However, the Beta region becomes more complex to the south where arcuate cusps, convex to the east, break its linear aspect.

Finally, in Fig. 3 we present the first data obtained from the radar mapper operating in the imaging (rather than in the altimetry) mode. These data were obtained on orbits 105 through 141 during periods when the spacecraft altitude was less than 550 km. The image represents a composite of observations taken to the west and to the east of the suborbital surface track on most orbits. The radar image shows dark circular features (for example, 20°N, 331°E; 15°N, 226°E) with bright central spots; these features resemble impact craters 400 to 800 km in diameter. The corresponding altimetry data show shallow depressions 500 to 700 m deep, a shallowness which may result from mobility of the Venus crust. The tentative interpretation of these features as impact craters will be tested in the near future when the spacecraft overflies other similar objects identified as possible impact craters from Earth-based images (*10*).

In summary, the most significant discovery of the Pioneer Venus radar experiment is the strong evidence for tectonic activity. The large plateau is the most spectacular example of this, but the alignment of elevated regions and the elongate shapes of individual ridges also indicate major tectonic control of landforms. Moreover, the Pioneer Venus radar experiment has verified the existence and defined the topography of several large circular depressions that may have an impact origin. And its observations are consistent with a previous interpretation suggesting that at least one radar-bright elevated region may be a large shield volcano.

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Gravity Field of Venus: A Preliminary Analysis

Abstract. *The line-of-sight gravity field for Venus has been mapped by tracking the Pioneer Venus spacecraft in the vicinity of periapsis for a 45° swath of longitude eastward of 294°. There are consistent and systematic variations in the gravity signature from orbit to orbit, attesting to the reality of observed anomalies. Orbit 93 passes over a large positive topographic feature, the "northern plateau," for which there is no corresponding gravity signature. If this region has no isostatic compensation, the gravity signal would exceed the noise level by a factor of 7. The results of simulation modeling indicate that the northern plateau must be compensated at depths of about 100 kilometers or less. The long-wavelength anomalies seen in the Venus gravity data have been Fourier-decomposed along the orbital tracks and compared to analogous spectra for Earth. The gross power in the two mean spectra is approximately the same, but systematic variations among the harmonics suggest differences in dynamic processes or lithospheric behavior, or both, for the two planets.*

This report summarizes the gravity field results of the first 30 days of periapsis tracking of the Pioneer Venus orbiter. The spacecraft was placed in near-polar orbit around Venus on 4 December 1978 with the communication link to Earth in the vicinity of the spacecraft periapsis occulted by Venus. During this time and continuing through the present, the spacecraft mean Keplerian orbital elements have been calculated. With a sufficient number of orbits, the time variation of these elements will be used to estimate the low degree and order harmonics of the Venus gravity field; these results will be reported elsewhere (*1*).

In late February the periapsis region became visible from Earth and direct Doppler measurement of spacecraft velocity variations began. This tracking will continue until solar conjunction in August 1979 and will provide information for 210 degrees of longitude. This affords a data type for estimation of the higher-order spherical harmonics of the gravity field as well as for direct mapping (*2*) of the anomalous gravity field when the spacecraft is at altitudes less than 2000 km. Here we report the first results of gravity field mapping and provide preliminary insight on the isostatic compensation of the Venus topography. We also estimate the power in the long-wavelength gravity spectrum of Venus and compare this result to the power spectrum of Earth.

