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Radar Observations of Asteroid 1986 JK

S. J. OSTRO, D. K. YEOMANS, P. W. CHODAS, R. M. GOLDSTEIN,
R. F. JURGENS, AND T. W. THOMPSON

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

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Echoes from this near-Earth asteroid were obtained in May and June 1986, three weeks after its discovery, using the Goldstone 3.5-cm-wavelength radar. The asteroid's minimum distance during the observations was less than 0.029 AU, only 11 times further than the Moon and closer than for any other asteroid or comet radar observation to date. 1986 JK's circular polarization ratio μ_C, of echo power received in the same sense of circular polarization as transmitted (the SC sense) to that in the opposite (OC) sense, averages 0.26 ± 0.02, indicating that single backscattering from smooth surface elements dominates the echoes, although there is a moderate degree of wavelength-scale, near-surface roughness. Variations in μ_C and in the shapes of the OC and SC echo spectra suggest that the surface is at least moderately heterogeneous at structural scales no smaller than the wavelength and probably much larger. The asteroid's echo bandwidth provides the constraint $D_{\max} \geq P/5$, where P is the apparent spin period, in hours, and $D_{\max}$, in kilometers, is the maximum width of the asteroid's polar silhouette. Our estimate of 1986 JK's average OC radar cross section is 0.022 ± 0.007 km^2. Combining that result with an indirect size constraint based on W. Z. Wisniewski's (1987, *Icarus* 70, 566–572) photometry yields an interval estimate for 1986 JK's radar albedo that overlaps values reported to date for comets and the radar-darkest asteroids. A "working model" of 1986 JK postulates a 1- to 2-km object whose shape is not extremely irregular, with little elongation but some polar flattening; the rotation period is not more than a few hours longer than 10 hr and the near-surface bulk density is within a factor of 2 of 0.9 g cm^{-3}. The orbital and physical characteristics of 1986 JK are somewhat comet-like. However, the Earth passes within 0.005 AU of the asteroid's orbit, and evidence for recent meteor shower activity associated with this object is lacking. Estimates of the asteroid's echo Doppler frequencies (i.e., its radial velocities) were used in conjunction with the available optical astrometric data to provide refined orbital elements and ephemeris predictions. The radar astrometric data are extremely powerful for orbit improvement. At the next Earth close approach (0.12 AU in mid-2000), a search ephemeris based upon all optical and radar data will have a plane-of-sky, solid-angle uncertainty an order of magnitude smaller than that for an ephemeris based upon the optical data alone. A recovery attempt made on June 17, 2000, would have a plane-of-sky position uncertainty ~20′, so prospects for recovering 1986 JK are good. © 1989 Academic Press, Inc.

I. INTRODUCTION

Asteroid 1986 JK was discovered by C. S. Shoemaker and E. M. Shoemaker (1986) with the 0.46-m Schmidt telescope at Palomar, using photographic plates obtained during May 4–11, 1986. Initial orbital calculations (Marsden 1986) revealed 1986 JK to be approaching the Earth on a trajectory that would bring it into the Goldstone radar's detectability window during a several-day period 2 weeks later, at a distance of 0.03 AU and a declination near −22°. Additional astrometric measurements by astronomers at six observatories (including an especially critical pair of positions by A. C. Gilmore and P. M. Kilmartin at Mount John Observatory in New Zealand on May 23)

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TABLE I

OBSERVATIONS

Goldstone radar system			
Transmitter frequency	8495 MHz (λ = 3.5 cm)		
Antenna diameter	64 m		
Transmitter power	320 kW		
Antenna gain	$10^{7.15}$		
System temperature	22 K		
Half-power beamwidth	2.0 arcmin		
1986 JK: A priori parameters[a]			
1986 date	May 28	May 30	Jun 1
Time, UTC	10 hr	13 hr	17 hr
Apparent RA, dec	20.4 hr, −27°	22.8 hr, −18°	0.2 hr, −9°
Distance	0.029 AU	0.031 AU	0.042 AU
Echo time delay	29 s	31 s	42 s
Echo Doppler frequency	161,996 Hz	−321,671 Hz	−607,325 Hz

[a] Values listed here were derived from the same orbital elements used to generate the ephemeris for the 1986 radar observations.

refined our knowledge of the object's orbit (e.g., Yeomans 1986) and let us calculate ephemerides that proved adequate to point the Goldstone 64-m antenna and to tune the receiver to the echo's Doppler frequency. We obtained strong echoes from 1986 JK on May 28, when the Earth–asteroid distance was less than 0.029 AU—only 11 times further than the Moon and closer than for any other nonlunar planetary radar experiment to date. Additional echoes were obtained on May 30 and June 1.

1986 JK's postdiscovery lunar elongation, solar phase angle, and intrinsic dimness–its V magnitude increased from 13 in late May to 20 in mid-June—rendered it an extremely difficult optical target. Nevertheless, Wisniewski (1987) managed photoelectric observations that yield an apparent visual magnitude as well as color indices indicating taxonomic class C. He also obtained lightcurves at solar phase angles between 3 and 5° that show ~0.05 mag variation, but the data are inadequate to constrain the rotation period. As discussed below, combining his absolute magnitude estimate with the nominal range of C-class asteroid visual albedos places bounds on 1986 JK's size. However, apart from Wisniewski's photometry, the radar observations apparently constitute the only source of information about the physical nature of this object.

In the following sections we describe our experiment, data reduction/analysis, and constraints on 1986 JK's physical characteristics from its radar properties. Then we present results of incorporating our radar astrometric data in determining the asteroid's orbital elements, and discuss the outlook for recovering it optically during its next Earth close approach, in 2000.

