Mariner 9 S-Band Martian Occultation Experiment: Initial Results on the Atmosphere and Topography of Mars

Abstract. *A preliminary analysis of 15 radio occultation measurements taken on the day side of Mars between 40°S and 33°S has revealed that the temperature in the lower 15 to 20 kilometers of the atmosphere of Mars is essentially isothermal and warmer than expected. This result, which is also confirmed by the increased altitude of the ionization peak of the ionosphere, can possibly be caused by the absorption of solar radiation by fine particles of dust suspended in the lower atmosphere. The measurements also revealed elevation differences of 13 kilometers and a range of surface pressures between 2.9 and 8.3 millibars. The floor of the classical bright area of Hellas was found to be about 6 kilometers below its western rim and 4 kilometers below the mean radius of Mars at that latitude. The region between Mare Sirenum and Solis Lacus was found to be relatively high, lying 5 to 8 kilometers above the mean radius. The maximum electron density in the ionosphere (about 1.5 × 10⁵ electrons per cubic centimeter), which was found to be remarkably constant, was somewhat lower than that observed in 1969 but higher than that observed in 1965.*

In 1965 and again in 1969, the radio occultation technique was used to explore the atmosphere of Mars (*1–4*). The 1965 experiment disclosed the existence of a very low atmospheric pressure at the surface of Mars, a finding that was later supported by the results from the two Mariner flybys in 1969, which also provided information on the shape of Mars. In each case, only one set of entry and exit occultation measurements was obtained by each spacecraft for a total of six separate measurements. In contrast, the Mariner 9 spacecraft is occulted by Mars twice in each 24 hours, thus equaling in 1 day the total radio occultation information output of Mariner 6 and Mariner 7 in 1969. The occultations will continue for a period of about 40 days from orbital insertion; about 160 separate occultation measurements will be made.

Fifteen radio occultation measurements were made during the first 9 days in orbit when the spacecraft entered into occultation, beginning with revolution 1 on 14 November and ending with revolution 17 on 22 November 1971. Although data were also taken when the spacecraft exited from occultation, these data are more time-consuming to analyze and will be reported later, along with the data from the remaining revolutions. The data used in this analysis were provided by the closed-loop receivers at the deep space stations at Goldstone, California; Woomera, Australia; and Cebreros, Spain.

We analyzed the data by means of trajectory information provided by the Mariner 1971 navigation team, applying the technique of integral inversion (*2, 5*) to obtain a vertical profile of refractivity in the ionosphere and atmosphere of Mars. For purposes of profile inversion, the atmosphere of Mars was assumed to be spherically symmetric and it was postulated to consist solely of CO_2. The boundary temperature for inversion was chosen as 150°K at about 3440 km.

Locations of points at which the measurements described in this report were made are shown in Fig. 1. Because of the 12-hour orbital period of Mariner 9, successive occultation points fall about 180° apart in longitude; successive measurements in the same region are made every 24 hours and lie about 9° apart in longitude. The even-numbered occultations, observed from Goldstone, occurred in a region stretching from Mare Sirenum to Solis Lacus at latitudes from about 40°S to about 33°S. The odd-numbered occultations observed from Australia and Spain corresponded to measurements extending from Yaonis Regio to Trinacria crossing the classical bright area of Hellas.

Temperature profiles obtained from the data during revolutions 1 through 9 are shown in Fig. 2. (Revolutions 4 and 5 were plagued with bad data.) The irregular appearance of the profiles, caused by phase jitter noise in the Doppler data, and the scatter in temperature values, most likely caused by residual bias, are indicative of the current uncertainties in these measurements. It must be emphasized that a large portion of this systematic uncertainty can be removed through additional analysis. As shown in Fig. 2, the temperature remains approximately constant in most profiles from the surface to about an altitude of 3405 km, and lapses with altitude at about 2°K/km above that height. The near-isothermal nature of the lower atmosphere is not too surprising a Martian phenomenon; a similar condition was observed during the entry of Mariner 4 into occultation (*2*). However, the Mariner 4 and Mariner 9 measurements were made at different local times and solar illumination conditions. If we compare the Mariner 9 measurements with Mariner 6 and Mariner 7 entry data obtained for similar solar zenith angles and local times, we find that there has been a significant change in the thermal state of the atmosphere. The 1969 data yielded temperature profiles with somewhat subadiabatic lapse rates (3°K/km) (*3*), which were lower than those predicted by theory for a clean atmosphere (*6*). The fact that most Mariner 9 temperature profiles show this isothermal regime near the surface is significant and indicates that the mechanism causing this phenomenon is global in ex-

Table 1. Occultation measurements.