The approach used in reducing the Doppler data to gravity field measurement is precisely that used on the Mars Viking orbiter data (*3*). For each orbit (revolution) of the spacecraft about Venus, 2 hours of Doppler data centered about periapsis were used to estimate the spacecraft position and velocity based on a gravity model with only a central mass term (*4*). All primary planetary perturbations and Earth-spacecraft motions are included in the model; atmospheric parameters were excluded. The velocity residuals from this estimation procedure were spline fit and differentiated to produce line-of-sight (LOS) gravity accelerations, the component of the gravity vector along the direction from Earth to the spacecraft. The individual profiles from each orbit were then aligned geometrically at periapsis to evaluate consistency and obtain a first estimate of the amplitude variations. This is shown in Fig. 1, where the first seven profiles are plotted and show a systematic and consistent variation from orbit to orbit. A single large anomaly with a peak-to-peak variation of 20 to 25 mgal persists throughout

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the seven orbits, while a subtle "shoulder" seen just past periapsis on orbit 92 evolves systematically into a well-defined peak.

Besides the usual concerns of least-squares effects and geometry variations in LOS data reduction (5), there are two additional effects that must be considered for the Pioneer Venus orbiter: atmospheric drag at periapsis and the interplanetary plasma effect on the radio signal as solar conjunction is approached. A simulation was performed in which a realistic atmospheric model (6) was used to simulate Doppler data over orbits similar to those reported here. Residuals were generated by fitting to the simulated data a trajectory model with *no* atmospheric parameters. Spline fitting and differentiation yielded a maximum LOS acceleration of only 0.8 mgal within ± 40 seconds of periapsis. The effects of the interplanetary plasma are seen directly in the profiles of Fig. 1. At the extreme right and left of the profiles the spacecraft is at relatively high altitude and high-frequency gravity variations should be attenuated. The variations, especially on orbits 95 and 96, are in fact plasma effects, which should be nearly random over an orbit as well as uncorrelated and variable from day to day, depending on solar activity. The plasma modulation of the radio signals introduces variations up to about 3 mgal on noisier days, and is the limiting noise source in gravity field mapping. Using adjacent orbits, the plasma effects can be minimized by averaging.

An initial test of the isostatic compensation of topography was carried out by analyzing the gravity data over the large, low-radar-albedo feature to the west of the bright feature "Maxwell" and centered at approximately 330°E longitude, 65°N latitude (7). The region is approximately 1400 km in diameter, and Pioneer Venus radar altimeter data show it to be an elevated region of about 3 km average height (8). For working purposes, we refer to this feature as the "northern plateau." Orbit 93, relatively free of plasma effects, passed across the southeast portion of this area, traversing from northeast to southwest from about 68° to 60°N latitude. The orbit 93 data are relatively smooth in this vicinity; there are excursions of less than 1 mgal on the shoulder of the large signal to the south. We have modeled the northern plateau as a spherical cap 1400 km in diameter, 3 km high, with a density of 3 g cm^{-3}. The procedure for modeling fully accounts for important nonlinear effects in LOS gravity (9) and has been extensively tested against the more classical dynamic procedures of estimation with Doppler tracking data (5). The chief nonlinear effect is manifested as a 30 to 40 percent reduction in the peak amplitude of an anomaly; this type of distortion must also be considered when estimating power in the true gravity spectrum (see below).

If this elevated region were totally uncompensated by a density deficiency in the interior, then a peak LOS gravity anomaly of about 7 mgal would result, which is significantly in excess of the estimated noise level of 1 mgal on this portion of orbit 93. Since essentially no anomaly is seen, there must be a mass deficiency in the interior canceling the gravity effect. On Earth, vertical weight balance (isostasy) is the general rule for topography with a horizontal scale of at least several hundred kilometers. It is a result of the elements of a thermomechanical system tending toward a state of minimum stress. Departures from isostasy on Earth often arise when the stresses associated with plate tectonics and mantle convection are effective. A subsurface mass of equal magnitude and opposite sign was modeled, in addition to the surface feature, to simulate isostatic compensation of the northern plateau. In Fig. 2 we show the peak anomaly magnitude as a function of the depth to the compensating mass. While isostatic compensation may be distributed over a range of depths, the results indicate that the mean depth of compensation is no greater than approximately 100 km. If the plateau is only partly compensated, then this depth bound is even less.