II. OBSERVATIONS

May 28 Observations

Table I lists nominal radar system characteristics and a priori target parameters for all three observation dates. Each transmit/receive cycle, or "run," began with transmission of an unmodulated (cw), circularly polarized signal for a duration dictated partially by the target's round-trip echo time delay and partially by the fact that the antenna employs *different* feed horns for transmitting and receiving. To switch between transmit and receive configurations, the antenna's subreflector must rotate through 36°, a procedure that typically took 8 to 16 sec. The integration time per run was the round-trip time less the time to rotate the subreflector.

Two separate receiver channels permitted simultaneous reception in the same sense of circular polarization as transmitted (the SC sense) and the opposite (OC) sense. The received signals were amplified, filtered, and down-converted to baseband (video) frequencies. We continuously tuned the receiver to the echo Doppler frequency, using a prediction ephemeris based on an orbital solution that incorporated astrometric data through May 23. Complex voltage samples were digitized and recorded on disk for later transfer to tape, but we simultaneously accumulated real-time power spectra that were displayed on a monitor.

May 28 Observations

The spectra from the first few runs on this date showed strong echoes at a Doppler frequency about 800 Hz lower than predicted, and only ~100 Hz from the roll-off of our passband, whose total unaliased bandwidth was limited to 3.7 kHz by difficulties encountered with recently installed computer hardware. Changing the transmitter frequency by several hundred hertz shifted the echo into a more convenient portion of the passband. (Were it not for the May 23 optical astrometry, the prediction ephemeris would have been insufficiently accurate to place the echo in the passband.) A total of 38 runs on May 28 yielded useful echo spectra.

May 30 Observations

We completed 28 runs during a 2-hr period on this date, with 1986 JK only 7% further from Earth than on May 28 but receding rapidly. As on May 28, detection of strong echoes was evident from the real-time display of power spectra. Unfortunately, modifications to the data-acquisition software made on May 29 had inadvertently eliminated the Fortran statements that wrote the data to disk. This mistake was not discovered until after the asteroid view period, when we tried to copy the nonexistent data to tape. Our only record of the May 30 echoes is in photographs of the real-time display.

June 1 Observations

By this date, the asteroid was almost 50% further from Earth than on May 28, and we expected that the corresponding fourfold reduction in the signal-to-noise ratio would make it difficult to identify echoes in the real-time display. Using photographs of the video monitors taken during the runs on the previous 2 days, we extrapolated corrections to the June 1 ephemeris and began observing with a transmitter frequency calculated to bring the echo within our narrow observing band. However, echoes were not evident after several runs. Because we did not know how big the true Doppler error in the ephemeris was, we cycled through a wide range of transmitter frequencies, hoping that an a posteriori ephemeris would eventually let us find echoes in spectra for some of the several dozen runs we had completed.

III. DATA REDUCTION

Our initial analyses concentrated on the May 28 data. We Fourier-transformed the recorded time series to form power spectra with an element spacing of 0.92 Hz. Over the course of the 1.5-hr observing period, it became apparent that the echo's Doppler frequency was drifting with respect to the prediction ephemeris at a rate ~50 Hz/hr, so each run's spectrum was smeared by up to a quarter of a hertz. Thus, the effective frequency resolution of each of our final single-run spectra is about 1.2 Hz. This is small compared to the maximum edge-to-edge bandwidth (typically ~20 Hz; see below) seen for any run and, given the available signal-to-noise levels, is sufficiently fine for subsequent data analysis.

For each spectrum, the mean noise background was estimated by fitting a five-term polynomial to spectral elements in two 200-Hz bands adjacent to the echo. We then subtracted this background, which was nearly linear over the bandwidth of interest. Finally, we divided by the rms noise fluctuation, whose radar cross-section equivalent varied from run to run, primarily because of variations in transmitter power and integration time.

Estimation of Echo Doppler Frequencies

We experimented with several different ways of extracting Doppler frequencies from the May 28 echoes before settling on the following approach. First, we divided the data into nine subsets, each of which contained three to five runs and spanned receiving intervals no longer than 7 min. For each subset we formed weighted sums of the OC spectra and then calculated *three different measures* of the offset of the echo's "central" Doppler frequency (i.e., the frequency corresponding to echoes from the asteroid's center of mass) from the value predicted by the ephemeris. The first two, f_0 and f_{+1}, *ignore the shape* of the echo spectrum and simply take the average of the two frequencies on either side of the echo peak where the echo strength first drops to some specified level, zero for f_0 or one standard deviation for f_+. The third estimator, $\bar{f}_{\mathrm{mod}}$, *is sensitive to the shape* of the echo spectrum; to obtain it, we fit by least squares a symmetrical model of the form $S(f) = S_0[1 - (f - f_{\mathrm{mod}})^2/(B/2)^2]^{n/2}$, fixing the shape parameter n to 2 or 4 and the bandwidth B to 10 or 20 Hz, and then averaged the four resulting values of f_{mod} to get $\bar{f}_{\mathrm{mod}}$. For any given group, the span of the four values of f_{mod} was between 0.4 and 3.0 Hz.

