Recent radar observations of asteroid 1566 Icarus

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Abstract

We report Doppler-only radar observations of Icarus at Goldstone at a transmitter frequency of 8510 MHz (3.5 cm wavelength) during 8–10 June 1996, the first radar detection of the object since 1968. Optimally filtered and folded spectra achieve a maximum opposite-circular (OC) polarization signal-to-noise ratio of about 10 and help to constrain Icarus’ physical properties. We obtain an OC radar cross section of 0.05 km\(^2\) (with a 35% uncertainty), which is less than values estimated by Goldstein (1969) and by Pettengill et al. (1969), and a circular polarization (SC/OC) ratio of 0.5 ± 0.2. We analyze the echo power spectrum with a model incorporating the echo bandwidth \(B\) and a spectral shape parameter \(n\), yielding a coupled constraint between \(B\) and \(n\). We adopt 25 Hz as the lower bound on \(B\), which gives a lower bound on the maximum pole-on breadth of about 0.6 km and upper bounds on the radar and optical albedos that are consistent with Icarus’ tentative QS classification. The observed circular polarization ratio indicates a very rough near-surface at spatial scales of the order of the radar wavelength.

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1. Introduction

Radar observations of Apollo asteroid 1566 Icarus during an apparition within 0.043 AU of the Earth in 1968 marked the beginning of asteroid radar astronomy. The encounter caused considerable concern because of unfounded fears of a collision (Nature, 1967; Newsweek, 1968), triggered discussions on ways to counter such collisions (Kleiman, 1968), and led to serious pleas for monitoring asteroids and exploring them by spacecraft (New York Times, 1967, 1968, 1969). A large number of articles were published on the topic during 1967–70 (see website http://pdsbn.astro.umd.edu/SBNast/archive/refs.tab at the University of Maryland, Astronomy Department). Table 1 lists some of the news items and various sorts of articles of the time, indicating the extraordinary level of professional and popular interest generated by the 1968 encounter.

As an asteroid with a relatively long observational history, Icarus’ orbit is well known and estimates for many of its physical properties such as its rotation period, diameter, and optical geometric albedo have been reported (Table 2). Its taxonomic classification is uncertain: Tholen (1989) and McFadden et al. (1989; Table 1) do not assign a class, whereas Chapman et al. (1975) prefer an S classification and Hicks et al. (1998) prefer a Q classification (Table 2). From optical observations of polarization and the phase factor of reflectivity, Gehrels et al. (1970) estimated Icarus’ geometric albedo to be 0.26, from which they deduced its radius as 0.54 km, assuming a spherical shape. Recently Harris (1998) reanalyzed thermal infrared observations obtained by Veeder et al. (1989) and obtained a diameter of 1.27 km and an optical albedo of 0.33.

With a rotation period of 2.273 h, Icarus is among the fastest known rotators. Rotation periods for only two asteroids have been reported to date that are faster than that of Icarus: 1995 HM with a period of 1.62 h (Steele et al., 1997), and 1998 KY26, which has a rotation period of about 11 min (Ostro et al., 1998; Pravec and Sarno, 1998; Hicks and Rabinowitz, 1998). Icarus has a perihelion \(q = 0.19\) AU that is among the smallest known; the only known asteroids with smaller perihelia are 3200 Phaethon \((q = 0.14\) AU), 1995 CR \((q = 0.12\) AU), and 1998 KN\(_{3}\) \((q = 0.18\) AU). The small perihelion and the high orbital eccentricity make Icarus a more attractive object than Mercury for testing gravitational theories (Shahid-Salass and Yeomans, 1994). The same orbital parameters have led to speculation that the object

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may be a spent comet (Gehrels et al., 1970; Weissman et al., 1989).

We observed Icarus in 1996 using an improved Goldstone radar system. This paper presents the results of that study and, while putting them in perspective with the pioneering observations of 1968, touches upon some of the intervening developments.

2. The first radar view

The 1968 apparition of Icarus was observed by Goldstein (1968, 1969) at Goldstone with a continuous-wave (CW) transmission at a frequency of 2388 MHz, and by Pettengill et al. (1969) at 7840 MHz at Haystack. Goldstein (1968) derived a radar cross section \( \sigma_{rad} \) of 0.1 km\(^2\) and constrained the radius and rotation period to be 0.3–0.6 km and 1.5–3.3 h. Subsequently the rotation period of Icarus became available through lightcurve studies by Gehrels et al. (1970). Using that result, Goldstein (1969) refined the radius estimate to be \( \geq 490 \) m, and constrained the average radar albedo to be \( \leq 0.13 \).

