Mars: Radar Observations

Abstract. *Radar studies of Mars indicate that certain areas are quite smooth. Rough, strongly reflecting regions have also been found, as well as poorly reflecting ones. Mars as a whole is significantly smoother to radiation of 12.5-centimeter wavelength than Venus.*

Mars was once again the object of radar study during its recent opposition (*1*). The planet was observed almost every night during February, March, and half of April by a small group at the Jet Propulsion Laboratory's Goldstone Tracking Station.

An echo of a very narrow band was received from the region of Trivium Charontis (longitude 180° to 200°); reception ended abruptly when the neighboring area of Elysium was the target. One may conclude that there is a very smooth, strongly reflecting area, extending 20° to 30° in longitude and of unknown latitudinal extent, in the region of Trivium Charontis.

A similar sequence of echoes, of wider band, was received from the region of Nodus Laocoontis (240° to 250°). Surprisingly, the northern tip of Syrtis Major did not show a strong echo, and the dark markings Ascraeus Lacus and Albis Lacus returned the weakest echoes. The large "desert" region Amazonis was also a poor reflector.

Mars is a much more difficult radar target than Venus (*2*). The received power is less by a factor of almost 100, and the signal spectrum is broader (because of the larger Doppler effect) by a factor of over 200. Because of the extremely weak, diluted nature of the echoes, only spectral analysis was attempted. That is, spectrally pure waves were transmitted, and the spectra of the received signals were measured. The echoes were not spectrally pure; they were considerably broadened because of the Doppler effect resulting from the rapid rotation of Mars.

The result of spectral analysis of the echo is the same as the result that would be obtained by scanning the disk of Mars with a very fine, fan-beam antenna oriented parallel to the rotation axis. Thus, even though the real antenna beam is hundreds of times wider than the disk of Mars, spectral analysis technique permits the echoes from different regions of Mars to be isolated for study. Figure 1 shows contours of constant frequency shift which are caused by the rotation of Mars.

If Mars were very shiny (to 12.5-cm radar waves), most of the echo would originate from the central, or sub-Earth area. The corresponding spectrum would then be highly peaked in the region of zero frequency shift. As is shown below, this was the case for certain portions of Mars.

The radar parameters have been improved: transmitted power, 100 kw; antenna gain (two-way, including losses), 108.5 db; wavelength, 12.5 cm; system noise temperature, 27°K.

The experimented procedure consisted of transmitting to Mars for a period of 11 minutes (the round trip time of electromagnetic waves) and then receiving for 11 minutes. The frequency spectrum of the signal was then measured with an instrument of 3700-cy/sec bandwidth and 84-cy/sec resolution. The limb-to-limb Doppler broadening which Mars produces in the signal is 7670 cy/sec; thus the small amount of power which is returned outside of the 3700-cy/sec bandwidth is not detected.

Altogether, almost 1300 such 11-minute runs were made. The signal was too weak to be detected clearly in any one run. However, when runs were averaged, positive detection was obtained. All of the runs were assorted into 36 sets, according to the 10° interval of Martian longitude which was

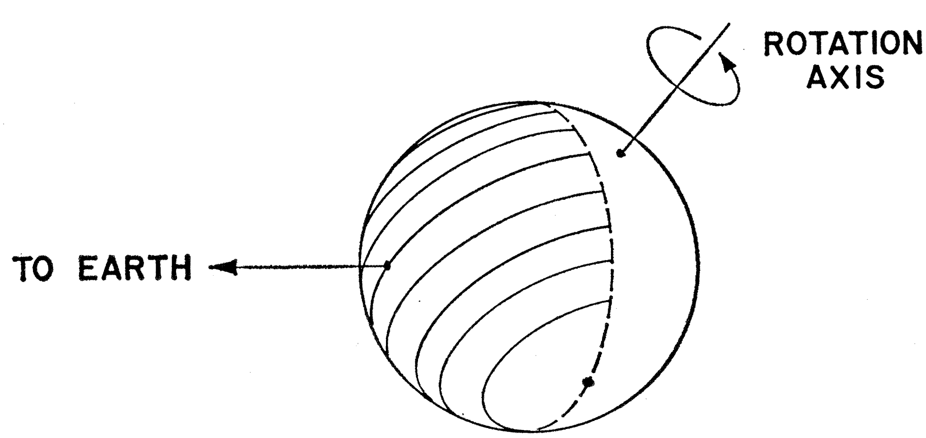

Fig. 1. Contours of constant frequency shift.