For the nine subsets, the three frequencies f_0, f_{+1}, and $\bar{f}_{\mathrm{mod}}$ occupy an interval whose width averages 1.3 Hz and ranges from 0.5 to 3.2 Hz. We adopted the average, $\hat{f} = (f_0 + f_{+1} + \bar{f}_{\mathrm{mod}})/3$, as our "final" Doppler estimator. Using a straight-line fit to the nine subsets' values of $\hat{f}$, we calculated frequencies for the nine even-minute epochs closest to the subsets' weighted mean receive times (Table II). The 3-Hz error assigned to each May 28 Doppler measurement is intended to account for the dispersion of results for the different estimators as well as the uncertainty in the accuracy of the estimators.

TABLE II

DOPPLER FREQUENCIES MEASURED FOR ASTEROID 1986 JK[a]

UTC date	Time (h : m)	Doppler frequency for 8495 MHz transmission (Hz)	Residual (Hz)
1986 May 28	09:50	163,427 ± 3	−4
1986 May 28	09:58	161,625 ± 3	−4
1986 May 28	10:25	155,476 ± 3	1
1986 May 28	10:32	153,863 ± 3	0
1986 May 28	10:40	152,014 ± 3	1
1986 May 28	10:48	150,158 ± 3	2
1986 May 28	10:55	148,527 ± 3	1
1986 May 28	11:04	146,427 ± 3	3
1986 May 28	11:14	144,080 ± 3	0
1986 May 30	12:35	−314,665 ± 30	7
1986 Jun 1	17:25	−607,300 ± 3	1

[a] Epochs are for the instant of echo reception. All frequencies are rounded to the nearest hertz. Residuals are with respect to the final a posteriori ephemeris.

For May 30, our "data set" is a pair of photographs of the screen displaying the OC spectrum from two 30-sec integrations. The photographs were taken at 12:32 and 12:39 UTC, and correspond to receive periods centered on times approximately 2 min earlier. We used the photographs to measure the echo frequencies, we calculated the echo's offset from the ephemeris prediction, and we used the result to obtain the single entry for this date in Table II. Our quoted error is intended to encompass the difficulties associated with the data format.

Using the Doppler frequencies from May 28/30 and optical astrometric data obtained during May–October 1986, we calculated an improved orbit. The corresponding a posteriori site ephemeris revealed that, for a series of nine runs on June 1, the transmitter frequency had placed echoes within the radar receiver's passband. We then reduced those data and found the echoes 9 Hz from their expected location. Analysis of the nine-run spectral sum yielded the June 1 Doppler estimate in Table II. Finally, we combined this datum with all other radar and optical astrometry in calculating a "final" estimate of 1986 JK's orbit (see Section V below). This orbit was used to generate a final a posteriori site ephemeris, which let us shift our May 28 and June 1 echo spectra so as to compensate for the Doppler error in the a priori ephemeris that had been used to take the data. The frequency smear in any single-run spectrum, due to Doppler-frequency drift during the run's integration period, is rather small (<0.3 Hz for the May 28 data and <0.1 Hz for the June 1 data), and we have not removed it. Re-estimation of Doppler frequencies using the shifted spectra provided an overall check of our analysis.

Our final a posteriori ephemeris indicated that the pointing error in the a priori ephemeris was 24 arcsec on May 28 but only 2.5 arcsec on June 1. The May 28 pointing error degraded our round-trip antenna gain by 20%, and we have recalibrated those data accordingly.

IV. 1986 JK'S RADAR SIGNATURE AND PHYSICAL PROPERTIES

Radar Cross Section

Figure 1 presents, at two different frequency resolutions, the weighted means of all our OC and SC echo spectra obtained on May 28 and June 1. Combining the total power in the OC echo with values for system parameters and target distance (Table I), we estimate 1986 JK's OC radar cross section, σ_{OC}, to be 0.022 ± 0.007 km^2. The quoted ($\frac{1}{3}$ fractional) error is 16 times larger than the standard error associated with receiver noise and is intended to allow for systematic sources of error associated primarily with uncertainty in pointing the antenna and in the antenna's gain in the transmit configuration. We note that the same radar system (including transmitter and receiver hardware, and data-acquisition/reduction software and procedures) used for 1986 JK was also used during May–June 1986 to observe Mercury, which is an extremely strong radar target and whose radar signature has been known for decades. The Mercury experiments confirmed the overall integrity of the Goldstone radar system and disclosed no systematic problems with pointing or with calibration of two-way antenna gain, transmitter power, or OC/SC receiver system temperatures. Therefore, we consider the absolute error assigned to σ_{oc} to be realistic.

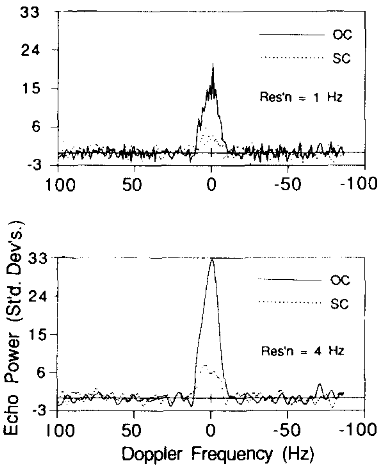

FIG. 1. Weighted mean of all May 28 and June 1 radar echo spectra obtained for asteroid 1986 JK in the OC and SC polarizations (solid and dotted curves, respectively), shown at frequency resolutions of 1 Hz (top) and 4 Hz (bottom). Echo power, in standard deviations of the receiver noise, is plotted against Doppler frequency. Zero Doppler corresponds to echoes from the asteroid's center of mass, as calculated from the final a posteriori ephemeris.

