Venus: Mass, Gravity Field, Atmosphere, and Ionosphere as Measured by the Mariner 10 Dual-Frequency Radio System

Abstract. *Analysis of the Doppler tracking data near encounter yields a value for the ratio of the mass of the sun to that of Venus of 408,523.9 ± 1.2, which is in good agreement with prior determinations based on data from Mariner 2 and Mariner 5. Preliminary analysis indicates that the magnitudes of the fractional differences in the principal moments of inertia of Venus are no larger than* 10^{-4}, *given that the effects of gravity-field harmonics higher than the second are negligible. Additional analysis is needed to determine the influence of the higher order harmonics on this bound. Four distinct temperature inversions exist at altitudes of 56, 58, 61, and 63 kilometers. The X-band signal was much more rapidly attenuated than the S-band signal and disappeared completely at 52-kilometer altitude. The nightside ionosphere consists of two layers having a peak density of* 10^4 *electrons per cubic centimeter at altitudes of 140 and 120 kilometers. The dayside ionosphere has a peak density of* 3×10^5 *electrons per cubic centimeter at an altitude of 145 kilometers. The electron number density observed at higher altitudes was ten times less than that observed by Mariner 5, and no strong evidence for a well-defined plasmapause was found.*

As Mariner 10 flew by Venus on its way to Mercury on 5 February 1974, dual-frequency transmissions from the spacecraft were received on Earth. These transmissions are now being used to refine and increase our knowledge of the planet's interior and environment.

In the following sections we describe the unique properties of the Mariner 10 radio system and the preliminary scientific results obtained from the analysis of the radio signals.

Radio system. The X-band radio system which is being flown on Mariner 10 is new to the National Aeronautics and Space Administration (NASA) stable of experiments and has demonstrated its capability as a scientific instrument. It is the natural outgrowth of several developing scientific and technological fields—one which uses the best characteristics of spacecraft radio systems for the transmission of engineering and science data while at the same time providing fundamental radiometric data for both science and navigation. Before the Mariner 10 mission, telemetry was handled by spacecraft S-band radio systems. The signal arriving at Earth was also used for occultation measurements of planetary atmospheres and ionospheres (*1*). During the years of development of this capability, it was not possible to modify the telemetry systems. For that reason, separate scientific instruments were flown to obtain dispersive measurements of the interplanetary medium and environment of Venus (*2, 3*).

A simplified block diagram of the overall system is shown in Fig. 1. In the normal two-way communication mode, a command- and range-modulated 2115-Mhz signal is transmitted to the spacecraft for reception on its omnidirectional antenna. This antenna is used for reception throughout the mission to assure that Mariner 10 can receive commands during maneuvers and roll calibrations. The S-band receiver removes the modulation and provides a phase-coherent output to drive the S- and X-band transmitters. In the absence of an uplink signal, the receiver switches on an auxiliary crystal oscillator to provide a downlink carrier. The received range code is applied to both transmitters. The modulated outputs, 20 watts at S-band and 200 mw at X-band, in the precise frequency ratio of 3 to 11, are separately routed to the spacecraft transmitting antenna, a 54-inch (1.37-m) fully articulated paraboloid dish.

For the Mariner 10 mission, simultaneous ground reception of the S- and X-band signals was possible at only one Deep Space Net (DSN) station—the 64-m antenna located at Goldstone, California, Deep Space Station (DSS) 14. As shown in Fig. 2, a microwave optical system directs the S- and X-band signals to separate feed horns which drive masers tuned to 8415 and 2295 Mhz. System noise temperatures obtained were 21.5°K at X-band and 13.4°K at S-band.

The normal ground receiver is a coherent dual-frequency, phase-lock-loop system which demodulates the telemetry and range code while extracting absolute and differential Doppler information. Range code and Doppler data are fed back to the dual-channel ranging system for processing. Doppler