Revolution	Latitude (°S)	Longitude (°W)	Location	Radius (km)	Surface pressure (mb)	Surface temperature (°K)
1	40.3	319	Yaonis Regio	3388.1	4.7	251
2	39.9	142	Mare Sirenum	3391.2	4.1	230
3	39.4	326	Hellespontus	3391.9	4.0	248
6	38.2	140	Mare Sirenum	3392.1	3.9	244
7	37.7	315	Yaonis Fretum	3389.6	5.2	255
8	37.3	130	Sirenum Sinus	3392.3	3.9	222
9	36.8	305	Hellas	3383.5	8.3	222
10	36.3	121	Icaria	3394.6	3.4	241
11	35.9	296	Hellas	3384.4	8.1	239
12	35.4	111	Daedalia	3393.3	3.7	228
13	35.0	286	Hellas	3384.6	8.2	232
14	34.5	101	Claritas	3396.7	2.9	224
15	34.0	276	Mare Hadriacum	3387.2	7.1	256
16	33.5	91	Solis Lacus	3395.6	3.4	250
17	33.0	266	Trinacria	3388.7	5.9	237

tent, at least for the latitudes and local times of measurement. One possible explanation could be the extensive dust storm that had been obscuring the surface in the visible and near-visible wavelengths during the time of the occultation measurements. It is probable that the isothermal effect is caused by solar radiation being absorbed by fine dust suspended in the atmosphere, thus raising the temperature of the dust particles and in turn heating the atmosphere. This hypothesis suggests that dust is present in the atmosphere of Mars to altitudes of at least 15 to 20 km.

Additional temperature profiles from data taken during revolutions 10 through 17 are shown in Fig. 3. These profiles are similar in appearance to those of Fig. 2; however, there is the suggestion that the profiles for the latest revolutions (16 and 17) are less isothermal.

A summary of the 15 measurements appears in Table 1. The present uncertainties associated with the radius, surface pressure, and surface temperature are, respectively, about ±2.5 km, 0.5 mb, and 15°K. Immediately apparent from Table 1 is the large variation between measurements in the distance and those at the center of mass (hereafter called radius), amounting to about 13 km, with an accompanying variation in the surface pressure from 2.9 to 8.3 mb. These large excursions, in both radius and surface pressure, are not surprising, as the topographic measurements of the surface of Mars made with Earth-based planetary radars had indicated surface relief of precisely that magnitude (*7*).

The measured surface pressures are plotted versus the radius in Fig. 4. The measurements of radius and surface pressure by means of the radio occultation technique are almost entirely independent. The first depends primarily on the distance of the radio beam from the center of Mars at the time of interruption of signal; the second depends primarily on the total refractive effect upon the propagation velocity and direction of the radio waves. It is obvious from Fig. 4 that the surface pressure is well correlated with the measured radius. In fact, the variation of surface pressure with radius

