RADAR ASTROMETRY OF ASTEROIDS, COMETS AND PLANETARY SATELLITES

STEVEN J. OSTRO
Jet Propulsion Laboratory,
California Institute of Technology

Groundbased radar has considerable astrometric potential for asteroids, comets and natural satellites that enter the detectability windows of available telescopes. For very closely approaching asteroids and comets, measurements of the distribution of echo power in time delay (range) and Doppler frequency (radial velocity) can achieve a fractional precision between 10^{-5} and 10^{-9}, and consequently are invaluable for refining orbits and prediction ephemerides. Even for mainbelt asteroids and the more readily detectable planetary satellites whose orbits are very well known, radar can collapse range uncertainties from a few target radii to a few percent of a target radius, with direct implications for the navigation of spacecraft on flyby or rendezvous trajectories.

Radar refinement of orbits is tightly coupled to radar determination of physical properties. For this reason, almost every radar measurement that produces new information about a target's size, shape, rotation, or surface properties also provides an astrometrically useful measurement. The relative utility of the different kinds of information provided depends on the caliber of the radar data and the available prior information, as well as on the sophistication of analysis techniques.

The tally of radar-detected targets includes the Moon, Venus, Mercury, Mars, Saturn's rings, the Galilean satellites, Phobos, Titan, five comets, 37 mainbelt asteroids (MBAs), and 34 near-Earth asteroids (NEAs, almost all of which are Earth-crossers). The Arecibo and Goldstone radars are responsible for almost all this work. Ostro (1993) offers a review of planetary radar astronomy, including an outline of techniques and observational highlights. The terrestrial bodies have been subjected to delay-Doppler radar observations for decades. Whereas lunar radar time-delay measurements (”ranging”) have become less useful than laser measurements, radar ranging to the inner planets still helps to maintain the accuracy of ephemerides

S. Ferraz-Mello et al. (eds.), Dynamics, Ephemerides and Astrometry of the Solar System, 365–372.

TABLE 1 – Residuals for optical (O) and optical+radar (OR) predictions of the sky positions of four Earth-crossing asteroids during the post-discovery apparition when they were recovered optically. The last column in the table demonstrates that radar astrometry produced a several-order-of-magnitude reduction in the sky area that one would have to search to achieve any given probability of recovering one of these objects. Each object's designation starts with the year of discovery.

Object	Recovery Date	Residuals O	Residuals OR	O/OR	(O/OR)^2
1989 PB	May 1990	24"	0.4"	60	3.6×10^3
1991 AQ	Sep 1994	57°	0.15°	380	1.4×10^5
1986 DA	Oct 1994	56"	0.9"	60	3.6×10^3
1991 JX	Mar 1995	3600"	4.6"	780	6.1×10^5

and in the case of Mercury is motivated also by long-term tests of gravitation theories. The first radar ranging to Ganymede and Callisto was reported by Harmon et al. (1994). Those authors' interpretation of the ranges used antiquated values for the satellite radii and has been redone by E. M. Standish (pers. comm.), who assess the consistency between the radar data and the most recent planetary and satellite ephemerides. Radar ranging has been carried out on 3 MBAs and 14 NEAs (in two cases during two different apparitions), but all observations of comets, Io, Phobos and Titan have been Doppler-only. The bulk of asteroid/comet radar astrometry was reported by Ostro et al. (1991), and has been incorporated in orbit estimates by Yeomans et al. (1992).

Radar astrometry of a near-Earth asteroid (NEA) during its discovery apparition can ensure its optical recovery (Yeomans et al. 1987). Observational experience has demonstrated that radar astrometry commonly improves upon the accuracy of optical-only ephemerides of newly discovered NEAs by one to five orders of magnitude (e.g., Table 1).

Radar can image NEAs if the echoes are strong enough, and if the orientational coverage of the images is adequate, inversion of the data by the methods introduced by R. S. Hudson (1993) can yield a three-dimensional model and an estimate of the delay-Doppler trajectory of the center of mass with very fine precision: a few decameters for work reported so far (Hudson and Ostro 1994, 1995) and a few meters for results of observations and/or analyses anticipated for the next few years. Radar aperture-synthesis observations of asteroids (currently possible only by transmitting from Goldstone and receiving with the Very Large Array) can measure absolute angular positions in the quasar reference frame at a level approaching 0.01 arc-

