LUNAR GRAVITY: APOLLO 15 DOPPLER RADIO TRACKING*

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Abstract. New detailed gravity measurements were obtained over a 10- to 70-km surface strip from $-70°$ to $+70°$ long. during low-altitude orbits (≈ 12 km at periapsis). The trajectory path (Figure 1) went over the centers of both Maria Serenitatis and Crisium, providing a complete center gravity profile of two large mascons. Consistent with the previous results for Mare Nectaris and Mare Humorum, both Serenitatis and Crisium mascons are approximately disk-shaped near-surface mass anomalies of net uncompensated loading, 800 kg cm^{-2}. This strengthens Booker's contention that all mascons are approximately the same thickness. Also revealed for the first time are significant positive gravity measurements over mountain ranges – Apennines (near Hadley Mountain) and the Marius Hills. The data suggests that the Apennines have undergone some isostatic compensation, whereas the Marius Hills have not. The crater anomalies detected are all consistently negative as observed before, implying loss of mass from the impact event which formed them.

1. Introduction

The technique for extracting local lunar gravity measurements from Doppler radio tracking data has been employed for the past four years. The method attributes the high-frequency variations in spacecraft orbital velocity to local gravity effects. The results from the first application of this technique are given by Muller and Sjogren (1968) and further results and description can be found from Muller and Sjogren (1969), Muller and Sjogren (1972), and Gottlieb (1970). This article will present the results from Apollo 15 data with an analysis and interpretation.

The extent of surface coverage was limited to the trajectory paths of the command and service module during revolutions 3 through 11, when it was at a relatively low periapsis altitude just prior to undocking with the lunar module. Only the data during this period will be considered, since the data during the higher orbits of 100 km or more are essentially redundant with the initial results presented by Muller and Sjogren (1968). The trajectory was close to the most optimal for study of the details of the Serenitatis and Crisium mascons. Periapsis altitude was about 12 km at the center of Mare Serenitatis, one of the largest mascons, and the one in the most favorable viewing geometry. The orbit trace is shown in Figure 1. All orbits crossed each other at the center of the figure (0° long.) and provided narrow coverage there, while coverage west of Crisium was about 70 km wide.

2. Observations

The contoured line-of-sight accelerations obtained from the reduction are shown in

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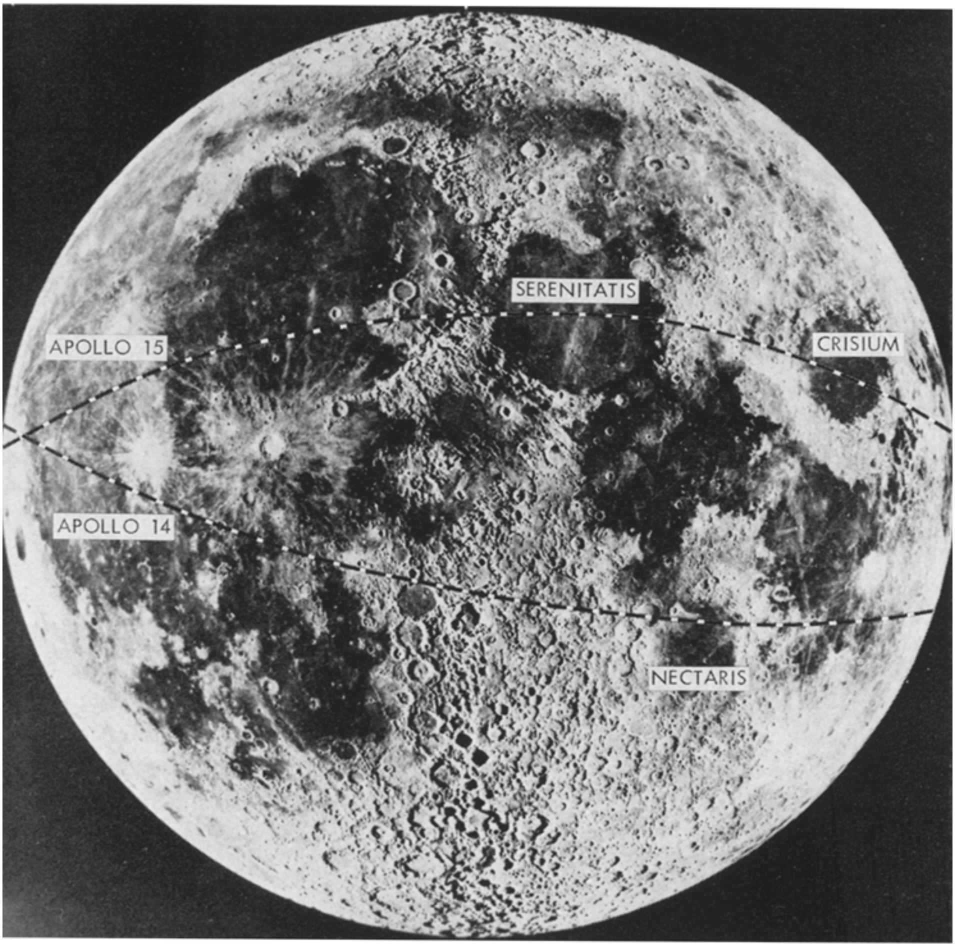