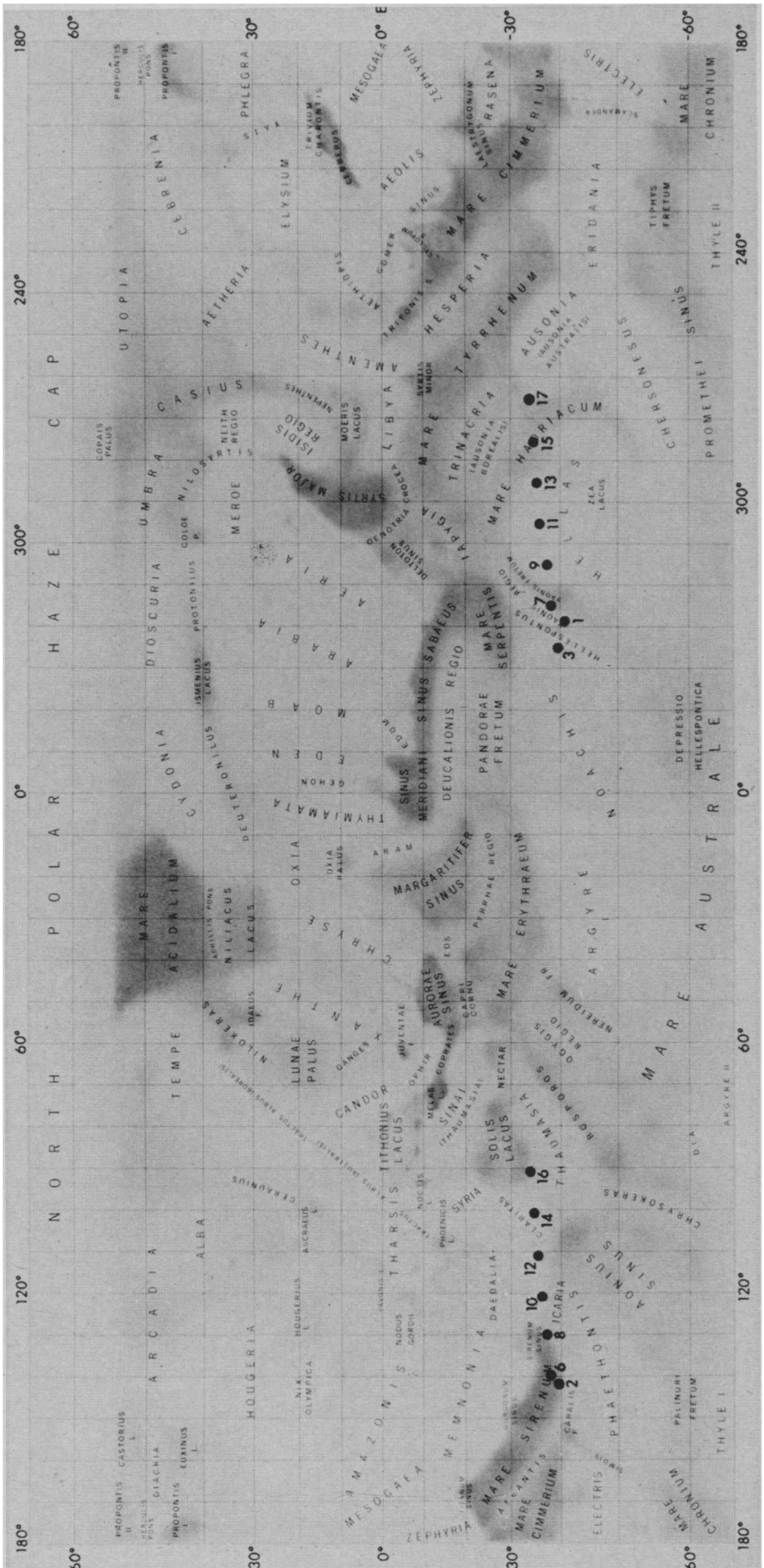

Fig. 1. Location of occultation measurement points on the surface of Mars. The map was prepared under the direction of Dr. G. de Vaucouleurs of the University of Texas.

is almost totally consistent with the 12-km scale height implied by the temperature measurements.

