Radar Reconnaissance of Potentially Hazardous Asteroids and Comets

Steven J. Ostro, JPL/Caltech

300-233 Jet Propulsion Laboratory, Pasadena, CA 91109-8099, ostro@reason.jpl.nasa.gov

Groundbased radar is an intelligence-gathering tool that is uniquely able to reduce uncertainty in NEO trajectories and physical properties. A single radar detection secures the orbit well enough to prevent "loss" of newly discovered asteroids, shrinking the instantaneous positional uncertainty at the object's next close approach by orders of magnitude with respect to an optical-only orbit. This conclusion, reached initially by Yeomans *et al.* (1987) through Monte Carlo simulations, has been substantiated quantitatively by comparison of residuals for radar+optical and optical-only positional predictions for recoveries of NEAs during the past decade (Ostro *et al.* 2002).

Integration of an asteroid's orbit is afflicted by uncertainties that generally increase with the length of time from epochs spanned by astrometry. Eventually the uncertainties get so large that the integration becomes meaningless. The duration of accurate orbit integration defines our window of knowledge about the object's whereabouts. Presumably we want to find out if any given NEO might threaten collision and if so, we would like as much warning as possible. Radar observations dramatically extend NEO trajectory predictability intervals far beyond what is possible with optical data alone, often approaching the end of this millennium (e.g., 1999 JM8; Benner *et al.* 2002).

One interesting example is 2002 FC. An eight-week arc of discovery-apparition optical astrometry could not reliably identify any close Earth approaches before or after 2002, but with Arecibo astrometry from May 24 and Goldstone astrometry from June 6 (the object's last radar opportunity until 2040), close approaches could be identified reliably during the 1723 years from 488 to 2211. At this writing, with a much longer, 3.3-month optical arc, the corresponding intervals are 1951 years with radar (464 to 2415) and 137 years without it (2002 to 2139).

For 29075 (1950 DA), integration of the radar-refined orbit by Giorgini *et al.* (2001) revealed that in 2880 there will be a possibly hazardous approach to Earth that was not foreseeable from the half-century arc of pre-radar optical data. This event could represent a risk as large as 50% greater than that of the average background hazard due to all other asteroids from now through 2880, as defined by the Palermo Technical Scale (PTS value = +0.17). 1950 DA is the only known asteroid whose danger could be above the background level. The uncertainty in the probability of a collision in 2880 is due mostly to uncertainty in the Yarkovsky acceleration, which depends on the object's shape, spin state, and thermal properties. This example establishes the fundamental inseparability of the physical properties of NEAs and long-term prediction of their trajectories: if we take the hazard seriously, physical characterization of these objects deserves high priority.

For most NEAs, radar is the only Earthbased technique that can make images with useful spatial resolution (as fine as ~10 m). With adequate orientational coverage, delay-Doppler images can be used to construct geologically detailed three-dimensional models (e.g., Hudson *et al.* 2000), to define the rotation state, and to constrain the internal density distribution.

The wavelengths used for NEAs at Arecibo (13 cm) and Goldstone (3.5 cm), in combination with the observer's control of the transmitted and received polarizations, make radar experiments sensitive to the surface's bulk density and to its roughness at scales larger than a few centimeters (e.g., Magri *et al.* 2001). The fact that NEAs' circular polarization ratios (SC/OC) range from near zero to near unity means that the surfaces of these objects are extremely variegated and in some cases much more complex than any seen by spacecraft that have landed on Eros (whose SC/OC is about 0.3, near the NEA average), the Moon, Venus, or Mars.

Radar-derived shape models of small NEAs open the door to a wide variety of theoretical investigations that are central to a geophysical understanding of these objects. With realistic models, it is possible to explore the evolution and stability of close orbits (e.g., Scheeres *et al.* 1998) with direct application to the design of spacecraft rendezvous and landing missions. Given information about the internal density distribution, one can use a shape model to estimate the distribution of gravitational slopes, which can constrain regolith depth and interior configuration. A shape model also allows realistic investigations (Asphaug *et al.* 1998) of the potential effectiveness of nuclear explosions in deflecting or destroying hazardous asteroids.

The most basic physical properties of an asteroid are its mass, its size and shape, its spin state, and whether it is one object or two. Radar is uniquely able to identify binary NEAs, and at this writing, has revealed six (Margot *et al.* 2002 and references therein, Nolan *et al.* 2002), all of which are designated Potentially Hazardous Asteroids (PHAs). Analysis of the echoes from these objects is yielding our first information about the densities of PHAs. Current detection statistics suggest that between 10% and 20% of PHAs are binary systems.

References

Asphaug E. *et al.* (1998). Disruption of kilometre-sized asteroids by energetic collisions. *Nature* **393**, 437-440.

Benner L. A. M. *et al.* (2002). Radar observations of asteroid 1999 JM8. *Meteoritics Planet. Sci.* **37**, 779-792.

Giorgini J. D. *et al.* (2002). Asteroid 1950 DA's encounter with Earth in 2880: Physical limits of collision probability prediction. *Science* **296**, 132-136.

Hudson R. S. *et al.* (2000). Radar observations and physical modeling of asteroid 6489 Golevka. *Icarus* **148**, 37-51.

Magri C. *et al.* (2001). Radar constraints on asteroid regolith compositions using 433 Eros as ground truth. *Meteoritics Planet. Sci.* **36**, 1697-1709.

Margot J. L. *et al.* (2002). Binary asteroids in the near-Earth object population. *Science* **296**, 1445-1448.

Nolan M. C. *et al.* (2002). 2002 KK_8. IAU Circ. No. 7921.

Ostro S. J. *et al.* (2002). Asteroid radar astronomy. In *Asteroids III* (W. Bottke, A. Cellino, P. Paolicchi, and R. P. Binzel, Eds.), Univ. of Arizona Press, Tucson.

Scheeres D.J. *et al.* (1998). Dynamics of orbits close to asteroid 4179 Toutatis. *Icarus* **132**, 53-79.

Yeomans D. K. *et al.* (1987). Radar astrometry of near-Earth asteroids. *Astron. J.* **94**, 189-200.