Radar Reflectivity

If we knew 1986 JK's size (i.e., its projected area $A_{\text{proj}} \equiv \pi(D_{\text{sph}}/2)^2$, with D_{sph} the effective spherical diameter), we could calculate its radar albedo, $\hat{\sigma}_{OC} \equiv \sigma_{OC}/A_{\text{proj}}$. Wisniewski (1987) reports color indices that place this asteroid in the C taxonomic class (Tholen 1984). He also reports an apparent brightness, $V = 14.06$

mag, for the epoch 1986 May 20.28. Using orbital elements estimated from all the available radar astrometry (see Section V below), we calculate values for the asteroid's geocentric distance ($\Delta = 0.0792$ AU), heliocentric distance ($r = 1.0909$ AU), and solar phase angle ($\alpha = 4.7°$) for that epoch. We use those quantities, Wisniewski's value for V, and the appropriate equation in Bowell *et al.* (1979) to calculate the asteroid's absolute visual magnitude:

$$\begin{aligned} V(1,0) &= V - 5 \log r\Delta + 0.538 \\ &\qquad - 0.134\, \alpha^{0.714} - 0.273 \\ &= 19.24. \end{aligned}$$

Then, combining that result with the nominal range for the visual geometric albedos of C-class asteroids ($\sim 0.01 \leq p_v \leq 0.065$; Zellner 1979), we use Zellner's (1979) equation,

$$2 \log D_{\mathrm{sph}} = 6.244 - 0.4\, V(1,0) - \log p_v,$$

to constrain 1986 JK's size:

$$0.74 \text{ km} \leq D_{\mathrm{sph}} \leq 1.9 \text{ km}. \qquad (1)$$

The corresponding interval estimate (e.g., Freund and Walpole 1980) for the radar albedo is

$$0.0053 \leq \hat{\sigma}_{\mathrm{OC}} \leq 0.067,$$

where the bounds include the uncertainty in the radar cross section. The upper bound on 1986 JK's radar albedo is comparable to the lunar value ($\sim$0.07) and falls at the low end of the range of values (0.047 to 0.20) reported for C-class mainbelt asteroids (Ostro *et al.* 1985a). On the other hand, 1986 JK's radar albedo interval overlaps values estimated for comets. For example, with regard to comet IRAS–Araki–Alcock's nucleus, one can combine radar cross sections reported by Harmon *et al.* (1989) and Goldstein *et al.* (1984) with the Hanner *et al.* (1985) diameter estimate, $D_{\mathrm{sph}} = 10.0 \pm 1.2$ km, to obtain albedo estimates satisfying $0.017 \leq \hat{\sigma}_{\mathrm{OC}} \leq 0.042$ at 13 cm and $0.045 \leq \hat{\sigma}_{\mathrm{OC}} \leq 0.073$ at 3.5 cm. For comet Halley, Campbell *et al.* (1989) place an upper bound of 0.051 on the 13-cm radar albedo of the nucleus.

The possible resemblance of 1986 JK's radar albedo to those of comets is intriguing given arguments (e.g., Hahn and Rickman 1985, Shoemaker and Wolfe 1982, Shoemaker *et al.* 1979) that some asteroids with orbital characteristics like 1986 JK's might be extinct cometary nuclei. In this context, let us consider a physical implication of our radar albedo estimate. Taking $\hat{\sigma}_{\mathrm{OC}}$ as a first approximation to the surface's Fresnel power-reflection coefficient ρ (Ostro *et al.* 1985a) and relating ρ to bulk density d via an empirical formula ($d = 3.2 \ln[(1 + \rho^{1/2})/(1 - \rho^{1/2})]$) developed by Garvin *et al.* (1985), we find that our interval estimate for $\hat{\sigma}_{\mathrm{OC}}$ corresponds to surface bulk densities between 0.47 and 1.7 g cm^{-3}. Various lines of evidence suggest a similar range of values for Halley's mean bulk density; e.g., Sagdeev *et al.* (1988) argue for a value of $0.6^{+0.9}_{-0.4}$ g cm^{-3}. Thus, it is conceivable that 1986 JK's surface might resemble Halley's, at least in terms of bulk density. In any event, if the size constraint (1) is valid, the center of our interval estimate for 1986 JK's radar albedo is extremely low by asteroid standards, so this object might be an "outlier" in terms of its physical/chemical nature as well.

Echo Bandwidth: Constraints on Dimensions and Spin Vector

From Fig. 1, we find that the OC echo spectrum's amplitude drops to zero at frequencies separated by 21.6 Hz. An asteroid's instantaneous spectral bandwidth is $B = (4\pi D/\lambda P)\sin \alpha$, where P is the apparent rotation period, α is the aspect angle, between the line of sight and the apparent spin vector, and D is the width, measured normal to the line of sight, of the asteroid's polar silhouette (Ostro *et al.* 1988). Since 1986 JK's rotation period is unknown, we do not know how much the asteroid rotated during our observations, and we certainly do not know whether any rotational phases θ sampled by our data correspond to a width extremum. However, taking into consideration the effective resolution of our summed spectra, we can state that the maximum value $B_{\max}$ of $B(\theta)$ probably is no smaller than 20 Hz. Therefore, the polar silhouette's maximum width $D_{\max}$ satisfies

$$\begin{aligned} D_{\max} &\equiv B_{\max}\, \lambda P/(4\pi \sin \alpha) \\ &\geq 20\, \lambda P/(4\pi \sin \alpha) \end{aligned}$$

or, expressing $D_{\max}$ in kilometers and P in hours,

$$D_{\max} \geq 20\, P/(98.9 \sin \alpha)$$

or simply

$$D_{\max} \geq P/5. \qquad (2)$$

The shortest asteroid rotation period reported so far is 1.97 hr for 3671 Dionysius (1984 KD; Zeigler and Florence 1987), so unless 1986 JK rotates more rapidly, the maximum breadth of its polar silhouette is at least 0.4 km. However, as discussed above, the asteroid's absolute visual magnitude and VIS/IR spectral class argue for the mean effective spherical diameter $D_{\rm sph}$ being two to five times larger than 0.4 km.