Fig. 1. Apollo 14 lunar surface track.

Figure 2. Over 2500 Doppler observations were reduced in the least-squares filter and then differentiated for the gravity information. No corrections have been applied to account for (1) viewing geometry, or (2) the leastsquares filtering effects (Gottlieb, 1970), which reduced the true amplitude by 30%, or (3) altitude, which varied from 30 km at +70° long to 12 km at 17° periapsis long., and to 52 km at −70° long. Features identifiable on the plots are: (1) the western edge of Oceanus Procellarum at −65 mgal, (2) the Marius Hills at +65 mgal, (3) several positive and negative anomalies in Oceanus Procellarum that do not appear to correlate with any surface feature, (4) two positive anomalies in the outer Imbrium basin of +54 and +61 mgal at −27° and −19° long., respectively, which seem to correlate with wrinkle ridge regions, (5) the −150 mgal anomaly in Palus Putredinis, (6) the Appenines at −9 mgal (however, the relative local anomaly as seen in the Figure 3 profile is 85 mgal), (7) Mare Serenitatis at 235 mgal, (8) the −225 mgal anomaly at 32° long., (9) the

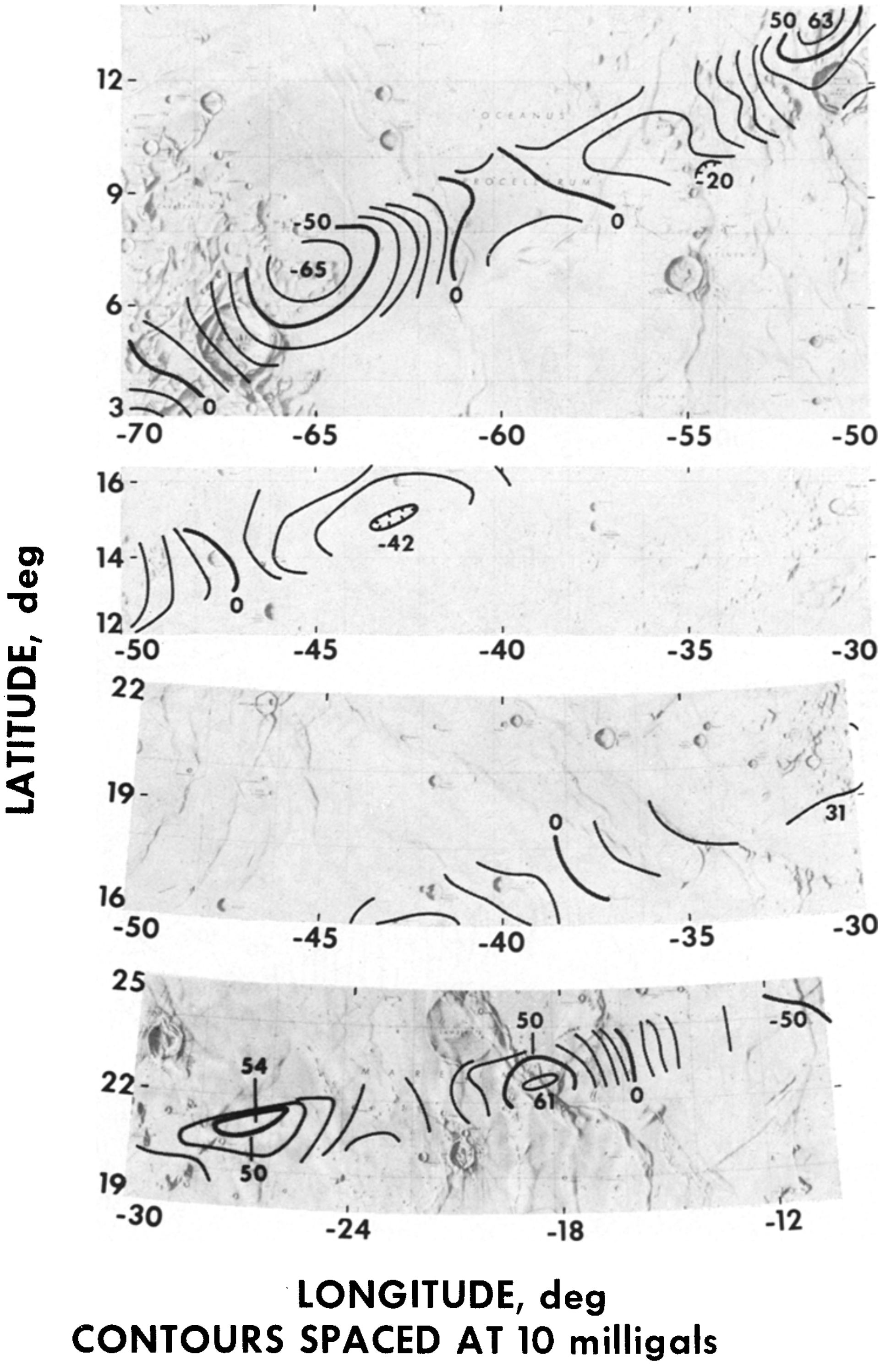

Fig. 2a. Gravity contours from Apollo 15 data: − 70° to − 10° long.