The compensating mass implied by this analysis must be supplied by a chemical inhomogeneity or a temperature anomaly. Compensation by a phase change is unlikely. Mass balance by a lateral variation in subsurface density in a layer, whether from temperature or chemical differences, is known as Pratt compensation. Alternatively, the mass may be balanced by variations in the depth of a density boundary; this is termed Airy compensation. On Earth,

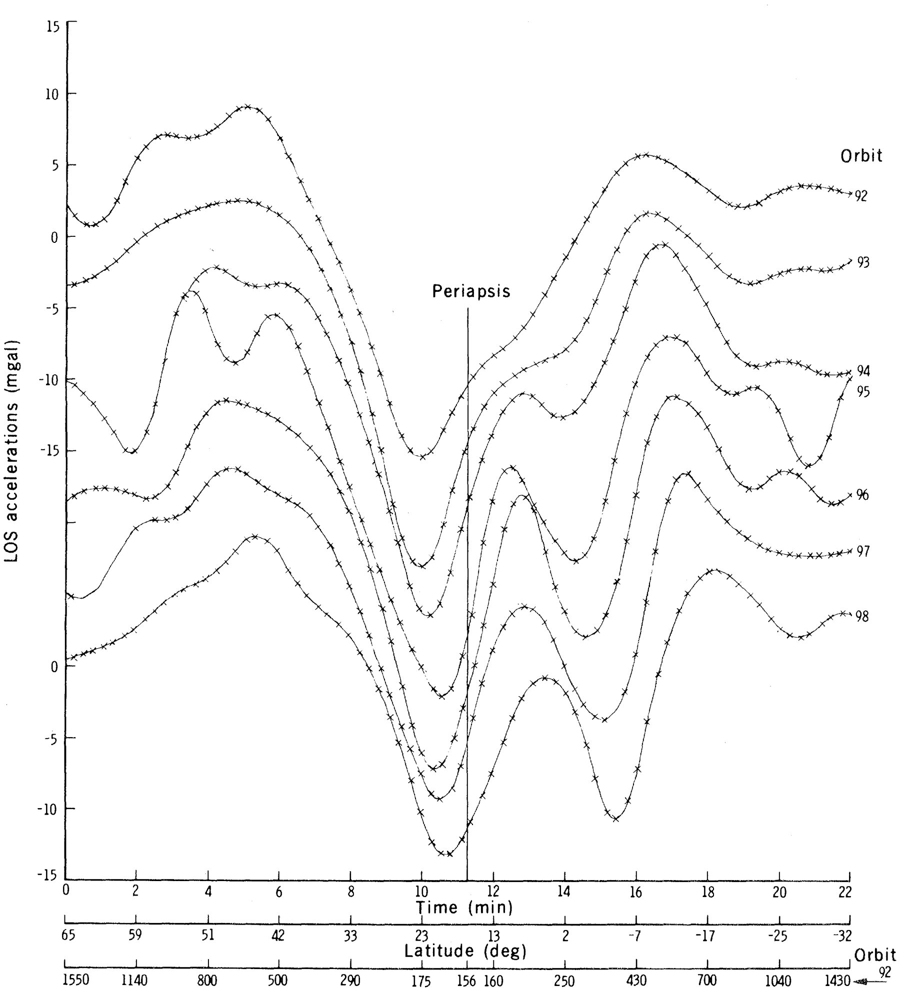

Fig. 1. Line-of-sight (LOS) acceleration profiles from orbits 92 to 98 acquired 6 March through 13 March 1979. The zero lines for orbits 92 and 98 are shown. The zero lines for the other orbits are evenly spaced at 5-mgal (1 gal = 1 cm sec^{-2}) intervals. Periapsis altitude varies from 156 km on orbit 92 to 161 km on orbit 98.