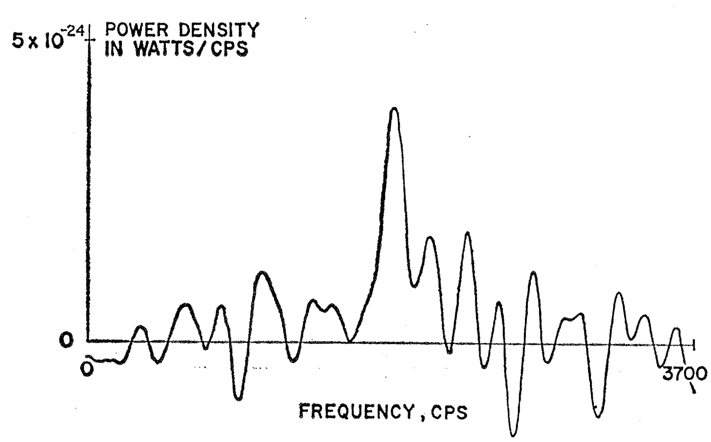

Fig. 2. Mars spectrogram, longitude 180° to 190°.

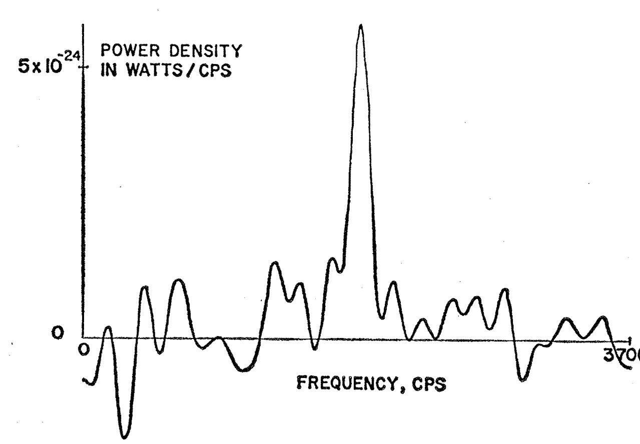

Fig. 3. Mars spectrogram, longitude 190° to 200°.

facing Earth at the time. The runs in each set were then averaged. The result is a set of 36 spectrograms, each corresponding to a different point of view of Mars. The latitude of the sub-Earth point was nearly constant (+21°) during the entire experiment.

Most of the spectrograms show a small amount of power reflected diffusely by the disk. Some of them, however, show relatively strong, narrow-band reflections which originate from an area less than 2° in extent about the sub-Earth point.

Figures 2 through 5 are samples of these spectrograms from successive 10° strips of Mars. The narrow-band echo increases, reaching a maximum at 200° to 210° (the region of Trivium Charontis), and then it drops off quite abruptly. Figure 6 is a sample of a wider-band echo from the region of Laocoontis.

Figure 7 is a plot of power density versus longitude. It was obtained by scaling the height at the center frequency of each spectrogram. This curve represents the power which would be measured if Mars were observed through a narrow-band filter. Figure 8 is a plot of the total power received as a function of Martian longitude, expressed in terms of the radar cross-section. Because some of the reflected