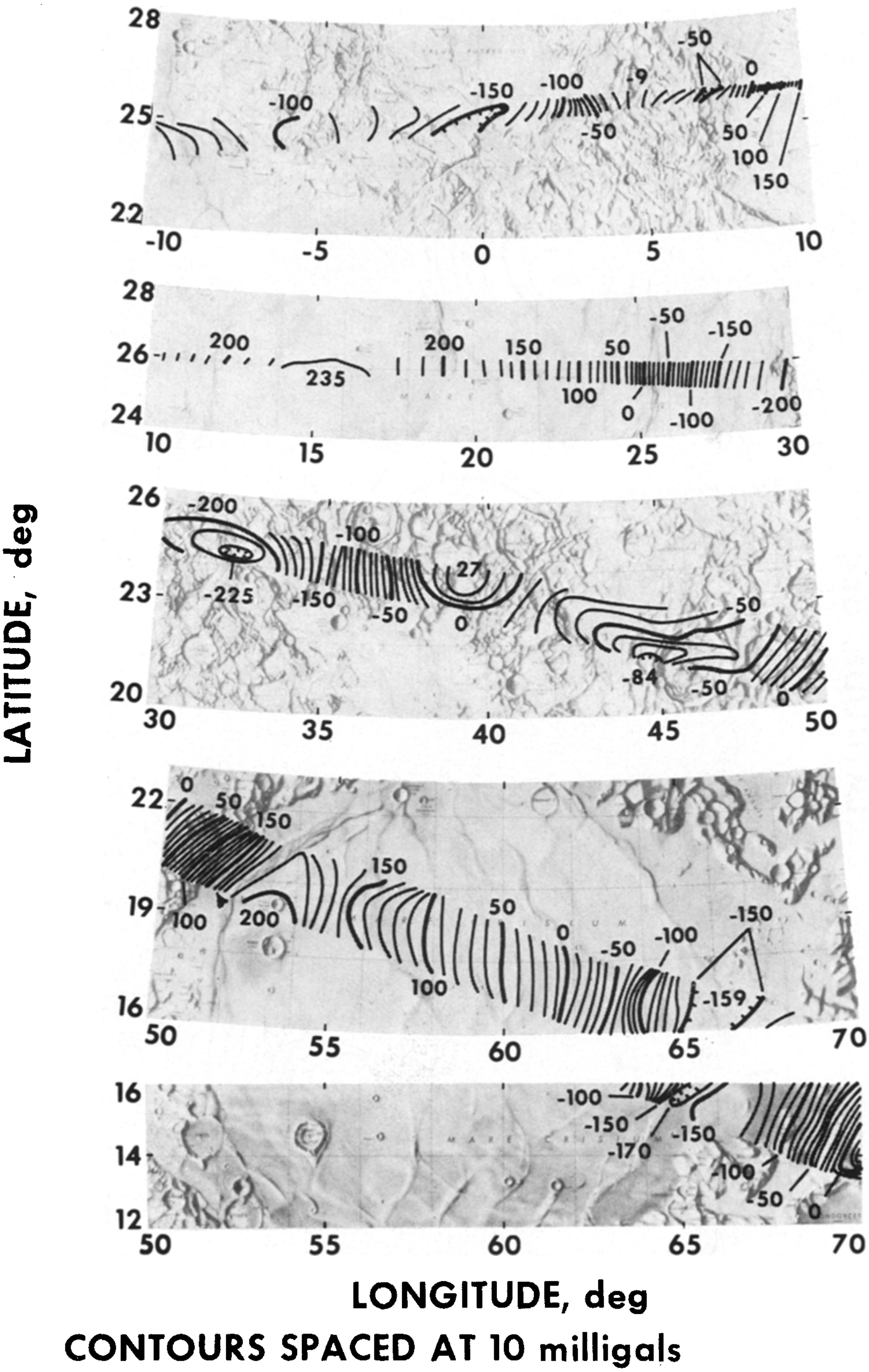

Fig. 2b. Gravity contours from Apollo 15 data: $-10°$ to $+70°$ long.

