respective metals (8). Tensile bars made of steel, Be-Cu, and stainless steel with considerably higher yield strengths remained undeformed after pressure cycles to 14 kb.

It is not possible, with the available data, to give a complete explanation of the origin of the stress field. However, the shear strength of the solidified gas (9) at this temperature and these pressures is certainly of significance in any detailed analysis.

R. E. STAJDOHAR
McGraw-Edison Power Systems Division, Research and Development Department, P. O. Box 160, South Milwaukee, Wisconsin 53712

P. F. HETTWER, D. R. MCCANN
Allis-Chalmers Manufacturing Company, Research Division, Milwaukee, Wisconsin 53201

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23 August 1968

Radar Observations of Icarus

Abstract. *Radar observations of Icarus were made in mid-June 1968, at the time of closest approach. From the data, it is estimated that the radius is between 0.3 and 0.6 kilometer and the rotation period between 1.5 and 3.3 hours. A set of round-trip Doppler shift measurements is given.*

Advantage has been taken of the recent, and rare, close approach of the asteroid Icarus to observe it by means of radar. Measurements of the radio frequency spectrum of the echoes were made. They provide data dependent upon the size, shape, spin, velocity, and radar cross section of the target.

The orbit of Icarus is such that it comes within 4 million miles of Earth only once in 19 years, and the last occurrence, on 14 June 1968, was the first opportunity for radar study. Icarus is an extremely difficult radar target; its radar detectability is only 10^{-3} times that of Mercury (at closest approach) and 10^{-12} that of Moon. Only the most powerful and sensitive radars of modern technology can detect this asteroid.

The measurements to be described were performed at the Jet Propulsion Laboratory's Goldstone Tracking Station. A newly developed 450 kw transmitter had just been installed on an 85-foot (26-m) dish antenna. The receiver was connected to a 210-foot antenna, approximately 14 miles (23 km) away from the transmitter. Because of this separation, it was possible to transmit and receive simultaneously most of the time. However, when the elevation angle was low or during the several hours of closest approach when the Doppler went through zero, it was necessary to transmit and receive in alternate cycles. Each cycle lasted 43 seconds, the round-trip time of flight.

The radar station parameters were as follows:

Power	450 kw
Frequency	2388 Mhz
Two-way antenna gain	116.0 db
System temperature	21°K

Pure monochromatic waves were beamed at Icarus. The frequency spectrum of the weak echoes was measured at the receiver. Any rotation that Icarus might have would broaden the spectrum of the echo and leave a characteristic signature upon it. Three functions of the radar were controlled by ephemerides: pointing of each of the two antennas and tuning of the receiver to account for the relative velocities of Icarus and the radar station.

Ordinarily, receiver runs of 30 minutes were made, and the resulting spectrum was displayed. Because of the unusually low power level of the echo, none of these runs produced a clear detection of Icarus. Although there were indications of an echo, they were obscured by the random fluctuations of the spectra. When 4 hours of data were averaged, however, the result was not only positive detection of Icarus, but also an indication of power bandwidth and center frequency. Altogether, seven such average spectra were taken. They are reproduced in Fig. 1. Each is the result of 3 to 4 hours of averaging.

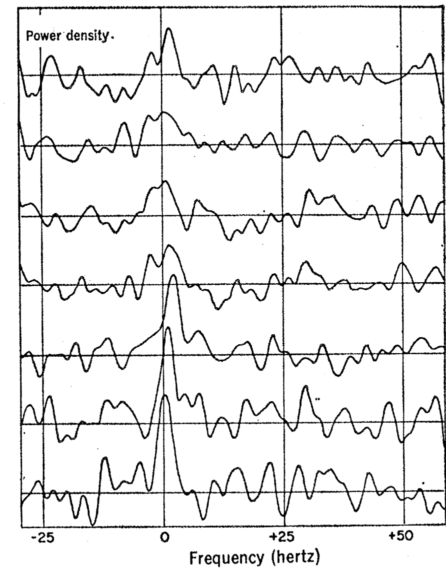

Fig. 1. Individual spectra of the Icarus echo. The averaging time was 3 to 4 hours each.