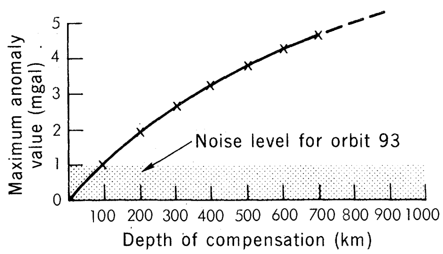

Fig. 2. Maximum value of LOS gravity predicted for orbit 93 for two spherical disks 1400 km in diameter. One disk, placed at the surface of Venus and coinciding with the location of the northern plateau, is 3 km high with a density of 3 g cm^{-3}. The second disk, of equal negative mass to isostatically balance the surface disk, was placed in the subsurface at various depths of compensation as shown.

isostatic balance takes place on the continents by a combination of Airy compensation, largely at the crust-mantle boundary, and Pratt compensation, largely arising from compositional variations in the upper mantle. The young oceanic lithosphere is largely compensated by the variation in its thickness associated with a temperature decrease with distance from the midocean ridges.

In summary, the northern plateau appears to be compensated at a mean depth of less than 100 km, strongly implying a subsurface temperature and/or compositional inhomogeneity. A lateral inhomogeneity in composition strongly implies that the outer portion of Venus has been differentiated.

The variations in the gravity data shown in Fig. 1 are long-wavelength features by Earth standards. The dominant wavelength in Fig. 1 is about 5000 to 6000 km. For Earth, wavelengths longer than about 2000 km (spherical harmonic degree $\ell < 18$) receive little contribution from the topography and crust, arising mainly from the mantle (*10*). Most likely these density anomalies are related to subsolidus convective flow processes (*11*). Our interest here is in estimating the power in the Venus gravity spectrum, relative to Earth, with the small amount of Venus data on hand.

We selected seven Pioneer Venus orbits (93, 98, 103, 108, 113, 118, and 123), representing longitude coverage of 45°, and performed a Fourier analysis of the LOS gravity data along an arc of each orbit extending from approximately 70°N to 30°S latitude. Earth's gravity field has been sampled by using the Pioneer Venus orbit 93 in the presence of Goddard Earth Model (GEM) 10 (*12*). Earth was sampled in 16 orbits with equal node spacings of 22.5°, and the resultant LOS gravity, generated by an orbit simulation procedure (*5*), was Fourier analyzed, using the same approach as for the Venus data. The Earth-spacecraft-Venus angle is nearly orthogonal for orbit 93, so the LOS gravity is dominated by the horizontal component normal to the orbit plane. With increasing orbit number, there is an increasing amount of vertical or in-plane component in the LOS data. Since more power is expected in the vertical component than in the horizontal component, a bias exists in the Venus data when the span of 30 orbits is compared to the Earth simulation with orbit 93 only. The bias has been corrected by assuming that the relative distribution of vertical and horizontal power arises from a random distribution of density anomalies in the interior (*13*).

In Fig. 3 we compare the mean and maximum power coefficients of Venus and Earth for the first five Fourier harmonics of the 100° arc; the first harmonic corresponds to a wavelength of approximately 11,000 km. The mean values of the first harmonics are the same; Earth exceeds Venus for the second harmonic, while the Venus power exceeds the Earth power for harmonics 3 to 5. There is a clear indication that the means are dominated by the maximum values. In particular, the strong second harmonic for Earth results from the specific characteristics of the orbital sampling of two groups of strong gravity anomalies. The first group includes the maxima of the Andes and North Atlantic gravity highs and the minimum of the western North Atlantic gravity low. The second group is dominated by the Indian Ocean gravity low and the strong positive anomaly associated with Indonesia and the Java Trench. These anomalies are associated with lithospheric plate boundaries and with specific regions of enhanced dynamic activity in the sublithosphere (*14*).

