1991AJ....102.1490O

THE ASTRONOMICAL JOURNAL VOLUME 102, NUMBER 4 OCTOBER 1991

ASTEROID RADAR ASTROMETRY

S. J. OSTRO
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

D. B. CAMPBELL
National Astronomy and Ionosphere Center, Cornell University, Ithaca, New York 14853

J. F. CHANDLER AND I. I. SHAPIRO
Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138

A. A. HINE AND R. VELEZ
National Astronomy and Ionosphere Center, Box 995, Arecibo, Puerto Rico 00613

R. F. JURGENS, K. D. ROSEMA, R. WINKLER, AND D. K. YEOMANS
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109
Received 9 April 1991; revised 30 May 1991

ABSTRACT

We report all useful measurements of time delay and Doppler frequency for asteroid radar echoes obtained at Arecibo and Goldstone during 1980–1990. New radar astrometry is presented for 23 near-Earth asteroids and three mainbelt asteroids. These measurements, which are orthogonal to optical, angular-position measurements, and typically have a fractional precision between 10^{-5} and 10^{-8}, permit significant improvement in estimates of orbits and hence in the accuracy of prediction ephemerides. We also report estimates of radar cross section and circular polarization ratio for all asteroids observed astrometrically during 1980–1990.

1. INTRODUCTION

Near-Earth asteroid (NEA) discoveries have increased sharply during the past decade, raising the number of known NEAs from 53 in 1980 to 88 in 1985 and more than 180 at present (e.g., Helin & Dunbar 1990; Shoemaker *et al.* 1990; Rabinowitz *et al.* 1990; Davis *et al.* 1990). Whenever possible, a discovery is followed by astrometry to secure the orbit and by observations using the available astronomical techniques to determine the new object's physical characteristics (see review by McFadden *et al.* 1989). For mainbelt asteroids (MBAs) as well as NEAs, considerable effort is devoted to the estimation of orbital elements and to maintaining the accuracy of asteroid ephemerides (Marsden 1979; Bowell *et al.* 1989), which are a prerequisite to each phase of asteroid investigations. Especially stringent demands on ephemeris accuracy arise for asteroids targeted for spacecraft flyby and rendezvous missions.

Radar measurements of echo Doppler frequencies and time delays permit significant refinements of orbital elements and commensurate improvements in the accuracy of prediction ephemerides because these measurements have fine fractional precision and are orthogonal to optical, angular-position measurements. Yeomans *et al.* (1987) used numerical experiments to explore the extent to which delay/Doppler astrometry can refine orbit estimates for NEAs. They concluded that radar measurements can reduce ephemeris uncertainties dramatically for asteroids having short optical-data histories. They noted that a few radar observations of a newly discovered NEA could mean the difference between successfully recovering the object during its next close approach and losing it entirely. Even for asteroids with very long astrometric histories and secure orbits, radar measurements can significantly shrink their positional error ellipsoids for at least a decade.

Asteroid radar astronomy began on 14 June 1968, with the detection of 1566 Icarus from Goldstone (Goldstein 1969) and Haystack (Pettengill *et al.* 1969). By the end of the 1970's only five other asteroids had been detected (Pettengill & Jurgens 1979), but observational efforts expanded rapidly during the 1980's and at present a total of 63 asteroids (35 MBAs and 28 NEAs) have been detected (e.g., Ostro 1989). Any asteroid radar observation yields Doppler or delay/Doppler measurements, and the primary purpose of this paper is to present all previously unpublished asteroid radar astrometry that is useful for orbit refinement. Yeomans *et al.* (1991) describe procedures for incorporating such data in orbit estimations and present "radar + optical" orbits for 34 targets; earlier results for a subset of those targets were presented by Yeomans (1991).

Our asteroid radar dataset also contains much information about asteroid physical characteristics. In this paper we tabulate estimates of two disk-integrated quantities, radar cross section (i.e., radar brightness) and circular polarization ratio (a measure of wavelength-scale roughness) for all the targets that we observed astrometrically, and we also show echo power spectra and/or range profiles for selected asteroids. Implications of our results that are unrelated to orbits will be, or already have been, reported elsewhere (e.g., Ostro 1989; Ostro *et al.* 1983–91).

2. TECHNIQUES

This paper reports results of asteroid radar observations conducted during 1980–1990 with the 2380 MHz, 13 cm system of the Arecibo Observatory in Puerto Rico and the 8495 MHz, 3.5 cm system of Goldstone's DSS 14 antenna in California. Experimental procedures used in asteroid radar observations at Arecibo and Goldstone are fundamentally similar. [See Pettengill (1970) and Ostro (1987) for de-

 0004-6256/91/041490-13$00.90 © 1991 Am. Astron. Soc.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

scriptions of radar techniques.] A typical transmit/receive cycle, or run, consists of signal transmission for a duration close to the roundtrip light time between the radar and the target, i.e., until the first echoes are about to come back, followed by reception of echoes for a similar duration. In continuous wave (cw) observations, one transmits a nearly monochromatic waveform and measures the distribution of echo power as a function of frequency. The resultant echo spectra can be thought of as one-dimensional images, or brightness scans across the target through a slit parallel to the asteroid's apparent spin vector. In ranging observations, time coding of the waveform permits measurement of the distribution of echo power in time delay (range) as well.

An asteroid's apparent radial motion introduces a continuously changing Doppler shift into the echoes. One avoids spectral smear by tuning the receiver according to an ephemeris based on an orbit determined from astrometric asteroid observations. For the observations reported here, the prediction ephemerides were adequate to avoid noticeable spectral smear over timescales comparable to the roundtrip time.

Let $[\tau_{\rm COM}(t), f_{\rm COM}(t)]$ be the roundtrip time delay and Doppler frequency shift of hypothetical echoes from the asteroid's center of mass (COM) that are received at the telescope's reference point at UTC epoch t, and let $[\tau_{\rm EPH}(t), f_{\rm EPH}(t)]$ be the ephemeris predictions of those functions. [Arecibo's reference point is the center of curvature of the telescope's main reflector and Goldstone's is the top of the antenna cone. The Earth-fixed coordinates of those points are tabulated by Yeomans *et al.* (1991).] For observations reported here, it is adequate to think of the residuals, or offsets, $\tau_0(t) = \tau_{\rm COM}(t) - \tau_{\rm EPH}(t)$ and $f_0(t) = f_{\rm COM}(t) - f_{\rm EPH}(t)$ as being constant over the pertinent measurement time scales, which range from one roundtrip time to several days. In practice, one measures τ_0 and/or f_0 and reports $\tau(t') = \tau_{\rm EPH}(t') + \tau_0$ and/or $f(t') = f_{\rm EPH}(t') + f_0$, where t' is a convenient epoch near the weighted mean time of the measurements.

Reliable identification of $f_{\rm COM}$ and/or $\tau_{\rm COM}$ places demands on echo strength, delay/Doppler resolution, and rotation-phase coverage that have been realized in only a few asteroid radar experiments; see discussions by Ostro *et al.* (1990a, 1990b, 1990c). Consequently, most of the astrometric measurements presented here refer to the *peak* of the delay/Doppler distribution of echo power. For any given Doppler estimate $f_{\rm est}$, the assigned error is intended to be larger than $|f_{\rm COM} - f_{\rm est}|$ and it is never less than the data's frequency resolution. Some of our echo spectra are very asymmetrical or have more than one peak, and for these our estimates of $f_{\rm est}$ refer to the mean of estimated edge frequencies. For any given delay estimate $\tau_{\rm est}$, the assigned error is never less than the data's time resolution; at least for the main-belt asteroids, we expect $\tau_{\rm est}$ to be between $\tau_{\rm COM}$ and the delay of echoes from the nearest part of the target.