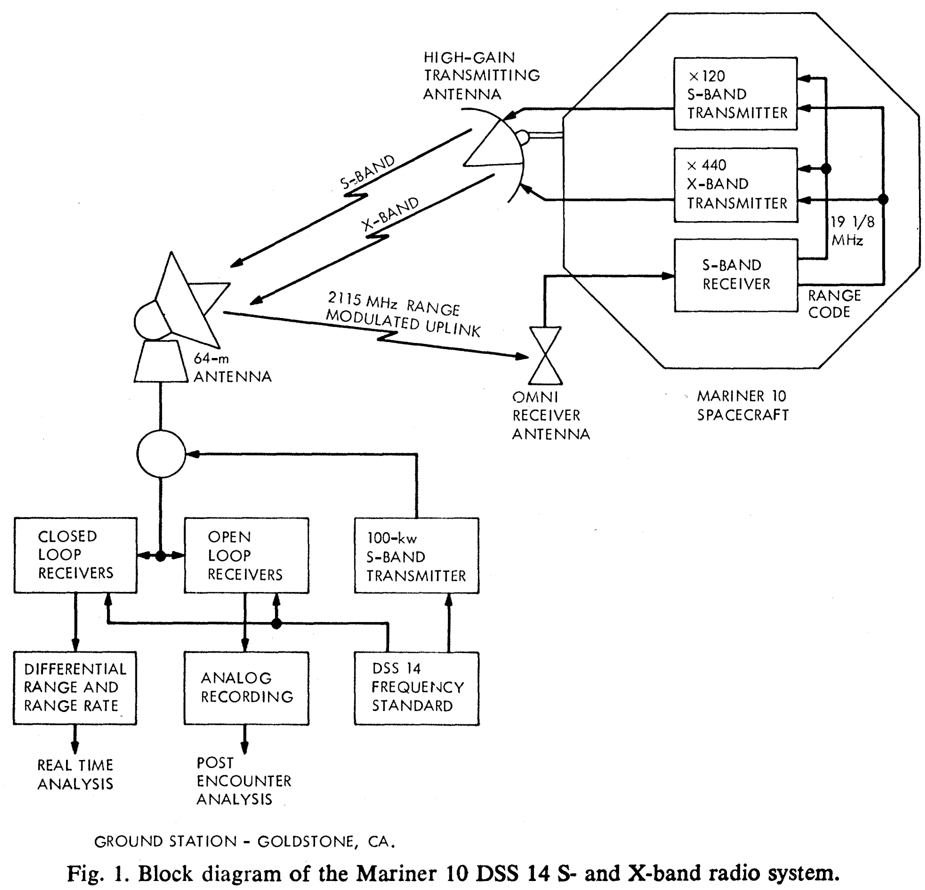


Fig. 1. Block diagram of the Mariner 10 DSS 14 S- and X-band radio system.

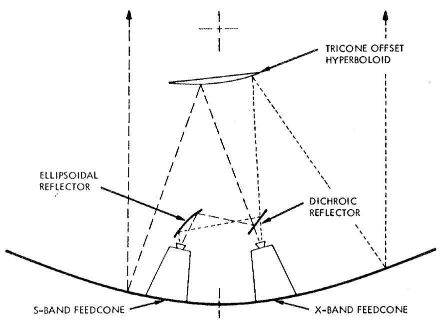


Fig. 2. Microwave optics system of the NASA 64-m antenna at Goldstone, California.

and range outputs are available in printed and plotted form in real time. The receiver system used for occultation is a wide-band, open-loop type with bandwidth selected to accommodate the full frequency excursion of the signal during planetary encounter. These bands are recorded coherently, along with appropriate sampling and timing signals, on analog magnetic tape recorders. The tapes are later digitized and processed by a digital simulation of the phase-locked loops. These recordings allow the occultation to be "reflown" as many times as necessary to complete the analysis. They are of particular value at occultation emersion where the recordings can be read backward in time, thus avoiding the problem of weak-signal acquisition.

As implemented for Mariner 10, the dual-frequency system has proven fully capable of performing interplanetary columnar electron content measurements while achieving the prime goals of the celestial mechanics and radio science team at Venus.

Mass and gravity field. The determination of the mass and the gravitational potential of Venus is one of the major objectives of the celestial mechanics part of the radio science experiments. The effects of the gravitational force exerted by Venus on the spacecraft can be discerned in the characteristic signatures imparted to the radio-tracking signals (*4*). The analysis of these signals from the Venus encounter is still in its preliminary stages. We present here first a brief discussion of the scientific importance of a knowledge of the mass and gravity field of Venus and then our preliminary results.