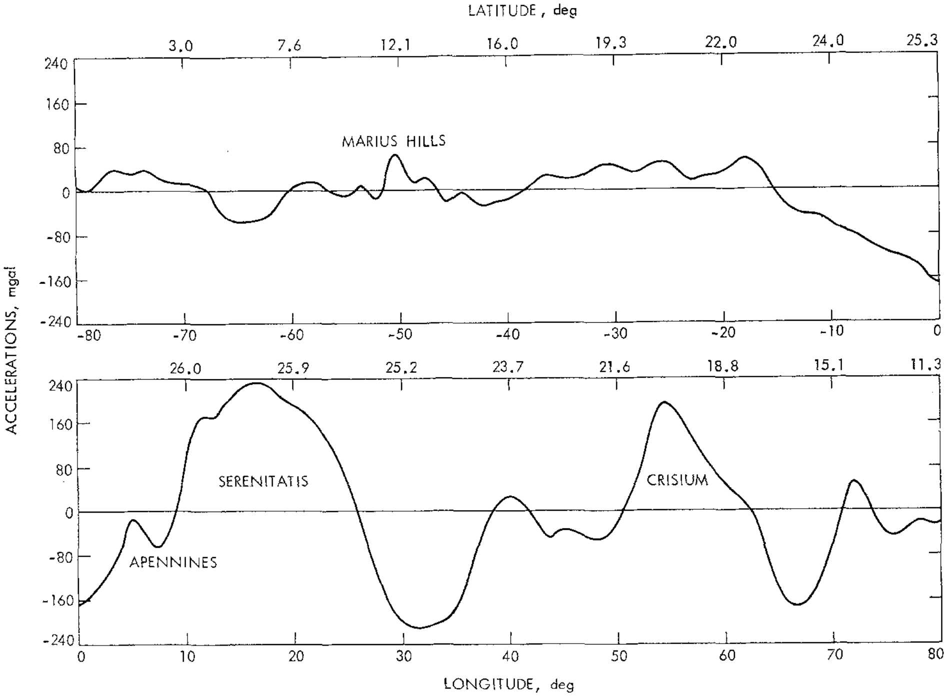

Fig. 3. Gravity profile orbit 9 Apollo 15.