In cw experiments, voltage samples of the received signal are Fourier transformed and the results are squared to obtain an estimate of the power spectrum, with the frequency resolution equal to the reciprocal of the time series length, i.e., of the coherence time. The sampling rate is chosen to provide an unaliased bandwidth many times larger than both the *a priori* Doppler uncertainty and the echo bandwidth, so $f_{\rm est}$ can be determined unambiguously from the received power spectrum. Normally, a number of these "single-look" spectra are averaged to improve the spectral estimates.

In principle, range resolution can be obtained by using a coherent pulsed cw waveform—the transmitter's carrier-frequency oscillator operates continuously but radio-frequency power is radiated only during intervals that are one delay resolution cell long and occur at intervals called the pulse repetition period (PRP). The PRP is normally much greater than the target's intrinsic delay dispersion, thereby ensuring that the echo will consist of successive, nonoverlapping range profiles. Fourier transformation of N time samples taken at the same position (i.e., the same delay relative to τ_0) within each of N successive range profiles yields the echo power spectrum for the corresponding range cell on the target. This spectrum has an unaliased bandwidth $B = 1/[(\text{PRP})(\text{NCOH})]$ and a frequency resolution B/N, where NCOH is the number of code cycles for which voltage samples have been coherently summed prior to Fourier transformation.

The sensitivity of radar systems for observations of small bodies such as asteroids is dependent on the average transmitted power, and this can most easily be maximized by using cw transmitters. At both Arecibo and Goldstone, time delay measurements are implemented by phase encoding the transmitted signal. At a basic time interval, the "baud length," the phase of the transmitted signal is either shifted or not shifted by 180°, depending on a pseudorandom, repetitive sequence, or code. Shift-register codes, which have length $2^n - 1$ elements, with n an integer, are normally used because of the sharply peaked nature of their autocorrelation functions. The ambiguity function (i.e., the response to a point target; see Deley 1970) for a radar system utilizing a phase-coded cw transmitted signal is very similar to that of an amplitude modulated, or pulsed, system; the baud length is equivalent to the pulse length and the baud length times the code length is equivalent to the PRP. These repetitive ranging waveforms let one measure an echo's time delay modulo the PRP. This delay ambiguity can be resolved by doing two time-delay experiments with slightly different PRPs, e.g., with two slightly different baud lengths. At Arecibo, samples of the received signal's voltage are recorded on tape, and decoding and spectral analysis are done after the observations. At Goldstone, these processes are usually done in real time.

3. OBSERVATIONS

Table 1 gives general observational parameters for each target that we observed astrometrically. It also gives estimates of the average ratio (μ_c) of echo power received in the same circular polarization as transmitted (the SC sense) to that received in the opposite sense (OC), and the average OC radar cross section, $\sigma_{\rm oc}$. The OC polarization dominates echoes due primarily to single back reflections from large, smooth surface elements. SC echo power can arise from multiple reflections, from subsurface refraction scattering, or from single reflections off dielectric interfaces whose radii of curvature are comparable to, or smaller than, the wavelength. Hence the SC/OC ratio is a convenient measure of the degree of near-surface "roughness."

Table 2 presents our delay/Doppler astrometric measurements, $\tau_{\rm est}$ and/or $f_{\rm est}$, for each target listed in Table 1. Figures 1 and 2 show examples of range profiles and power spectra. For completeness, Tables 1 and 2 include results from previously reported, 1980–1990 observations and Table 3 assembles all asteroid radar astrometry from pre-1980 observations as well as all available comet radar astrometry.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

TABLE 1. Observations. Each entry identifies observations at either Arecibo (A) or Goldstone (G) and gives the total numbers of cw and ranging runs done during the specified range of dates. The target's average position (apparent right ascension, declination, and distance) during the observations is also given. Estimates of radar cross section (σ_{oc}) and circular polarization ratio (μ_c) are for weighted means of cw spectra. Uncertainties in σ_{oc} are dominated by systematic uncertainties in radar system sensitivity, which typically are between 20% and 50%. Uncertainties quoted for μ_c are standard errors due to receiver noise fluctuations; see Appendix I of Ostro *et al.* (1983). Many asteroids show dramatic, orientation-dependent variations in σ_{oc} and μ_c about the quoted means. The entries cover the period 1980–1990.

Asteroid	Obs.	Dates spanned (UTC)	# runs (cw,rg)	RA (h)	Dec.	Dist. (AU)	σ_{oc} (km^2)	μ_c (SC/OC)	Note
7 Iris	A	1980 Sep 26 - Oct 01	7,2	23.6	10°	0.94	5900	0.08 ± 0.03	1
105 Artemis	A	1988 Jun 10 - Jun 13	6,4	16.8	16°	1.07	1800	0.15 ± 0.04	
433 Eros	A	1988 Nov 30 - Dec 05	35,0	23.9	30°	0.49	75	0.22 ± 0.06	
654 Zelinda	A	1988 Jan 17 - Jan 20	9,6	5.7	21°	0.89	2200	0.17 ± 0.03	
1036 Ganymed	A	1985 Oct 02 - Oct 07	32,0	5.1	23°	0.65	75	0.18 ± 0.06	
1580 Betulia	G	1989 May 22 - May 26	149,0	14.2	32°	0.19	4.2	0.18 ± 0.03	
1580 Betulia	A	1989 May 25 - May 29	32,12	13.9	18°	0.19	3.9	0.16 ± 0.01	
1620 Geographos	A	1983 Feb 25 - Mar 02	62,5	11.0	5°	0.14	0.9	0.19 ± 0.05	
1627 Ivar	A	1985 Jul 05 - Jul 10	68,7	22.9	9°	0.20	7.5	0.21 ± 0.01	2
1685 Toro	A	1980 Jul 19 - Jul 25	73,0	22.5	24°	0.20	1.6	0.18 ± 0.04	3
1685 Toro	A	1988 Jul 21 - Jul 25	14,47	23.3	28°	0.21	1.2	0.12 ± 0.05	
1862 Apollo	A	1980 Nov 13 - Nov 20	209,6	22.0	19°	0.06	0.2	0.33 ± 0.01	
1866 Sisyphus	A	1985 Dec 06 - Dec 12	67,0	0.8	13°	0.25	8	0.32 ± 0.04	
1915 Quetzalcoatl	A	1981 Mar 05 - Mar 10	207,0	11.3	20°	0.09	0.02	0.27 ± 0.08	
1917 Cuyo	A	1989 Sep 26 - Sep 30	85,0	20.3	9°	0.17	2.5	0.22 ± 0.02	
1917 Cuyo	G	1989 Oct 09 - Oct 11	177,0	21.3	-22°	0.14	≥1	0.20 ± 0.05	
1981 Midas	G	1987 Sep 23 - Sep 27	223,0	20.2	-25°	0.08	≥0.1	0.65 ± 0.13	
2100 Ra-Shalom	A	1981 Aug 23 - Aug 26	72,0	21.3	23°	0.18	0.5	0.14 ± 0.02	4
2100 Ra-Shalom	A	1984 Aug 18 - Aug 22	108,0	18.0	22°	0.21	0.8	0.29 ± 0.02	
2101 Adonis	A	1984 Jul 14 - Jul 18	148,0	8.9	8°	0.11	0.02	1.0 ± 0.2	
2201 Oljato	A	1983 Jun 13 - Jun 17	61,0	10.6	9°	0.19	0.65	0.31 ± 0.02	
3103 (1982 BB)	A	1986 Jul 16 - Jul 20	66,0	23.1	6°	0.22	0.62	0.80 ± 0.11	
3199 Nefertiti	A	1986 Sep 05 - Sep 09	83,0	23.3	20°	0.22	1.2	0.47 ± 0.04	
3757 (1982 XB)	A	1987 Dec 02 - Dec 06	154,0	9.0	18°	0.08	0.018	0.27 ± 0.05	
3908 (1980 PA)	A	1988 Sep 25 - Sep 30	71,76	23.0	26°	0.08	0.13	0.78 ± 0.02	
3908 (1980 PA)	G	1988 Oct 06 - Oct 25	262,184	3.1	50°	0.06	0.09	0.72 ± 0.04	
4034 (1986 PA)	A	1989 Mar 24 - Mar 27	58,0	21.5	26°	0.16	0.021	0.21 ± 0.14	
4544 (1989 FB)	A	1990 Nov 19	27,0	16.4	22°	0.17	0.13	0.25 ± 0.14	
1986 DA	A	1986 Apr 18 - Apr 21	57,8	12.1	17°	0.21	2.4	0.09 ± 0.02	5
1986 JK	G	1986 May 28 - Jun 01	75,0	22.8	-18°	0.03	0.022	0.26 ± 0.02	6
1989 JA	A	1989 May 24 - May 26	25,0	11.9	8°	0.11	0.08	0.14 ± 0.05	
1989 JA	G	1989 Jun 28 - Jun 09	140,0	10.0	-11°	0.09	0.07	0.24 ± 0.08	
4769 (1989 PB)	A	1989 Aug 19 - Aug 22	53,84	0.1	17°	0.04	0.15	0.29 ± 0.01	7
4769 (1989 PB)	G	1989 Aug 30	6,0	10.8	45°	0.06	0.15	0.32 ± 0.04	7
1990 MF	A	1990 Jul 04 - Jul 06	23,38	16.3	28°	0.04	0.038	0.19 ± 0.02	
1990 OS	A	1990 Aug 02 - Aug 03	68,0	0.6	-16°	0.05	0.02	0.23 ± 0.03	

