RADAR CONTRIBUTIONS TO ASTEROID ASTROMETRY AND DYNAMICS

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Introduction

Almost every radar observation of asteroids has measured some characteristics of the distribution of echo power in time delay (range) and Doppler frequency (radial velocity). Such measurements, which are orthogonal to optical plane-of-sky angular astrometry, are also done in the well-known, "absolute" reference frame of the planetary ephemerides, often with fractional precision that is much finer than can be achieved with other kinds of groundbased observations; they therefore can dramatically refine orbits and ephemerides. This statement is most true for near-Earth asteroids (NEAs), which constitute the most prolifically observed radar targets and are likely to be observed in increasing abundance as instrumental capabilities improve and CCD-based, NEA search programs expand. Moreover, studies of closely approaching NEAs benefit tremendously from the inverse fourth-power dependence of echo strength on target distance. For these reasons, I devote the bulk of this paper to NEAs.

Systems and Techniques

The Arecibo and Goldstone radar systems, the most sensitive on the planet, are responsible for the vast majority of radar observations reported to date, although radar astronomy has a long history in Russia and, during the past few years, two-station asteroid radar observations have used international combinations of antennas in Russia, Germany, Japan, and the United States. The upgraded Arecibo 305-m telescope, expected to become operational in late 1996, will be nearly a factor of 40 more sensitive than the Goldstone 70-m antenna (DSS14), which in turn is many times more sensitive than other available radar systems. Arecibo will have twice the range and will see three times the volume of Goldstone, while Goldstone, which is fully steerable, will see twice the plane-of-sky solid angle and will cover three times more hour angle than Arecibo, which cannot point more than ~20 degrees from the zenith.

Whereas sensitivity is the primary factor that limits a radar system's capabilities in astrometry or imaging, it is riot the only one. It turns out that two-station (bistatic) systems can have significant advantages over single-station (monostatic) systems in observations of very close, and/or very rapidly moving targets (NEAs). Full steerability is generally advantageous even for the most distant radar-detectable targets (in the Saturn system). Bistatic configurations using Goldstone's 70-m antenna to transmit and either a second Goldstone antenna (the 34-m DSS13) or the 27-antenna Very Large Array (VLA) in New Mexico to receive have made unique measurements. For example, interferometric observations with the Goldstone-VLA configuration can synthesize a beamwidth as small as 0.25" (vs. 2' for single-dish observations), and is capable of 0.01" astrometry in the radio reference frame. Future bistatic experiments may link Arecibo or Goldstone to the 100-m Greenbank Telescope (GBT, under construction) or to each other.

The simplest radar experiment s transmit a highly monochromatic, continuous-wave (cw) signal (2380-MHz, 13 cm for Arecibo; 8510 MHz, 3.5 cm for Goldstone). One tunes the receiver continuously to the echo's Doppler-shifted frequency using a prediction ephemeris calculated from an orbit solution that, at least initially, is based on optical astrometry only. A correction to the ephemeris is measured, and the resultant Doppler datum is used in a next-generation orbit. solution, which yields a refined Doppler ephemeris. Similarly, "ranging" observations use time-modulated waveforms and measure corrections to time-delay predictions. (My 1993 review of planetary radar astronomy describes waveforms and observational techniques in more detail.)

To do any radar observations, one prefers to be able to point within -2.0" to avoid significant losses of echo power. One also prefers small Doppler uncertainties, so the receiver anti data-acquisition system can use a narrow frequency window and hence a slow data-acquisition rate. Generally, one must integrate echoes to fight noise, so there are limits on how fast the echo can "drift through" the ephemeris before smear degrades echo strength (and resolution).

The rate of change of the delay-prediction error is the Doppler-prediction error times the negative reciprocal of the transmitter frequency. A Doppler error of 1 Hz (one-half wavelength per second) corresponds to a delay error rate of ~ 36 and - 10 microseconds per day at the Arecibo and Goldstone transmitter frequencies. In practice, one iterates, using increasingly fine-resolution delay-Doppler astrometry to produce increasingly accurate orbit solutions, aiming to freeze the target in the ephemeris.

Astrometry

In reporting radar astrometry, one specifies the reference points on the transmitting antenna, the receiving antenna, and the target. The target's center of mass (COM) is what matters for orbit estimations, but echoes are reflected from the surface, so eventually uncertainty about the target's size and shape may be the dominant source of astrometric error, and hence in the degree to which radar can refine an orbit estimate. Therefore, orbit refinement is tightly coupled to determination of physical properties. Radar measurements that produce new information about a target's size, shape, rotation, or surface properties also may provide useful astrometry, and vice versa. 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. Time-resolved measurements generally can achieve finer fractional precision than Doppler-only measurements and are thus more useful, but they also require stronger echoes.