Goldstein (1968) reported a splitting of the spectral peak into a bimodal shape as the spectrum evolved during 14–16 June 1968, but Pettengill et al. (1969) did not notice any spectral splitting. Pettengill et al. obtained “a radar cross section of about 0.1 km\(^2\), a radius of 1 km, and an effective reflectivity of about 0.05,” with “an uncertainty of about a factor of 2.”

3. Intervening developments

Since the first experiments in asteroid radar, numerous developments have occurred in the related disciplines. Upgrades of the Goldstone and Arecibo radars have included transmitter power enhancement, improvements of the antenna and feed structures, and, in the case of the latter, installation of ground interference screening structures. Importantly, both telescopes now have simultaneous dual polarization reception capability, adding a new dimension of information to astronomical observations.

This period has also seen rapid technological development in the areas of data handling, reduction, processing, storage, and display. Automated radar operation and real-time signal and data processing enables more efficient utilization of the limited windows of opportunity...
Table 2
A priori information about Icarus

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major axis ($a$)</td>
<td>1.078 AU</td>
<td>JPL Solar System Dynamics Database</td>
</tr>
<tr>
<td>Eccentricity ($e$)</td>
<td>0.827</td>
<td>JPL Solar System Dynamics Database</td>
</tr>
<tr>
<td>Inclination ($i$)</td>
<td>22.870°</td>
<td>JPL Solar System Dynamics Database</td>
</tr>
<tr>
<td>Taxonomic class</td>
<td>$S$</td>
<td>Chapman et al. (1975)</td>
</tr>
<tr>
<td></td>
<td>$Q$</td>
<td>Hicks et al. (1998)</td>
</tr>
<tr>
<td>Visual absolute magnitude ($H_v$)</td>
<td>15.95</td>
<td>Tedesco (1989)</td>
</tr>
<tr>
<td></td>
<td>$16.3 \pm 0.3$ mag</td>
<td>Harris (1998)</td>
</tr>
<tr>
<td>Rotation period ($P$)</td>
<td>$2.25 \pm 0.05$ h</td>
<td>Veverka and Liller (1969)</td>
</tr>
<tr>
<td></td>
<td>$2.268 \pm 0.005$ h</td>
<td>Miner and Young (1969)</td>
</tr>
<tr>
<td></td>
<td>$2.273 \pm 0.001$ h</td>
<td>Gehrels et al. (1970)</td>
</tr>
<tr>
<td></td>
<td>$2.2735 \pm 0.0002$ h</td>
<td>De Angelis (1995)</td>
</tr>
<tr>
<td>Rotation sense</td>
<td>direct</td>
<td>De Angelis (1995)</td>
</tr>
<tr>
<td>Maximum light-curve amplitude ($\Delta m$)</td>
<td>0.22 mag</td>
<td>Gehrels et al. (1970)</td>
</tr>
<tr>
<td>Optical geometric albedo ($p_v$)</td>
<td>0.33</td>
<td>Harris (1998)</td>
</tr>
<tr>
<td>Diameter ($D$)</td>
<td>1.27 km</td>
<td>Harris (1998)</td>
</tr>
<tr>
<td>Principal axis ratio $a:b:c$</td>
<td>1.23/1.0/0.7</td>
<td>De Angelis (1995)</td>
</tr>
<tr>
<td>Pole direction</td>
<td>$0 \pm 3^\circ$ lat., $49 (or 229) \pm 3^\circ$ long.</td>
<td>Gehrels et al. (1970)</td>
</tr>
<tr>
<td></td>
<td>$5 \pm 5^\circ$ lat., $214 \pm 5^\circ$ long.</td>
<td>De Angelis (1995)</td>
</tr>
</tbody>
</table>

*a Multiple entries for a single parameter or characteristic signify alternative values taken from quoted sources.

*b http://ssd.jpl.nasa.gov/cgi-bin/eph

c With reference to J2000 ecliptic

d Based on a reanalysis of photometry obtained by Gehrels et al. (1970).

e Based on a reanalysis of thermal infrared observations by Veever et al. (1989).

f Based on a reanalysis of photometry obtained by Veverka and Liller (1969), Miner and Young (1969), Gehrels et al. (1970).

for asteroid observation. It is now possible to perform multi-parameter (Range-Doppler-Polarization) observation and processing of asteroid signals, under favorable conditions, to constrain asteroid shapes and surface features (Ostro, 1993; Ostro et al., 1995).