The mass of Venus has already been determined to within about 5 parts in 10^6 from the analysis of the Mariner 2 and Mariner 5 tracking data (*5*). The further improvement that will be obtained as a result of the Mariner 10 mission is of importance primarily for its indirect aid in the testing of gravitational theories. The mass of Venus affects, in particular, the motion of Mercury, whose orbit is most sensitive to relativistic anomalies because of its proximity to the sun and its relatively high eccentricity. For other purposes, such as the setting of boundary conditions for theoretical models of the interior of Venus, the mass determinations from prior spacecraft missions have already provided more than sufficient accuracy.

One of the most important scientific questions that the Mariner 10 tracking data can help to resolve concerns the apparent resonance between the spin of Venus and the relative orbital motion of Venus and Earth (*6*). A spin period for Venus of exactly 243.16 days (retrograde direction) implies that at every inferior conjunction Venus presents the same face to Earth and that Earth, therefore, controls the spin of Venus. The period of Venus's spin appears to be within 1 part in 2500 of that value (*7*). Dynamically, such control could be exerted only if the equatorial principal moments of inertia of Venus differed sufficiently for the gravitational torque exerted by Earth on Venus to dominate the net tidal torque exerted by the sun on Venus. Although the arguments lack rigor, it seems that a fractional difference in the equatorial moments of inertia of about 10^{-4} is required (*6*). The second-order terms in the harmonic expansion of the gravitational field are directly proportional to the fractional differences in the principal moments of inertia. Thus, the determination of these second-order terms with uncertainties small compared to 10^{-5} will provide crucial information on the possible existence of this spin-orbit resonance.

Preliminary results for the mass and gravity field of Venus were obtained as follows. Taking the best available locations of the radio-tracking stations and ephemerides of Earth and Venus, reasonable models for the acceleration of the spacecraft induced by solar radiation pressure and for the effect of the propagation medium on the tracking signal, and the Doppler data (*8*) collected from 5 days before to 5 days after Venus encounter, we have estimated the six parameters defining the trajectory of Mariner 10, the mass of

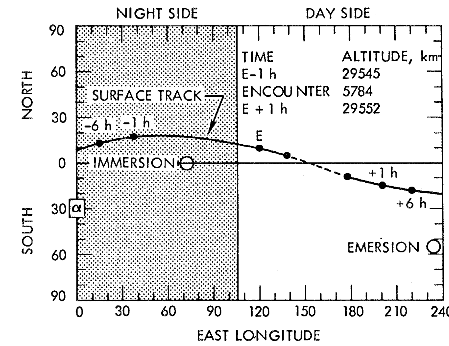


Fig. 3. Near-encounter geometry of Mariner 10. Surface track is shown for ± 6 hours (occulted portion is shown dashed).

Venus, and the second-degree terms in the spherical-harmonic expansion of the gravitational potential. The coefficients of all harmonics higher than the second degree were set equal to zero. The results, in conjunction with those from numerous similar analyses with somewhat different subsets of these data and parameter sets, lead us to conclude that (i) the ratio of the sun's to Venus's mass is $408{,}523.9 \pm 1.2$ (*9*) and (ii) the magnitudes of the fractional differences in the principal moments of inertia are less than 1 part in 10^4 (*10*). These results are consistent with the Mariner 5 solution that was (*5*) obtained under the assumption that all harmonic coefficients vanished, except for the second zonal harmonic.

The postfit residuals for the Mariner 10 solutions are remarkably small—a root-mean-square value of only a few millihertz (*11*)—but there are some systematic trends, with small amplitude, and periods ranging from a few minutes to diurnal.

This upper bound on the fractional difference for the principal moments of inertia is too large to eliminate the possibility that Earth's gravitational torque controls Venus's spin. Moreover, we must emphasize the possibly crucial effect on this bound of the assumption that all third- and higher-degree harmonics are zero. Preliminary tests indicate that if, for example, the third-degree terms are estimated simultaneously, the resultant strong correlations produce an instability in the estimates of the second-degree terms. In view of this difficulty with the higher harmonics, the possibility remains open that the second-degree terms may be larger than given above. Simultaneous analysis of the Mariner 5 and Mariner 10 data may allow a resolution of this difficulty, but, in any case, the dual-frequency altimeter (12) and the radio-tracking data from the projected Venus Orbiter will certainly allow a definitive determination of these very important second-degree terms.