Notes to TABLE 1

1. Ostro *et al.* (1985).
2. Ostro *et al.* (1990b).
3. Ostro *et al.* (1983).
4. Ostro *et al.* (1984).
5. Ostro *et al.* (1991).
6. Ostro *et al.* (1989).
7. Ostro *et al.* (1990c).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

TABLE 2. Asteroid radar astrometry. All available measurements made during 1980–1990 are listed here. As discussed in the text, epochs refer to the instant of reception at the telescope reference point and most measurements refer to the peak of the observed delay/Doppler distribution of echo power. The transmitter frequency was 2380 MHz at Arecibo (A) and 8495 MHz at Goldstone (G).

Target	UTC epoch of echo reception (hh:mm)	Obs.	Doppler frequency (Hz)		Time delay (UTC μs)		Note
7 Iris	1980 Oct 01, 02:52	A			941,213,826	± 140	
7 Iris	1980 Oct 01, 03:38	A			941,224,093	± 80	
105 Artemis	1988 Jun 12, 04:05	A			1,068,551,691	± 140	
105 Artemis	1988 Jun 13, 03:50	A			1,071,430,809	± 140	
433 Eros	1988 Dec 02, 23:30	A	-39,889	± 10			
654 Zelinda	1988 Jan 19, 02:23	A			901,115,212	± 140	
654 Zelinda	1988 Jan 20, 02:06	A			905,426,430	± 140	
1036 Ganymed	1985 Oct 05, 08:35	A	48,527	± 30			
1580 Betulia	1989 May 23, 12:00	G	501,134	± 20			
1580 Betulia	1989 May 26, 01:42	A			185,537,450	± 12	
1580 Betulia	1989 May 28, 01:38	A			185,094,484	± 12	
1580 Betulia	1989 May 29, 00:20	A	-72,175	± 5			
1620 Geographos	1983 Feb 27, 05:00	A	161,795	± 5			
1620 Geographos	1983 Feb 28, 05:04	A			142,007,628	± 30	
1627 Ivar	1985 Jul 08, 08:00	A	20,560	± 6			1
1627 Ivar	1985 Jul 09, 08:09	A			202,574,571	± 16	1
1685 Toro	1980 Jul 22, 07:00	A	161,393.5	± 0.2			2
1685 Toro	1988 Jul 21, 07:30	A	151,627	± 3			
1685 Toro	1988 Jul 22, 07:34	A			218,310,206	± 20	
1685 Toro	1988 Jul 23, 07:20	A			213,324,675	± 20	
1685 Toro	1988 Jul 24, 07:35	A			208,567,250	± 20	
1685 Toro	1988 Jul 25, 07:42	A			204,181,567	± 20	
1862 Apollo	1980 Nov 13, 21:51	A	-11,441	± 2			
1862 Apollo	1980 Nov 14, 22:19	A	-68,200	± 2			
1862 Apollo	1980 Nov 15, 22:13	A	-116,132	± 2			
1862 Apollo	1980 Nov 16, 22:07	A	-115,158	± 4			
1862 Apollo	1980 Nov 18, 00:02	A	-190,851	± 2			
1862 Apollo	1980 Nov 18, 23:54	A	-213,090	± 2			
1862 Apollo	1980 Nov 20, 00:31	A	-231,568	± 2			
1862 Apollo	1980 Nov 21, 00:42	A	-244,953	± 2			
1862 Apollo	1980 Nov 15, 23:48	A			60,502,961	± 20	
1862 Apollo	1980 Nov 16, 22:59	A			65,410,020	± 20	
1862 Apollo	1980 Nov 16, 23:52	A			65,622,708	± 20	
1862 Apollo	1980 Nov 18, 00:25	A			72,158,416	± 20	
1866 Sisyphus	1985 Dec 08, 00:00	A	-295,248	± 20			
1915 Quetzalcoatl	1981 Mar 08, 03:40	A	-106,796	± 2			
1917 Cuyo	1989 Sep 29, 23:00	A	117,822	± 5			
1917 Cuyo	1989 Oct 10, 05:00	G	-10,620	± 20			
1981 Midas	1987 Sep 25, 04:00	G	-1,130,345	± 15			
2100 Ra-Shalom	1981 Aug 25, 02:00	A	-18,021.4	± 0.2			3
2100 Ra-Shalom	1984 Aug 21, 00:00	A	-98,092	± 1			
2101 Adonis	1984 Jul 14, 18:20	A	-328,238.7	± 0.3			
2101 Adonis	1984 Jul 15, 18:20	A	-341,813.1	± 0.3			
2101 Adonis	1984 Jul 16, 17:40	A	-350,648.0	± 0.3			
2101 Adonis	1984 Jul 17, 17:30	A	-358,654.3	± 0.3			
2101 Adonis	1984 Jul 18, 17:20	A	-365,447.2	± 0.3			
2201 Oljato	1983 Jun 13, 21:00	A	174,592.08	± 0.25			
2201 Oljato	1983 Jun 14, 21:10	A	149,972.38	± 0.25			
2201 Oljato	1983 Jun 16, 21:00	A	96,790.67	± 0.25			
2201 Oljato	1983 Jun 17, 21:50	A	65,179.60	± 0.25			
3103 (1982 BB)	1986 Jul 18, 07:50	A	202,602	± 6			
3199 Nefertiti	1986 Sep 07, 05:10	A	8,804	± 5			
3757 (1982 XB)	1987 Dec 05, 08:33	A	-23,990.8	± 0.2			
3757 (1982 XB)	1987 Dec 06, 08:42	A	-29,470.2	± 0.2			

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

TABLE 2. (continued)

