated radar’s capability to map the distribution of lava flows on Mars in the Tharsis and Chryse regions and to map the extent of the ice deposits at the south pole of Mars. These observations complement the higher resolution surface imagery from the current orbiters. Mars will be in view of the Arecibo telescope during the oppositions of ’07, ’10 and ’12 allowing similar observations over a wide range of latitudes.

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