Our bandwidth estimate and the available information about 1986 JK's size can be combined to constrain the spin period. Let us assume, somewhat conservatively, that $D_{\max} \leq 2D_{\rm sph}$ and that $D_{\rm sph} \leq 2.0$ km. Concatenating these inequalities with Eq. (2) yields an upper limit of 20 hr for 1986 JK's rotation period. Wisniewski's (1987) lightcurves are consistent with a nearly spherical shape and/or an aspect not far from polar. If the shape's elongation is negligible, then the rotation period probably does not exceed 10 hr. Of course, if the radar had a nonequatorial view of the asteroid, the upper bound on P should be reduced by sin α. The constraint on 1986 JK's rotation period can be summarized as

$$P \leq 10\, (D_{\max}/D_{\rm sph}) \sin \alpha. \qquad (3)$$

Polarization Ratio

From the spectra in Fig. 1 we calculate a circular polarization ratio $\mu_{\rm c}$, of SC to OC power, equal to 0.26 ± 0.02, where the uncertainty is a standard error due to the receiver noise; see Appendix I of Ostro *et al.* (1983). $\mu_{\rm c}$ would be zero if all the echo arose from single backscattering from smooth surface elements. It could be as large as unity for echoes due to high-order multiple scattering or to backscatter from interfaces characterized by radii of curvature comparable to the wavelength. Hence, $\mu_{\rm c}$ serves as a measure of the degree of generalized, near-surface, structural complexity or "roughness" near the scale of the radar wavelength.

1986 JK's mean $\mu_{\rm c}$ indicates a moderate degree of roughness. It is a bit smaller than the only other 3.5-cm value of $\mu_{\rm c}$ reported for an asteroid (0.33 for the ~20-km S-class object 433 Eros; Jurgens and Goldstein 1976), but it is identical to the 3.5-cm value measured for the nucleus of comet IRAS–Araki–Alcock (Goldstein *et al.* 1984). That object's 13-cm $\mu_{\rm c}$ estimate is 0.105 ± 0.005 (Harmon *et al.* 1989), so it appears much rougher at 3.5 cm than at 13 cm. A similarly precise pair of $\mu_{\rm c}$ estimates at two wavelengths is unavailable for any asteroid. Still, it is worth noting that 1986 JK's 3.5-cm circular polarization ratio is comparable to 13-cm values measured for seven near-Earth asteroids (Ostro *et al.* 1985b), and is three times larger than the mean value (0.08) obtained at 13 cm for nine mainbelt, C-class asteroids (Ostro *et al.* 1985a).

Several-Run Subsets: Heterogeneity

Figure 2 shows OC/SC spectral pairs at 4-Hz resolution for the weighted sum of the June 1 observations and for the same nine subsets of May 28 data used for the Doppler frequency analysis described above. Receive epochs are indicated along with estimates for $\sigma_{\rm oc}$ and $\mu_{\rm c}$.

For the nine May 28 groups, values obtained for $\sigma_{\rm oc}$ range from 0.017 to 0.028 km^2. The *relative* uncertainties among the nine values are less than the *absolute* uncertainties, but probably a bit larger than the standard errors arising from receiver