Target	UTC epoch of echo reception (hh:mm)	Obs.	Doppler frequency (Hz)	Time delay (UTC μs)	Note
3908 (1980 PA)	1988 Sep 25, 02:30	A	67,856.4 ± 1.0		
3908 (1980 PA)	1988 Sep 25, 03:35	A		83,363,235 ± 20	
3908 (1980 PA)	1988 Sep 26, 03:08	A		81,027,438 ± 2	
3908 (1980 PA)	1988 Sep 27, 03:00	A		78,763,284 ± 2	
3908 (1980 PA)	1988 Oct 06, 07:45	G		63,835,350 ± 10	
3908 (1980 PA)	1988 Oct 19, 07:00	G		66,513,356.1 ± 1.4	
3908 (1980 PA)	1988 Oct 19, 09:00	G		66,612,701.5 ± 1.4	
4034 (1986 PA)	1989 Mar 26, 14:00	A	56,566 ± 2		
4544 (1989 FB)	1990 Nov 19, 17:00	A	-11,375 ± 1		
1986 DA	1986 Apr 19, 02:00	A	-20,592.8 ± 1.0		4
1986 DA	1986 Apr 21, 02:56	A		209,263,398 ± 8	4
1986 JK	1986 May 28 09:50	G	163,427 ± 3		5
1986 JK	1986 May 28 09:58	G	161,625 ± 3		5
1986 JK	1986 May 28 10:25	G	155,476 ± 3		5
1986 JK	1986 May 28 10:32	G	153,863 ± 3		5
1986 JK	1986 May 28 10:40	G	152,014 ± 3		5
1986 JK	1986 May 28 10:48	G	150,158 ± 3		5
1986 JK	1986 May 28 10:55	G	148,527 ± 3		5
1986 JK	1986 May 28 11:04	G	146,427 ± 3		5
1986 JK	1986 May 28 11:14	G	144,080 ± 3		5
1986 JK	1986 May 30 12:35	G	-314,665 ± 30		5
1986 JK	1986 Jun 01 17:25	G	-607,300 ± 3		5
1989 JA	1989 May 25, 00:00	A	108,937 ± 2		
1989 JA	1989 May 26, 00:00	A	100,742 ± 2		
1989 JA	1989 May 28, 04:00	G	282,916 ± 6		
1989 JA	1989 Jun 03, 22:10	G	6,477 ± 6		
1989 JA	1989 Jun 09, 22:00	G	-269,340 ± 6		
4769 (1989 PB)	1989 Aug 19, 06:23	A	223,401 ± 2		6
4769 (1989 PB)	1989 Aug 19, 07:04	A		59,512,323 ± 10	6
4769 (1989 PB)	1989 Aug 19, 07:14	A		59,456,416 ± 10	6
4769 (1989 PB)	1989 Aug 19, 07:23	A		59,406,173 ± 10	6
4769 (1989 PB)	1989 Aug 20, 05:42	A	215,029 ± 2		6
4769 (1989 PB)	1989 Aug 20, 07:16	A	211,450 ± 1		6
4769 (1989 PB)	1989 Aug 21, 06:14	A		44,374,924 ± 3	6
4769 (1989 PB)	1989 Aug 21, 06:18	A		44,354,892 ± 3	6
4769 (1989 PB)	1989 Aug 21, 07:24	A	195,785 ± 1		6
4769 (1989 PB)	1989 Aug 22, 06:45	A	173,116 ± 1	37,453,066 ± 2	6
4769 (1989 PB)	1989 Aug 30, 19:35	G	-785,297 ± 8		6
1990 MF	1990 Jul 04, 00:53	A	95,494 ± 5		
1990 MF	1990 Jul 04, 01:30	A	94,276 + 19		
1990 MF	1990 Jul 04, 03:10	A	90,956 ± 1		
1990 MF	1990 Jul 05, 00:45	A	87,041 ± 1		
1990 MF	1990 Jul 05, 01:42	A	85,142.44 ± 0.10	42,103,700 ± 10	
1990 MF	1990 Jul 06, 01:05	A	75,642.01 ± 0.06	39,277,841 ± 2	
1990 MF	1990 Jul 06, 01:25	A	74,971.72 ± 0.10	39,239,872 ± 10	
1990 MF	1990 Jul 06, 01:54	A	73,995 ± 1		
1990 MF	1990 Jul 09, 08:10	G		33,184,859 ± 5	
1990 MF	1990 Jul 09, 09:10	G	68,863.3 ± 1.0	33,154,813.6 ± 1.4	
1990 MF	1990 Jul 09, 09:40	G		33,140,417.9 ± 0.4	
1990 MF	1990 Jul 15, 07:50	G	-280,957 ± 1		
1990 OS	1990 Aug 02, 10:40	G	348,392 ± 6		
1990 OS	1990 Aug 03, 09:00	G	298,666 ± 6		

Notes to TABLE 2

1. Astrometry refers to hypothetical echoes from Ivar's COM (Ostro *et al.* 1990b).
2. From Ostro *et al.* (1983).
3. From Ostro *et al.* (1984).
4. Astrometry refers to hypothetical echoes from 1986 DA's COM (Ostro *et al.* 1991).
5. From Ostro *et al.* (1989).
6. Astrometry refers to hypothetical echoes from 1989 PB's COM (Ostro *et al.* 1990c).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

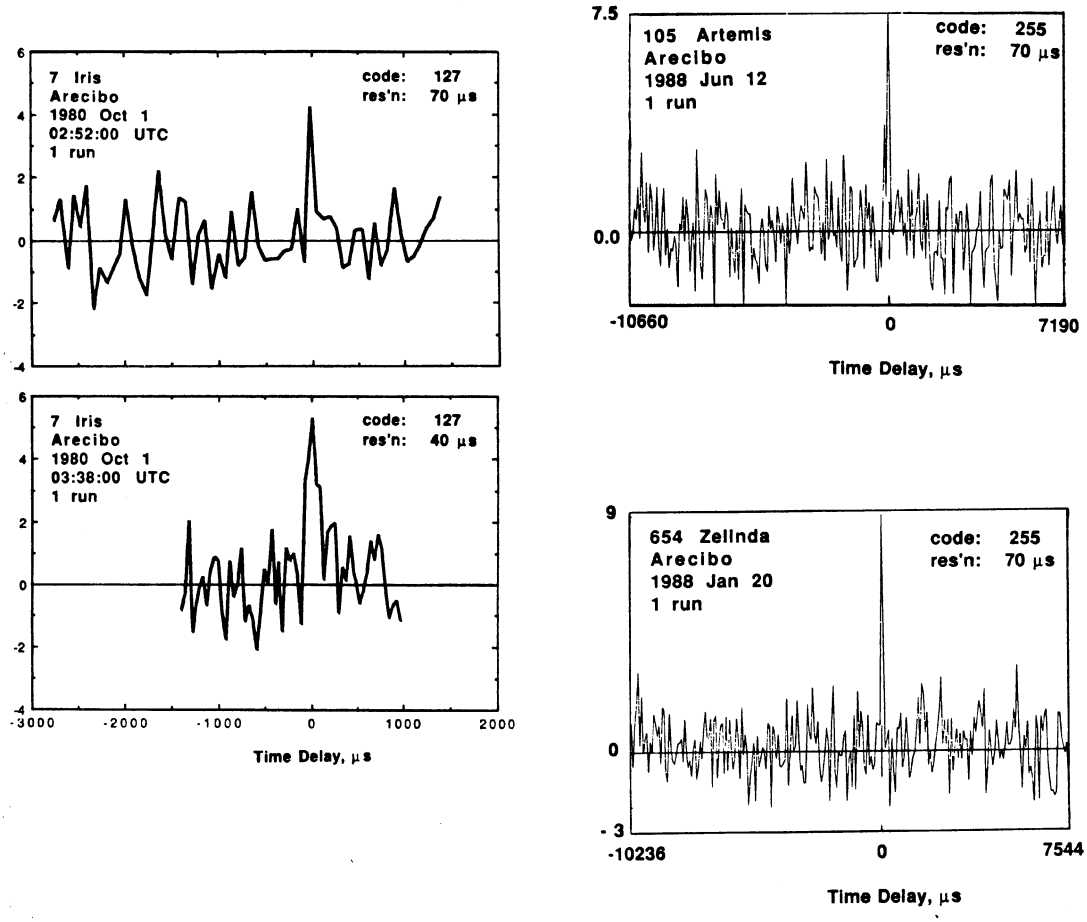

FIG. 1. Examples of range profiles. Echo power obtained in the OC polarization is plotted on a linear scale vs time delay relative to τ_{est}. In most plots, the vertical axis is labeled in units of standard deviations and/or a vertical bar at the origin indicates $\pm$ 1 standard deviation. Labels identify the number of runs combined in making each plot, as well as the time-delay resolution (i.e., the baud length) and the code length used in the observations. The data's original delay window (PRP) has been vignetted in many of the plots.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