The radar was calibrated by directing it at the planet Mercury. Everything was unchanged except for the three ephemerides. Figure 2 is a sample result of averaging 9 minutes of echoes from Mercury. Note the different scales in frequency of the two figures.

The total received power is obtained from the area under each spectrum. An average echo power of 0.63×10^{-22} watts was obtained for Icarus. When the radar parameters of range, antenna gain, and so forth are taken into account, the result is the radar cross

Table 1. Values of radius and period derived from the spectrograms, assuming various reflection models for Icarus.

Type	Radius (km)	Period (hr)
Mercury	0.6	0.7
Venus	.5	.5
Moon	.7	.9
Rough, metallic	.3	1.5
Rough, stony	.6	3.3

Table 2. Measured values of Doppler shift along with the corresponding time for each spectrogram.

Spectrum	Received time (U.T.)	Doppler (hertz)
1	14 June 1968, 0530	+115,417.1±0.3
2	14 June 1968, 2220	−10,324.1
3	15 June 1968, 0430	−61,207.2
4	15 June 1968, 0940	−104,441.9
5	16 June 1968, 0140	−202,453.5
6	16 June 1968, 0630	−234,710.0
7	16 June 1968, 1000	−255,404.7

Table 3. Transmitter and receiver locations.

Transmitter	Receiver
Geocentric latitude	
$35.06662° \pm 24°$N	$35.24665° \pm 24°$N
Geocentric longitude	
$243.20507° \pm 24°$E	$243.11062° \pm 24°$E
Geocentric radius (meters)	
$6,372,260 \pm 26$	$6,372,158 \pm 26$

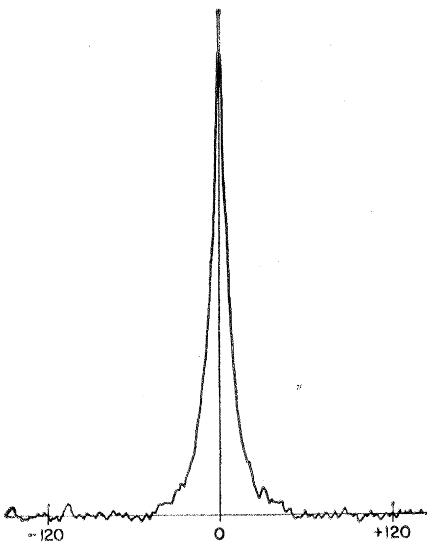

Fig. 2. A sample spectrum of an echo from Mercury, used to calibrate the radar. Only 9 minutes of averaging were required.

section σ. For Icarus, the result of the experiment is

$$\sigma = 0.1 \text{ km}^2$$

Radar cross section is defined as the effective cross-sectional area of the target. Two factors, reflectivity and directivity (which are properties of the surface), are multiplied on to the actual cross-sectional area. In order to estimate the target radius, it is necessary to assume a reflection model. Radii were computed under the assumption that Icarus reflects as either Mercury, Moon, or Venus, and the results are tabulated in Table 1.

The bandwidth B of the spectra at the half-power points are related to the spin rate of Icarus by the equation

$$B = \omega r / Q$$

where ω is the effective spin rate; r, the radius; and Q, an unknown shape factor of the spectrum which depends on the roughness of target. For Mercury, Q equals 7.4.

Once again one has to assume a reflection model in order to compute the spin rate. The rotation period for the same models was estimated as before and these results are also listed in Table 1. The effective spin rate is the projection of the actual one, across the line of sight. There is in addition a small orbital component of effective spin, but for Icarus this is negligible.