Significant advance has also been made in the knowledge base of asteroid radar signatures and their interpretation, with 37 MBAs (main-belt asteroids) and 49 NEAs observed through the end of 1998. The interpretation of these radar data, by themselves and together with optical and infrared data, have generated a fair degree of understanding regarding the behavior of asteroids of different classes as radar targets and have augmented the fundamental knowledge of these bodies (Ostro et al., 1991a; Ostro, 1994).

Efforts to detect echoes from Icarus at Arecibo in June 1987, when it came within 0.16 AU of the Earth, were unsuccessful. That was the first indication that the actual radar cross section of Icarus may be smaller than 0.1 km².

4. A recent radar view
4.1. Data collection and integration

We observed Icarus at Goldstone during 8–12 June 1996. As the echoes were expected to be weak, only CW data were collected during the first three days (Table 3). Each run consisted of transmission of a circularly polarized wave for a period close to the expected

Table 3
Parameters of CW radar data collection

<table>
<thead>
<tr>
<th>Date</th>
<th>RA (°)</th>
<th>Dec (°)</th>
<th>Runs</th>
<th>$\Delta t$(UTC h)</th>
<th>RTT (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08 June</td>
<td>338</td>
<td>10</td>
<td>43</td>
<td>11:58–15:52</td>
<td>109</td>
</tr>
<tr>
<td>09 June</td>
<td>331</td>
<td>6</td>
<td>27</td>
<td>13:08–14:57</td>
<td>104</td>
</tr>
<tr>
<td>10 June</td>
<td>324</td>
<td>2</td>
<td>54</td>
<td>11:52–15:14</td>
<td>101</td>
</tr>
</tbody>
</table>

Data acquisition parameters:
Transmitter frequency ($f$) = 8510 MHz
Wavelength ($\lambda$) = 3.5 cm
Transmitted polarization: RCP
Received polarization: simultaneous OC and SC
Sampling rate: 2 kHz
Basic processing: 1024-point FFT
No. of frequency hops = 4 (Ostro et al., 1992)
Doppler frequency resolution ($\Delta f$) = 1.953 Hz

Abbreviations:
$\Delta t$: Observation interval
RA: Right ascension
Dec: Declination
RTT: Round Trip Time
RCP: Right Circular Polarization
OC: Opposite Circular Polarization
SC: Same Circular Polarization
round-trip light travel time to the target, followed by reception of echoes for a comparable duration. Attempts to obtain range-Doppler echoes on 11 and 12 June using phase-coded transmission were not successful.

The signal-to-noise ratios (SNRs) of the single-run spectra were very weak. We therefore summed the spectra across all the three days. The data covered multiple rotations of Icarus (Fig. 1), so such integration sacrifices rotational resolution.

4.2. Heuristic analysis

We first perform a simple visual analysis of the raw 3-day weighted sum spectra (Fig. 2a). As the SNR in this spectrum is still low (peak SNR ~ 3), we smoothed it with a 10-Hz filter (Fig. 2b), yielding SNR = ~ 7. To enhance the SNR even further, we folded the Doppler spectrum about the DC line, (i.e. inverted the spectrum of Fig. 2b about the zero-Doppler axis and added it to the uninverted spectrum). Such an operation on a rotationally averaged spectrum is admissible if the echo’s center-of-mass frequency offset is small compared to the spectral resolution, which is the case here. For Icarus, analysis of all available optical and radar astrometry (available on the internet at http://ssd.jpl.nasa.gov/radar.data.html) yields an orbit (http://ssd.jpl.nasa.gov/cgi-bin/eph) which predicts that the correction to the Goldstone Doppler ephemeris was 0.65 Hz, i.e. ~ 1/3 of our raw spectral resolution. The folded spectrum, which has SNR close to 10, is shown in Fig. 2c and indicates an edge-to-edge or zero-crossing bandwidth $B$ of about 45 Hz for the OC spectrum. Since the 10-Hz smoothing would have stretched the bandwidth by about the same amount (i.e. about 10 Hz), the actual value of $B$ is likely to be about 35 Hz. There would also be a small bias in the bandwidth estimate due to the FFT resolution of 1.95 Hz which is neglected.