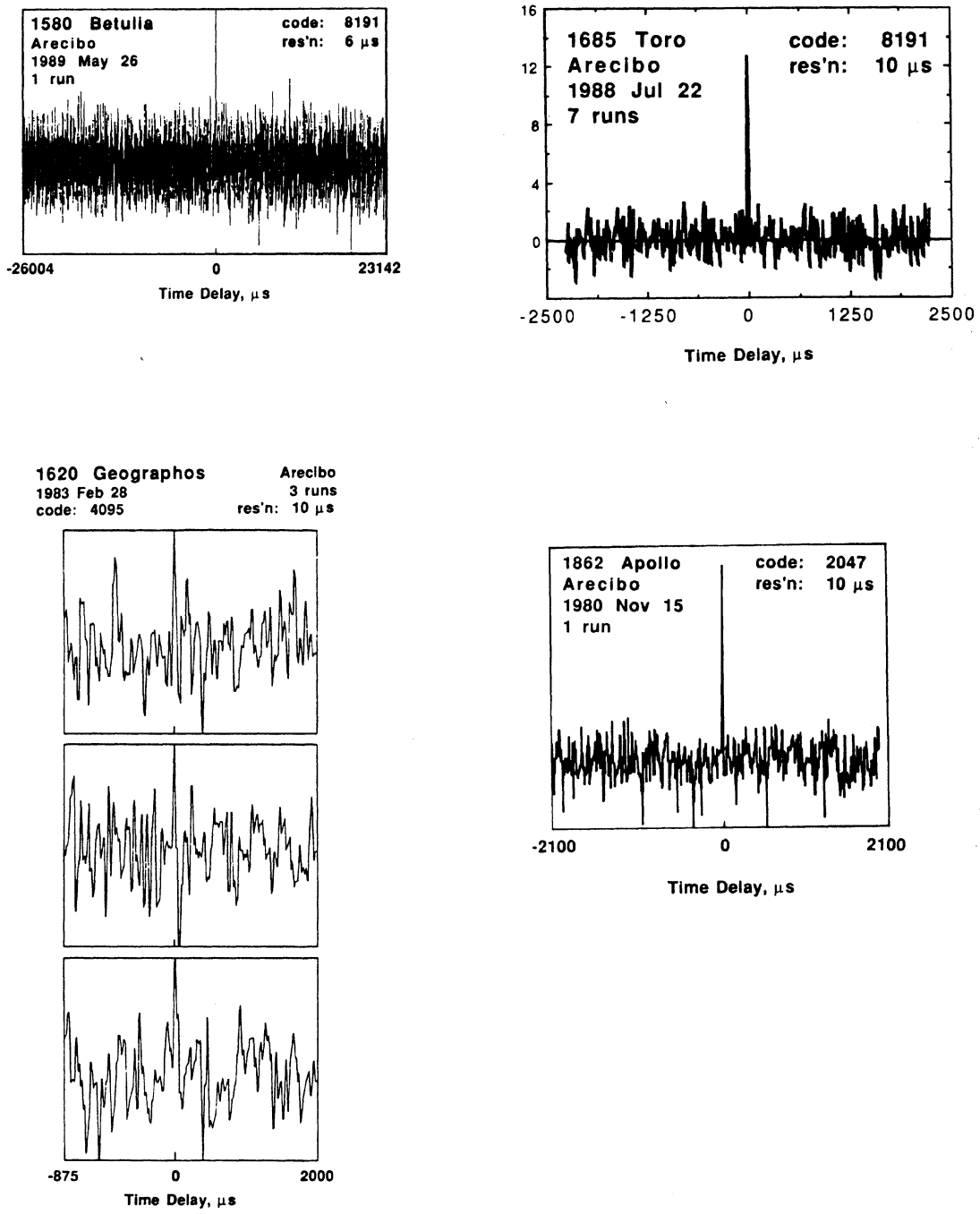

FIG. 1. (continued)

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

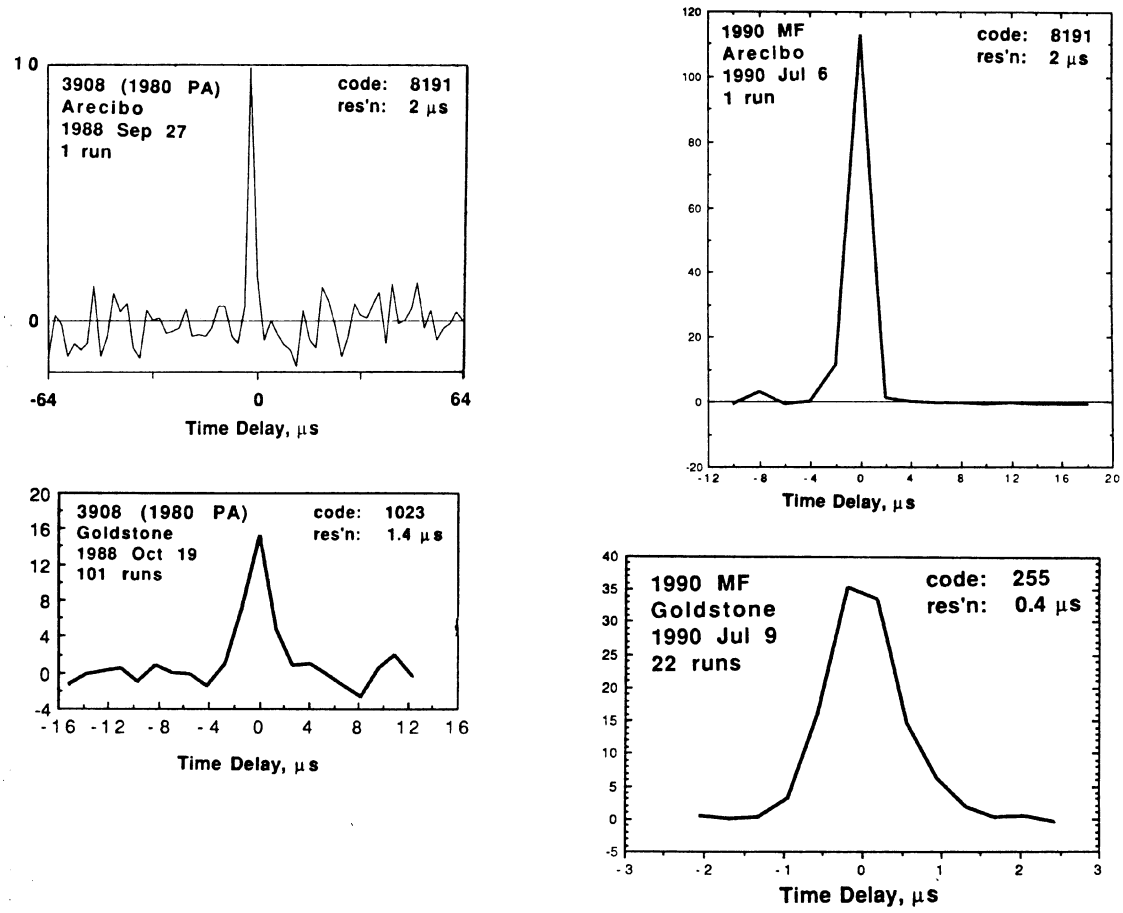

FIG. 1. (continued)