The 4-hour average spectra of Fig. 1 are very noisy, and one can draw conclusions from them only at considerable risk. However, a trend does appear in these records. The first two show a single frequency of maximum response, whereas the last four appear bimodal; the third spectrum appears to be transitional. Figure 3 is the result of averaging the last five spectra, so that the bimodal structure shows up clearly. This change cannot be interpreted as the result of Icarus' rotation, since each spectrum is the result of almost 4 hours (hence more than one period) of averaging. However, the sub-radar point on Icarus moved appreciably during the 2½ days of the experiment. Figure 4 shows this motion, with the position at the time of each spectrum marked.

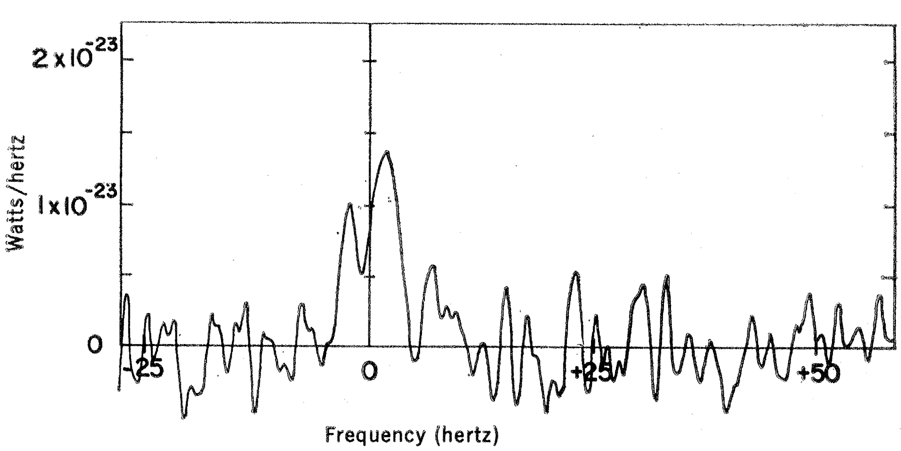

Fig. 3. Average spectrum (Nos. 3 through 7) of 17 hours of observation of Icarus. This spectrum has twice the frequency resolution of the spectra of Fig. 1.

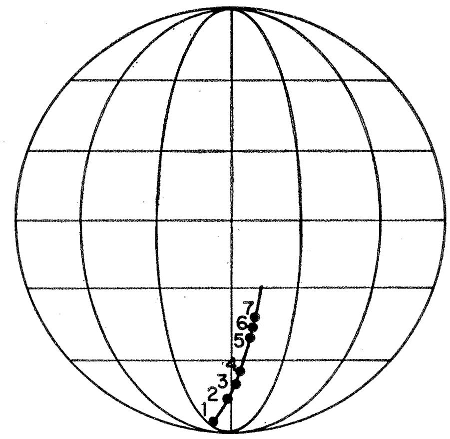

Fig. 4. Position of the sub-radar point on Icarus, assuming no rotation for Icarus.

If one assumes that Icarus is rough, even jagged, and not necessarily round, then the spectrum would be expected to change with the motion of the sub-radar point. In particular, the slow change from unimodal to bimodal can be explained in terms of the motion of the sub-radar point and the supposed irregular shape of Icarus.

Because of these considerations the radius and spin were computed for two additional models of reflectivity: rough and metallic; and rough and stony. The rough assumption leads to a Q factor of $\sqrt{2}$. Reasonable reflectivities for metallic and stony surfaces are 0.5 and 0.1, respectively. The corresponding values of the radius and rotation period are listed with the others in Table 1.

The center frequency of each spectrum gives the Doppler shift and hence the line-of-sight velocity of Icarus. Because of the irregular shape of the spectra, the center frequency is imperfectly determined. The "center of gravity" of the spectra was chosen as the estimate. The resulting Doppler measurements are given in Table 2. These data, along with the station locations given in Table 3, can be used to improve the ephemeris of Icarus.

R. M. GOLDSTEIN

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

Notes

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2. This report represents the results of one phase of research carried out at the Jet Propulsion Laboratory under contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

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