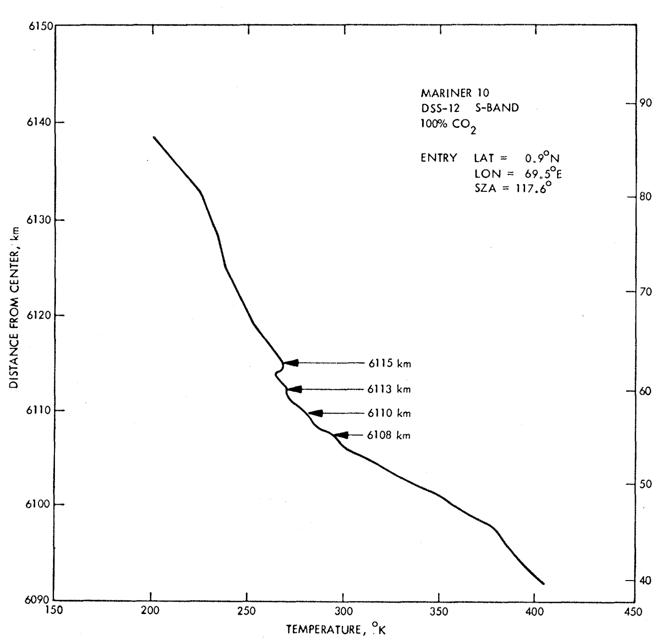
Atmosphere. Information on Venus's atmosphere was deduced from analysis of the radio signals during occultation. Figure 3 shows a Mercator projection of a portion of Venus's surface with the ground track and occultation points shown. The dashed portion of the ground track indicates the period of occultation during which no Doppler tracking data are available. Occultation immersion at an altitude of 65 km occurred on the night side at 0.9°N, 69.5°E with a solar zenith angle of 117.6°. Emersion took place on the day side with a solar zenith angle of 67.1° at 56.3°S, 236.4°E. All latitudes and longitudes correspond to the International Astronomical Union convention. During occultation the spacecraft high-gain antenna was steered in a tear-drop shaped pattern to track the southern limb of Venus. Because of the shallowness of the occultation, the maximum bending angle of the radio ray was 12.6°, corresponding to about the 40-km level in the atmosphere of Venus.

During the flight of Mariner 10 to Venus, a study of the spacecraft auxiliary oscillator revealed that its stability was less than adequate for radio science purposes. The entrance into occultation was therefore performed in the two-way mode, with DSS 14 transmitting to the spacecraft, which then coherently retransmitted the received frequency to Earth, where it was received by both DSS 14 and DSS 12. Thus, useful measurements of the atmosphere of Venus extend to the point at which the Mariner 10 receiver lost uplink lock, at which point the radio system switched to the auxiliary oscillator for its frequency reference. All subsequent frequency data, including those obtained during the exit from occultation, were perturbed not only by short-time instabilities in the oscillator but also by a long-term drift having a time constant of more than 30 minutes. Amplitude and differential frequency data were not affected by this problem.

Data were obtained from the closed-loop, phase-lock receivers in the form of nondestructively counted Doppler data and from the open-loop receivers in the form of analog recordings of a frequency-translated signal at S- and X-bands. Substantial amounts of closed-loop data were obtained. The open-loop recordings contain all S- and X-band open-loop data redundantly recorded throughout the duration of the occultation. As of the writing of this report, the open-loop data had not been completely processed and all of the results described below are based on a preliminary analysis of the closed-loop entry data.

Details of the processing of radio occultation data have been described previously (1). The Doppler data are differenced, in this case at intervals of 1 second, to obtain the Doppler frequency, which is then subtracted from predictions computed on the basis of a precisely determined orbit of the spacecraft to obtain Doppler residuals. After removing bias and drift components, these residuals are then used along with geometric quantities obtained from a precisely known trajectory of the probe to obtain a profile of refractivity in the atmosphere of Venus as a function of radius by means of the Abel integral transform (1, 13). Given the gaseous composition of the atmosphere, which in turn provides the mean molecular weight and the specific refractivity of the gas mixture, one can convert the refractivity into mass or number density. The hydrostatic equation is then used to integrate the density from the top of the sensible atmosphere to obtain the atmospheric pressure at any height, which then can be used to determine the temperature by applying the perfect gas law.