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

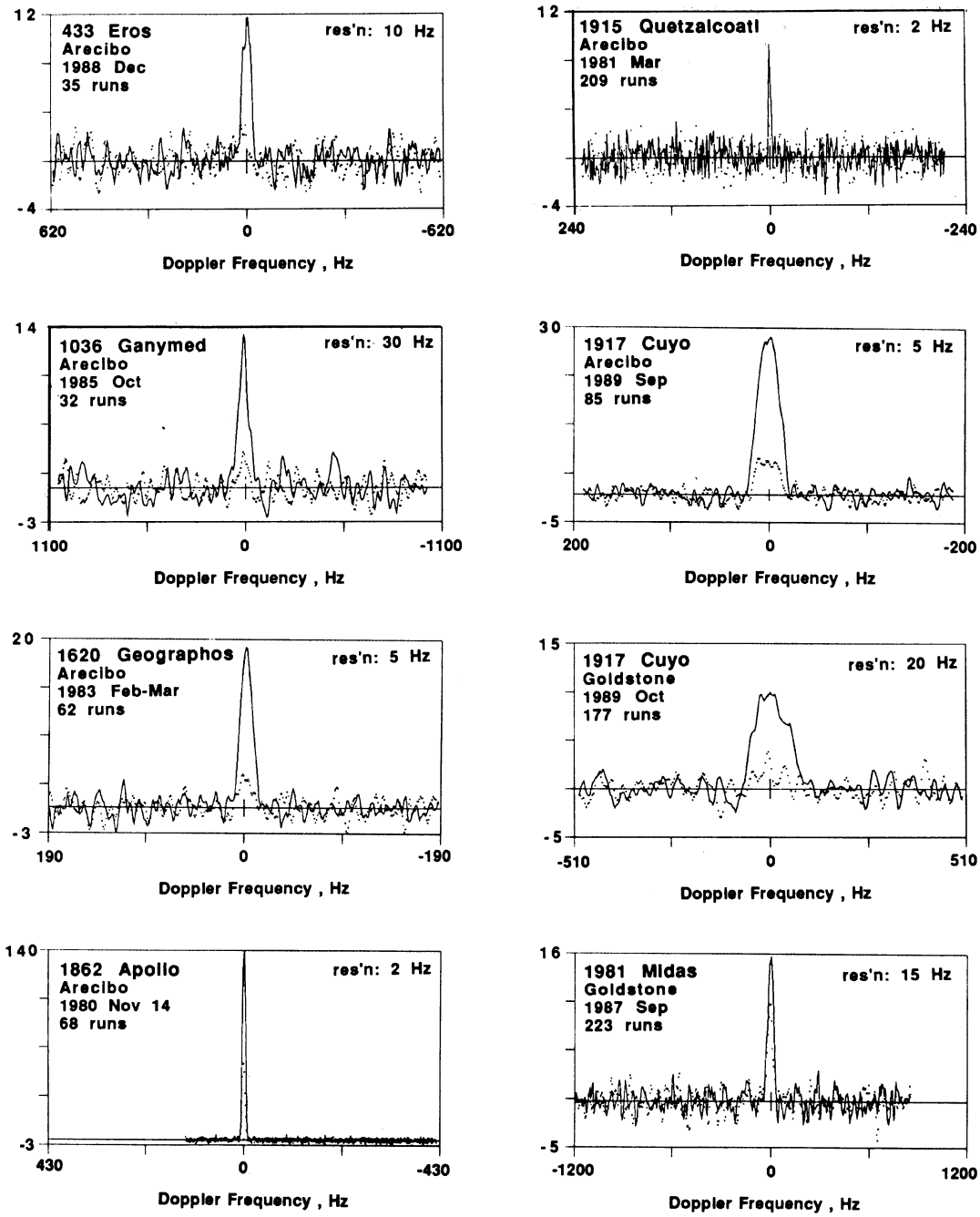

FIG. 2. Examples of power spectra. Echo power, on a linear scale, is plotted vs frequency relative to f_{est}. Solid and dotted curves correspond to OC and SC echoes, respectively. For most of the plots, the vertical axis is labeled in units of standard deviations and/or a vertical bar at the origin indicates ± 1 standard deviation. Labels identify the number of runs combined in making each plot as well as the frequency resolution of the plotted curves. Most spectra have been smoothed to a resolution coarser than the original frequency-sampling interval.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

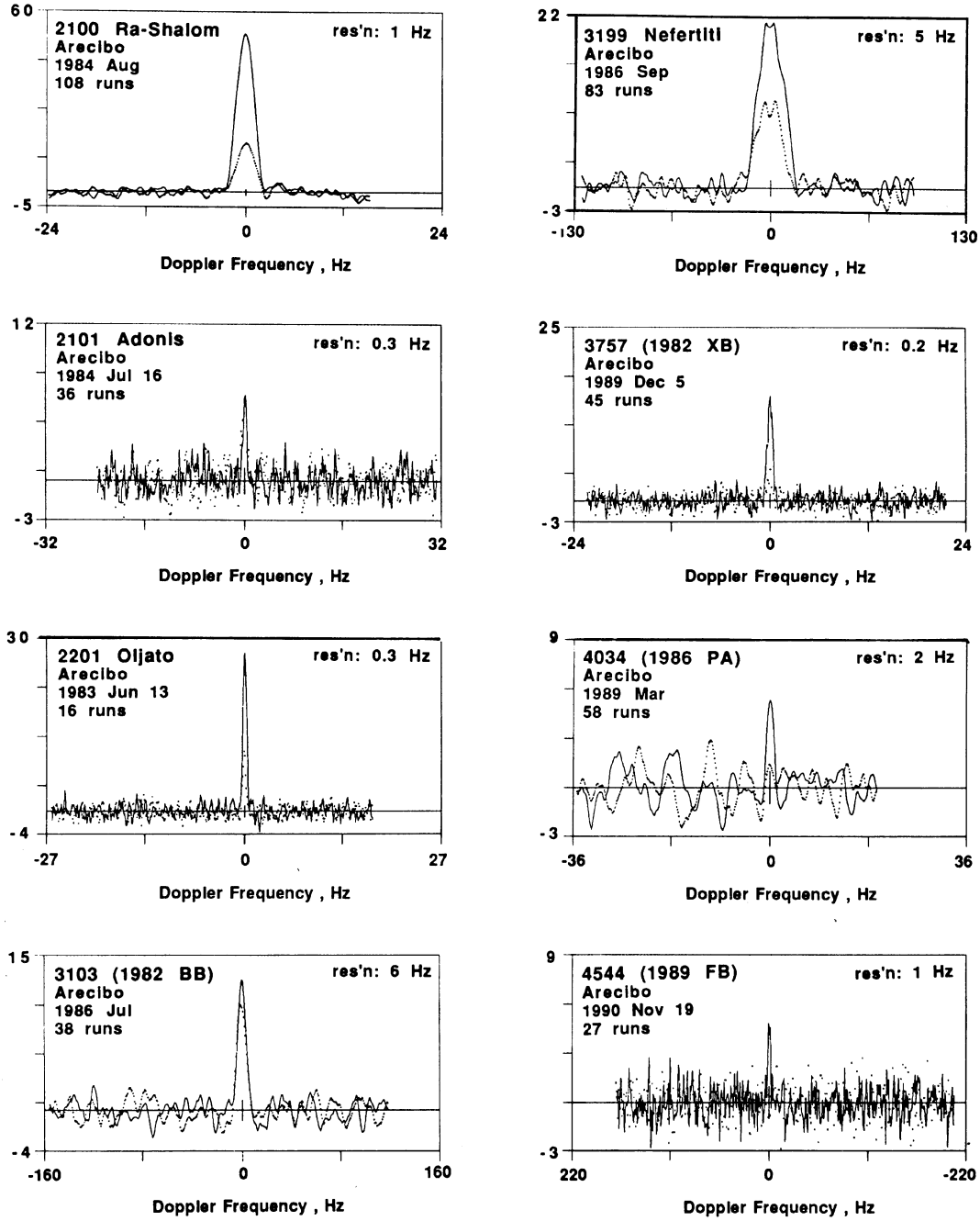

FIG. 2. (continued)