27-mgal high at 39° long., (10) the crater Macrobius at −84 mgal, (11) Mare Crisium at 200 mgal, and (12) the −170 mgal anomaly on the eastern edge of Crisium. The large negative regions both to the east and west of the mascons are overenhanced due to the filter (as will be explained in the following). A profile along the trajectory ground path for revolution 9 is shown in Figure 3.

3. Analysis

Analysis began with the large mascon anomalies in Serenitatis and Crisium. We studied these in detail, using theoretical models to simulate the raw radio observational data resulting from assumed masses, shapes, and depths. These simulated data were then filtered in identically the same manner as the real observations, and the acceleration profiles from both real and simulated data were compared. In our previous reports this type of comparison was accomplished with a trial-and-error input. The results in this article are based, in part, on an actual least-squares convergence of two acceleration profiles (real and simulated) where the masses, diameters of the disks, and longitudes of the disks were optimized. The results from various mass models are shown in Figure 4 for Serenitatis and Figure 5 for Crisium. It was shown by Sjogren (1972), Sjogren and Wollenhaupt (1973), Muller and Sjogren (1972), and Phillips *et al.* (1972) that the best model is a near-surface disk, as both the point

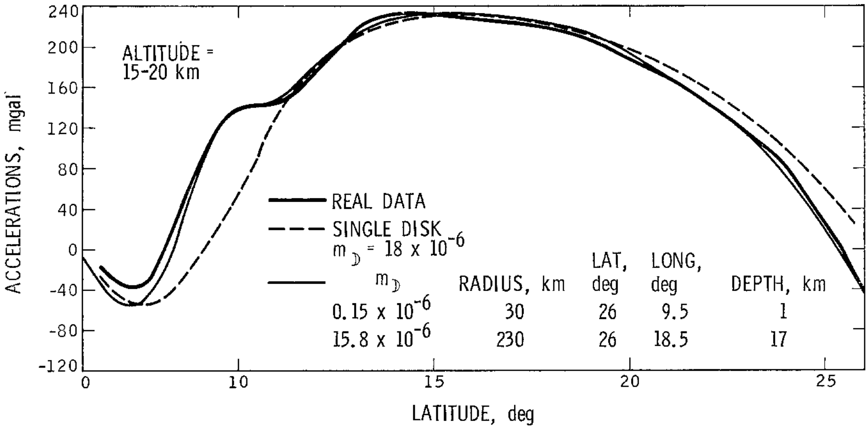

Fig. 4. Serenitatis gravity profile and models.

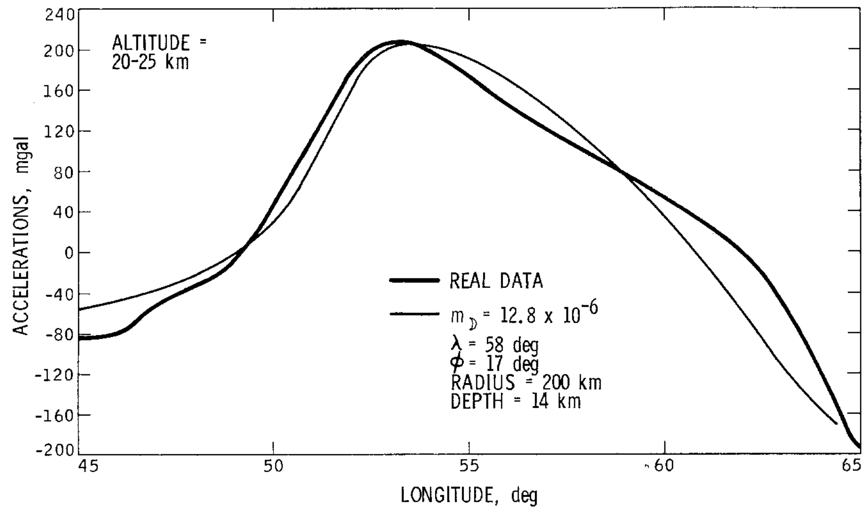

Fig. 5. Crisium gravity profile and models.

mass for a deeply buried sphere or a disk at depth do not provide as good a fit. In this paper, only disk-shaped masses are simulated.