The lower bound on the size of the asteroid is determined from the equation

$$B(\delta) \leq \frac{4\pi D \cos \delta}{\lambda P}$$

where $D$ is the breadth of the plane-of-sky projection of the asteroid’s pole-on silhouette, $P$ is its apparent rotation period, $\delta$ is the angle between the radar-asteroid line and the equatorial plane of the asteroid, and $\lambda$ is the radar wavelength. For a lower bound of 35 Hz on $B$, eqn (1) yields $D \geq 0.8$ km.

4.3. Formal analysis

We now make a formal analysis that is more robust against noise effects and explicitly takes into account the radar scattering behavior of Icarus. This is done by least-squares-fitting the unimodal function

$$y(f) = a \left[ 1 - \left( \frac{f - d_{00}}{B/2} \right)^2 \right]^{n/2}$$

(2)

to the raw spectrum, where $a$ is the amplitude of the model function, $f$ is the Doppler frequency, $d_{00}$ is the offset of the center frequency of the target spectrum with respect to the Doppler-prediction ephemeris, and $n$ describes the shape of the echo spectrum. The function (2) corresponds to the spectral shape of the echo signals from a rotating spherical object of uniform surface scattering law modeled as \( \cos^2 \theta \) where $\theta$ is the angle from the incidence direction. In general $n$ depends on the radar backscattering behavior of the asteroid surface with respect to the angle of incidence, the shape of the object, and the reflectivity or ‘feature’ distribution on the surface. With integration over multiple rotations, $n$ would depend primarily on the average surface backscattering property of a spheroidal asteroid.

Figure 3 shows $\chi^2$ values for the best-fitting model curve over a range of $B$ and $n$ values. A clear minimum exists for any given value of $n$ or $B$, but the surface has a diagonal trough which defines a coupled constraint for $B$ (and hence $D$) and $n$.

As seen from Fig. 2a, the power in the OC and SC spectra varies with a certain degree of independence over the spectral domain, and their ratio $\mu$, is a function of the particular frequency band chosen. Table 4 shows that $\mu$, varies between 0.38 and 0.76 over the bandwidths from 15–60 Hz. These high values suggest considerable surface...
Fig. 2. Weighted sums of all 124 single-run spectra, plotted in terms of noise standard deviation: (a) raw spectra; (b) spectra smoothed to a frequency resolution of 10 Hz; (c) folded and smoothed spectra shown on an expanded scale.
roughness at spatial scales of the order of $\lambda$. One would thus be justified in assuming a fairly diffuse scattering law, possibly with $n$ in the range of 3–5 (this assumption would break down for a sufficiently nonspherical target). The corresponding $B$ from Fig. 3 is between 25 and 35 Hz, with eqn (1) yielding a lower bound for $D$ between 0.57 and 0.77 km for a quasi-spherical shape. The absolute lower bound of 0.57 km is significantly less than the estimates made by both Goldstein (1969) and Pettengill et al. (1969).

If the pole direction obtained by De Angelis (1995, Table 2) is correct, then the sub-radar point on Icarus would have been at latitudes between about $-35$ and $-20$ degrees during the observations. If so, then $B$ between 25–35 Hz and $D$ between 0.6–0.8 km should encompass the maximum bandwidth and breadth of Icarus. However, that range of $D$ contradicts the radiometrically-determined diameter of 1.3 km obtained by Harris (1998), suggesting that either the radiometric diameter, the pole direction, or both are incorrect.

### 4.4. Radar cross section and albedo

Our estimate of Icarus’ OC radar cross section, $\sigma_{OC} = 0.050 \text{ km}^2 \pm 35\%$, (Table 4), is only about one-half of the 12.5-cm $\sigma_{OC}$ estimated by Goldstein (1968, 1969) and the 3.8-cm value of $0.1 \pm 0.05 \text{ km}^2$ obtained by Pettengill et al. (1969). Since we also observed from Doppler analysis a smaller lower bound for $D$ than earlier estimates, a lower $\sigma_{OC}$ appears plausible. Within the 1-sigma uncertainties, our radar cross section is consistent with that obtained by Pettengill et al., but we cannot assess the degree to which our value conflicts with the 12.5-cm $\sigma_{OC}$ because Goldstein did not state the uncertainty in that value. The difference between our radar cross section and Goldstein’s nominal value could be due to the difference in the radar wavelengths, the low SNR of both the 1968 and 1996 observations, or to systematic calibration errors.