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

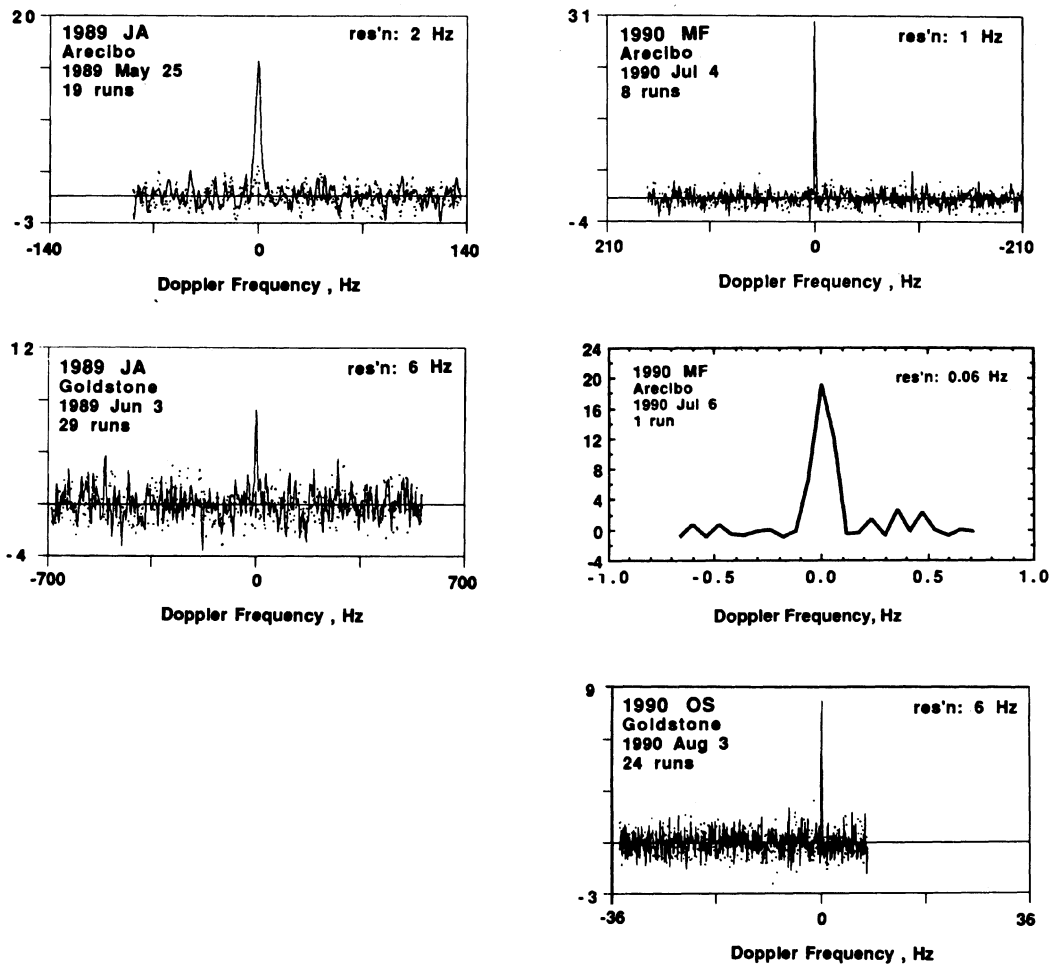

FIG. 2. (continued)

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

TABLE 3. Additional small-body radar astrometry. This table shows (i) results from asteroid measurements made before 1980 and (ii) results from comet radar astrometry. See Table 2 caption.

Target	UTC epoch of echo reception (hh:mm:ss)	Obs.	Transmitter frequency (MHz)	Doppler frequency (Hz)	Time delay (UTC μs)	Note
433 Eros	1975 Jan 22, 04:30:00	A	430		150,885,360 ± 15	1
433 Eros	1975 Jan 22, 04:30:00	A	430	-1.3 ± 2.0		2
433 Eros	1975 Jan 23, 07:00:00	G	8495	2,430 ± 15		3
1566 Icarus	1968 Jun 14, 05:30:00	G	2388	115,417.1 ± 0.3		4
1566 Icarus	1968 Jun 14, 22:20:00	G	2388	-10,324.1 ± 0.3		4
1566 Icarus	1968 Jun 15, 04:30:00	G	2388	-61,207.2 ± 0.3		4
1566 Icarus	1968 Jun 15, 09:40:00	G	2388	-104,441.9 ± 0.3		4
1566 Icarus	1968 Jun 16, 01:40:00	G	2388	-202,453.5 ± 0.3		4
1566 Icarus	1968 Jun 16, 06:30:00	G	2388	-234,710.0 ± 0.3		4
1566 Icarus	1968 Jun 16, 10:00:00	G	2388	-255,404.7 ± 0.3		4
1566 Icarus	1968 Jun 14, 19:00:00	H	7840	50,487.7 ± 4		5
1566 Icarus	1968 Jun 15, 03:00:00	H	7840	-167,331.6 ± 4		5
1580 Betulia	1976 May 18, 05:56:50	A	2380	225,980.0 ± 1.0		6
1580 Betulia	1976 May 19, 05:52:16	A	2380	186,012.5 ± 1.0		6
P/Encke	1980 Nov 05, 14:44:00	A	2380	-280,334.5 ± 1.0		7
P/Grigg-Skjellerup	1982 May 26, 22:17:00	A	2380	36,969.2 ± 0.5		8
P/IRAS-Araki-Alcock	1983 May 11, 22:00:00	A	2380	-221,306.4 ± 0.1		9
P/Sugano-Saigusa-Fujikawa (SSF)	1983 Jun 10, 09:18:00	A	2380	611,820.2 ± 0.1		10
P/SSF	1983 Jun 11, 07:13:00	A	2380	472,340.3 ± 0.1		10
P/SSF	1983 Jun 12, 06:19:00	A	2380	200,135.4 ± 0.1		10

Notes to TABLE 3

1. The time delay given is an estimate of τ_{COM} obtained by combining an estimate of τ_{est} reported by Campbell *et al.* (1976) with an estimate of the difference, $\tau_{COM} - \tau_{est} = 65 \pm 10$ ms, reported by Ostro *et al.* (1990a).
2. From Campbell *et al.* (1976).
3. The Doppler frequency given is an estimate of f_{COM} obtained by adding an estimate, $f_0 = -17 \pm 16$ Hz, reported by Ostro *et al.* (1990a) to a value for f_{EPH} from the observing ephemeris. Our result rectifies an incorrect value for f_{COM}, given by Ostro *et al.* (1990a), the calculation of which used an incorrect value of f_{EPH}.
4. From Goldstein (1968) and Lieske & Null (1969). Goldstone's DSS 13 and DSS 14 antennas were used for transmitting and receiving, respectively.
5. Haystack results from Pettengill *et al.* (1969).
6. From Pettengill *et al.* (1979).
7. From Kamoun *et al.* (1982).
8. From Kamoun (1983).
9. From Harmon (1991); see also Harmon *et al.* (1989).
10. From Harmon (1991); see also Campbell *et al.* (1983).