A set of temperature profiles determined by such analysis from the S-band data obtained from DSS 14 is shown in Fig. 4. For simplicity, the composition was assumed to be 100 percent



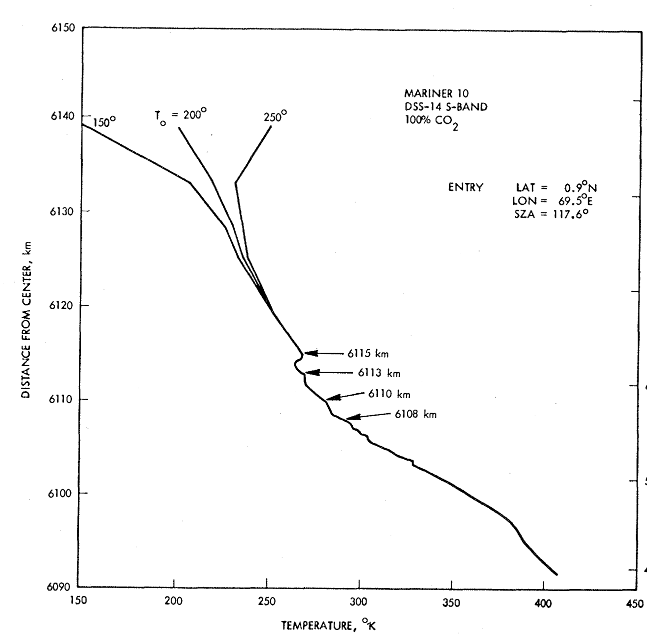


Fig. 4 (left). Temperature profiles obtained from Mariner 10 S-band, closed-loop entry data received at DSS 14. The initial temperatures were 150°, 200°, and 250°K. Note the temperature inversions at 6108, 6110, 6113, and 6115 km. Fig. 5 (right). Temperature profile from Mariner 10 S-band closed-loop data received from DSS 12. The initial temperature was 200°K. The temperature inversions are seen to be identical to those of Fig. 4.

carbon dioxide. For the integration of the hydrostatic equation, it is necessary to assume the initial conditions. Three profiles, with initial temperatures corresponding to 150°, 200°, and 250°K, respectively, are shown. Although there is some divergence in the temperature profiles at the upper levels, all converged to a single profile below a radius of about 6120 km. The altitude scale on the right side of Fig. 4 is based on a planet radius of 6052 km, which is determined from computations based on radar data (*14, 15*) and on a combination of radar and Mariner 5 tracking data (*16, 17*).

The temperature profile, although obtained at a different latitude and solar zenith angle, is, in general, quite similar to those obtained from the Mariner 5 radio occultation experiments (*3, 18, 19*). This profile, determined only from the closed-loop data extends down to a radius of 6092 km, compared to about 6085 km for the profiles from Mariner 5 (*19*). The geometry of the Mariner 10 encounter was such that the ray path could not penetrate below the 40-km level.

