ASTEROID CHARACTERISTICS BY RADAR

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The techniques of radar offer a potentially powerful tool for the study of planetoids. It is a new approach, having been applied to extraterrestrial targets only recently in the history of astronomical study. Although the Moon was first, Venus has been observed by radar only since 1961. Since that time the techniques and capability of radar have evolved rapidly and many important new facts about Venus have been gathered. Further, the more distant and difficult targets, Mercury and Mars, have also yielded up secrets to radar probing. Finally, during the close approach of June 1968 Icarus itself was observed by radar from two different observatories (Goldstein, 1969; Pettengill et al., 1969). Review articles on radar studies of the planets are given in Shapiro (1968) and Goldstein (1970).

It is to be hoped that radar study of the asteroids will prove as fruitful as the study of the inner planets. However, asteroids present extra difficulties to radar as compared to the familiar planets. A diagram of the radar situation is given in figure 1. A tight beam of microwaves (0.1° is the current state of the

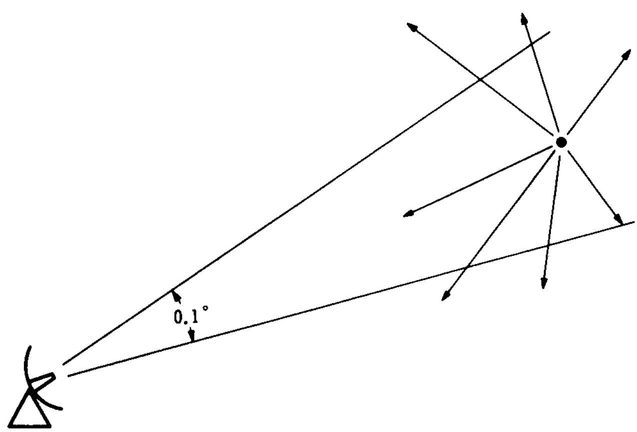

Figure 1.–Illustration of geometric difficulties of radar asteroid astronomy. The received power is extremely weak, and the antenna beam cannot resolve individual parts of the target.

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art) is directed toward the target. However, only a minute fraction of the power is actually intercepted. Of that amount, most is dissipated by the surface as heat. The balance, which contains the desired information, is scattered more or less uniformly throughout the solar system. The echo power received by the antenna is incredibly small. For the Icarus measurements of 1968, the transmitted power was 450 kW; the echo power was 6×10^{-23} W. Thus the overriding problem of radar asteroid astronomy is one of signal-to-noise ratio (SNR).

The second important difficulty, related to the first, is angular resolution. It is necessary to be able to relate the echo to specific areas of the surface—to isolate different parts of the surface for separate study. It can be seen from the figure that angular resolution of the antenna is quite inadequate. However, radar commonly allows two dimensions to effect this separation: time delay and Doppler shift. Both of these dimensions consist of two parts: an orbital part, measured to the closest (or sub-Earth) point, and a part that relates other points on the surface to the sub-Earth point. Generally, the orbital part is accounted for by tuning, automatically, the radar receiver to track the sub-Earth point. This is analogous to sidereal drive on a telescope to hold the image still during a long time exposure. The contours of constant time delay and constant Doppler shift for the balance of the effect (for a spherical surface) are given in figure 2. For time delay the contours are circles, concentric about the sub-Earth point. The Doppler shift is caused by any rotation the target might have relative to the radar. The constant Doppler contours are also concentric circles, but seen edgewise from the radar.

Radar echoes from the inner planets have been analyzed into time-delay rings and into Doppler-shift rings and, in fact, both simultaneously. However, for asteroid study, only Doppler analysis has been used. The reason for this is the much weaker received power and the fact that narrowband signals are inherently easier to detect in the presence of noise. The narrowest band signals, of course, are those originating along a constant Doppler contour.