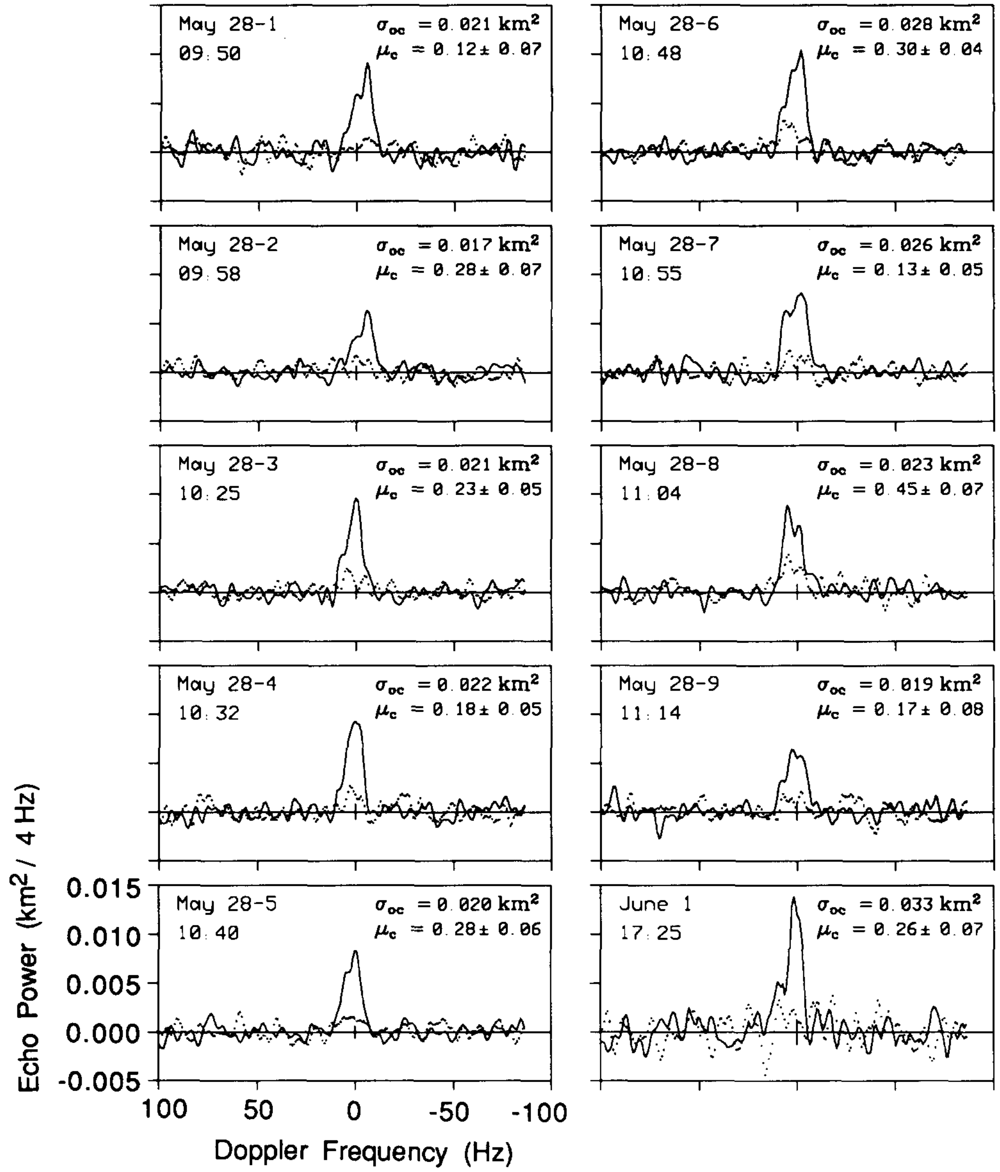

FIG. 2. 1986 JK echo spectra for nine subsets of the May 28 data and for the sum of June 1 data. The May 28 subsets are the same as those used for the Doppler analysis described in Section II, and the receive epochs given in the figure are from Table II. Echo power, in km^2 of radar cross section per 4-Hz frequency resolution cell, is plotted against Doppler frequency. The OC and SC echoes are shown as solid and dotted curves, respectively. Zero Doppler corresponds to echoes from the asteroid's center of mass, as calculated from the final a posteriori ephemeris. The vertical bar at the origin of each plot shows ±1 standard deviation of the noise. Estimates of OC radar cross section (σ_{OC}) and circular poloarization ratio (μ_C) are indicated. See text.

noise, which range from 5 to 9% of the σ_{oc} values. In this context, we can state that the true excursion in the asteroid's radar brightness during the 1.5-hr observing period on May 28 could have been as high as ~30% about the mean, but the possibility of negligible variations cannot be ruled out.

There is some evidence for variation in

OC spectral shape among the May 28 subsets: The first two groups show "excess" echo at negative Doppler frequencies (i.e., from the receding portion of the asteroid's disk), whereas the opposite situation exists for group 8, and the other six subsets have more symmetrical spectra.

The dispersion of May 28 μ_c values is significant at the several-standard-deviation level. Moreover, for at least one group (Fig. 2, May 28-6), μ_c seems to vary across the spectral band. Using the spectra for that group, we calculate that μ_c reaches 0.71 ± 0.18 at 6.4 Hz and dips to 0.11 ± 0.07 at −0.9 Hz. These results suggest that 1986 JK is at least mildly heterogeneous at centimeter-or-larger scales. 1986 JK's radar reflectivity appears to be extremely low, so the radar wave could have penetrated many meters below the surface and at least some of the apparent roughness and its variations might be due to subsurface structure.

The radar signature variations apparent from the May 28 echoes presumably arise from the asteroid's changing rotational phase over the course of the observations. If, as argued above, the rotation period is unlikely to exceed 20 hr, then our May 28 observations span a rotation phase interval $\Delta\theta$ no smaller than 1.5/20 cycles, or 27°. It is plausible that the variations in radar signature discernible in Fig. 2 could arise over an interval that short, but we suspect that $\Delta\theta$ really is much larger, i.e., that the true rotation period is much shorter than 20 hr. If so, the lack of severe bandwidth variations over, say, one-sixth of a rotation would argue against 1986 JK's polar silhouette being highly noncircular; i.e., it would argue against an elongated shape.

Whereas the June 1 circular polarization ratio is indistinguishable from the May 28 average, the June 1 radar cross-section estimate (σ_{oc} = 0.033 km^2) is ~50% greater than the May 28 mean value (0.021 km^2). Here, again, our comment on relative uncertainties applies, so it seems likely that the May 28 and June 1 views of the asteroid were different. If one assumes that the difference in σ_{oc} corresponds to a difference in projected area, then one could explain the two dates' results in terms of a rotational phase effect. However, since the asteroid's geocentric directions on May 28 and June 1 differed by ~57°, another hypothesis—and one favored by the previous paragraph's argument against an elongated shape—postulates that our view was further from equatorial on June 1 than on May 28 and that the asteroid is flattened at the poles. Thus the larger value of σ_{oc} on June 1 arose because the asteroid's more pole-on orientation presented more projected area to the radar. In this case, we would expect the June 1 spectra to be narrower than the May 28 spectra. Although noise levels in the spectra preclude reliable comparison of edge-to-edge echo bandwidths, it is interesting that the half-power bandwidths of the 4-Hz-resolution spectra from May 28 (Fig. 1) and June 1 are in the ratio ~1.5, i.e., roughly the same as the ratio of the June 1 and May 28 OC radar cross sections. We conclude that 1986 JK's pole direction (modulo 180°) is probably closer to right ascension = 20.4 hr, declination = −27° than 0.2 hr, −9°.