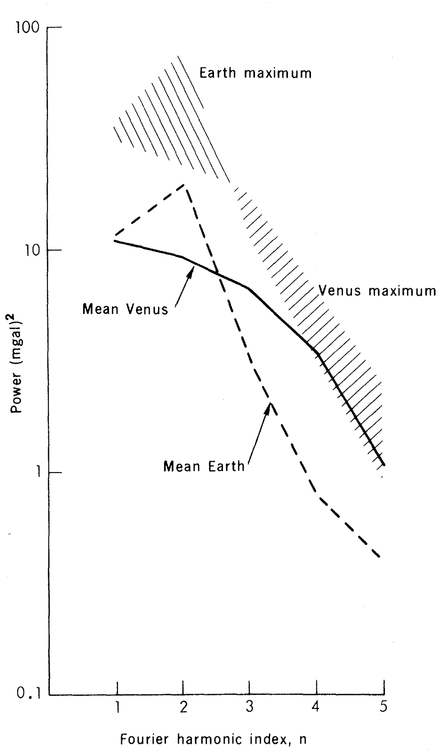

Fig. 3. Gravity spectra for Venus and Earth obtained by Fourier-decomposing gravity anomalies along a 100° arc centered about the periapsis latitude. For Venus, orbits 93, 98, 103, 108, 113, 118, and 123 were used. For Earth, the characteristics of orbit 93 were used to sample the GEM 10 gravity model with 16 orbits of equal node spacing. The first harmonic corresponds approximately to a wavelength of 11,000 km. The mean and maximum curves for both planets are shown with the area between the two maxima hatched. The Earth maximum exceeds the Venus maximum for harmonics 1 and 2, while the converse is true for harmonics 3 to 5.

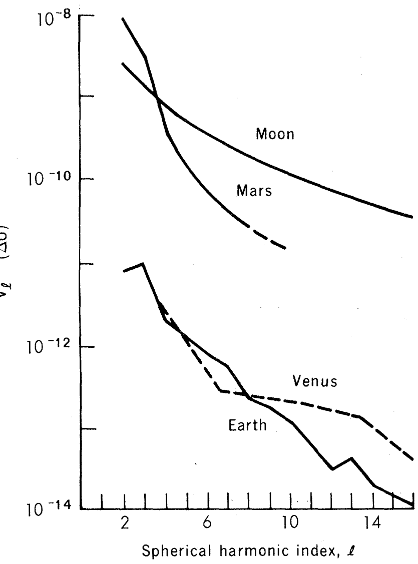

Fig. 4. The spherical harmonic gravitational potential power spectra, V_ℓ^2 (ΔU), for Earth, the moon, and Mars adopted from (*10*), with an estimate of the Venus spectrum obtained by converting the mean Fourier spectrum of seven orbital arcs covering a 45° longitude span.

It is useful to take the spectral results for this limited region of Venus and place them in context with the actual spherical harmonic spectra of Earth, moon, and Mars (*10*). This is accomplished with the Venus spectrum by relating the wavelengths associated with the Fourier components to the spherical harmonic index ℓ and using the ratio of Venus power to Earth power of Fig. 3 to transfer the Venus spectrum to a spherical harmonic base. The most striking result (Fig. 4) is that the Venus gravity spectrum is far more like that of Earth than that of the moon or Mars. The increasing power from Earth to Mars to moon most likely results from an increase in density anomalies from progressively thicker, colder lithospheres.