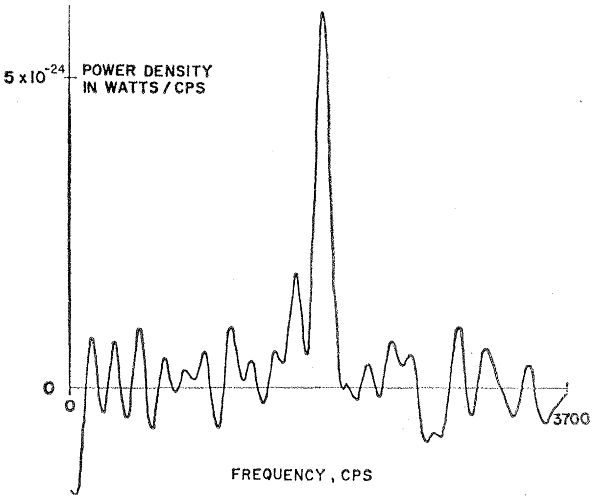

Fig. 4. Mars spectrogram, longitude 200° to 210°.

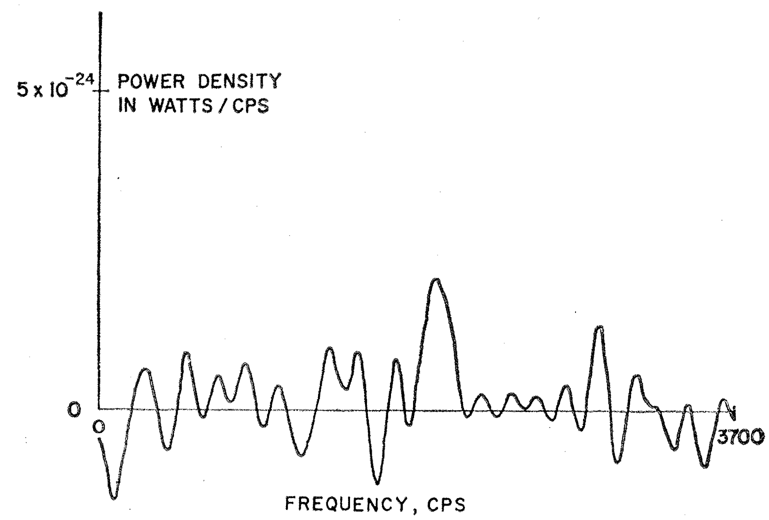

Fig. 5. Mars spectrogram, longitude 210° to 220°.

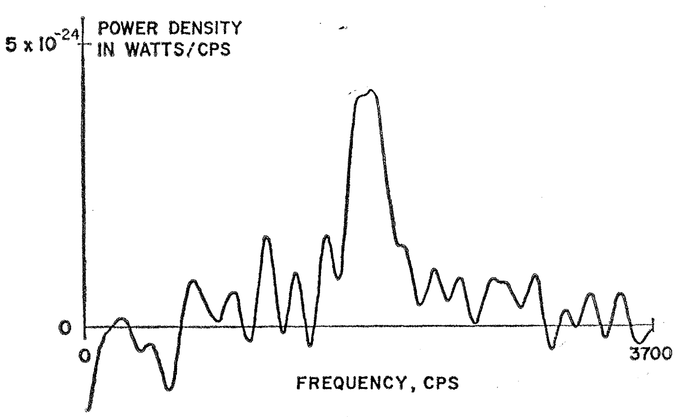

Fig. 6. Mars spectrogram, longitude 240° to 250°.

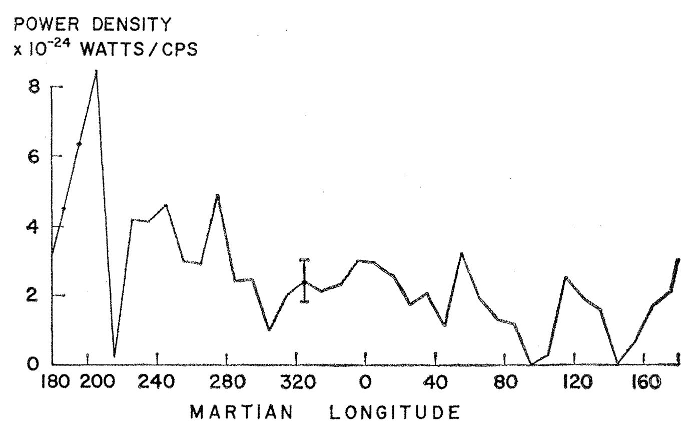

Fig. 7. Power density versus longitude.