Summary: A Tentative Description of 1986 JK

The radar and optical measurements suggest a "working model" of this asteroid as an object whose size is 1 to 2 km and whose shape is not highly irregular, with little equatorial elongation but modest polar flattening. Its rotation period is probably not more than a few hours longer than 10 hr. The top few meters of the surface possess a moderate degree of centimeter- to meter-scale structure and have a bulk density on the order of 0.9 g cm^{-3}. (We stress that this description rests on the assumption that 1986 JK's visual albedo is within the range of values spanned by C-class asteroids.)

All these conjectures can be tested observationally if 1986 JK is recovered during its next favorable apparition, in 2000.

TABLE III

ORBITAL ELEMENTS FOR ASTEROID 1986 JK[a]

	Epoch	
	1988 Aug. 27.0 ET (JDE 2447400.5)	2000 Sep. 13.0 ET (JDE 2451800.5)
Time of perihelion, T	1986 Jul. 1.59491	2000 Jul. 15.97116
Mean anomaly, M	165.70337°	12.41985°
Mean motion, n	$0.21044235° \text{ d}^{-1}$	$0.21040303° \text{ d}^{-1}$
Semimajor axis, a	2.7992861 AU	2.7996348 AU
Eccentricity, e	0.6795276	0.6799288
Arg. of perihelion, ω	232.36536°	232.45312°
Longitude ascending node, Ω	62.23241°	62.12512°
Inclination, i	2.13929°	2.13680°
Period, P	4.684 y	4.684 y
Perihelion distance, q	0.8970941 AU	0.8960825 AU
Aphelion distance, Q	4.7014782 AU	4.7031871 AU

[a] The angular elements are referred to the ecliptic plane and the equinox of 1950.0. For the six orbital elements determined in the weighted least-squares solution (T, e, ω, Ω, i, q) at the 1988 epoch, the formal standard errors are, respectively, 3×10^{-5} day, 31×10^{-7}, 11×10^{-5} degrees, 10×10^{-5} degrees, 3×10^{-5} degrees, and 4×10^{-7} AU. These uncertainties are lower limits because they reflect only the data noise and not other unmodeled error sources. However, we have retained enough precision in the tabulated orbital elements to allow them to be used as initial conditions for numerical integrations.

V. 1986 JK'S ORBIT AND EPHEMERIS

Radar observations are an exceptionally powerful data type (Yeomans *et al.* 1987), and here we report asteroid orbit determinations in which radar astrometric data have been used to refine the "optical-only" result.

The orbital solution used to provide predictions for the radar observations was based upon 27 optical astrometric positions from May 4 to 23, 1986. The rms position residual, in the sense observed-minus-computed, was 1.0 arcsec. Subsequent to the radar experiment, additional optical astrometric data became available, and there now are a total of 73 observations covering the interval from May 4 through October 30, 1986. Seven of these optical observations were not employed in our orbit solutions because their residuals exceeded 3 arcsec.

We have combined the 11 Doppler observations in Table II with the 66 retained optical observations to obtain a much improved orbit for asteroid 1986 JK. In our weighted least-squares, differential correction procedure, we used the uncertainties (3 or 30 Hz) assigned to the Doppler estimates in Table II, and weighted all the optical data equally, using a noise value of 1 arc sec. The Jet Propulsion Laboratory's planetary ephemeris DE118 and associated constants were used in computing the perturbations of all nine planets at each time step in the numerical integration process. The improved orbital elements are given in Table III. The postfit, rms, optical residual is 0.96 arcsec and the normalized, rms residual for both the radar and optical data (i.e., root-reduced χ^2) is 0.94. Table II lists the Doppler residuals; the largest value, 7 Hz, corresponds to a line-of-sight velocity residual of 12 cm sec^{-1}.

Meteor Stream Association?

In light of 1986 JK's comet-like physical and orbital characteristics, we consider the possibility of a meteor stream being associated with this object. Using the 1988 orbit in Table III, we find that 1986 JK passed closest to Earth (0.028 AU) on 1986 May 29.0. However, the length of the shortest line segment connecting the *orbits* of 1986 JK and Earth was only 0.0052 AU (two lunar distances). Let r_{JK} and r_{E} represent the endpoints of that line segment. We find that the asteroid passed through r_{JK} on May 30.4 (a week after passing through its descending node), and Earth passed through r_{E} 2 days later. If particle debris from 1986 JK were located 2 days behind the asteroid and 0.005 AU outside its orbit, a meteor shower might have occurred on 1986 June 1.452 UT with a radiant at (1950.0) right ascension 220.09° and declination −9.65°, in the constellation Libra. While we have been unable to locate reports of any recent shower activity associated with 1986 JK, Olsson-Steel (1988) has pointed out possible associations with three minor meteoroid streams listed by Cook (1973).