The nondimensional normalized power spectra (V_ℓ^2) of the anomalous gravitational potential (ΔU) for Earth, moon, and Mars are approximately described by the Kaula rule (*15*): $V_\ell^2\ (\Delta U) \simeq A(2\ell + 1)10^{-10}\ell^{-4}$, where A is a constant. Such a power law can be explained by a random distribution of density anomalies (*16*). Mars departs significantly from this rule for the second and third harmonics because of the Tharsis gravity anomaly (*10, 11*). The best fit of the Kaula rule for the Earth harmonics plotted in Fig. 4 shows an excess of gravity in the vicinity of the sixth harmonic. This corresponds to the second harmonic Fourier spectral peak shown in Fig. 3 and can be considered a nonstochastic component, related to, as previously discussed, plate boundaries and regions of enhanced mantle flow. The Venus harmonics are also fairly well described by a Kaula rule; the constant A is about 1.5 times that for Earth, but we do not consider this significant. There is a deficiency of power around the sixth harmonic for Venus and an excess for higher harmonics. If the gravity field of the region of Venus thus far sampled arises from dynamic processes in the mantle, such processes must take on a different planform than for the whole Earth. Certainly, anomalies comparable in magnitude and spacing to the largest dynamically related anomalies on Earth are absent from this portion of Venus. The enhanced Venus spectrum for harmonics greater than eight may indicate a shift to shorter wavelengths for these phenomena. Alternatively, this enhanced portion of the spectrum may indicate an origin from a lithosphere thicker than that of Earth. Further elucidation of the origin of these long-wavelength anomalies must await detailed comparison with the surface tectonics as revealed by radar imagery and altimetry.

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Ionosphere of Venus: First Observations of Day-Night Variations of the Ion Composition

Abstract. *The Bennett radio-frequency ion mass spectrometer on the Pioneer Venus orbiter is returning the first direct composition evidence of the processes responsible for the formation and maintenance of the nightside ionosphere. Early results from predusk through the nightside in the solar zenith angle range 63° (dusk) to 120° (dawn) reveal that, as on the dayside, the lower nightside ionosphere consists of F_1 and F_2 layers dominated by O_2^+ and O^+, respectively. Also like the dayside, the nightside composition includes distributions of NO^+, C^+, N^+, H^+, He^+, CO_2^+, and 28^+ (a combination of CO^+ and N_2^+). The surprising abundance of the nightside ionosphere appears to be maintained by the transport of O^+ from the dayside, leading also to the formation of O_2^+ through charge exchange with CO_2. Above the exobase, the upper nightside ionosphere exhibits dramatic variability in apparent response to variations in the solar wind and interplanetary magnetic field, with the ionopause extending to several thousand kilometers on one orbit, followed by the complete removal of thermal ions to altitudes below 200 kilometers on the succeeding orbit, 24 hours later. In the upper ionosphere, considerable structure is evident in many of the nightside ion profiles. Also evident are horizontal ion drifts with velocities up to the order of 1 kilometer per second. Whereas the duskside ionopause is dominated by O^+, H^+ dominates the topside on the dawnside of the antisolar point, indicating two separate regions for ion depletion in the magnetic tail regions.*

An investigation of the composition of the nightside ionosphere of Venus has been performed with results from the Pioneer Venus orbiter ion mass spectrometer (OIMS) experiment. These results are based on data obtained during the period December 1978 through March 1979. In this period, the location of periapsis (fixed in latitude at 18°N) precessed from a solar zenith angle (SZA) of ~63° at insertion on 5 December 1978, through the highest SZA

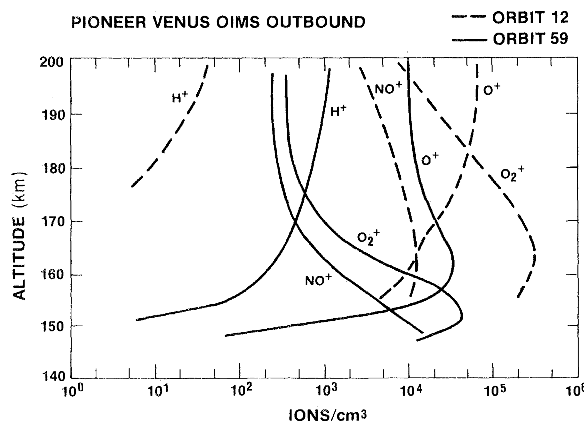

Fig. 1. A comparison of representative ion profiles from orbit 12 (dayside, predusk) and orbit 59 (nightside), with solar zenith angles of 80° and 150°, respectively.