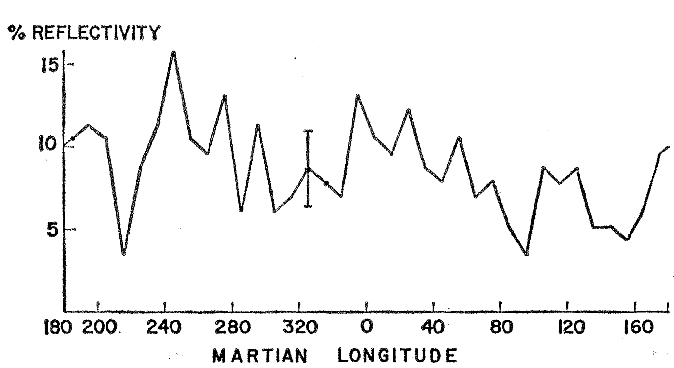

Fig. 8. Total power versus longitude.

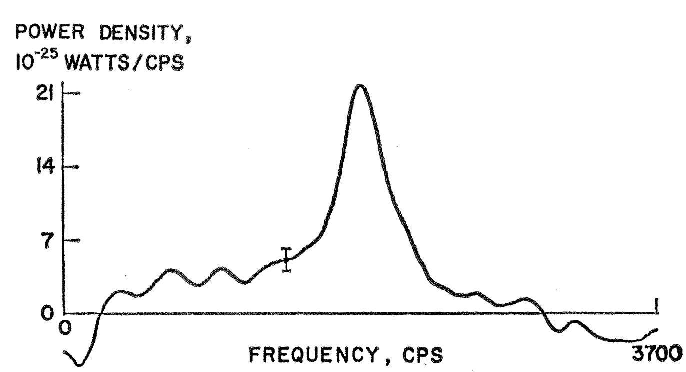

Fig. 9. Average Mars spectrogram.

power was beyond the spectrometer bandwidth, this must be considered as a lower bound. The curve was obtained by scaling the area under each spectrogram. The $\pm\sigma$ marked on these curves is the result of both calculation and measurement; the agreement between the two is excellent.

All of the runs of the experiment were averaged together to produce the average Mars spectrogram shown in Fig. 9. Because so many runs have been averaged, the $\pm\sigma$ interval has been reduced to a very small value. The asymmetry in this spectrogram may be explained in two ways. (i) The surface may have a slightly preferred slope, as sandy places on Earth have when winds from a preferred direction ruffle the surface. (ii) The spectrogram is the result of the integration of hundreds of *hours* of signal plus noise and the subtraction of an equally long (but interleaved) integration of noise only. The asymmetry of the spectrogram may be the result of some residual instability of that process.

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References and Notes

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3. Research supported by NASA contract 7-100.

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Theory of Rotation for the Planet Mercury

Abstract. *The theory of the rotation of the planet Mercury is developed in terms of the motion of a rigid system in an inverse-square field. It is possible for Mercury to rotate with a period exactly two-thirds of the period of revolution; there is a libration with a period of 25 years.*

By radar, Pettengill and Dyce (*1*) have observed that the rotation of the planet Mercury is direct with a sidereal period of 59 ± 5 days. McGovern *et al.* (*2*) have refined this value to 58.4 ± 0.4. Mercury's period of revolution is 87.97 days; for synchronous rotation the sidereal period of rotation would be the same. The observed value of 58.4 ± 0.4 days, has interesting theoretical implications. The role of tidal torque and tidal friction in bringing Mercury to this period has been calculated by Peale and Gold (*3*), and by Goldreich (*4*).