The dashed line in Fig. 4 is a theoretical pressure profile based on a pressure of 8.3 mb at a radius of 3384 km and a scale height of 12 km. Even with this crude approximation, the fit is excellent, in agreement with the observed isothermal temperature structure in the lower atmosphere. The individual deviations of the measured points from the computed curve probably are due to differences in temperature between the measurements. The vertical lines in Fig. 4 indicate the bounds of the mean radius of Mars computed on the basis of a model for the physical shape of Mars that consists of an ellipsoid with an equatorial radius of 3394 km and a flattening of 0.0057. This model was computed from measurements of the radius of Mars on Mariner 4, Mariner 6, and Mariner 7 flybys (*8*). Because the latitude at the point of the measurement changes from about 40°S for revolution 1 to about 33°S for revolution 17, the mean radius increases by about 2 km. It can readily be seen from Fig. 4 that most of the measurements were made in regions that lie above the mean radius and only a few of the points lie below the mean radius. This conclusion can be amplified with reference to Figs. 5 and 6. Figure 5 shows the variation of the radius and surface pressure with longitude in the Hellas region. All of Hellas lies substantially below the mean radius, and the atmospheric pressure at its surface is higher than the average. In a cross section extending for about 30° of longitude (corresponding to approximately 1200 km at the latitude in question), the surface of Hellas lies about 4 km below the mean radius. Its western rim, in the regions of Hellespontus and Yaonis Fretum, lies about 2 km above the mean radius; thus there is a drop in altitude of 6 km in a horizontal distance of approximately 550 km, corresponding to a slope on the scale of 550 km of about 0.6° in the region.

During the flyby of Mariner 7 in 1969, Hellas was the subject of a pressure-mapping experiment by the ultraviolet spectrometer (UVS) based on the observed amount of Rayleigh scattering (*9*). Because the latitudes at which the Mariner 7 UVS viewed Hellas are almost equal, at least at the western edge of Hellas, to those measured during the Mariner 9 occultations, it is interesting to compare the

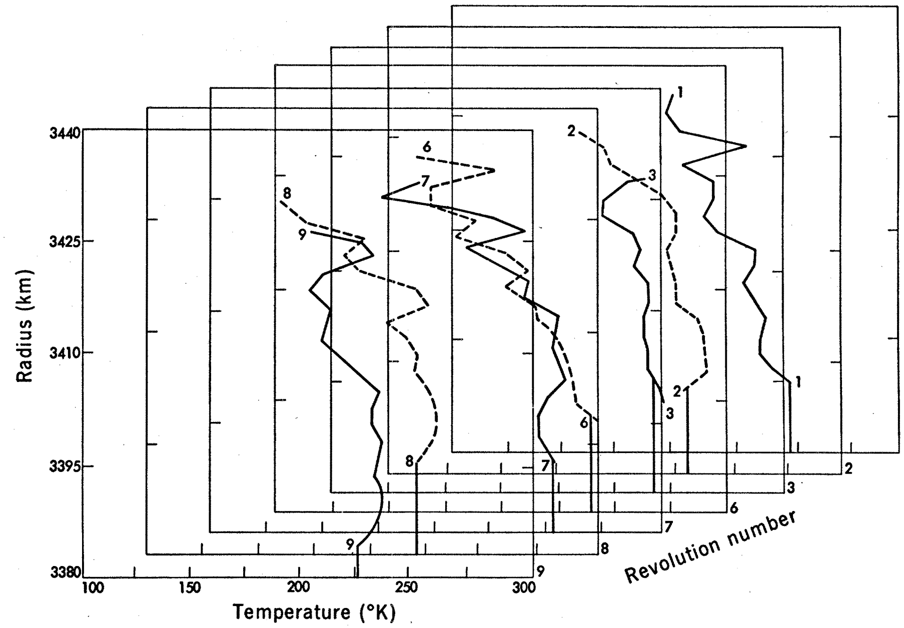

Fig. 2. Atmospheric temperature profiles for revolutions 1 through 9. The uneven appearance of the profiles and the scatter of temperature values are indicative of the uncertainties associated with the mesurement.

