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NOTE

Radar Observations of Asteroid 1862 Apollo

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Arecibo radar echo spectra show the Q-class asteroid 1862 Apollo to have an elongation within 10% of 1.27, a pole-on silhouette with an average dimension of about 1.7 km, and disc-integrated radar properties that are typical for radar-detected near-Earth asteroids. © 2002 Elsevier Science (USA)
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1862 Apollo, the namesake of the dynamical class of Earth-crossing asteroids with semimajor axis $a > 1.0$ AU and perihelion distance $q < 1.017$ AU, was discovered by K. Reinmuth at Heidelberg on April 24, 1932. Photometry by Harris *et al.* (1987) yielded estimates of the asteroid's sidereal spin period, 3.065436 ± 0.000012 h, and pole direction, $(56°, -26°) \pm 10°$. It is a Q-class object (Tholen and Barucci 1989) that spectroscopically resembles ordinary chondrite meteorites (McFadden *et al.* 1985, Zellner *et al.* 1985, Binzel *et al.* 1996).

Apollo's passage within 0.056 AU from Earth on Nov. 13, 1980, the closest approach of an asteroid predicted in advance since that of 1566 Icarus in June 1968, was expected to produce extremely strong echoes at the Arecibo Observatory, whose sensitivity had been dramatically increased in the mid-1970s by resurfacing of the main reflector and installation of an S-band (2380-MHz, 12.6-cm) radar system. We used that system to observe Apollo on Nov. 13 and on each of the next seven days (see Table I). [Apollo was also observed with the Goldstone 3.5-cm radar (Goldstein *et al.* 1981).]

Almost all our observations were Doppler-only (continuous-wave, or cw), yielding echo power spectra in both senses of circular polarization (OC and SC); see Ostro *et al.* (1983) for descriptions of our observation and data-reduction techniques as well as relevant radar astronomical terminology. On the first date, we dealt with a large error in our pointing ephemeris, which put the asteroid in a sidelobe of the antenna beam. Since this was the first Arecibo radar observation of a target with a round-trip time delay of less than one minute, we also experimented with procedures for manually switching the system between transmit and receive configurations that frequently, while alternating the receiver between the OC and SC polarizations. By the second date, we had mastered those procedures well enough to obtain a flawless series of echo spectra that spanned 80% of a rotation. Those Nov. 14 data are the basis for the analysis reported here. On subsequent dates, the object's increasing distance rendered the echoes progressively weaker, and much of the observing periods were devoted to measurements with time-delay (range) resolution. Although the range resolution available at that time was too coarse to resolve Apollo, we did obtain useful range astrometry, which was reported by Ostro *et al.* (1991).

Figure 1 shows examples of our echo spectra, which generally are broad, like most asteroid echoes obtained since then. The echoes' 1.22-Hz frequency

TABLE I
Observations

1980 Nov.	RA (h)	DEC (deg)	Distance (AU)	cw runs OC	cw runs SC	Start–Stop hhmm–hhmm
13	20.7	9.1	0.056	26	19	2047–2249
14	21.4	14.3	0.057	34	34	2107–2336
15	22.0	18.6	0.060	3	3	2206–2218
16	22.6	22.0	0.066	3	3	2158–2211
17	23.1	24.4	0.072	7	4	2236–0014
18	23.6	26.2	0.080	5	6	2337–0007
19	23.9	27.3	0.088	38	0	2322–0123
20	0.2	28.1	0.097	23	0	2358–0116

Note. For each date, we give Apollo's right ascension (RA), declination (DEC), and distance near the midpoint of the cw observations; the number of cw runs in the OC and SC polarizations; and their receive start and stop times (UTC). Nominal radar system parameters were: transmitter power = 400 kW, minimum system temperature = 33 K, and maximum antenna gain = 71.5 db (sensitivity = 6.5 K/Jy).

[1] Present address: Blue Origin, LLC, 13 South Nevada Street, Seattle, Washington 98134.

