Reports

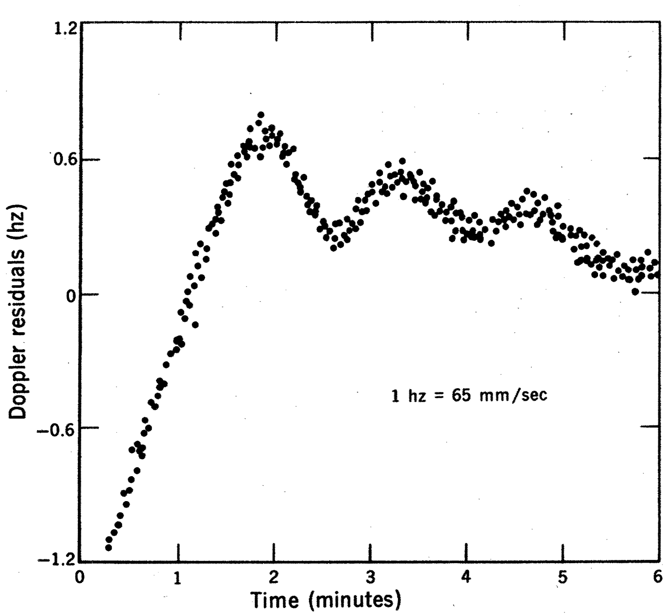
Lunar Gravity via Apollo 14 Doppler Radio Tracking

Abstract. *Gravity measurements at high resolution were obtained over a 100-kilometer band from + 70° to − 70° of longitude during the orbits of low periapsis altitude (approximately 16 kilometers). The line-of-sight accelerations are plotted on Aeronautical Chart and Information Center mercator charts (scale 1 : 1,000,000) as contours at 10-milligal intervals. Direct correlations between gravity variations and surface features are easily determined. Theophilus, Hipparchus, and Ptolemaeus are negative features, whereas Mare Nectaris is a large positive region. The acceleration profiles over Mare Nectaris are suggestive of a broad disk near the surface rather than a deeply buried spherical body. These data are in good agreement with the short arc of Apollo 12 lunar module descent data.*

With a new trajectory design placing the orbits of the command service module (CSM) and the lunar module (LM) at a 16-km periapsis altitude for 12 revolutions prior to the LM's descent, Doppler gravity measurements at high resolution have been obtained. Previous Doppler radio tracking from the Lunar Orbiter and Apollo missions has been at 100-km altitudes, causing the resolutions to be at least a factor of 5 worse. The scant Apollo 12 LM descent data (*1*) provided the first low-altitude results, which have been incorporated in the present analysis. These data have been processed in the same manner as reported in (*2*). Essentially, the line-of-sight velocity residuals, obtained by removing all the known motion of the spacecraft relative to the ground antenna from the observations, were differentiated to obtain "least-squares-filtered" estimates of the line-of-sight accelerations. These accelerations represent, approximately, the vertical component of the gravity near the central portion of the frontside face and provide feature resolution of better than 40 to 50 km.

Typical Doppler residuals are shown in Fig. 1 for a 6-minute portion of the seventh revolution; here, the sample rate is one per second. Figure 1 shows the redundancy of the observations in describing each variation. An optimum sample rate of 1 Doppler point per 10 seconds was used in the final reduction, which smoothed the noise while still providing a sufficient number of points for the geometric resolution. The entire pass of the seventh revolution is shown in Fig. 2 at the 10-second sample rate. Also shown are the patched cubic spline fit (second derivative continuous) to the velocity (Doppler) residuals and the analytically differentiated accelerations, plotted as circles. Only three revolutions, which were nonadjacent, were omitted because of communication problems and spacecraft maneuvering events that would corrupt the free-fall gravity analysis. Since the inclination of the trajectory was only 15 degrees to the lunar equator, there was enough redundancy in adjacent orbits so that no significant information was lost.

The acceleration data from the nine Apollo 14 orbits and the short pass of the Apollo 12 LM descent were plotted on Aeronautical Chart and Information Center (ACIC) mercator charts (scale 1 : 1,000,000) and contoured. No normalization factor was applied for altitude variations (that is, the periapsis altitude was 16 km at 5° longitude and 30 km at 50° longitude). These results are displayed in Fig. 3 as a 100-km band from + 70° to − 70° of longitude, contoured at 10-mgal intervals. The dashed lines are continuations from the Apollo 14 to the Apollo 12 data.