There is now data for four mascons: Serenitatis, Crisium (from Apollo 15), Nectaris (Sjogren *et al.*, 1972) and Humorum (Sjogren and Wollenhaupt, 1973) which indicate that they are all very similar near-surface disk-shaped masses approximately centered in their topographic basins, with uncompensated net mass-loadings of 800 kg cm^{-2}. This is consistent with Booker's claim (Booker *et al.*, 1970) that all mascons are approximately the same thickness. Note also the additional mass-disk required at +9.5° longitude (Figure 4) to better fit the observed data.

Figure 3 reveals large negative anomalies on both sides of Serenitatis and Crisium. This effect was noted by Muller and Sjogren (1968), and further comment was provided by Gottlieb (1970), which cast serious doubt on their validity. However, since the direct dynamic method of surface mass determinations (Wong *et al.*, 1971) does produce negative mass solutions in these regions, we have studied simulations and find that about -50 mgal is added by the least-squares processing in trying to minimize the large anomalies from the mascons. Therefore, a large portion of these negative anomalies are valid and may have a geophysical interpretation.

Two other major features shown in Figures 2 and 3 are defined by the Marius Hills and the Apennine Mountains. While determinations of mountain volumes from lunar altimetry and geophysical maps are quite uncertain, it is clear that the Apennines contain several times the mass of the Marius Hills. In our opinion, this conclusion remains true even when we consider the gravimetric 'footprint' or 'region of influence'

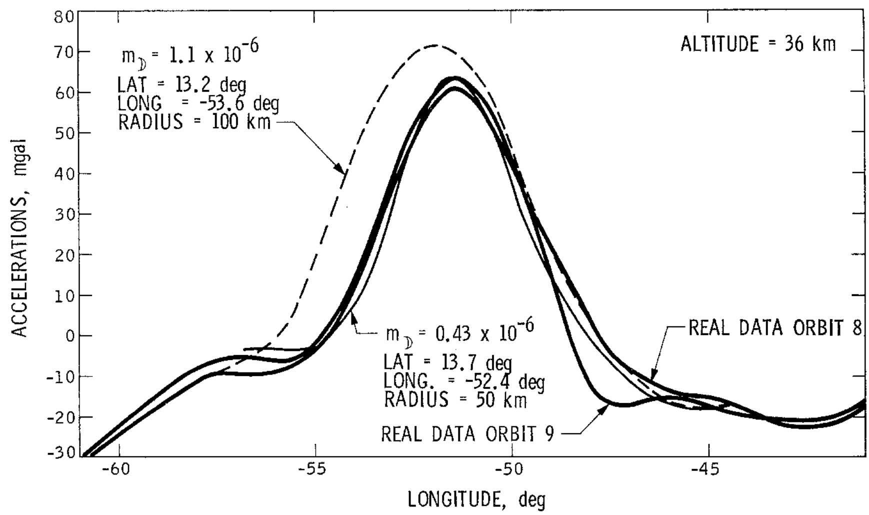

Fig. 6. Marius Hills gravity profile and models.

of the spacecraft, which is our gravitational sensor. Since the local high-frequency gravity anomalies are similar (80 vs 65 mgal), we undertook to study this phenomenon in more detail.

Figure 6 provides a close look at the Marius Hills data and the results of comparative simulations, using several mass models. Since the Marius Hills are not in a region affected by large negative anomalies like those bordering Serenitatis, we utilized the gravimetry directly without any other masses. For comparison, an initial model was plotted, 1.1×10^{-6} lunar masses (0.81×10^{20} g). This was too large a mass, as can be seen by comparison with the actual data for Revolutions 8 and 9. A good fit was obtained with a 50-km radius disk having 0.43×10^{-6} lunar masses (0.316×10^{20} g) and located at lat 13.7°, and long. $-52.4°$.