Prospects for Recovery

1986 JK is in a 3 : 14 resonance with Earth; i.e., it makes a close Earth approach

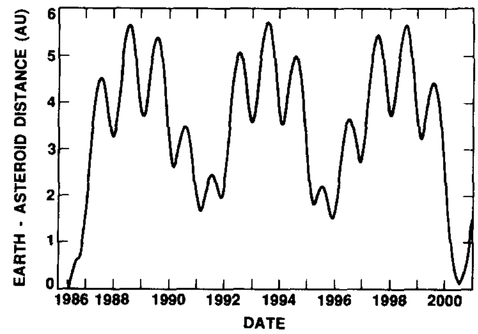

FIG. 3. 1986 JK's geocentric distance vs calendar date, calculated from an orbit solution that incorporates all available optical and radar astrometry. The text describes prospects for recovering the asteroid during its 2000 apparition.

every 14 years (Fig. 3). Forward integration of its motion reveals an approach to within 0.12 AU in mid-July 2000. This apparition probably provides the first opportunity to recover the asteroid.

Using the error-analysis techniques described by Yeomans *et al.* (1987), we have evaluated the plane-of-sky position uncertainties in the asteroid's ephemeris for 2000 June 17, when the geocentric distance (0.20 AU), apparent magnitude (V = 18.5 mag), solar elongation (78°), and lunar elongation (103°) should provide excellent observing conditions. Table IV lists the standard deviations in plane-of-sky position for seven different astrometric data sets. The first six of these are listed chronologically and show how increments in the optical and/or radar astrometric data sets permit improvements in our knowledge of the orbit, thus reducing the ephemeris uncertainties and providing more favorable odds for recovering the asteroid.

The first line in Table IV shows that a search ephemeris based on the twenty-five May 4–20 optical astrometric measurements would yield a prediction ephemeris for 2000 June 17 with a plane-of-sky standard error of 79°. Since this value represents the semimajor axis of the plane-of-sky uncertainty ellipse, the actual search field would have a full width of 158°, so the asteroid would be hopelessly lost. Line 2 cor-

TABLE IV

UNCERTAINTIES IN 1986 JK'S EPHEMERIS FOR 2000 JUNE 17.0[a]

	Optical astrometry		Radar astrometry		Plane-of-sky uncertainty
	Positions	Dates	Dopplers	Dates	
1.	25	May 4–May 20	None	—	79°
2.	34	May 4–May 23	None	—	67°
3.	34	May 4–May 23	10	May 28/30	1° 47′
4.	34	May 4–May 23	11	May 28/30, Jun 1	18′
5.	48	May 4–Aug 16	11	May 28/30, Jun 1	9.8′
6.	66	May 4–Oct 30	11	May 28/30, Jun 1	8.1′
7.	66	May 4–Oct 30	None	—	29′

[a] Standard errors in plane-of-sky position, predicted for an epoch during the first apparition favorable to optical recovery of 1986 JK, are listed for seven different astrometric data sets. The first six entries show how our knowledge of the orbit improved as the optical and radar measurements accumulated during 1986. The last entry shows that the 1-standard-deviation search area in June 2000 would be 13 times larger without the radar data than with it. Because of various sources of systematic error neglected in our error analysis, the uncertainties listed here are likely to be several tens of percent smaller than the "true" uncertainties.

responds to the data set used to prepare the ephemeris for the 1986 radar observations. Although these observations were sufficient to ensure the success of the radar experiment, these data by themselves would produce an ephemeris that leads to an *incorrect* prediction of 1995 for the year of the asteroid's next close approach. (Compare Fig. 3 here to Fig. 6 in Yeomans *et al.* 1987.)

Line 3 in Table IV shows the dramatic improvement (by a factor of 38) in the June 2000 search ephemeris when we include the 10 radar Doppler measurements from May 28 and 30 (see Table II) in the orbit calculation. From line 4 we see that an additional, nearly sixfold improvement results from inclusion of the June 1 Doppler datum. The magnitude of this effect from a single observation arises, in part, because the June 1 Doppler measurement enlarged, by about a radian, the arc spanned by the other high-precision Doppler astrometry from May 28. Moreover, as shown by the simulations of Yeomans *et al.* (1987; see also Shapiro 1968) the effect of a Doppler measurement at a specified precision (i.e., noise level) increases with the absolute value of the Doppler frequency itself, and 1986 JK's radial velocity during the June 1 observation (10.7 km sec^{-1}) was much larger than on May 28 (−2.7 km sec^{-1}) or on May 30 (5.8 km sec^{-1}).

Lines 5 and 6 in Table IV show continued, modest reductions in ephemeris uncertainties from optical measurements accumulated through October 1986. Line 7 shows that an "optical-only" June 2000 ephemeris would have a plane-of-sky, solid-angle uncertainty an order of magnitude larger than one that also incorporates the radar data.

VI. CONCLUSION

The ground-based observations of 1986 JK were successful in that they have provided an interesting, albeit limited, physical characterization and have probably secured optical recovery of the asteroid. They also demonstrate the value of a rapid response by astronomers using a variety of techniques when an Earth-approaching small body is discovered. If 1986 JK is recovered, efforts should be made to measure its rotation period and to obtain an IR radiometric constraint on its size.

There is considerable room for improving upon the radar experiment reported here. Our use of the radar astrometry to improve 1986 JK's orbit, first to find the June 1 echoes and then to refine an optical-only prediction ephemeris, illustrates a process that should be speeded up. It is desirable to streamline procedures for scheduling antenna time, calculating ephemerides, and passing refined ephemerides to optical and radar observatories. Radar data-acquisition/reduction software and procedures should also be made more efficient and less unwieldy, so Doppler frequencies can be extracted as soon as echoes are first detected. In principle, with an ephemeris refined by those Doppler measurements, one could advance from simple cw observations to experiments employing time-coded radar waveforms for ranging and delay/Doppler imaging, all within hours of the initial radar detection, on a date within weeks of the object's discovery.

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