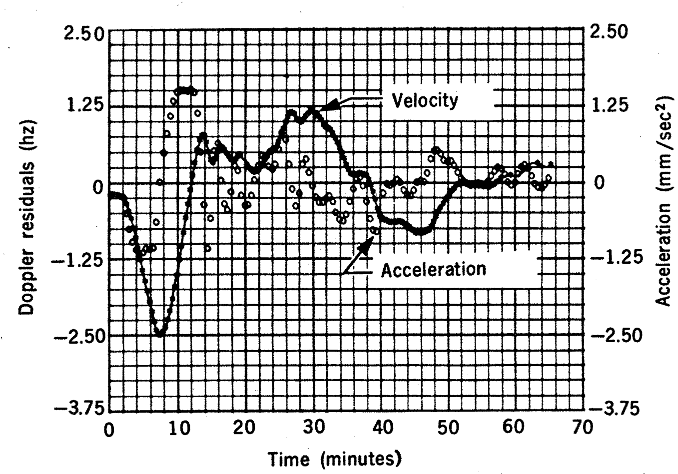


Fig. 1 (left). Doppler residuals from the seventh revolution of the Apollo 14 spacecraft, at a one-second sampling rate. The time is given from 4 February 1971, 19 hours, 38 minutes, Greenwich Mean Time. Fig. 2 (above). Sample data reduction for the Apollo 14 seventh revolution.

The two missions tie together very well at their common features, Ptolemaeus and Nectaris.

The information on the gravitational features of the large craters is summarized in Table 1, based on both Apollo 12 and Apollo 14 data. This table compares the least-squares estimated residual accelerations at typical points with those calculated for the same points from the mass defects implied by the topographic contours on the latest ACIC charts (*3*). These defects were assumed to have a thin ellipsoidal disk shape, with a density of -3 g/cm^3 and the thicknesses indicated in Table 1. (It should be noted that the value of residual acceleration used for Ptolemaeus from Apollo 14 has been reduced by 50 mgal compared with the value in Fig. 3 because of the background in that area.) In comparing the theoretical and observed values of the gravity anomaly, we have also enhanced the residual acceleration by 30 percent to compensate for the typical effect of the least squares filter (*4*). The final comparison shows almost complete agreement, so the visual mass defect explains the negative anomaly without any need to postulate a significant degree of isostatic compensation. This is consistent with the notion that the craters were