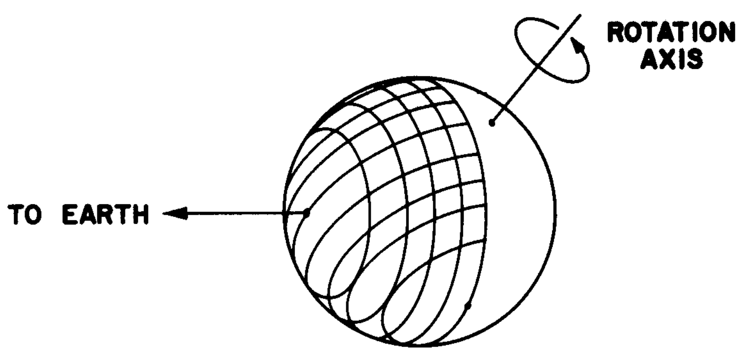

Figure 2.—Contours of constant time delay and of constant Doppler shift for a spherical target.

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The most likely asteroid radar experiment, then, consists of transmitting a spectrally pure, monochromatic wave toward the target. The received signals are analyzed by a process such as the fast Fourier transform to yield the power spectrum of the echoes. This is equivalent to a scan across the disk with a narrow slit, parallel to Doppler contours. As usual, there is an essential compromise between high resolution (narrowness of the slit) and SNR.

A result of applying this technique to the planet Mercury is given in figure 3. These data were taken when Mercury was 0.6 AU distant, spinning such that the limb-to-limb bandwidth was 100 Hz. It required 1 hr of integration time (time exposure).

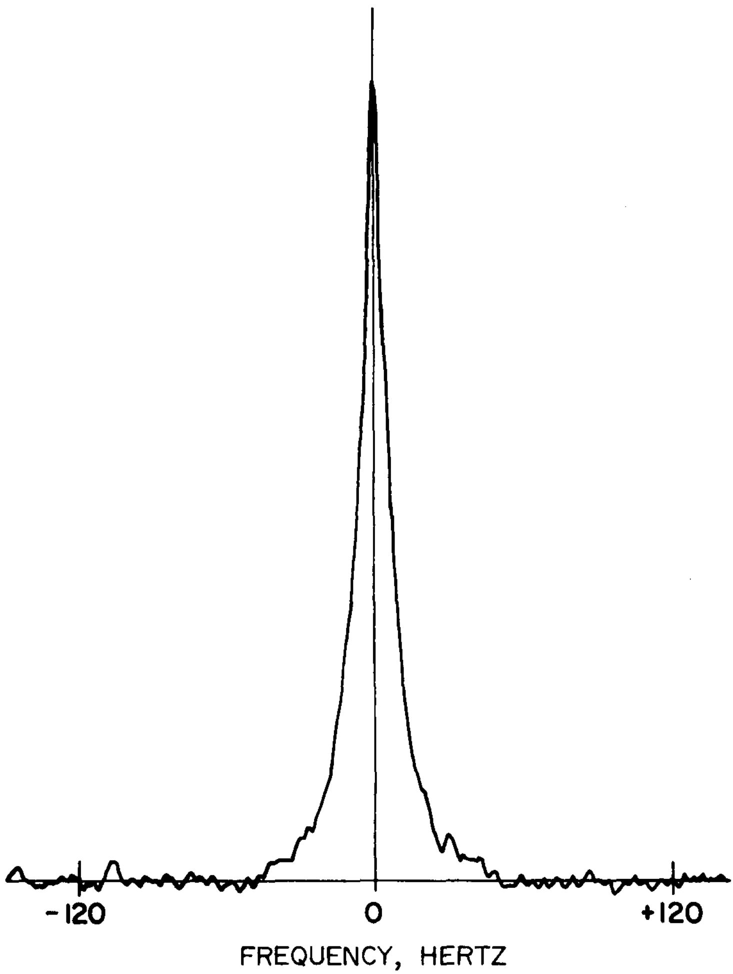

Figure 3.–Spectrogram of echoes from Mercury. Power density is plotted against Doppler frequency shift.

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The center frequency of this spectrum is a direct measure of the relative velocity between Mercury and the radar, accurate to about 15 cm/s. Such data can be used to refine the orbit of an asteroid as it has been used for Venus. This is a bootstrap procedure, however, because knowledge of the orbit is needed to take the data. During the long time exposure, the receiver must be tuned continuously to keep the spectrum from moving, and hence blurring the data. For the weakest signals, appreciable blurring would render the signals undetectable. The bootstrapping converges very quickly if a fairly good orbit can be obtained in advance. For the Icarus radar experiment, a good orbit was obtained with the help of last-minute optical observations and reduction by Elizabeth Roemer.