Asteroid radar astrometry dates to 1968, but nearly two decades passed before Yeomans et al. (1 98"/) carried out the first systematic exp] oration of the utility of delay-Doppler data for the refinement of asteroid and comet orbits and prediction ephemerides. They demonstrated that a single radar detection can ensure the recovery of newly discovered asteroids, shrinking the instantaneous positional uncertainty by orders of magnitude with respect to an optical-only orbit. Even for an asteroid with an extensive optical-data history, a few radar measurements can shrink the positional error ellipsoid by a factor of 2 for at least a decade,

Useful Doppler astrometry has been obtained for all 38 radar detected NEAs and time-delay astrometry has been obtained for 17 NEAs and 3 MBAs. All 1980-1990 delay/Doppler was reported by Ostro et al. 1991, who also tabulated all other asteroid and comet radar astrometry through 1990; Yeomans et al. (1 992) estimated the orbits for each of those objects. Errors in optical-only ephemerides have been found to be as large as -100,000 km for newly discovered NEAs, but rarely exceed several target radii for MBAs.

The following table conveys the state of the art for radar reconnaissance of a fairly large asteroid during a close Earth approach:

Asteroid Radar Measurement Precision

	Range (meters)	Radial Velocity (meters/sec)
Best Radar Resolution	-lo	0.0001
Asteroid "size"	-1 000	0.01 to 1
Asteroid "location"	-lo 000 000 000	10000

in principle, it. is not hard to resolve such a target into 10,000 imaging pixels. Given adequate orientational coverage, a sequence of delay-Doppler images can be inverted to produce a detailed physical model (Hudson 1993) and simultaneously to locate the COM's position with an uncertainty that is comparable to or smaller than the delay-Doppler cell resolution. in other words, COM astrometry with sub-decameter accuracy is within the reach of modern radar capabilities.

Examples of NEA Experiments

Let me try to communicate the progress and potential of asteroid radar astrometry by relating some of our experiences with NEAs.

1862 Apollo

The 1980 Arecibo observations of this object (Ostro et al. 1991) achieved the first. ranging to an Earth-crosser, with difficulty. Shortly after the observations began, B. G. Marsden notified us via telephone! that new optical astrometry had revealed our prediction ephemeris to be in error by several arcminutes. We implemented pointing corrections, ant] then saw echoes that were: much stronger than in any previous asteroid radar experiment.

The available delay-Doppler-resolution was limited by the data-acquisition hardware and software, lettingus resolve the object into only IO cells in Doppler and about 1.5 in delay. '1'lie> initial delay corrections to original ephemeris was - 21 ms.

4769 Castalia (1989 PB)

Castalia was discovered on August 9, 1989, by E. F. Helin. Two days later, orbital calculations showed that this object was approaching the Earth and would pass within the Arecibo Observatory's field of view during August 19-22 at distances likely to provide echoes much stronger than in previous asteroid radar observations, during time windows that had already been allocated for 12 Victoria. The asteroid's trajectory passed within 0.027 AU (11 lunar distances) from Earth on August 25, when the Voyager 2 spacecraft was making its closest approach to Neptune. (The Goldstone "/0-meter antenna was occupied with Voyager communications during the Neptune encounter and was unavailable for radar astronomy unti] Aug. 30, when cw spectra were obtained.) More infer-nlat.ive observations were conducted at Arecibo on August 19-22, thanks in part. to follow-up astrometry by several dedicated optical astronomers, whose? measurements during the previous week ensured that we would

be able to point accurately. R. McNaught provided critical astrometry at Siding Spring despite the asteroid's proximity to the nearly full moon, and two observers in Great Britain (J. D. Shanklin at Cambridge and B. Manning at Stakenbridge) made useful measurements during the Aug. 1-/ total lunar eclipse.

The initial Arecibo observations disclosed ephemeris errors of about 200 Hz and 60 ms (1.5 Earth radii). By Aug. 22, J. F. Chandler at the Center for Astrophysics had used the radar astrometry to make an improved delay-Doppler ephemeris, which he sent to Arecibo via email. (Prior to email, this process would have relied on express airmail.) The improved ephemeris was used to make a 64-frame radar movie. Each frame placed no more than a -30 pixels on the asteroid, but the 150 x ~170-m resolution was adequate to reveal a consistently bimodal distribution of echo power, suggesting a bifurcated shape. Analysis of the data yielded astrometry with uncertainties set by the imaging resolution: 2 microseconds and 1 Hz. The asteroid was recovered by McNaught in May 1990, - 0.4 arcsec from the position predicted from radar+optical data and - 24 arcsec from that based on an optical prediction.