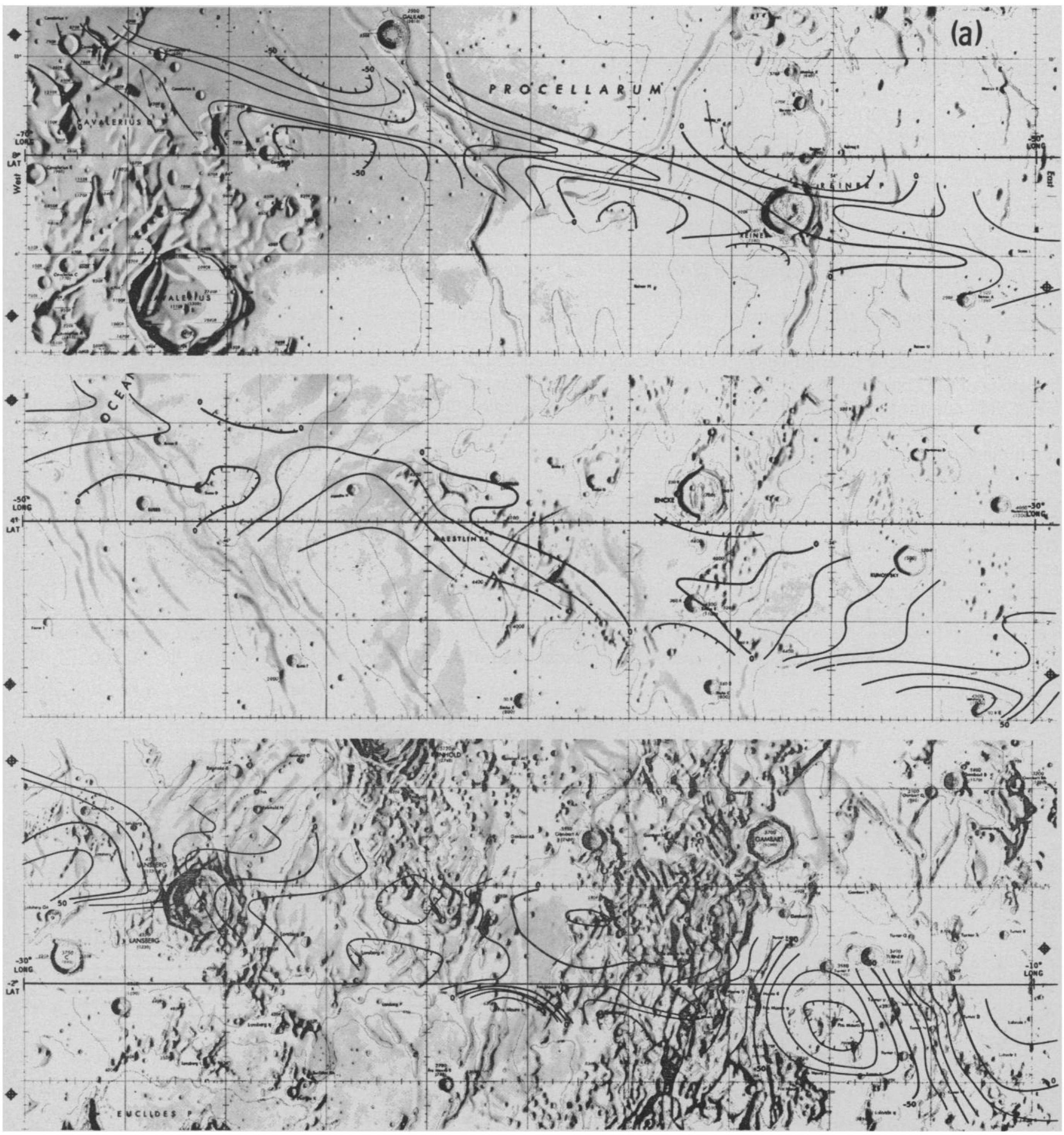


Fig. 3.(a) Lunar gravity map from $-70°$ to $-10°$ longitude. (b) Lunar gravity map from $-10°$ to $+70°$ longitude. The contour interval in both maps is 10 mgal.

formed relatively recently, after the lunar crust had become quite rigid.

Other features of interest apparent from the contour plots are:

1) Cyrillus B seems to be centered in an old crater basin about the size of Cyrillus itself.

2) The Fra Mauro formation is a relative high between the two low adjacent mare areas.

3) Oceanus Procellarum is devoid of large gravity variations. The largest variation is $+60$ mgal near $-30°$ longitude, which does not seem to correlate with any prominent feature.