Orbital solutions that incorporate delay/Doppler measurements as well as optical astrometry are presented by Yeomans (1991) and Yeomans *et al.* (1991).

4. DISCUSSION

Asteroids tend to have angles much smaller than an arcsecond, often by several orders of magnitude. Primarily due to errors in measurement and in the reference star positions, uncertainties in optical astrometric measurements of asteroid positions are typically about 1 arcsec (5×10^{-6} radian). However, radar measurements achieve spatial resolution not from the angular width of the antenna beam (about 2 arcmin) but from resolution of the echo in time and frequency, so asteroids that are easily detected are generally at least marginally resolvable.

A crude figure of merit, M, for astrometry is the ratio of the measurement to its uncertainty. For optical astrometry, $M \sim 2 \times 10^5$. For the delay astrometry in Table 2, $1.4 \times 10^6 \leqslant M \leqslant 8.2 \times 10^7$, and for the Doppler astrometry, $1.1 \times 10^3 \leqslant M \leqslant 1.3 \times 10^6$. That is, our delay measurements have higher astrometric figures of merit than our Doppler measurements. Of course, even the low-M Doppler measurements are useful by virtue of their orthogonality to plane-of-sky astrometry.

The delay/Doppler resolution of most of our measurements was limited severely by the radar system's sensitivity, i.e., by factors like antenna gain and transmitter power. We expect that improvements being implemented at Arecibo and Goldstone will greatly enhance the astrometric utility of both radars within a few years. Arecibo's range limits for detection of asteroids with diameters of 0.1, 1, and 100 km will be approximately 0.1, 0.3, and 1.6 AU. For any given target, Goldstone's range limit will be less than half that of Arecibo, but Goldstone's declination window (− 35° to

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1991AJ....102.1490O

90°) is much wider than Arecibo's (− 2° to 38°). With these two instruments, radar astrometry with M between 10^7 and 10^8 should become routine for NEAs and MBAs, and it should be possible to make astrometric measurements of most newly discovered NEAs. In principle, given currently available computational and communications capabilities, these radar observations could be carried out within hours of the discovery itself.

We thank the staff of the Arecibo Observatory and the Goldstone Radio Astronomy/Radar Group for help with the observations; we are especially grateful for the assistance of the chief transmitter engineers, A. Crespo at Arecibo and D. Choate at Goldstone. Part of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). J. F. C. and I. I. S. were supported in part by NASA. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation and with support from NASA.

REFERENCES

Bowell, E., Chernykh, N. S., and Marsden, B. G. 1989, in Asteroids II, edited by R. P. Binzel, T. Gehrels, and M. S. Matthews (University of Arizona Press, Tucson), p. 21
Campbell, D. B., Pettengill, G. H., and Shapiro, I. I. 1976, Icarus, 28, 17
Campbell, D. B., Harmon, J. K., Hine, A. A., Shapiro, I. I., Marsden, B. G., and Pettengill, G. H. 1983, BAAS, 15, 800
Davis, D. R., Hartmann, W. K., Friedlander, A., Collins, J., Niehoff, J., and Jones, T. 1990, The Role of Near-Earth Asteroids in the Space Exploration Initiative, A study for the Office of Aeronautics and Exploration Technology, Science Applications International Corporation Report No. SAIC-90/1464, Study No. 1-120-232-S28
Deley, G. W. 1970, in Radar Handbook, edited by M. I. Skolnik (McGraw-Hill, New York), Chap. 3
Goldstein, R. M. 1969, Sci, 162, 903
Harmon, J. K. 1991, private communication
Harmon, J. K., Campbell, D. B., Hine, A. A., Shapiro, I. I., and Marsden, B. G. 1989, ApJ, 338, 1071
Helin, E. F., and Dunbar, R. S. 1990, Vistas in Astronomy, 33, 21
Jurgens, R. F., and Goldstein, R. M. 1976, Icarus, 28, 1
Kamoun, P. G. D. 1983, Ph.D. thesis, Massachusetts Institute of Technology, Cambridge
Kamoun, P. G., Campbell, D. B., Ostro, S. J., Pettengill, G. H., and Shapiro, I. I. 1982, Sci, 216, 293
Lieske, J. H., and Null, G. W. 1969, AJ, 74, 297
Marsden, B. G. 1979, in Asteroids, edited by T. Gehrels (University of Arizona Press, Tucson), p. 77
McFadden, L. A., Tholen, D. J., and Veeder, G. J. 1989, in Asteroids II, edited by R. P. Binzel, T. Gehrels, and M. S. Matthews (University of Arizona Press, Tucson), p. 442
Ostro, S. J. 1987, in The Encyclopedia of Physical Science and Technology, edited by R. A. Meyers (Academic, San Diego), Vol. 10, p. 611
Ostro, S. J. 1989, in Asteroids II, edited by R. P. Binzel, T. Gehrels, and M. S. Matthews (University of Arizona Press, Tucson), p. 192
Ostro, S. J., Campbell, D. B., and Shapiro, I. I. 1983, AJ, 88, 565
Ostro, S. J., Harris, A. W., Campbell, D. B., Shapiro, I. I., and Young, J. W. 1984, Icarus, 60, 391
Ostro, S. J., Campbell, D. B., and Shapiro, I. I. 1985, Sci, 224, 442
Ostro, S. J., Yeomans, D. K., Chodas, P. W., Goldstein, R. M., Jurgens, R. F., and Thompson, T. W. 1989, Icarus, 78, 382
Ostro, S. J., Rosema, K. D., and Jurgens, R. F. 1990a, Icarus, 84, 334
Ostro, S. J., Campbell, D. B. Hine, A. A., Shapiro, I. I., Chandler, J. F., Werner, C. L., and Rosema, K. D. 1990b, AJ, 99, 2012
Ostro, S. J., Chandler, J. F., Hine, A. A., Shapiro, I. I., Rosema, K. D., and Yeomans, D. K. 1990c, Sci, 248, 1523
Ostro, S. J., Campbell, D. B., Chandler, J. F., Hine, A. A., Hudson, R. S., Rosema, K. D., and Shapiro, I. I. 1991, Sci, 252, 1399
Pettengill, G. H. 1970, in Radar Handbook, edited by M. I. Skolnik (McGraw-Hill, New York), Chap. 33
Pettengill, G. H., and Jurgens, R. F. 1979, in Asteroids, edited by T. Gehrels (University of Arizona Press, Tucson), p. 206
Pettengill, G. H., Shapiro, I. I., Ash, M. E., Ingalls, R. P., Rainville, L. P., Smith, W. B., and Stone, M. L. 1969, Icarus, 10, 432
Pettengill, G. H., Ostro, S. J., Shapiro, I. I., Marsden, B. G., and Campbell, D. B. 1979, Icarus, 40, 350
Rabinowitz, D., Scotti, J. V., Perry, M. L., Gehrels, T., and McMillan, R. S. 1990, BAAS, 22, 1117
Shoemaker, E. M., Wolfe, R. F., and Shoemaker, C. S. 1990, in Global Catastrophes in Earth History; An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality, edited by V. L. Sharpton and P. D. Ward (Geological Society of America Special Paper No. 247, Boulder, CO), p. 155
Yeomans, D. K. 1991, AJ, 101, 1920
Yeomans, D. K., Ostro, S. J., and Chodas, P. W. 1987, AJ, 94, 189
Yeomans, D. K., Chodas, P. W., Keesey, M. S., Ostro, S. J., Chandler, J. F., and Shapiro, I. I. 1991, AJ (submitted)

© American Astronomical Society • Provided by the NASA Astrophysics Data System