Ground-Based Radar Observations

Enabling Small-Body Science, Planetary Defense, and Solar System Exploration

Patrick A. Taylor[1], L. A. M. Benner[2], M. C. Nolan[3], M.W. Busch[4], E. G. Rivera-Valentin[1], and A. K. Virkki[1]

[1]Arecibo Observatory/USRA, [2]JPL/Caltech, [3]University of Arizona, [4]SETI Institute ptaylor@naic.edu

State of the Art

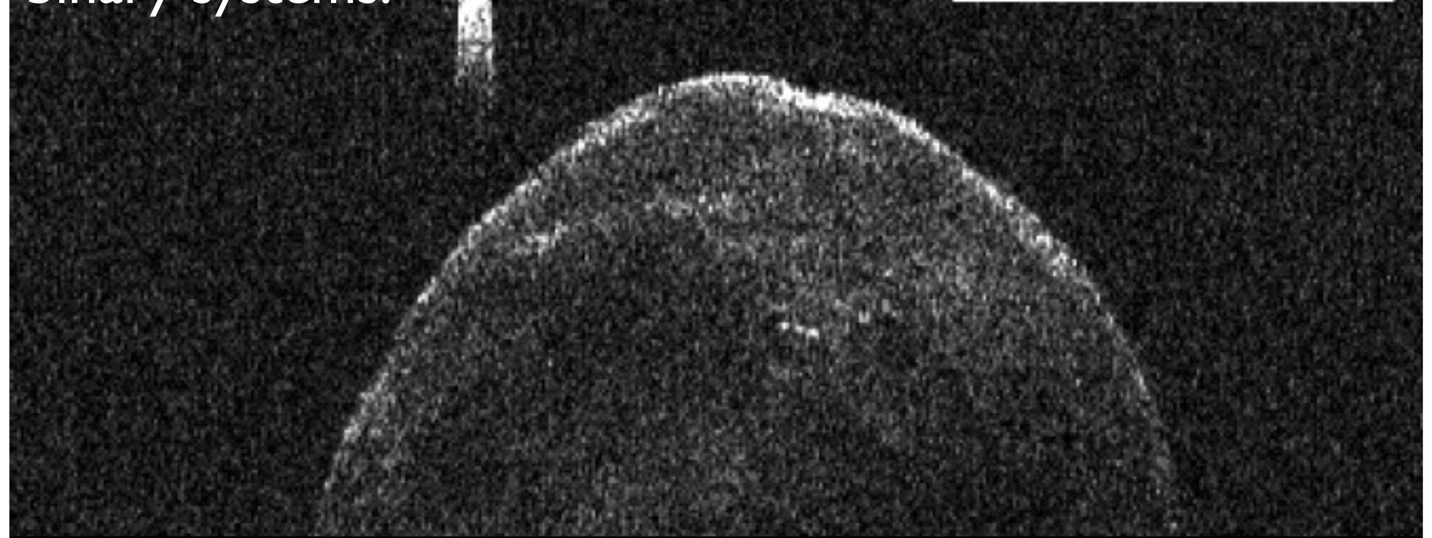
Arecibo Observatory and the Goldstone Solar System Radar complex house the largest, most powerful, most sensitive, and most active planetary radars in the world:

- Arecibo: 305 m, 1 MW @ 12.6 cm/2.38 GHz
- Goldstone DSS-14: 70 m, 450 kW @ 3.5 cm/8.56 GHz
- Goldstone DSS-13: 34 m, 80 kW @ 4.2 cm/7.16 GHz

- Technical capabilities:
  - line-of-sight range resolution as fine as 3.75 m
  - line-of-sight velocity resolution as fine as ~1 mm/s
  - astrometric precision of ~1 part in 10 million