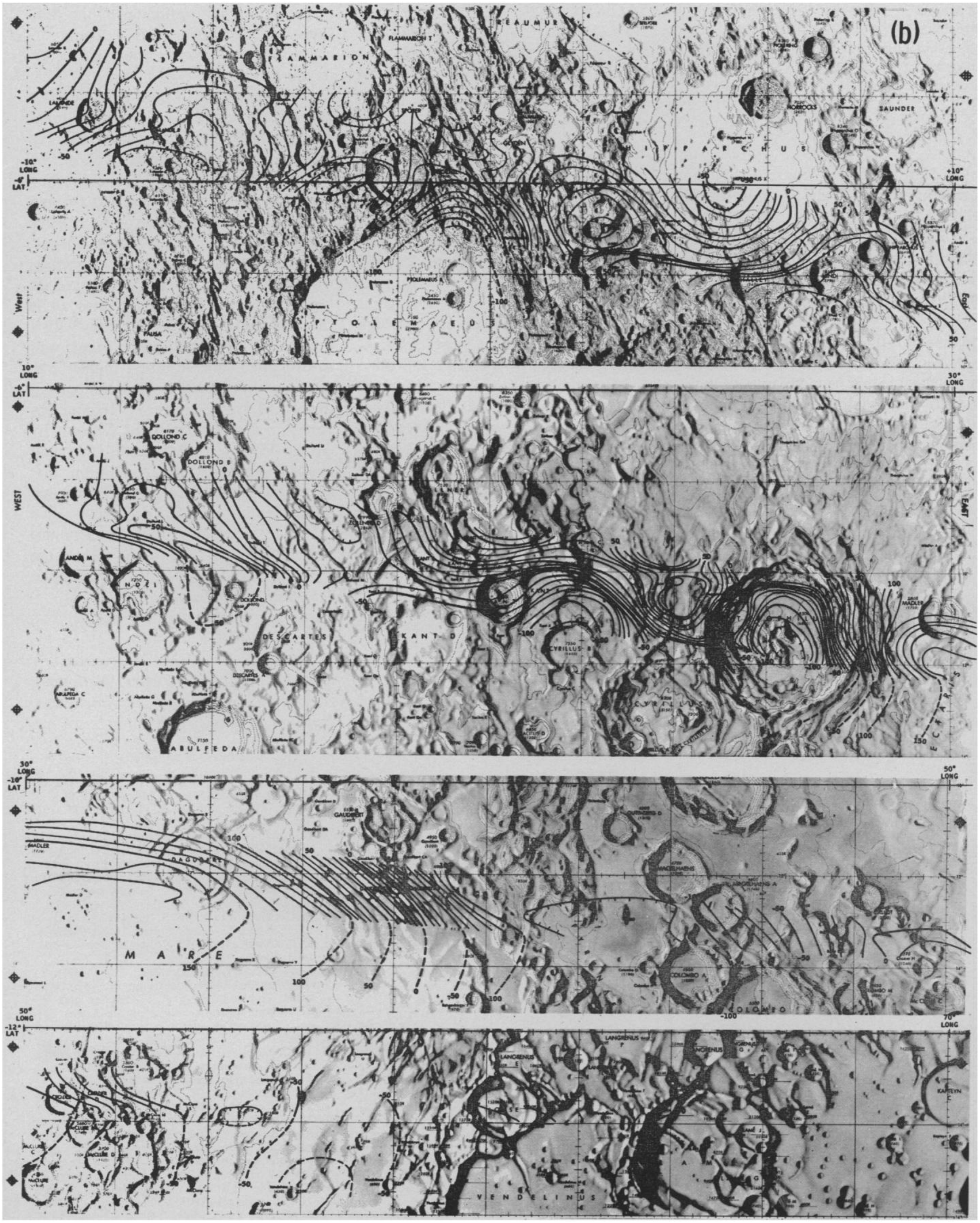


Table 1. Calculated and observed anomalies at selected points over large craters.

Feature	Defect thickness (km)*	Acceleration (mgal)	
		Calculated	30% enhanced residual
Hipparchus	0.9	−79	−67
Theophilus	2.	−152	−145
Ptolemaeus (Apollo 14)	1.5	−55	−78
Ptolemaeus (Apollo 12)	1.5	−135	−158
Albategnius (Apollo 12)	2.2	−162	−127

* From ACIC.

4) Mare Nectaris (mascon) is the dominant gravity high for this set of orbits.

5) There is a definite gravity low in Mare Fecunditatis at 55° longitude, which confirms again that, in general, the "irregular" seas have gravity lows (*2*).

Three of the acceleration profiles over Nectaris are shown in Fig. 4. The consistency in shape and amplitude is evident. The amplitude should increase with the later orbits, since the moon is rotating the center of Nectaris closer to the orbit plane (that is, the first orbit is at the top of the contoured area in Fig. 3 and the last orbit is at the bottom). The flat top profile is very similar to that predicted by Kane (*5*). Simulated accelerations for a 100-km-deep spherical mass and for disks 150 and 200 km in radius are shown for the 11th orbit in the lower part of Fig. 4. The point mass curve is low in amplitude, although it was made 50 percent larger than required to match the Apollo 12 LM data. Its shape is also a poor match because it is too broad at the edges. The 150-km disk, 50 km deep, is too peaked and too broad at the edges. The 200-km disk, 50 km deep, is much too broad at the edges. The 200-km surface disk does a fairly good job of matching; however, the top is still not flat enough, and it appears that some mass should be removed from the center or added to the eastern edge. A follow-up reduction of these data with estimates of the densities of concentric rings is being attempted in a dynamic least-squares fit to the raw data.