The torque exerted by the sun on Mercury arises from a term in the potential which varies inversely with the cube of the distance. For an eccentricity of 0.2, the variation between perihelion and aphelion in this term is a factor of 3.4. Hence, as pointed out by Peale and Gold (*3*) and by Goldreich (*4*), the rotation of Mercury tends to be controlled by the situation at perihelion; it tends to rotate so as to match the rotation velocity with the instantaneous orbital angular velocity at perihelion or near it.

But since the period demanded by this condition is nearly two-thirds of the orbital period, it is reasonable to ask whether a resonance lock is possible at exactly two-thirds of the orbital period, or 58.65 days. This seems plausible because the second-harmonic term in the planetary potential will have fore-and-aft symmetry; up to the second degree, the two ends of the axis of minimum moment of inertia behave in the same way in the gravitational field of the sun. Colombo (*5*) has already surmised that the lock is possible; our own work was begun before we were aware of his.

If $A < B < C$ are the principal moments of inertia at time t, and if C is taken perpendicular to the orbit plane, then the potential energy of the planet Mercury is, by MacCullagh's formula

$$V = \frac{-KM}{r} - \frac{K(A+B+C-3I)}{2r^3} \qquad (1)$$

where K is the gravitational parameter, M is the mass of Mercury, and I is the moment of inertia around the radius vector r

$$I = A\cos^2\phi + B\sin\phi \qquad (2)$$

where ϕ is the angular displacement of the principal axis, A, in the counterclockwise direction as seen from north, from the position vector, r.

The Lagrangian of Mercury's motion is

$$L = \tfrac{1}{2}M\left[\left(\frac{dr}{dt}\right)^2 + r^2\left(\frac{df}{dt}\right)^2\right] + \tfrac{1}{2}C\left(\frac{d\phi}{dt}+\frac{df}{dt}\right)^2 + \frac{KM}{r} + \frac{K[A+B+C-3I]}{2r^3} \qquad (3)$$

where f is the true anomaly.

To the second order in ϕ, rotation of the planet Mercury is governed by

$$\frac{d}{dt}\left[C\frac{d(\phi+f)}{dt}\right] + 3\frac{K}{r^3}(B-A)\cos\phi\sin\phi = 0 \qquad (4)$$

The instantaneous motion of the planet Mercury is described by

$$r = a(1-e^2)/(1+e\cos f) \qquad (5)$$

where a is the semimajor axis and e the eccentricity of the orbit. From the law of invariant areal velocity, the orbital angular momentum, h, is

$$h = r^2(df/dt) \qquad (6)$$

If the independent variable is changed from the time t to the true anomaly f, then Eq. 4 becomes, if A, B, and C are constant,

$$\frac{d^2\phi}{df^2} - \frac{2e\sin f}{1+e\cos f}\left(\frac{d\phi}{df}+1\right) + \frac{3\lambda}{1+e\cos f}\cos\phi\sin\phi = 0 \qquad (7)$$

where $\lambda = (B-A)/C$.

In a circular orbit ($e = 0$) and in the case of a body with dynamic symmetry and the axis of symmetry perpendicular to the plane of the orbit ($\lambda = 0$), Eq. 7 can be integrated by quadratures. Hence for small e and λ, one can find an approximate expression for the solution of this equation, working from the Poincaré small-parameter method or the Krylov-Bogolyubov averaging method. Since $e \neq 0$ and $\lambda \neq 0$ represents a nonintegrable case, only qualitative investigation and numerical analysis of Eq. 7 appear to be readily obtainable.

By repeated numerical integration of Eq. 7 over a period of 100 years we find that for $\lambda = 0.00005$ (that is, somewhat less distortion than the moon) Mercury will lock at an average period of 58.65. The instantaneous period oscillates with an amplitude of the order of 0.008 days and a period of 25 years.

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4. P. Goldreich, *ibid.* **208**, 375 (1965).
5. G. Colombo, *ibid.*, p. 575.
6. We thank R. K. Squires and E. R. Lancaster for assistance. The numerical analysis was performed by W. R. Trebilcock.

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