results. The pressure measurements obtained in the Mariner 7 UVS experiment are plotted as open circles in Fig. 4. The corresponding values of altitude relative to the mean radius are plotted at the latitudes of measurement as open squares in Fig. 5. Although, in general, the agreement is good, toward the eastern edge of Hellas the altitude measured by UVS mapping rises much more sharply than that obtained from the occultation measurements of the radius, and the pressure seems to drop more sharply. Furthermore, the maximum depth at the western edge of Hellas is about 1 km less in the UVS determinations than it is in the Mariner 9 occultation measurements. The most probable explanation for these discrepancies is the divergence in latitudes of the occultation and UVS swaths toward the eastern edge of Hellas. (The latitudes differ by about 5° over Mare Hadriacum.) However, the differences also could be caused by a permanent obscuration in Hellas caused by aeolian phenomena (*10*) similar to those that are causing a global obscuration of the surface of Mars during this mission. In

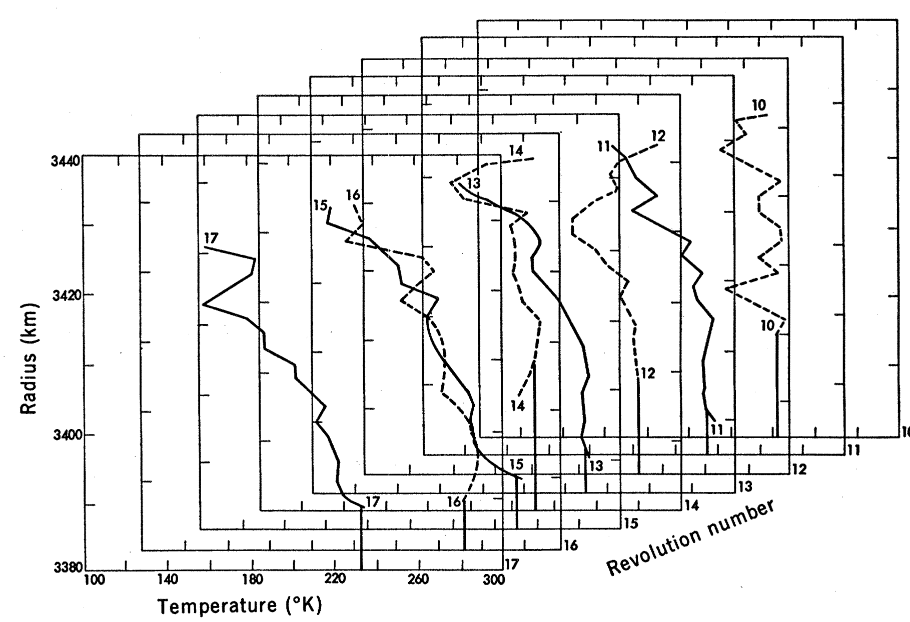

Fig. 3. Temperature profiles for revolutions 10 through 17.

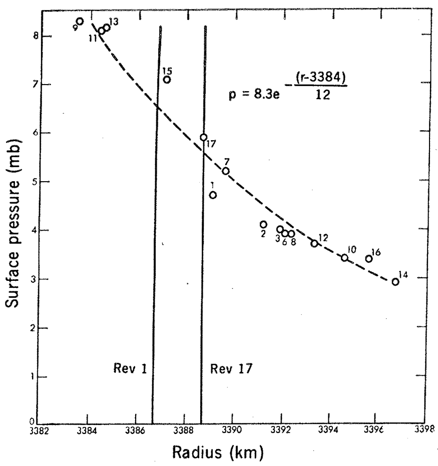

Fig. 4. Surface pressure p and distance from the center of mass (radius, r) for the initial measurements. The numerals next to the open circles refer to the number of the revolution. The two vertical lines indicate the values of the mean radius of Mars (if we assume an equatorial radius of 3394 km and a flattening of 0.0057) corresponding to the latitudes of the measurements made during revolutions 1 and 17.

that case, the UVS instrument would be able to view the atmosphere only to the tops of the dust clouds, and possibly the lower 1 or 2 km of the Hellas basin were not mapped by the UVS in 1969.