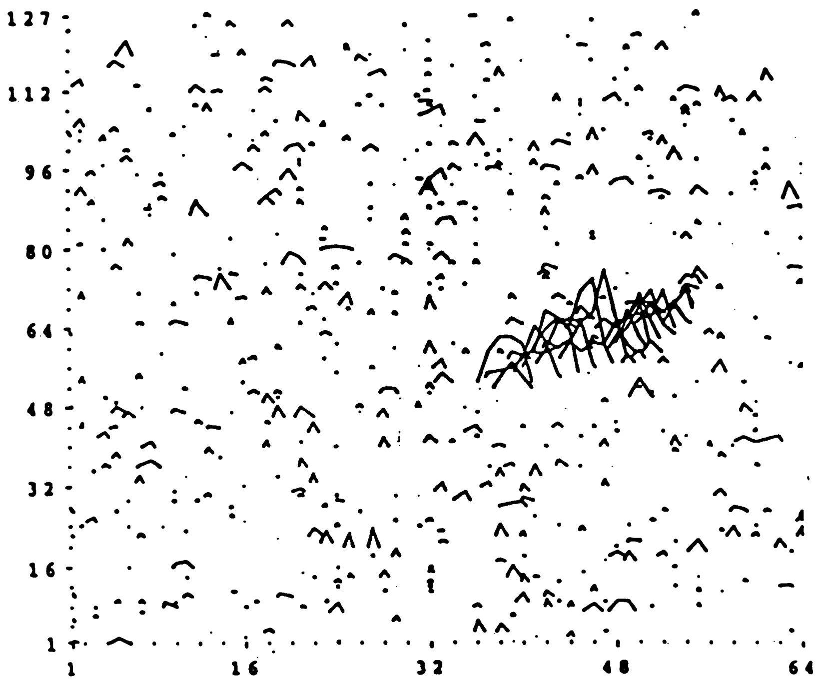

FIGURE 1 – Real-time display of a Goldstone radar image of asteroid 1620 Geographos. Power above half the peak value is plotted for 64 Doppler-frequency cells and 127 time-delay cells. The delay-Doppler resolution (1 μs by 2.9 Hz) corresponds to spatial resolution of 150 m by 151 m; prior knowledge of the spin vector from optical lightcurves indicated that our view was equatorial and set the Hz-to-m conversion. Range increases toward the top of this figure and frequency (or radial velocity) increases toward the right. The asteroid, rotating clockwise, is illuminated from below. The "leading edge" of the asteroid is seen prominently in this display. The asteroid's orientation is between end-on and broadside, and the spatial extent of the echo is $\sim$ 4.7 km. The total integration time is 46 s. The data were obtained less than one hour after the beginning of observations on 1994 Aug. 28, the first day of a one-week experiment. Analysis of radar movies from Aug. 28-29 indicates that at the beginning of the Aug. 28 imaging the correction to the range-prediction ephemeris was $-10.9\pm$ 0.3 km and was becoming more positive at a rate of about 0.16 km/h. (Here "range" is the distance from the asteroid's center of mass to a reference point on the Goldstone 70-m antenna.) See Ostro et al. (1996) and Ostro, Rosema et al. (1995).

TABLE 2 – Geographos radar astrometry reported by Ostro, Rosema et al. (1995). Goldstone (8510 MHz) time delays and Doppler frequencies correspond to hypothetical echoes from Geographos' center of mass received at the intersection of the azimuthal and elevation axes of the 70-m antenna, DSS-14. Postfit residuals are with respect to an orbit calculated by D. K. Yeomans and J.D.Giorgini and reported in the same paper.

UTC epoch of echo reception (hh:mm)	Time delay (UTC μs) Estimate	Residual	Doppler frequency (Hz) Estimate	Residual
1994 08 28 07:10	38936537.06±1.76	-0.91	-364880.6±0.9	-0.7
1994 08 29 04:40	42596456.40±1.13	0.33	-427851.0±0.2	-0.1
1994 09 02 07:20			-615553.2±0.5	0.1

sec, complementing delay-Doppler measurements (P. Palmer, unpublished results).

With adequate radar support, it would be possible for a spacecraft lacking onboard optical navigation to be guided into orbit around, or collision course with, an asteroid. For example, consider how Goldstone observations would have shrunk the positional error ellipsoid of Geographos just prior to a Clementine flyby of that target on Aug. 31, 1994. Before the Goldstone observations, the error ellipsoid's typical overall dimension was ~11 km. Ranging on Aug. 28-29 (e.g., Fig. 1) and a preliminary shape reconstruction collapsed the ellipsoid's size along the line of sight to several hundred meters, so its projection toward Clementine on its inbound leg would have been 11 × 2 km. Goldstone-VLA radar aperture synthesis could have shrunk the error ellipsoid's longest dimension to about 1 km, about half of Geographos's shortest overall dimension. Table 2 gives radar astrometry from analysis of a low-resolution subset of the Geographos data (Ostro et al. 1996).