Reconstruction of Castalia's shape (11094) established the asteroid's contact-binary shape and also produced refined COM astrometry with uncertainties of 0.3 microseconds and 0.1 Hz. The current plane-of-sky and range uncertainties in Castalia's position during its next close approach (to 0.025 AU in 2046) are about 3 arcmin and 2000 km (D. K. Yeomans, pers. comm.).

4179 Toutatis (1989 AC = 1934 CT)

Toutatis was (re)discovered in early 1989, nearly four years before its approach to 0.024 AU on Dec. 8, 1992. Despite the long optical-astrometric time base (1934 to Nov. 1992), the initial radar measurements corrected the ephemerides by 2.5 ms. After radar refinements in the orbit during the week before the closest approach, the radar corrections were all smaller than the asteroid's delay-Doppler dispersion (typically 1 y - 2 Hz and - 10 microsecond); that is, uncertainty in astrometry tied to Toutatis' COM was due to uncertainty in the asteroid's size and shape. The images showed a bizarre, partially bifurcated object in a highly unusual, non-principal-axis (NPA) spin state with several day character st i c t ime scales. Detailed definition of Toutatis' spin state (and shape) required inversion (Hudson 1993) of the image sequence with a comprehensive physical model. Hudson and Ostro (1995) carried out such an inversion on a 1 ow-resolution (typical 1 y 0.5 microsecond x 0.1-Hz) subset of the images, estimating the asteroid's shape and inertia tensor, their mutual orientation, initial conditions for the asteroid's spin and orientation, the radar scattering properties of the surface, and the COM's delay-Doppler trajectory. For example, for monostatic 8510-MHz observations with 1) SS-14 on Dec. 8, the estimates of the time delay and Doppler frequency of echoes from Toutatis' COM received at 14:40:00 UTC are 24.2028192"10 sec +/- 0.12 microseconds and - 58768.687 +/- 0.02 Hz. The radar+optical orbit solution, estimated with DE 245 and confirmed with PEP740, yielded weighted rms residuals of 0.83 arc seconds, 0.08-/ Hz (1.5 mm/s in radial velocity) and 0.39 microseconds (59 m in range). This solution indicates that Toutatis will pass 0.010360 AU (four lunar distances) from Earth on 29 September 2004, the closest approach predicted for any asteroid or comet between now and 2060 (Yeomans and Chodas 1994).

Toutatis' dimensions along the principal axes are 1.92, 2.40, and 4.6 km. It is rotating in a long-axis mode characterized by periods of 5.41 days (rotation about the long axis) and '/.35 clays (average for long-axis precession about the angular momentum vector). The principal moments of inertia are in ratios within 3% of 3.19 and 3.01, and the inertia tensor is indistinguishable from that of a homogeneous body. (Such information has yet to be determined for any other asteroid or comet, and probably is impossible to acquire in a fast spacecraft flyby.) At this writing, the highest-resolution (0.125-microsecond x 0.008-Hz) images are being incorporated into the inversion. It will be interesting to fit shape, spin state, and orbital parameters simultaneously to images with decameter resolution.

Geographos' Aug. 25,1994, approach to 0.0333 AU, the closest for at least the next two centuries, provided a unique opportunity for Goldstone radar observations. This experiment was given special impetus by the Clementine mission, which planned a 10 .-/ km/s flyby of Geographos on Aug. 31 at a miss distance of approximately 100 km (Nozette anti Garrett 1994; a computer malfunction led to cancellation of the flyby.) . We intended to use radar astrometry to improve the pre-encounter ephemeris ancl to use imaging with complete rotational coverage to crptimize the post-encounter physical model of the asteroid.

The asteroid entered Goldstone's declination window on Aug. 28 anti Ostro et al. (1996, Icarus) observed it. daily for a week, obtaining over 400 images whose linear spatial resolutions range from ~75 m to ~151 m, The images contain an intrinsic north/south ambiguity, but the equatorial view allowed accurate determination of the shape of the rada-facing part of the asteroid's pole-on silhouette at any rotation phase. Sums of co-registered images defined the extremely elongated shape of that silhouette (Ostro et. al. 1995, Nature 375, 474-477), revealed craters and other contrast features "inside" the silhouette, and also showed curious protuberances at the asteroid's ends that may be related to the pattern of ejecta removal and deposition caused by the asteroid's gravity field. The delay-Doppler trajectory of Geographos' center of mass was determined to about 200 m on Aug. 28 anti to about 100 m on Aug. 31, an improvement of two orders of magnitude over pre-observation ephemerides.