The width of the spectrum at the base gives directly the line-of-sight velocity of the limbs, which equals the relative angular velocity, projected across the line of sight, times the target radius. When the SNR is good enough to detect the edges of the spectrum over an applicable arc as the asteroid passes Earth, the bandwidth data are sufficient to recover all three components of the spin vector and the radius. This is true because the Doppler broadening has two components: one due to spin and the other due to orbit-induced relative angular motion. The presumably known orbital part can be used to calibrate the effect of the spin.

The shape of the spectrum contains important information about surface slopes. For example, the Mercury spectrum of figure 3 is highly peaked at the center (although not so much as for Venus). This shows that most of the received power is reflected from regions near the sub-Earth point, where the Doppler shift is small. Hence the surface is relatively smooth, to a scale somewhat larger than the wavelength used (12.5 cm for the Goldstone radar). Under the assumption of a uniform surface, the spectrum can be converted uniquely to a backscattering function (Goldstein, 1964), which shows how the radar cross section of an average surface element varies with the angle of incidence. This backscattering function can be considered directly as the distribution of surface slopes. That is, the backscattering function of a surface element at a given angle represents that portion of the element which is perpendicular to the incident rays. Of course, the slope distribution, per se, gives no knowledge of the linear extent of any given slope.

Surface roughness can be tested to a scale smaller than the wavelength by a polarization technique. Right-handed circular polarized waves are transmitted. Because reflection from a smooth dielectric sphere reverses the sense, the receiver is usually set for left-handed polarization. A rough surface, however, will reflect signals equally into both polarizations. To measure this effect, right circular polarization is both sent and received. Figure 4 presents spectrograms from Venus and Mercury taken in this so-called depolarized mode at similar SNR's.

The high central peaks of these spectra have been suppressed by the polarization in much the same way as optical glare can be removed by polarized sunglasses. Furthermore, for Venus, the signal power has dropped by

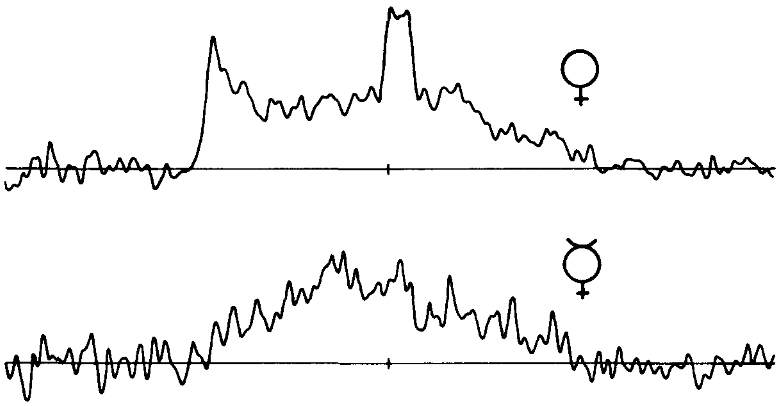

Figure 4.–Set of spectrograms taken in the depolarized mode. The upper curve is from Venus, the lower from Mercury. The individuality of the planets shows strongly here.

a factor of over 20, showing that most of the echo power had originated from the relatively smooth areas near the sub-Earth point. It is for this reason that the depolarized mode of radar observation has not yet been attempted for an asteroid. The power from Mercury, on the other hand, dropped only by a factor of 10, showing that Mercury is rougher (to the scale of a wavelength) than Venus.

Two very interesting features appear in the Venus data that do not appear in the Mercury data. These features were the first evidence that the surface of Venus, hidden under its cover of clouds, is not homogeneous. On the contrary, large topographic features exist on the surface, rotate with the planet, and appear year after year to radar view.