Figure 7 shows the gravity profile of the region bordering Serenitatis and containing the Apennine Mountains. Because of the large negative anomaly (Figure 3), we must apply a local correction to obtain the high-frequency gravity information corresponding to the Apennines. This was simulated effectively by placing a negative mass-disk at longitude zero under the trajectory. Figure 7 indicates the signature of the real data and that simulated by the two mass disks. The result for the Apennines was a mass disk of radius 50 km, mass 0.18×10^{-6} lunar masses (0.132×10^{20} g) at lat. 25.7°, long. 5.2°.

Examination of lunar topography from the ACIC Lunar Charts (1962–1970) and from the Apollo 15 laser altimetry (Kaula *et al.*, 1972), indicates clearly that the

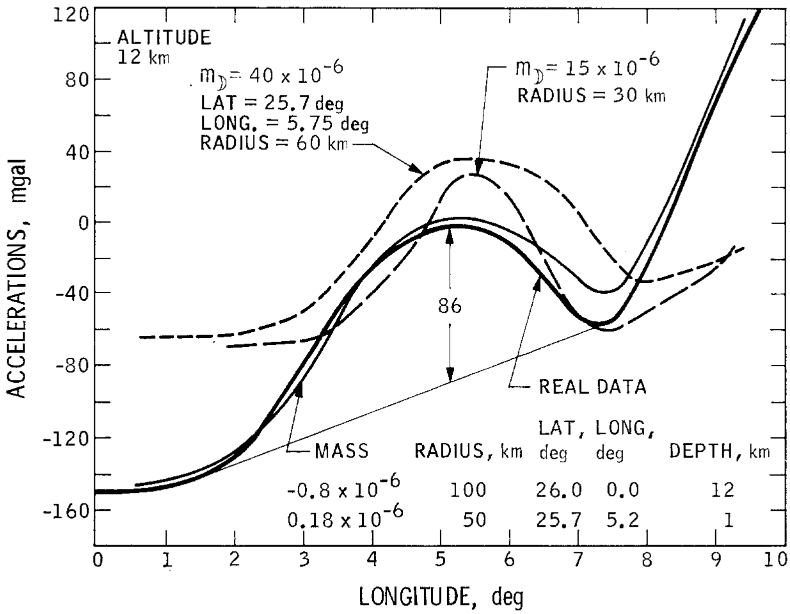

Fig. 7. Apennines gravity profile and models.

Apennines have at least one order of magnitude more mass above grade than the Marius hills. From this we can draw a qualitative conclusion, pending further detailed study, that the Marius Hills are not isostatically compensated, and the Apennines are isostatically compensated in large measure. The combination of altimetry and gravimetry is a powerful tool, and one which should have wide application in the near future. We have attempted to present the data in this paper in such a form that the interested reader can make his own calculations of relative isostasy.

The Cavalerius region (Figure 3) is the other major anomaly visible in this data. It corresponds to a 'trough' between highlands at $-70°$ long., and wrinkle ridges in Procellarum at longitude $-62°$. The altimetry (Kaula *et al.*, 1972) shows this as the edge of the western highlands, indicating a major geologic unit change that could reflect a gravity deviation.

Another interesting feature that surely has geological importance is the definite shoulder in the Serenitatis gravity anomaly at longitude 12°, there is a hint of similar behavior at long. 20°. Such an observation is an indication of abrupt mass change, implying a change in structure. This may be part of the ring structure of these seas revealed by wrinkle ridges and altimetry changes. The mascons, therefore, do not always precisely correspond with the geometric edges of the seas, and we feel that this is strong evidence for subsurface structuring in these basins which remains to be explained. Whitaker's UV–IR map (Whitaker, 1972) shows different maria material areas in the Serenitatis basin which could possibly be correlated with this shoulder.