The Geographos experience suggested that with adequate radar reconnaissance, it would be possible for a spacecraft lacking onboard optical navigation to be guided into orbit around, or collision course with, an asteroid. If onboard opnav capability were available, radar would nonetheless shrink the navigation uncertainties significantly, perhaps reducing the missions fuel requirements enough to allow a larger mass budget for science instrumentation. For example, 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 ellipsoid's typical overall dimension was -11 km. Ranging on Aug. 28-29 anti 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 x 2 km. Goldstone-VLA plane-of-sky astrometry could have shrunk the error ellipsoid's longest dimension to about 1 km, about half of Geographos's shortest overall dimension.

6489 Golevka (1991 JX)

This asteroid was ranged with sub-microsecond time resolution at, both Arecibo and Goldstone, shortly after Helin discovered it. in 1991 . It was recovered in March 1995, 5" and 3600" from positions based on radar+optical and optical-only predictions (D. K. Yeomans, pers. comm.) . By then, the cycle time for updating delay-Doppler predication ephemerides haci been shrunk dramatically by D. K. Yeomans anti J. I). Giorgini's JPL On site Orbit Determination Program (OSOD) . Installed at Goldstone prior to the Geographos experiment., this user-friendly software package made it possible for us to use radar (or optical) astrometry to refine ephemerides at the telescope . In June 1995, we took advantage of OSOD during an ambitious series of Goldstone observations . During June 3-8, we proceeded through three generations of orbit solutions, until our only limitation was uncertainty in the location of the asteroid's COM. That is, our ephemeris was "inside" the asteroid. Fortunately (for astrometry but not for imaging) , the asteroid is only several hundred meters across, so COM time-delay astrometry had an uncertainty of only 2 microseconds. By June 9, when the asteroid made its closest approach (0.034 AU) , we were using a refined ephemeris that was later found to be accurate to 0.01 Hz (0.2 mm/s in radial velocity) . On two

dates we conducted radar aperture-synthesis observations, with Goldstone transmitting anti the VLA receiving; the resultant images yield angular positions with absolute uncertainties of a few hundredths of an arcsec (P. Palmer, pers. comm.). On June 13-15 we carried out the! first intercontinental radar astronomy observations, consisting of Goldstone cw transmissions and reception of the asteroid's echoes with the Evpatoria (Ukraine) 70-m antenna on each of those dates and reception of echoes with the Kashima (Japan) 34-m antenna on June 15. The full 1991-1995 radar+optical astrometric data set allows an accurate orbit integration some seven centuries into the future (D. K. Yeomans, pers. comm.).

1996 JG

This asteroid was discovered by R. McNaught on May 8. Ten minutes of observations on May 26 revealed a 580-Hz (20 rids) correction to the optical only ephemerities. On the next day's five-hour track, we did two iterations with 0s01), producing ephemerides whose delay-prediction errors decreased from ~4600 microseconds to ~20 microseconds.

Expectations anti Concluding Remarks

At this writing, the upgraded Arecibo telescope appears to be within six months of first "radar 1 ight." The impact of this instrument on astrometric and physical studies of asteroids is likely to be far-reaching. During its first decade of operation, it should provide several-hundred-pixel images of ~100 MBAs and several-thousand-pixel images of ~50 NEAs, and the best radar COM astrometry should be good to a few meters for NEAs anti a few kilometers for MBAs. In the past, radar has barely skimmed the inner edge of the main belt, but the upgraded Arecibo will have access to asteroids throughout the belt. The instrument should be technically able to do ranging to an average of one MBA per week. Short-period comets, which generally lie at the edge of the current detectability window, will become easier targets, although NEA opportunities will be one to two orders of magnitude more frequent.

Apart from astrometry, asteroid radar is contributing to other arenas within dynamics through the production of the first detailed shape models of small NEAs. The Castalia and Toutatis models have been used by Scheeres et al. (1996 and 1995, respectively) to study close orbits around those bodies. Our goal is to explore the short-term evolution and long-term stability of those orbits, with application to robotic or pilot ed spacecraft, natural satellites, and non-escaping impact ejecta. Almost all these calculations rest on a gravity field calculated from a closed-form expression (Werner 1994) for a polygonal representation of the shape under the assumption of uniform density. Stable anti unstable periodic orbits exist about each body, and the fate of material launched from the surface is a strong function of initial velocity and surface location.

The Castalia model also is currently being used by E. Asphaug et al. (1996) to simulate the effects of impacts in various energy regimes; since one of those effects is to launch material into return orbits, the simulations provide initial conditions for dynamical investigations of many-particle systems in a novel dynamical regime.

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