For each assumed $B$ in Table 4, the radar albedo $\delta_{OC} = \sigma_{OC}/(\pi D^2/4)$ has been calculated using $\sigma_{OC} = 0.050 \text{ km}^2$ and $D$ equal to the bound obtained from eqn (1). For the $B$ interval of 25–35 Hz, $\delta_{OC}$ varies from about 0.20 to 0.10, which is in general agreement with $\delta_{OC} \leq 0.13$ claimed by Goldstein (1969). Such agreement, however, is the result of our estimates of both $\sigma_{OC}$ and $D$ being smaller than his by about the same factor. The mean and rms dispersion in $\delta_{OC}$ of 13 SQ-class NEAs is $0.14 \pm 0.07$ (Ostro et al., 1991a, 1996, 1999; Hudson and Ostro,

<table>
<thead>
<tr>
<th>Assumed echo bandwidth</th>
<th>Lower bound on diameter, km</th>
<th>OC cross section ($\sigma_{OC}$), km$^2$</th>
<th>SC cross section ($\sigma_{SC}$), km$^2$</th>
<th>Polarization ratio ($\mu$)</th>
<th>OC albedo</th>
<th>Total (OC+SC) albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.34</td>
<td>0.038 ± 0.005</td>
<td>0.014 ± 0.003</td>
<td>0.377 ± 0.121</td>
<td>0.412</td>
<td>0.567</td>
</tr>
<tr>
<td>20</td>
<td>0.46</td>
<td>0.045 ± 0.006</td>
<td>0.015 ± 0.002</td>
<td>0.335 ± 0.097</td>
<td>0.271</td>
<td>0.304</td>
</tr>
<tr>
<td>25</td>
<td>0.57</td>
<td>0.045 ± 0.006</td>
<td>0.021 ± 0.003</td>
<td>0.464 ± 0.130</td>
<td>0.173</td>
<td>0.253</td>
</tr>
<tr>
<td>30</td>
<td>0.69</td>
<td>0.052 ± 0.006</td>
<td>0.023 ± 0.003</td>
<td>0.441 ± 0.118</td>
<td>0.139</td>
<td>0.200</td>
</tr>
<tr>
<td>35</td>
<td>0.80</td>
<td>0.052 ± 0.006</td>
<td>0.027 ± 0.004</td>
<td>0.518 ± 0.133</td>
<td>0.103</td>
<td>0.157</td>
</tr>
<tr>
<td>40</td>
<td>0.92</td>
<td>0.053 ± 0.006</td>
<td>0.035 ± 0.004</td>
<td>0.757 ± 0.145</td>
<td>0.079</td>
<td>0.125</td>
</tr>
<tr>
<td>45</td>
<td>1.03</td>
<td>0.054 ± 0.006</td>
<td>0.032 ± 0.004</td>
<td>0.624 ± 0.155</td>
<td>0.064</td>
<td>0.104</td>
</tr>
<tr>
<td>50</td>
<td>1.15</td>
<td>0.051 ± 0.006</td>
<td>0.036 ± 0.005</td>
<td>0.714 ± 0.172</td>
<td>0.049</td>
<td>0.084</td>
</tr>
<tr>
<td>55</td>
<td>1.26</td>
<td>0.050 ± 0.006</td>
<td>0.038 ± 0.005</td>
<td>0.756 ± 0.182</td>
<td>0.040</td>
<td>0.070</td>
</tr>
<tr>
<td>60</td>
<td>1.38</td>
<td>0.050 ± 0.006</td>
<td>0.034 ± 0.004</td>
<td>0.681 ± 0.161</td>
<td>0.033</td>
<td>0.056</td>
</tr>
</tbody>
</table>

*Based on the raw 3-day-sum OC and SC spectra with 1.95 Hz resolution. The uncertainties quoted herein reflect the variances due to the statistical nature of the signal, and do not reflect the radar calibration errors, which raise the fraction uncertainty to $\sim 35\%$. 

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Fig. 3. Chi-square (i.e., the sum of squared residuals) from fitting the spectral model function of eqn (2) to the OC sum spectrum of Fig. 2a, shown as function of bandwidth and spectral shape parameter of the model function. Note the oblique, trough-like minimum.
so our \( \sigma_{\text{OC}} \) estimate for Icarus is consistent with its classification as an SQ-type object.