The area was also mapped in 1969 by the Mariner 7 infrared spectrometer (IRS) by means of CO_2 absorption measurements (*11*). The values of pressure obtained by the IRS mapping in Hellas are shown as solid circles in Fig. 5, and the corresponding altitude points, referred to the mean radius at the latitudes of the IRS measurements, are shown as solid squares. Because of the relatively high scatter of these data, it is difficult to draw conclusions. However, in the western part of Hellas, the IRS measurements indicate a somewhat higher pressure and lower altitude than the UVS measurements, a result more closely matching the current occultation measurements, and consistent with the dust obscuration hypothesis. Toward the eastern edge of Hellas both the UVS and IRS estimates diverge from the results of occultation measurements, most likely because of differing latitudes and the effects of oblique viewing on the accuracy of the spectral measurements.

Figure 6 shows the variation of the radius and pressure with longitude for the points lying in the Mare Sirenum–Solis Lacus region. In this region the measured radii lie substantially above the mean radius, and this result is reflected in the much lower values of the surface pressure. In the range from 140°W to about 90°W, the measured radii lie from 5 to about 8 km above the mean radius. Although there is no Earth-based radar or CO_2 absorption mapping coverage in this latitude region, the general high aspect of this area is in good agreement with planetary radar profiles obtained at 14.7°S (represented by triangles in Fig. 6).

By relating the measured surface pressure and topographical variations with the average measured temperature in the lower atmosphere, we can estimate the atmospheric pressure at the mean surface of Mars corresponding to the mean ellipsoid with an equatorial radius of 3394 km and a flattening of 0.0057. This value can be estimated to be about 5.5 mb, which is in good agreement with the results obtained from Mariner 6 and 7 flybys (*3*).

Data on the vertical distribution of ionization in the upper atmosphere of Mars have been obtained. A typical altitude profile is presented in Fig. 7. These data were obtained during entry into occultation on the day side of Mars near 142.8°W and 39.9°S. The local time was 16.7 hours; the solar zenith angle was 56.2°. The electron density reached a maximum of about 1.5×10^5 electron/cm^3 near 145-km altitude. The topside plasma scale height was 38 km. No clear signature of a nighttime ionosphere has been observed.

Ionospheric data processed so far cover local times from 15.9 to 16.7 hours and solar zenith angles from 54.5° to 56.6°. The results show the

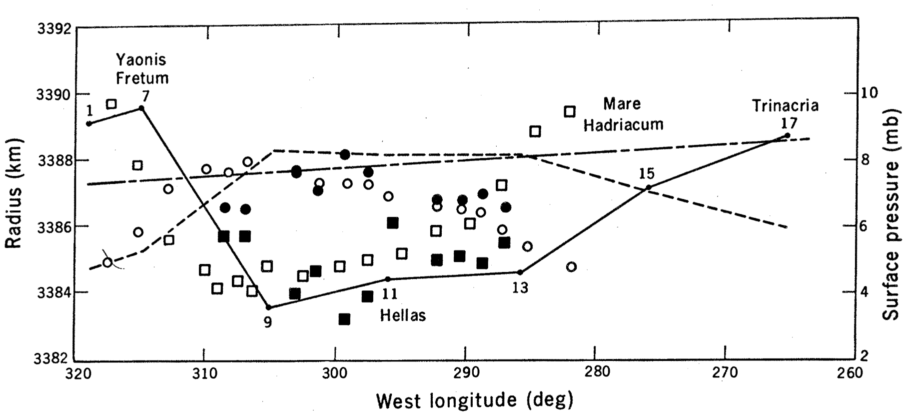

Fig. 5. Variation of radius (solid line) and surface pressure (equally dashed line) with longitude in the Hellas region. Most of Hellas lies about 4 km below the mean radius (unequally dashed line). The plotted points refer to the pressure-mapping results from the Mariner 7 UVS (open circles) and IRS (solid circles) instruments. Altitude points corresponding to the IRS mapping are plotted as solid squares; altitude points corresponding to the UVS mapping are plotted as open squares.