0019-1035/02 $35.00

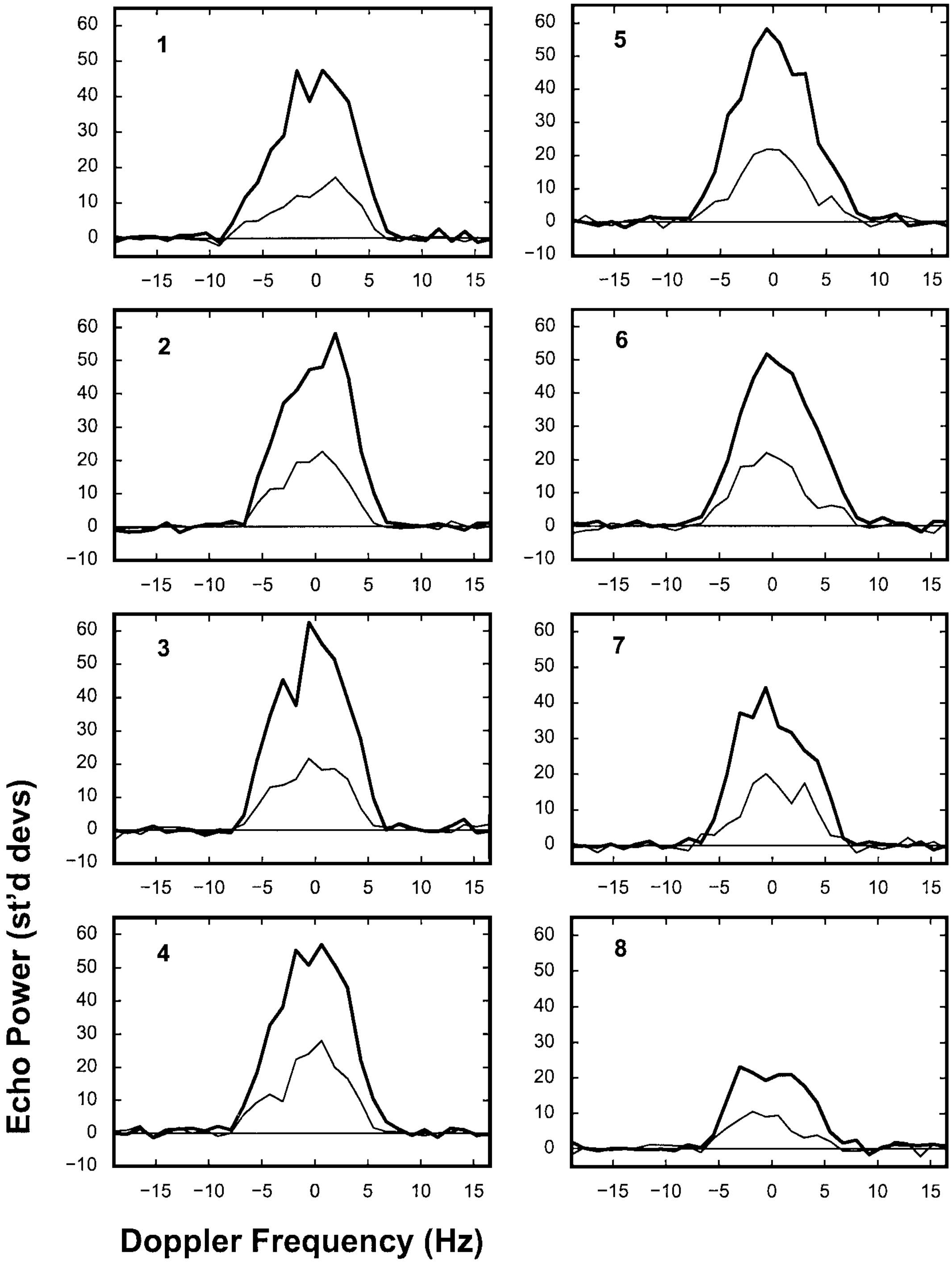

FIG. 1. Apollo echo power spectra in the OC and SC polarizations (thick and thin curves, respectively) from Nov. 14. Odd-numbered runs were SC and even-numbered runs were OC. Each spectrum in this figure is a four-run sum. In frame 1, the SC spectrum is a weighted sum of runs 1, 3, 5, and 7, and the OC spectrum is a weighted sum of runs 2, 4, 6, and 8, and so forth. Each frame spans about one-tenth of a rotation. The average rotation phases of the spectra shown in frames 1 through 8 are −23, 12, 45, 80, 118, 155, 191, and 222°, where 0° is the minimum-breadth orientation shown in Fig. 2. The spectra are centered on the Doppler frequency corresponding to the astrometry reported by Ostro *et al*. (1991).