4.5. Correlation with visual albedo

Figure 4 shows a plot of \( \sigma_{\text{OC}} \) as a function of \( D \) and depicts the variation of the visual geometric albedo \( p_v \) for \( H = 16.3 \) (Table 2). \( p_v \) is obtained from the relation (Zellner, 1979)

\[
\log p_v = 6.244 - 2\log D - 0.4H.
\]

Also marked on the \( \sigma_{\text{OC}}-D \) curves in Fig. 4 are the points whose ordinates correspond to the average radar albedo of NEAs and MBAs by taxonomic class. The lower bound of 0.57 km on the pole-on breadth of Icarus corresponds to an upper bound on \( \sigma_{\text{OC}} \) of 0.20 that is in the middle of the known asteroid radar albedo distribution. However, if the radiometric diameter of 1.27 km obtained by Harris (1998) is correct, then the radar albedo of Icarus is about 0.04, which is the lowest radar albedo estimated for any S-class main-belt or near-Earth asteroid to date. That estimate is also comparable to the radar albedo of comet IRAS-Araki-Alcock (0.04, Harmon et al., 1989), although visible spectroscopy does not suggest that Icarus is a comet.

4.6. Polarization ratio

In the \( B \) interval of 25–35 Hz, \( \mu_c \) is observed from Table 4 to be between 0.44 and 0.52. Even after accounting for the estimation uncertainty of 12–13\%, these values are high for NEAs, but are not unique. Ostro et al. (1991b) provide \( \mu_c \) values for 29 NEAs (at \( \lambda = 3.5 \) and 13 cm) which have a mean of 0.3 and 1-sigma dispersion of 0.22, with five objects yielding \( \mu_c \geq 0.42 \). Specifically, NEAs that have larger circular polarization ratios at \( \lambda = 3.5 \) cm are 1981 Midas (\( \mu_c \sim 0.65 \)) and 3908 (1980 PA) (\( \mu_c \sim 0.72 \)). Further, the asteroids 2101 Adonis, 3103 Eger, and 1992 QN have recently been found to have near-unity circular polarization ratios (Benner et al., 1997). If we adopt \( \mu_c = 0.5 \pm 0.2 \) as a nominal value for Icarus, then the 1-sigma lower bound on the circular

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Fig. 4. Radar albedo (dark solid curve) of Icarus as a function of its effective diameter, calculated with our estimated radar cross-section \( \sigma_{\text{OC}} = 0.050 \) km\(^2\). This curve is bounded by thin solid lines representing \( \pm 35\% \) uncertainty. The radar albedos of near-Earth and main-belt asteroids are superimposed on the radar albedo curve. The visual geometric albedo is also plotted (dash-dot line) for \( H = 16.3 \) (Harris, 1998). The asterisks and their accompanying thick solid curve segments represent, respectively, the mean and rms dispersion of the visual geometric albedos for principal taxonomic classes (Tedesco, 1989).
polarization ratio of Icarus exceeds about 70% of the values reported for S-class asteroids so far (28 objects), suggesting that Icarus has a near-surface that is among the roughest at centimeter-to-decimeter spatial scales observed among all S-class asteroids. This high degree of small-scale roughness may or may not arise from regolith structure. Although small and rapidly rotating asteroids are less likely to have loose surface regolith, McFadden et al. (1989) suggest that several NEAs do support regoliths (perhaps dusty), and that: “the controlling factors of regolith properties and processes are not simply due to scaling with size and gravity.” In the case of Icarus, based on its size and rotation period, the existence of surface regolith is plausible if Icarus’ density is greater than 1 g cm$^{-3}$, which is a reasonable assumption given that the smallest asteroid density presently known is 1.3 g cm$^{-3}$ for 253 Mathilde (Yeomans et al., 1997).

5. Conclusion

The SNR of the 1996 observations was not substantially better than those obtained during the first observations in 1968. Icarus was farther from the Earth in 1996 than in 1968 by a factor of 2.4, which, by the inverse-fourth-power dependence of the SNR on range, would yield an echo power over 30 times weaker if all other parameters remained invariant. It is due to the advances in the radar capabilities during the intervening decades that the 1996 observations’ SNR was possible. The next radar opportunity to observe Icarus will be in June 2015 when the asteroid will pass within 0.054 AU of Earth. Estimated SNRs per date in 2015 at Arecibo should approach ~2000, adequate for a 3-D shape reconstruction with decameter resolution.

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References

Hicks, M., Rabinowitz, D., 1998. IAU Circ. 6935.
Ostro, S.J., Jurgens, R.F., Rosema, K.D., Hudson, R.S., Giorgini, J.D., Winkler, R., Yeomans, D.K., Choute, D., Rose, R., Slade, M.A.,