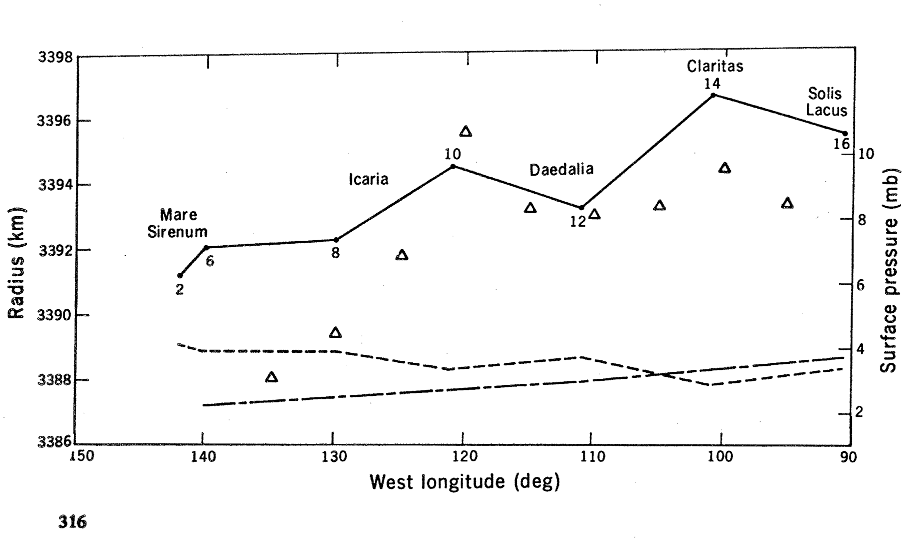

Fig. 6. Variation of radius (solid line) and surface pressure (equally dashed line) with longitude for the Mare Sirenum–Solis Lacus region. This area is elevated above the mean radius (unequally dashed line) by 4 to 8 km. The triangles indicate elevations measured to the planetary ranging radar at 14.7°S.

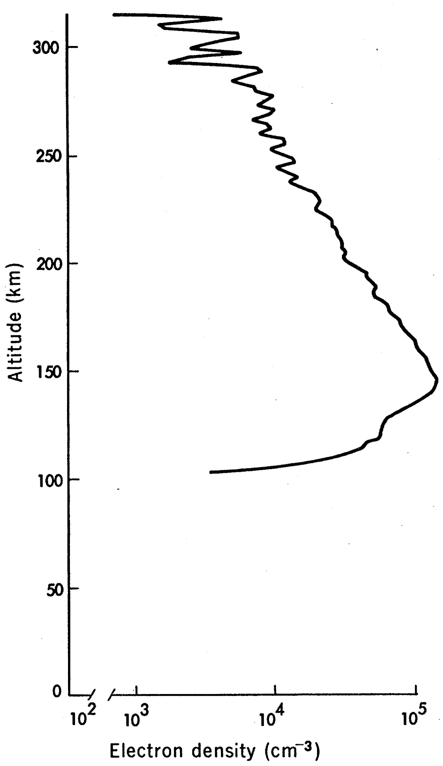

Fig. 7. Electron density in the ionosphere of Mars versus altitude. This measurement was made on the day side of Mars during revolution 2.

measurements to be remarkably reproducible from one pass to the next. For example, values obtained for the peak electron density and the topside scale height differ by less than 5 percent. The altitude of the ionization peak changes somewhat from one pass to another, but this effect is due partially to elevation differences on the surface.

The results reported here show that the density and temperature of the Martian ionosphere have been reduced since 1969 (*4*), but that they are higher than during the quiet solar conditions prevailing at the time of the Mariner 4 mission in 1965. However, the most notable difference between measurements from Mariner 9 and those from earlier spacecraft is the increased altitude of the ionization peak, which shows that the atmospheric region below 145 km is warmer than before. This observation is consistent with the measured temperatures in the lower atmosphere.