4. Conclusion and Summary

The Serenitatis and Crisium mascons join with Nectaris (Sjogren, 1972) and Humorum (Sjogren *et al.*, 1973) as uncompensated mass excesses of 800 kg cm^{-2}. This corresponds to a 2.7-km thickness of 3.0 g cm^{-3} material, and supports the suggestion of equal mass distribution per unit area (Booker *et al.*, 1970). The eastern gravitational boundary of Serenitatis is some 4 deg short of the geometrical edge, and correlates with a distinct ridge in the photography. This may indicate significant structure of an unusual nature. The Marius Hills and Apennine mountains yield anomalies with 50-km radius disk masses of 0.43 and 0.18×10^{-6} lunar masses (0.32 and 0.13×10^{20} g), respectively. It can be concluded from this and the topography data that the Marius Hills are essentially uncompensated, while the Apennines are largely isostatically compensated. There are also several large negative anomalies observed that are as yet unexplained but on which we have speculated below.

5. Some Speculations

Muller and Sjogren (1972) presented a schematic theory of mascon formation. First, the Moon forms a crust (presumably by differentiation of lower density than the interior. Second, the ringed-seas are formed by asteroidal impacts (the presently accepted explanation). Third, the initial impact-created ringed-seas backfill from below until isostasy is achieved, leaving a shallow basin of a few kilometers depth, due to the density contrast of crust versus interior. Fourth, the outer portion of the Moon achieves and retains sufficient strength to oppose further isostatic compensation of large stresses (50 to 400 bars) for the remainder of lunar history. Fifth, the basins are further filled above isostasy with some 2.7 km of additional matter to produce the observed anomalies. The apparent need for an early crust-differentiated Moon, with isostasy, and great crustal strength later, has been the crux of recent debates on lunar structure and history. The inference of great crustal strength for the Moon since the mascon formation has, in fact, been the main significance of the mascon observation. Runcorn and Urey (1973) present a model requiring a similar time-line of lunar crustal structure and behavior as part of an attempt to realize a satisfactory overall lunar structural history. It is possible that the core of the Moon has only recently reached upward to a depth of 800 km (epicenter of deep moonquakes according to

Latham (1972). If this is a valid interpretation, deep internal heating and core-formation has not yet played a significant role in lunar crustal history.

We believe that data presented in this and our previous work lend support to this kind of lunar structural history. The lunar craters such as Ptolemaeus, Alphonsus, and many others previously observed gravimetrically, plus the Marius Hills noted in the foregoing, have all retained close to their full gravitational anomalies. That is, they have not isostatically compensated. Presumably these features represent a recent, decidedly post-Imbrium set of events. The mascons themselves, also presumably post-Imbrium, present large, scale uncompensated nonisostatic stresses to the Moon. On the other hand, the Apennines, presumably formed simultaneously with the Imbrium impact, and the central highlands (presumably much older) have largely been isostatically compensated. The Apennine data is presented above, and that for the highlands can be found in the report by Sjogren *et al.* (1973). It can be seen from the data there that, while the highlands extend generally over the region lat. 0° to $-45°$ and long. 0° to $+30°$, the gravimetry ranges irregularly over the modest limits of -30 to $+30$ mgal, except for a small fraction of the total area in the region of the Altai Scarp, where there is a $+50$ to $+70$ mgal strip. It is possible that detailed altimetry and suitable calculation would reveal that this entire area, *including* Altai Scarp, is essentially isostatically compensated. However, it is clear that most of it is very close to isostasy, as was pointed out by O'Keefe (1968) from the early data. We suggest that several lines of reasoning and strong data support the conclusion that lunar crustal history has been one of early plasticity and later strength, rather than the reverse. These points are compatible with the mascon formation model of Muller and Sjogren, (1972) and the new lunar history model of Runcorn and Urey (1973).

The negative anomalies listed early in this paper, plus the negative rings around mascon seas previously noted (Muller and Sjogren, 1970; and Muller and Sjogren 1972) and easily visible in gravimetric mappings (Sjogren *et al.*, 1973) remain to be explained. We would like to suggest that some of these may represent the near-surface areas out of which material flowed to produce the mascons. The weaknesses, or structural waves, caused by the impacts could be a factor; for a set of alternating rings can be seen around Orientale, presumably the most recent mascon impact sea (Muller and Sjogren, 1969). Hopefully, suggestions of this kind can be investigated by attempting to correlate observed gravimetry with altimetry, spectral reflectivity, geological mappings, and the other data types available globally from the research teams participating in lunar study.

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