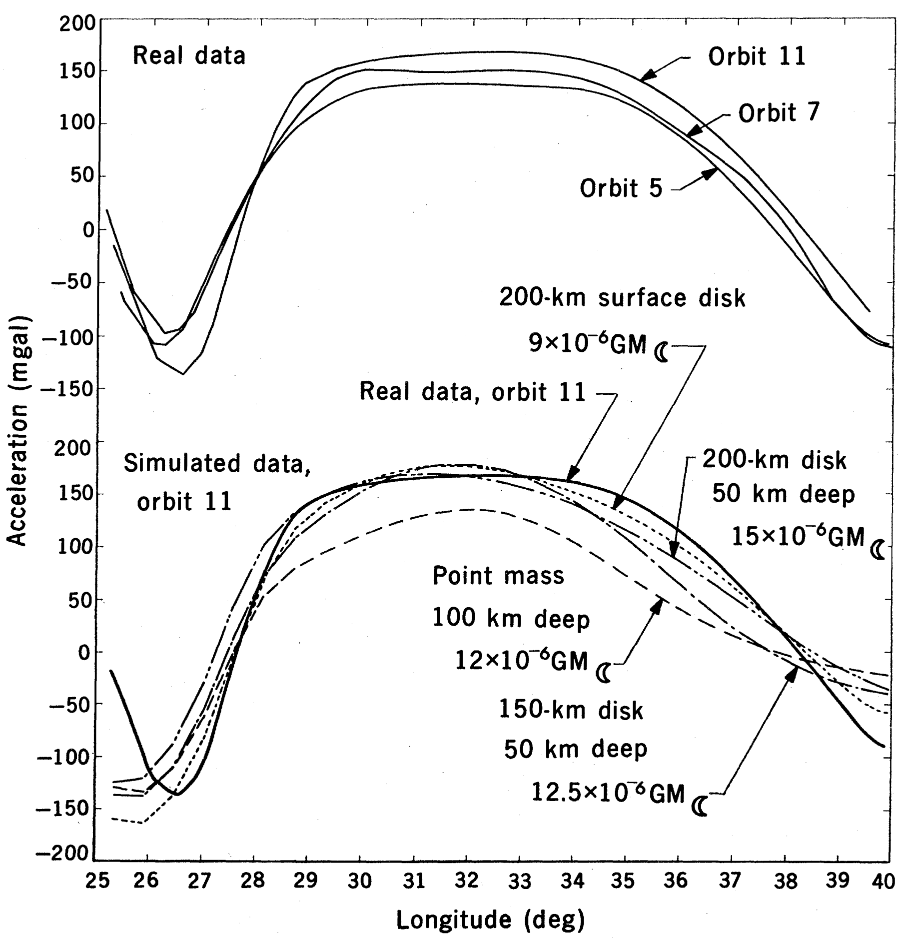


Fig. 4. Apollo 14 gravity profiles over Nectaris; $GM_{☾} = 4902.78$ km^3/sec^2.

It is interesting to note that the 200-km radius surface disk had a mass 800 kg/cm^2. If one assumes that the mascon density differential is 1 g/cm^3 (*6*), this implies a depth of 8 km for the mascon. If the mascon was formed by the transport of material of density 3.0 g/cm^3 (*7*) into a previously isostatically compensated basin, its thickness would be 2.7 km. To accommodate Urey's theory (*8*) that the mascon is the remnant of an impacting body with a density of 4.0 g/cm^3, which mixed and spread out in the resulting impact crater, an object with a radius of approximately 50 km is necessary. If data obtained over Serenitatis and Crisium by Apollo 15 give similar results, they will confirm Booker's (*9*) conclusion that all ringed maria have about the same filling depth.

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10. We thank Nancy Hamata, William Stapper, and Ravenel Wimberly for their excellent computer programming support. This report presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract NAS 7-100.

19 July 1971; revised 28 October 1971