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References and Notes

1. A. J. Kliore, D. L. Cain, G. S. Levy, in *Space Research VI* (North-Holland, Amsterdam, 1967), p. 226.

G. Fjeldbo and V. R. Eshleman, *Planet. Space Sci.* **16**, 1035 (1968).

3. A. J. Kliore, G. Fjeldbo, B. L. Seidel, in *Space Research XI* (Akademie-Verlag, Berlin, 1971), p. 165.
4. G. Fjeldbo, A. J. Kliore, B. L. Seidel, *Radio Sci.* **5**, 381 (1970).
5. A. J. Kliore, *Proceedings of the Workshop on the Mathematics of Profile Inversion* (Ames Research Center, Moffett Field, Calif., in press).
6. P. Gierasch and R. Goody, *Planet. Space Sci.* **16**, 615 (1968).
7. A. E. E. Rogers, M. E. Ash, C. C. Counselman, I. I. Shapiro, G. H Pettengill, *Radio Sci.* **5**, 465 (1970); R. M. Goldstein, W. G. Melbourne, G. A. Morris, G. S. Downs, D. A. O'Handley, *ibid.*, p. 475; G. H. Pettengill, A. E. E. Rogers, I. I. Shapiro, *Science* **174**, 1321 (1971).
8. A. Kliore, *Bull. Amer. Astron. Soc.* **2**, 202 (1970).
9. C. A. Barth and C. W. Hord, *Science* **173**, 197 (1971); C. W. Hord, *Icarus*, in press.
10. C. Sagan, J. Veverka, P. Gierasch, *Icarus* **15**, 253 (1971).
11. K. C. Herr, D. Horn, J. M. McAffee, G. C. Pimentel, *Astron. J.* **75**, 833 (1970).

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Mariner 9 Celestial Mechanics Experiment: Gravity Field and Pole Direction of Mars

Abstract. *Analysis of the Mariner 9 radio-tracking data shows that the Martian gravity field is rougher than that of Earth or the moon, and that the accepted direction of Mars's rotation axis is in error by about 0.5°. The new value for the pole direction for the epoch 1971.9, referred to the mean equatorial system of 1950.0, is right ascension* $\alpha = 317.3° \pm 0.3°$, *declination* $\delta = 52.6° \pm 0.2°$. *The values found for the coefficients of the low-order harmonics of Mars's gravity field are as follows:* $J_2 = (1.96 \pm 0.01) \times 10^{-3}$, *referred to an equatorial radius of 3394 kilometers;* $C_{22} = -(5 \pm 1) \times 10^{-5}$; *and* $S_{22} = (3 \pm 1) \times 10^{-5}$. *The value for* J_2 *is in excellent agreement with the result from Wilkins' analysis of the observations of Phobos. The other two coefficients imply a value of* $(2.5 \pm 0.5) \times 10^{-4}$ *for the fractional difference in the principal equatorial moments of inertia; the axis of the minimum moment passes near 105°W.*

The preliminary results on the gravity field of Mars and the direction of its spin axis obtained from the Mariner 9 radio-tracking data provide the basis for this report. These data consist primarily of counted Doppler data (changes in the round-trip phase delay of the radio signal), converted to values averaged over 1-minute count times (*1*). The observations span two periods (*2*): (i) from orbit insertion on 14 November to orbit trim on 16 Novem-

Table 1. Characteristics of the Mariner 9 orbit.

Parameter	Before trim	After trim
Epoch (U.T.)	14 Nov., 00:42	16 Nov., 02:58
Semimajor axis (km)	13,046	12,636
Eccentricity	0.63282	0.62173
Inclination to Martian equator (deg)	64.35	64.37
Latitude of periapsis (deg)	—22.7	—22.1
West longitude of initial periapsis (deg)	102.3	117.2
Periapsis altitude (km)	1397	1387
Anomalistic orbital period (hours)	12.567	11.980

Table 2. Direction of the pole of Mars. Pole is given for epoch 1971.9 and referred to the mean equinox and equator of 1950.0.

Angle	Nominal value (*6*)	Orbit phase radio-tracking data	Far-encounter TV pictures of landmarks	Far-encounter TV pictures of Martian satellites
Right ascension, α (deg)	316.9	317.3 ± 0.3	317.5 ± 0.9	317.2 ± 0.5
Declination, δ (deg)	53.0	52.6 ± 0.2	52.9 ± 0.9	52.9 ± 0.3