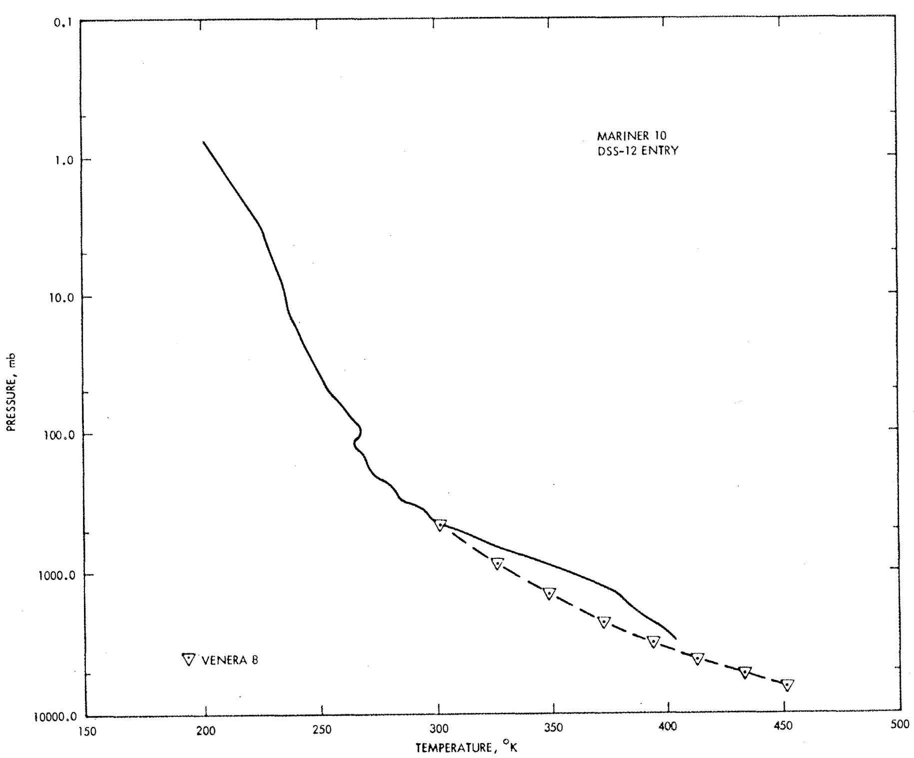


Fig. 6. Pressure and temperature from Mariner 10 DSS 12 S-band closed-loop measurements compared to those from Venera 8. The discrepancy is most likely due to the assumption of a pure carbon dioxide composition in our analysis.

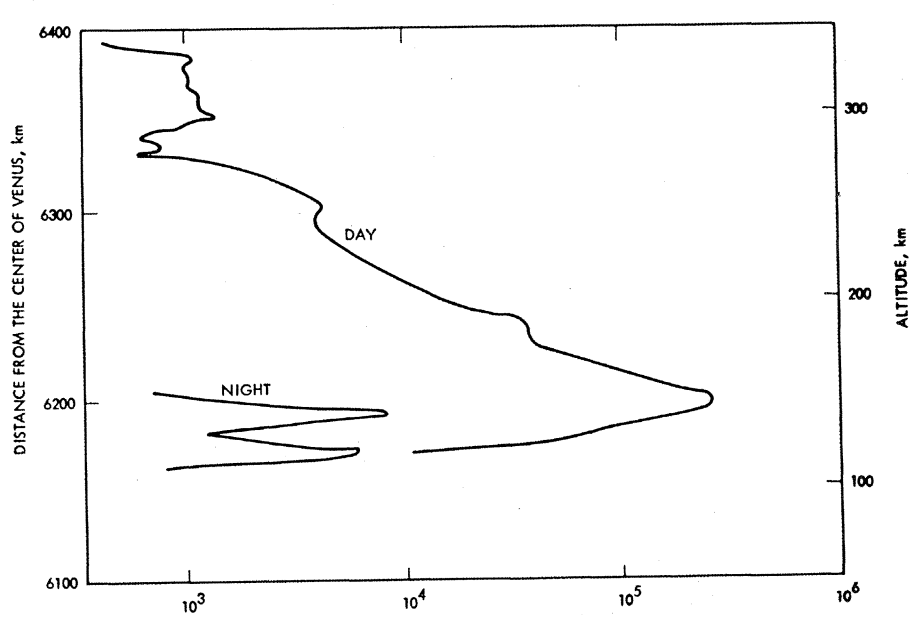


Fig. 7. Dayside and nightside electron number density from Mariner 10 open-loop differential S- and X-band measurements.

The most striking features of this temperature profile are the four distinct inversions occurring at radii of 6115, 6113, 6110, and 6108 km, as marked by the arrows in Fig. 4. These features are thought to be associated with dynamics and cloud structure in the atmosphere of Venus, and work is under way to correlate their positions with those of the stratified clouds observed in limb pictures obtained by the Mariner 10 television experimenters (*20*). The top inversion, at 6115 km, could mark the transition between the stable atmosphere above and the convective layers below.

A temperature profile obtained from S-band data received at DSS 12 is shown in Fig. 5. Here only one initial temperature of 200°K was used, and the composition was again assumed to be 100 percent carbon dioxide. This profile, obtained from data independent of those for Fig. 4, shows exactly the same features. In particular, the temperature inversions are observed at precisely the same altitudes and have the same magnitudes. In fact, when the profiles are overlaid, they match exactly, with the exception of a few points at the highest altitudes and some minor roughness in the DSS 14 data below 6105 km caused by counter errors.

The average temperature lapse rate in Figs. 4 and 5 between the radii of 6106 and 6098 km is about 9.0°K/km, which is very close to the dry adiabatic lapse rate for a carbon dioxide atmosphere. However, at 6098 km, the lapse rate abruptly changes to a somewhat lower value. This change in lapse rate is believed to correspond to the top of the cloud layer proposed by Fjeldbo *et al.* on the basis of Mariner 5 radio occultation data (*18*).