The imaging of 4179 Toutatis by Goldstone and Arecibo in 1992 was most elaborate asteroid radar experiment reported so far (Ostro, Hudson et al. 1995; Ostro and Hudson 1995). Inversion of a subset of the images yielded center-of-mass astrometry for which the estimation uncertainties and the postfit residuals in the orbit solution are typically a few mm/s in radial velocity and a few decameters in range. As noted by Yeomans and Chodas (1994), Toutatis will pass 0.010360AU (4 lunar distances) from Earth on 2004 Sep 29.56711 UTC, the closest approach predicted for any asteroid or comet between now and 2060. Inclusion of the recently reported radar astrometry reduces the uncertainty in the miss distance to 40 km.

In an asteroid radar imaging experiment, an error in the Doppler prediction ephemeris causes motion of the asteroid with respect to the predicted delay trajectory, so images will be smeared in delay. Hence the achievable delay resolution is limited by the accuracy of the Doppler prediction ephemeris. A standard strategy is to first obtain echoes using a coarse delay resolution, fold the resultant astrometry into a new orbit solution, generate a refined prediction ephemeris, and then image the object with a finer delay resolution. This iterative process continues until the motion of the target through the delay-prediction ephemeris is negligible, i.e., until it does not compromise the finest delay resolution achievable in light of the available echo strength (typically ~100 nanoseconds for modern radar systems). The cycle time for updating delay-Doppler prediction ephemerides has recently been shrunk dramatically by D. K. Yeomans and J. D. Giorgini's JPL On-site Orbit Determination Program (OSOD). Installed at Goldstone in 1994, OSOD contributed significantly to the most recent NEA imaging experiment, on 1991 JX in June 1995. We were able to cycle through three generations of orbit solutions before the object's closest approach, settling on an ephemeris that turned out to be accurate to 0.3 mm/s in radial velocity (0.02 Hz at the Goldstone frequency of 8510 MHz).

NEA radar opportunities will expand significantly upon completion of upgrades in the Arecibo telescope, which by 1996 should be producing thousand-pixel images of several NEAs annually. A dedicated optical search program (the so-called Spaceguard Survey) could discover some 100,000 NEAs, most of which could, in principle, be studied with groundbased radar at least once every few decades. However, Arecibo and Goldstone are already heavily oversubscribed, so observation of more than a small fraction of the objects discoverable in proposed optical surveys will require dedicated radar telescopes.

Acknowledgements

This research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

de Pater, I., Palmer, P., Mitchell, D. L., Ostro, S.J., Yeomans, D. K. and Snyder, L. E. (1994), "Radar Aperture Synthesis Observations of Asteroids". *Icarus* **111**, 489-502.

Harmon, J. K., Ostro, S. J., Chandler, J. F. and Hudson, R. S.(1994), "Radar Ranging to Ganymede and Callisto". *Astron. J.* **107**, 1175-1181.

Hudson, R. S. (1993), "Three-dimensional reconstruction of asteroids from radar observations". *Remote Sensing Revs* **8**, 195-203.

Hudson, R. S. and Ostro, S. J. (1994), "Shape of Asteroid 4769 Castalia (1989 PB) from Inversion of Radar Images". *Science* **263**, 940-943.

Hudson, R. S. and Ostro, S. J. (1995), "Shape and Non-Principal-Axis Spin State of Asteroid 4179 Toutatis". *Science* **270**, 84-86.

Ostro, S. J., Campbell, D. B., Chandler, J. F., Shapiro, I. I., Hine, A. A., Velez, R., Jurgens, R. F., Rosema, K. D., Winkler, R. and Yeomans, D. K. (1991), "Asteroid Radar Astrometry". *Astron. J.* **102**,1490-1502.

Ostro, S. J. (1993), "Planetary Radar Astronomy". *Reviews of Modern Physics* **65**, 1235-1279.

Ostro, S. J. (1994), "The Role of Groundbased Radar in Near-Earth Object Hazard Identification and Mitigation" In *Hazards Due to Comets and Asteroids* (T. Gehrels and M. S. Matthews, eds.), Univ.of Arizona Press, pp. 259-282.