Science, Defense, and Exploration

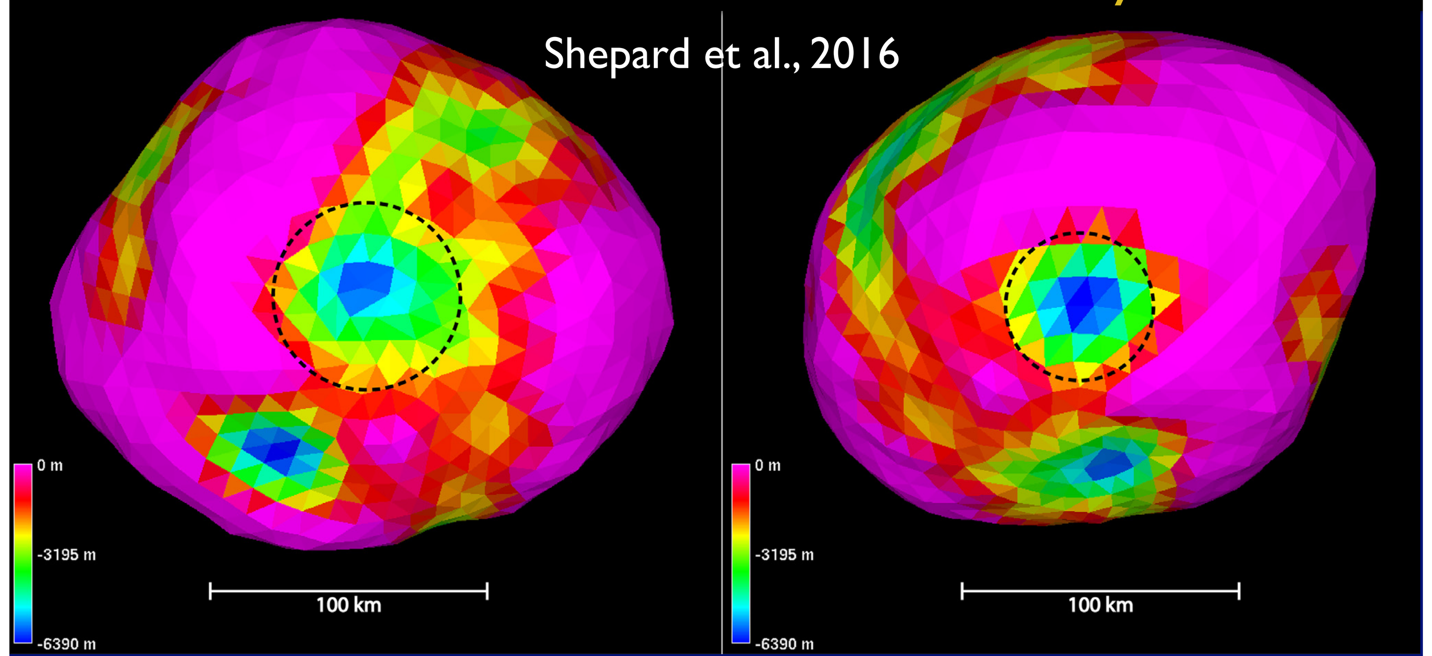
Radar provides ultra-precise astrometry and constraints on the size, shape, spin state, scattering properties, composition, and geology of asteroids, plus constraints on mass, density, and internal structure of binary systems.



An asteroid radar campaign is roughly equivalent to a spacecraft flyby at a cost orders of magnitude less.

Radar astrometry routinely prevents loss of newly discovered objects, reduces orbital uncertainties by orders of magnitude, and extends Earth-encounter predictability by decades if not centuries.

Radar reconnaissance is invaluable for missions such as *Hayabusa* (Itokawa), *EPOXI* (Hartley 2), *OSIRIS-REx* (Bennu), *AIDA* (Didymos), *Psyche*, and the Asteroid Redirect Mission. It is unlikely a spacecraft would fly to an asteroid that has not been characterized by radar first.