The nature of these clouds will be clarified when the dispersive absorption suffered by the S- and X-band signals, respectively, can be compared. Preliminary examination of both closed- and open-loop data reveals that, although the S-band signal persists for more than

7 minutes past geometric occultation, that is, down to 40-km altitude, the X-band signal fades rapidly and is completely gone before reaching 51 km.

Figure 6 shows the pressure obtained from the DSS 12 measurements plotted on a logarithmic scale as a function of temperature. Superimposed upon this profile, marked by triangles, are pressure and temperature measurements from the Soviet probe, Venera 8 (*21*). Although in general the two profiles are similar, there are significant variations. The most likely explanation for this deviation is the assumption of the pure carbon dioxide composition, although the uncertainties in the Venera 8 measurements ($\pm$ 1.5 percent of full scale) could also contribute to the discrepancy.

Ionosphere. Open-loop receiver differential Doppler data were used to measure the nightside and dayside ionospheres of Venus. Mariner 5 423.3-Mhz amplitude data (*3*) showed a peak density of approximately 2×10^4 electron/cm^3 near an altitude of 142 km on the night side. It was not possible from those data to produce a reliable estimate of the electron number density distribution below that altitude, for it was unclear whether the observed amplitude changes were due to spherical stratification or to scintillation effects caused by horizontal irregularities.

The Mariner 10 data revealed two peaks as shown in Fig. 7, labeled "night." The upper one is located at 140 km and has a peak density of approximately 10^4 electron/cm^3. A second peak with slightly lower density was observed at 120-km altitude. It is clear from both the closed- and open-loop differential Doppler data that these are thin, well-defined layers. The peak density obtained is in good agreement with that obtained from the Mariner 5 experiment where the immersion point was 30° farther north in latitude.

The dayside profile is also shown in Fig. 7. A peak number density of 3×10^5 electron/cm^3 was observed near 145-km altitude. The Mariner 5 dual-frequency experiment, which was more sensitive to tenuous plasmas as a result of the use of lower frequencies, indicated that an ionopause existed near 500-km altitude on the day side. The Mariner 10 differential Doppler data show a similar effect near 530 km. The density change, however, is only 10^3 electron/cm^3 across the ionopause boundary instead of the 10^4 electron/cm^3 seen by Mariner 5. This is very close to the S-X system noise level at this stage in processing the data and, therefore, may not be real.

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8. The averaging times for the Doppler data varied from 10 to 300 seconds.
9. The corresponding value for the product of Venus's mass and the gravitational constant is $324{,}858.6 \pm 1.0$ km^3/sec^2.
10. Estimates of the second-degree unnormalized coefficient, J_2, vary between 10^{-6} and 2×10^{-5}, and the longitudinal harmonics (C_{22} and S_{22}) fall within the range 10^{-6} to 10^{-5}. The definition of the spherical harmonic expansion of the gravitational potential is given in W. M. Kaula, *Theory of Satellite Geodesy* (Blaisdell, New York, 1966).
11. The root-mean-square value represents about 2 parts in 10^8 of the measured Doppler shift and about 6 parts in 10^8 of the change in Doppler shift during the day of encounter.
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Magnetic Field Observations near Venus: Preliminary Results from Mariner 10

Abstract. *The NASA-GSFC magnetic field experiment on Mariner 10 is the first flight of a dual magnetometer system conceived to permit accurate measurements of weak magnetic fields in space in the presence of a significant and variable spacecraft magnetic field. Results from a preliminary analysis of a limited data set are summarized in this report, which is restricted primarily to Venus encounter. A detached bow shock wave that develops as the super Alfvénic solar wind interacts with the Venusian atmosphere has been observed. However, the unique coincidence of trajectory position and interplanetary field orientation at the time of bow shock crossing led to a very disturbed shock profile with considerably enhanced upstream magnetic fluctuations. At present it is not possible to ascertain the nature and characteristics of the obstacle responsible for deflecting the solar wind flow. Far downstream disturbances associated with the solar wind wake have been observed.*

Introduction. Results from a preliminary analysis of a limited and at times low quality quick-look data set for the NASA-GSFC magnetic field experiment are summarized in this report. There appears to be sufficient evidence for an initial assessment of the results, particularly as related to the study of the solar wind interaction with Venus. What emerges is an interpretation based