Ostro, S. J., Rosema, K. D., Hudson, R. S., Jurgens, R. F., Giorgini, J. D., Winkler, R., Yeomans, D. K., Choate, D., Rose, R., Slade, M. A., Howard, S. D. and Mitchell, D. L. (1995), "Extreme Elongation of Asteroid 1620 Geographos from Radar Images". *Nature* **375**, 474-477.

Ostro, S. J., Hudson, R. S., Jurgens, R. F., Rosema, K. D., Winkler, R., Howard, D., Rose, R., Slade, M. A., Yeomans, D. K., Giorgini, J. D., Campbell, D. B., Perillat, P., Chandler, J. F. and Shapiro, I. I. (1995), "Radar Images of Asteroid 4179 Toutatis". *Science* **270**, 80-83.

Ostro, S. J., Jurgens, R. F., Rosema, K. D., Hudson, R. S., Giorgini, J. D., Winkler, R., Yeomans, D. K., Choate, D., Rose, R., Slade, M. A., Howard, S. D., Scheeres, D. J. and Mitchell, D. L. (1996), "Radar Observations of Geographos". *Icarus*, in press.

Yeomans, D. K., Ostro, S. J. and Chodas, P. W. (1987), "Radar Astrometry of Near-Earth Asteroids". *Astron. J.* **94**, 189-200.

Yeomans, D. K., Chodas, P. W., Keesey, M. S., Ostro, S. J., Chandler, J. F. and Shapiro, I. I. (1992), "Asteroid and Comet Orbits using Radar Data". *Astron. J.* **103**, 303-317.

Yeomans, D. K. and Chodas, P. W. (1994), "Predicting Close Approaches of Asteroids and Comets to Earth". In *Hazards Due to Comets and Asteroids* (T.Gehrels and M. S. Matthews, eds.), Univ.of Arizona Press, pp. 241-258.

Appendix

History of Asteroid Radar Detections (Table)

Observatory abbreviations (and wavelengths unless otherwise indicated)

[A]	Arecibo (13cm);
[H]	Haystack (3.8cm);
[G]	Goldstone (3.5cm);
[GV]	Goldstone-VLA (3.5cm);
[EF]	Evpatoria-Effelsberg (6cm);
[GE]	Goldstone-Evpatoria (3.5cm);
[GK]	Goldstone-Kashima (3.5cm).

(For multi-observatory experiments, the order in which observatories detected echoes is indicated).

Underlines identify single-polarization experiments.

^{2,3,4,5,6} means second, third, etc. apparition yielding radar detection.

History of Asteroid Radar Detections

Year	Mainbelt	Ref.	Near-Earth	Ref.
1968			1566 Icarus	1 [G], 2 [H]
1972			1685 Toro	3 [G, λ13]
1975			433 Eros	4 [G, λ3.5, λ13], 5 [A, λ70]
1976			1580 Betulia	6 [A]
1977	1 Ceres	7 [A]		
1979	4 Vesta	8 [A]		
1980	7 Iris	9,26 [A]	1685 Toro^2	10 [A]
	16 Psyche	9 [A]	1862 Apollo	20 [A], 12 [G]
1981	97 Klotho	9 [A]	1915 Quetzalcoatl	20 [A]
	4 Vesta^2	9 [A]	2100 Ra-Shalom	13 [A]
	8 Flora	9 [A]		
1982	2 Pallas	9 [A]		
	12 Victoria	9,26 [A]		
	19 Fortuna	9 [A]		
	46 Hestia	9 [A]		
1983	5 Astraea	9 [A]	1620 Geographos	20 [A]
	139 Juewa	9 [A]	2201 Oljato	20 [A]
	356 Liguria	9 [A]		
	80 Sappho	9 [A]		
	694 Ekard	9 [A]		
1984	9 Metis	9,26 [A]	2101 Adonis	20 [A]
	554 Peraga	9 [A]	2100 Ra-Shalom^2	20 [A]
	144 Vibilia	9 [A]		
	1 Ceres^2	9 [A]		
	7 Iris^2	14,26 [A]		
1985	6 Hebe	9 [A]	1627 Ivar	18 [A]
	41 Daphne	9 [A]	1036 Ganymed	20 [A]
	21 Lutetia	15 [A]	1866 Sisyphus	20 [A]
	33 Polymymnia	15 [A]		
	84 Klio	15 [A]		
	192 Nausikaa	15 [A]		
	230 Athamantis	15 [A]		
	216 Kleopatra	15,26 [A]		
	18 Melpomene	15 [A]		
	16 Psyche^2	* [A]		
1986	1 Ceres^3	* [A]	6178 (1986 DA)	11 [A]
	393 Lampetia	15 [A]	1986 JK	16 [G]
	27 Euterpe	14 [A]	3103 Eger	20 [A]
	19 Fortuna^2	14 [A]	3199 Nefertiti	20 [A]
	9 Metis^2	14,26 [A]		