These features have high radar contrast to the surrounding areas, and have a much stronger ability to depolarize radar waves. It is not known whether they are mountains or craters or some other formation such as lava flows. Their existence, however, permits the rotation of Venus to be determined to very high precision. By tracking the Doppler frequency shift of these objects, a period of rotation for Venus of 243.0 days, retrograde, has been deduced. The direction of the spin axis is (or almost is) perpendicular to the orbital plane.

At first glance, the Mercury spectrum of figure 4 contains no significant features. However, a left-right (east-west) asymmetry can be seen, and the motion of this lesser feature has been used to determine the rotation period of Mercury to an accuracy of 0.5 percent.

The important thing is that, to radar, Venus is different from Mercury and, presumably, both are different from asteroids. The study of these differences can add to our knowledge of asteroids.

We return now to the problem mentioned earlier, the extreme weakness of echoes from an asteroid. The radar equation shows that the received power is proportional to $R^2\Delta^{-4}$ where R is the radius of asteroid and Δ is the geocentric distance. Thus the small size of an asteroid compared to a planet reduces the received power by a factor of 10^6.

When considering the SNR, account must also be taken of the bandwidth of the echo and of the integration time t:

$$\mathrm{SNR} \simeq R^{3/2} \Delta^{-4} t^{1/2} \nu^{-1/2}$$

where ν is the perpendicular component of the velocity of rotation. For a calibration point, figure 5 is a spectrogram from Icarus, taken in June 1968 when the asteroid was 6.5×10^6 km from Earth. The spectrogram required 17 hr of integration.

As can be seen, this very noisy spectrogram cannot support much analysis. The edges of the spectrum are not distinguishable, so that it cannot be used to determine the rotation. The rotation, however, was measured with great precision optically (Gehrels et al., 1970), and the combination of the two data types is useful. A lower limit (0.5 km) was set to the radius of Icarus and an upper limit to the reflectivity. A surface model based on Mercury or Venus would not fit the data.

The close approach of Icarus was a rare opportunity for radar asteroid astronomy. The next weaker targets are the Jovian satellites Ganymede and Callisto, weaker than Icarus by a factor of 40. Next come the asteroids Vesta and Juno, down by an additional factor of 2. Another factor of 2 brings in Ceres and Pallas.

Radar capability continues to grow. The Goldstone radar is 5000 times stronger than when Venus was first detected in 1961. It is stronger by a factor of 6 than when the Icarus experiment was performed. Perhaps when Toro swings by in 1972 (an opportunity comparable to that of Icarus), much more of the potential of radar asteroid astronomy will be realized.

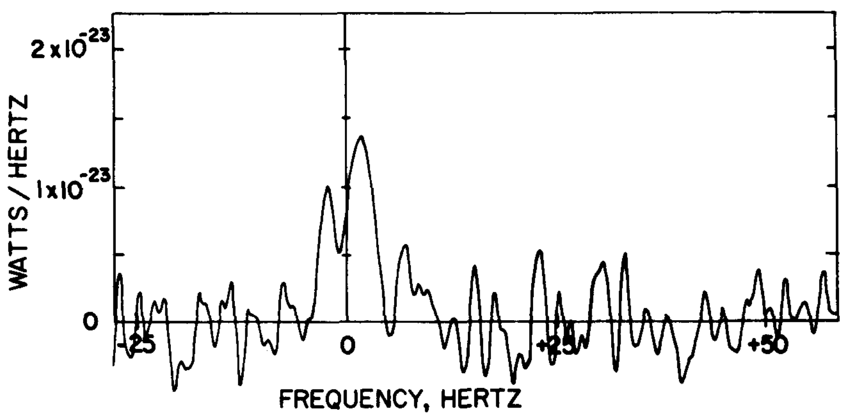

Figure 5.–Spectrogram of echoes from Icarus taken during closest approach of 1968.

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DISCUSSION

CHAPMAN: After the anticipated improvement in the Arecibo dish, do you expect the larger asteroids such as Ceres to be detectable by radar?

GOLDSTEIN: The largest asteroids may just marginally be detected with the Goldstone (64 m) dish now, and they certainly should be detectable when Arecibo resurfaces within a few years.