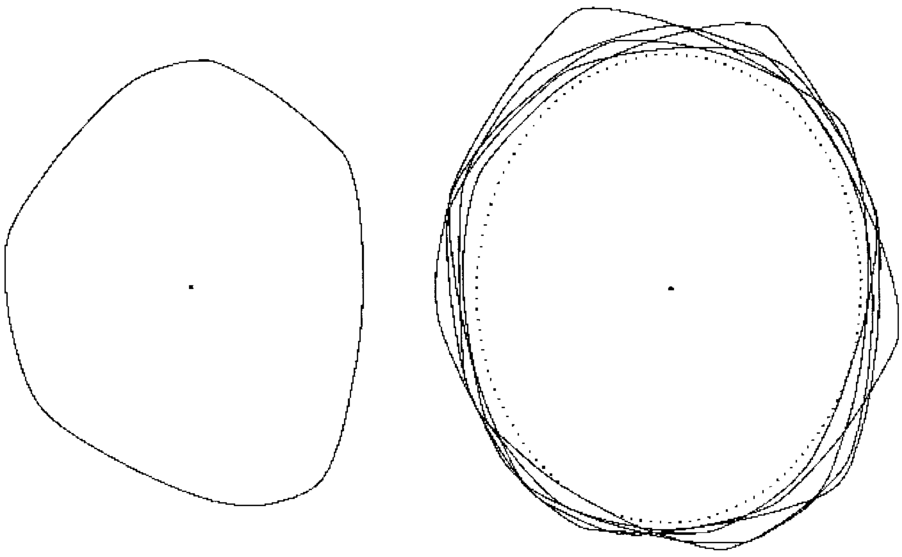

FIG. 2. Our estimate of Apollo's hull is on the left, and simulations intended to calibrate the uncertainty and bias in our hull estimator are on the right (see text). The hull rotates clockwise and presents its minimum-breadth toward the bottom of the page, corresponding to the asteroid's orientation toward the radar on 1980 Nov. 14.887.

resolution, the finest that was available at the time, was adequate to reveal that the echo bandwidth was more than 10 times larger and slightly variable.

We have now used techniques applied to several other asteroids (Ostro *et al.* 1988, 1990) to estimate the hull, or convex envelope, of the asteroid's pole-on silhouette. Figure 2 shows our estimate of Apollo's hull as well an example of hull estimations from spectra simulated for a model ellipsoid using the rotation-phase sampling, frequency resolution, and noise levels of our Apollo OC spectra. The distribution of the ellipsoid hull estimates that are superposed on the model ellipsoid's hull conveys a measure of the accuracy of our estimate of the shape of Apollo's hull. The simulations disclosed an overestimation of the ellipsoid's size by about 13%, and the values reported here for Apollo were corrected for this bias.

The hull's extreme bandwidths are within 10% of 17.16 and 13.50 Hz, so the asteroid's elongation is about 1.27, which is modest compared to many, but not all, elongations reported for radar-detected near-Earth asteroids (NEAs). Given the spin period, these bandwidths correspond to dimensions of (1.90×1.49) km/cos δ, where δ is the angle between Apollo's equatorial plane and the radar line of sight during our observations. The pole direction reported by Harris *et al.* (1987) corresponds to $|\delta| = 10^\circ \pm 10^\circ$. Thus the available information indicates that the extreme dimensions of Apollo's hull are conservatively within 15% of 1.9×1.5 km.

We estimate Apollo's average OC radar cross section to be within 25% of 0.24 km^2. The asteroid's polar extent is surely no more than the hull's shortest dimension (unless the object is spinning about its long axis or has an extremely unusual, heterogeneous density distribution). Therefore Apollo's average areal diameter is no more than $(1.9 \times 1.6 \times 1.6)^{1/3} = 1.6$ km. This result is consistent with the inference from thermal infrared measurements (Lebofsky *et al.* 1981) that the effective diameter varies with rotation from 1.2 ± 0.1 to 1.5 ± 0.1 km. If the effective diameter is less than or equal to 1.6 km, then the asteroid's OC radar albedo (i.e., the radar cross section divided by the asteroid's projected area) is at least 0.1, a number that falls in the lower half of values reported for other NEAs. The low end (1.1 km) of infrared values for the effective diameter corresponds to a radar albedo of 0.25, which falls in the upper half of the NEA distribution. (See http://echo.jpl.nasa.gov/~lance/asteroid_radar_properties.html for a tabulation of asteroid radar properties.)

The asteroid's average circular polarization (SC/OC) ratio, 0.33 ± 0.01, is virtually indistinguishable from the average value reported for NEAs and is about 50% larger than Eros' 13-cm value (Ostro *et al.* 1991). The 1862 Apollo ratio indicates substantial decimeter-scale roughness. There is the suggestion of small (~15%) variations in disc-integrated values of SC/OC with rotation phase, but our spectra show no significant evidence for frequency-resolved polarization features that persist with rotation phase.

The next opportunity for radar observations of Apollo is in Nov. 2005, when its approach to within 0.075 AU should produce Arecibo and Goldstone echoes strong enough for imaging and shape reconstruction at decameter resolution. The next radar opportunity after that is in 2046.

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