Year	Mainbelt	Ref.	Near-Earth	Ref.
1987	5 Astraea^2	14 [A]	1981 Midas	20 [G]
	532 Herculina	14 [A]	3757 (1982 XB)	20 [A]
	2 Pallas^2	* [A]		
	20 Massalia	14 [A]		
1988	654 Zelinda	20,26 [A]	1685 Toro^3	20 [A]
	4 Vesta^3	14 [A]	3908 (1980 PA)	20 [A,G]
	105 Artemis	20 [A]	433 Eros^2	20 [A]
1989	12 Victoria^2	26 [A]	4034 1986 PA	20 [A]
			1580 Betulia^2	20 [G,A]
			1989 JA	20 [A,G]
			4769 Castalia	19 [A,G]
			1917 Cuyo	20 [A,G]
1990	78 Diana	* [A]	1990 MF	20 [A,G]
	1 Ceres^4	* [A]	1990 OS	20 [G]
	194 Prokne	24 [G]	4544 Xanthus	20 [A]
1991	2 Pallas^3	* [A]	1991 AQ	21 [A]
	7 Iris^3	26[G],17[GV]	6489 1991 JX	21 [A,G]
	324 Bamberga	*[A,G],17[GV]	3103 Eger^2	24 [G]
	796 Sarita	* [A]	1991 EE	*[A],17[GV]
1992	4 Vesta^4	*[A],24[G]	1981 Midas^2	24 [G]
			5189 (1990 UQ)	24 [G]
			4179 Toutatis	22[G,A],23[VE], 17 [GV]
1994	97 Klotho^2	24 [G]	4953 (1990 MU)	24 [G]
			1620 Geographos^2	* [G]
1995	1 Ceres^5	** [G]	2062 Aten	* [G]
	18 Melpomene^2	** [G]	6489 1991 JX^2	*[G,GV], ***[GE],****[GK]
	7 Iris^4	** [G]		
Totals:	37 Mainbelt	+	34 Near-Earth	= 71 total

References [1] Goldstein (1969), *Icarus* **10**, 430; Goldstein (1969), *Science* **162**, 903. [2] Pettengill *et al* (1969), *Icarus* **10**, 432. [3] Goldstein *et al* (1973), *Astron. J.* **78**, 508. [4] Jurgens and Goldstein (1976), *Icarus* **28**, 1. [5] Campbell *et al* (1976), *Icarus* **28**, 17. [6] Pettengill *et al* (1979), *Icarus* **40**, 350. [7] Ostro *et al* (1979), *Icarus* **40**, 355. [8] Ostro *et al* (1980), *Icarus* **43**, 169. [9] Ostro *et al* (1985), *Science* **224**, 442. [10] Ostro *et al* (1983), *Astron. J.* **88**, 565. [11] Ostro *et al* (1991), *Science* **252**, 1399. [12] Goldstein *et al* (1981), *Icarus* **48**, 59. [13] Ostro *et al* (1984), *Icarus* **60**, 391. [14] Ostro *et al* (1988), *Bull. Amer. Astron. Soc.* **20**, 863 (abstract). [15] Ostro *et al* (1986), *Bull. Amer. Astron. Soc.* **18**, 796 (abstract). [16] Ostro *et al* (1989), *Icarus* **78**, 382. [17] de Pater *et al* (1994), *Icarus* **111**, 489. [18] Ostro *et al* (1990), *Astron. J.* **99**, 2012. [19] Ostro *et al* (1990), *Science* **248**, 1523. [20] Ostro *et al* (1991), *Astron. J.* **102**, 1490. [21] Ostro *et al* (1991), *Bull. Amer. Astron. Soc.* **23**, 1144 (abstract). [22] Ostro *et al* (1995), *Science* **270**, 80. [23] Zaitsev *et al* (1993), *Radiotekhnika Elektronika* **38**, 1842-1850. [24] Ostro *et al* (1994), *Bull. Amer. Astron. Soc.* **26**, 1165 (abstract). [25] Ostro *et al* (1995), *Nature* **375**, 474. [26] Mitchell *et al* (1995), *Icarus* **118**, 105-131. * Ostro *et al*, unpublished. ** Mitchell *et al*, unpublished. *** Zaitsev *et al*, unpublished. **** Koyama *et al*, unpublished.