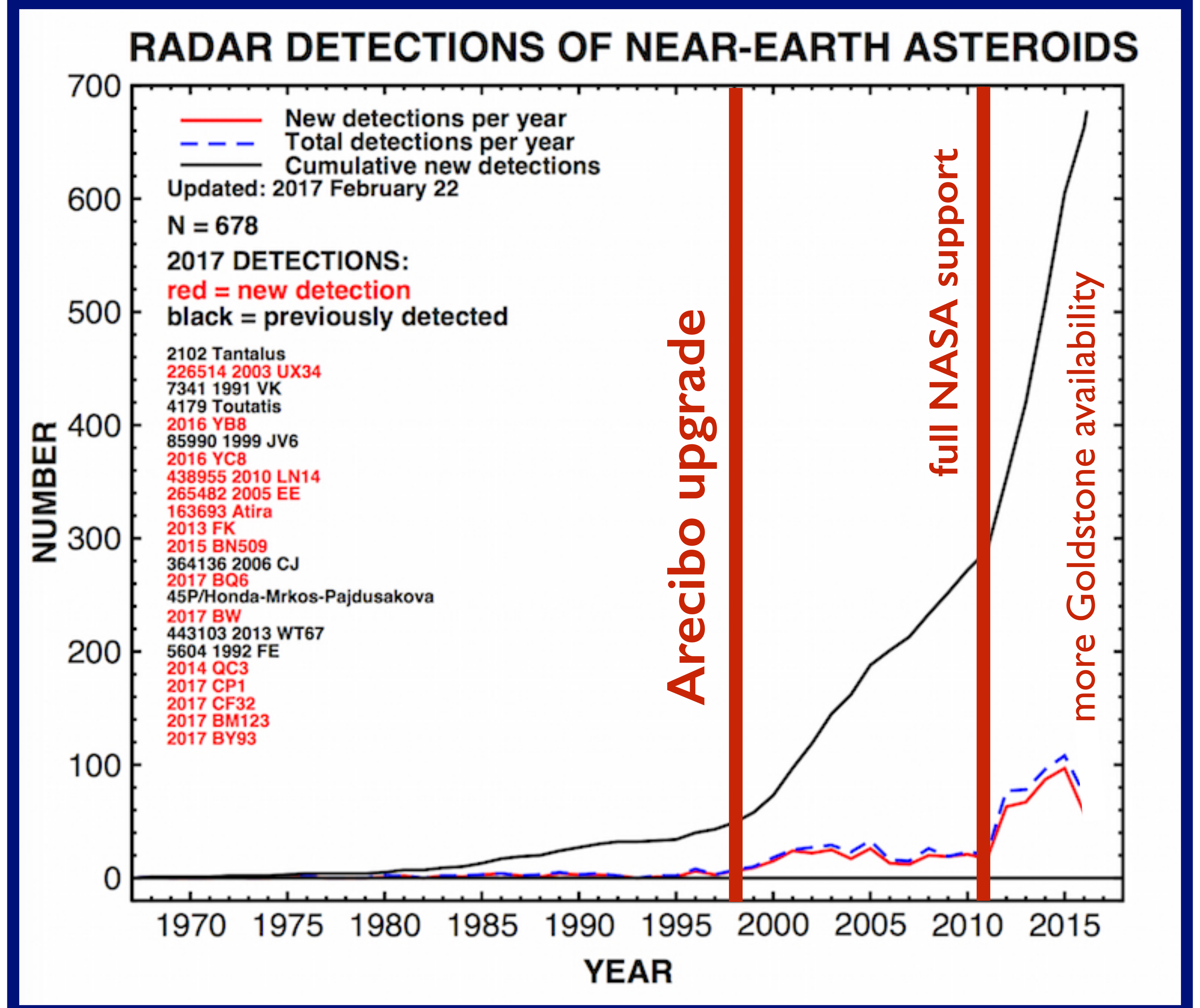


Crater-like depressions on the radar shape model of 16 Psyche

Dynamical and physical characterization by radar drives small-body science, informs planetary defense, and enables Solar System exploration.

Detectability of Asteroids

To date, 678 near-Earth asteroids (NEAs) have been detected with radar or 4.3% of the known population. Over half of all NEA detections occurred in the last five years and >90% since the Arecibo upgrade in 1998.



Naidu et al. (2016) showed that Arecibo and DSS-14 currently detect less than 30% of available radar targets. Many go undetected due to short warning times, limited scheduling flexibility at these shared-discipline facilities, and limited available manpower to operate the equipment.

Future of Facilities

Cadence: The number of detectable asteroids will continue to accelerate as surveys improve and next-generation ground- and space-based assets, e.g., LSST and NEOCam, come online. To keep pace, one must expand radar programs, improve observation automation, streamline data-analysis pipelines, and employ dedicated radar facilities.

Existing Stations: Antennae at Haystack (37 m and 46 m), EISCAT (32 m), TIRA/Effelsburg (100 m) are capable of detecting close-approaching asteroids. Arecibo could shift to higher frequencies, e.g., C band (~6 cm/~5 GHz) or higher, as weather and antenna surface accuracy allow.

Additional Stations: A 34-m antenna at each Deep Space Network site: Spain, South Africa, and Australia, equipped similarly to DSS-13 at Goldstone would add flexibility to observations of close-approaching objects. A Ka-band (1 cm/30 GHz) system on the Green Bank Telescope (GBT) would be more sensitive than DSS-14 and complement the existing S-, C-, and X-band systems, though a more arid location for Ka band is preferred, e.g., 100-m telescope(s) in the Atacama desert or at Goldstone. By 2050, Arecibo and DSS-14 will be ~85 years old and GBT will be 50 years old; new facilities must be considered in the coming decades.

Technological Advancements

Transmitters: X-band (3.5 cm/8.56 GHz) klystrons with 1.25-m resolution will allow for more precise astrometry, better shape determination, and finer detail of the surfaces and possible boulder fields of larger asteroids that are of interest for human exploration and resource identification. Ka-band (1 cm/30 GHz) klystrons capable of up to 1 MW output are a technological challenge for the near future. Preliminary work on the use of solid-state amplifiers as transmitters with 1.25-m resolution is promising and could replace expensive, highly specialized klystrons with "off-the-shelf" technology that is easily replaced, upgraded, and scalable up to 1 MW output.

Sensitivity vs. Detail: Doubling transmitter output power equates to "seeing" ~20% further into space and increasing the number of radar-detectable objects by a similar amount. One must ask: is extending our reach preferred over meter-scale characterization of those objects making the closest approaches to Earth?

Phased Arrays: The long-term future of ground-based radar may lie in phased arrays at higher frequencies, e.g., Ka band (1 cm/30 GHz) and higher, that could provide dedicated high-power, high-resolution stations for tracking and characterizing asteroids and comets. The NASA Ka-Band Objects Observation and Monitoring (KaBOOM) project and the 34-m antennae at Goldstone have experimented with coherent uplink arraying for communication and are testbeds for future radar systems aimed at having 5-cm resolution and active correction for atmospheric distortion. If successful, arrays of dozens of antennas with modest transmitters up to 25 kW each could be vastly more sensitive than Arecibo.

KaBOOM Ka-band three-element (12-m) phased array testbed

Comparison: A Ka-band, 100-m class, dedicated radar facility may cost as much as a Discovery-class mission, but could return flyby-level science for scores of asteroids per year. This should be weighed against the cost and scientific effectiveness of phased-array systems.

Take-Home Message

A healthy radar infrastructure is required to enable the objectives of planetary science, including small-body science, planetary defense, and Solar System exploration.