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A New Method of Planetary Gravimetry

by

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ABSTRACT

Before 1968, it had been impossible to make high-resolution global gravimetric maps of planetary bodies. To be sure, gravimetry traverses had been run over limited regions of the earth, and spacecraft perturbations had revealed the basic shapes of both the earth and moon. It has not been possible, however, to gravitationally map the earth or any other planetary body well enough to reveal the detailed local gravity variations so important to geophysical research and planetology.

This essay describes the new and unique method of direct gravimetry invented by the authors, and demonstrates how this technique was applied to making the first detailed gravity mapping of another planetary body (the moon). The consequent discovery of mass concentrations under the lunar ringed seas has had considerable impact on our understanding of lunar structure and history. It is likely that this technique will be a mainstay in the future determinations of earth and planetary gravimetry.

Spacecraft orbiting the earth have been used for over ten years as platforms from which physical observations could be made for a global scale. In orbital free-fall, however, it is clearly impossible to make direct on-board measurements of the acceleration due to gravity. Gravimetry from orbit can only be attempted by observing spacecraft velocities at a distance. For low earth orbiters, there is the additional difficulty of very short, widely spaced, tracking periods. These factors combine to limit the resolutions of the obtainable gravimetry.

With a spacecraft orbiting about a distant primary, the coverage problem is removed, and each orbital traverse of the distant planet is viewed completely from a single earth tracking station. The problem then becomes the extraction of all the gravimetric information contained in the complex data signatures obtained.

The precision radio-doppler tracking system is illustrated schematically in Figure 1. The Cesium clock controls the ground transmitter frequency, and supplies the same highly stable (1×10^{-12}) signal to be compared with the received frequency. The signal transmitted to the spacecraft, is amplified and multiplied coherently by the fixed ratio 240/241 , and is retransmitted. The received signal is compared with the Cesium frequency multiplied by the same ratio and the resulting Doppler (frequency difference) is a direct measurement of the spacecraft velocity relative to the station antenna. This system is capable of resolving velocity changes to an accuracy of approximately .05 mm/sec.

The doppler data contained many components of velocity that had to be removed before analysis of local lunar gravity could be started. Such motions as the earth rotation and the orbital motion about a point mass moon were the primary contributors. The remaining signal variations (residuals) were then attributed to the local gravity field. Other workers using these doppler observations had proceeded with the classical technique of determining coefficients of a spherical harmonic expansion of the potential function and viewing the residuals as their "goodness of fit". Our approach is to remove only the central point mass term from the potential and then directly evaluate the residuals. This could be done without much loss because of the unique geometry coverage (i.e. 180° arc) allowing frequencies in the gravity field smaller than 180° to be directly visible in the residuals. By fitting analytic functions* to the residuals and differentiating them, line-of-sight accelerations were obtained. Near the center of the moon, this is essentially the vertical component of gravity.

Using 80 orbits from a polar orbiter it was possible to have coverage of the entire front hemisphere of the moon. Each orbit was independently reduced and accelerations determined as mentioned previously. Since the orbital paths were only 2° apart there was considerable redundancy over many large features. The accelerations were plotted on a lunar map at the appropriate spacecraft latitude and longitude and then contoured. The resulting product is shown in Figure 2. (Ref. 1) It was the first detailed gravimetric map of a foreign body, providing more detail globally than our earth gravimetric maps.** The method is one that can be exploited for the earth using a high altitude relay satellite tracking a small low altitude satellite.

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* Patched cubic splines with 2nd derivatives continuous.

** Reference 2

The fact that no satisfactory explanation for the origin of lunar mascons has yet been offered is yet another testimonial to the frequently observed truth that gravity effects are among the most subtle and mysterious natural observations. During the last three years, we and our many colleagues in lunar studies, have begun to understand what they are, and more importantly, what they imply for lunar science.

If the gravity anomalies over the ringed sea basins (which are topographic depressions of 2 km) had been large negatives (lower than average gravity), then the map would have been just as good, the "Mascons" just as obvious, but the strong implications would have been lacking. We can also look at the earth, where small lakes and great mountain ranges alike, have long ago risen or fallen into isostatic equilibrium wherein the gravitational anomalies are small. Only very recent lava flows, or large convestional effects in the mantle, show up on earth gravimetry.

On the moon, however, the picture is quite different. We observe large gravity excesses over depressed basins. Ordinary physics quickly reveal three implications. (1) There is more mass than the average in these areas. This is true because only mass, in so far as we know, can produce gravity. (2) There is a considerable volume of significantly higher density matter in these basins. This follows from the extra mass in a reduced volume. (3) The mass concentrations are exerting a stress on the interior structure of the moon. This conclusion is less obvious, but even simple hand calculations based upon first principles show that 200 milligals anomalies cannot be produced under these circumstances by masses which are isostatically compensated (floating in the Archimedean sense on a lunar mantle). In fact, if such were the case, we should see about -20 milligals in Serenitatis, for example, rather than the observed +200 in the absence of large scale density inversions. Even recourse to this unpalatable geophysical assumption cannot produce reasonable isostatic models.

One of the first questions our colleagues asked us was "what shape or density models satisfy the mascon observation?" In the early work, the observations were taken from high altitudes (100-200 km) and we could not resolve this question. Low Apollo spacecraft,* which have the same navigation system as Lunar Orbiter, provided the answer with observations taken at 10 km altitudes. The mascons are very nearly disk-shaped, and are close to the surface. This observation has ruled out buried spheres at depths of hundreds of kilometers as had been earlier considered possible. They are equivalent to a plate of lunar rock some 3 km thick and 500 km in diameter for the largest examples such as Serenitatis and Imbrium. It need not be emphasized that this is a ponderable mass indeed!

The presence of this "weight" on the lunar surface has constituted a stress experiment on the lunar interior of presumable geologic origin. The force required to sustain the mascons from gravitationally fatal subsidence is 50 to 400 bars depending upon the depth at which they are supported. Low limits of 800°C on the internal temperature of the moon since mascon formation, presumably billions of years in the past, have been calculated from this information (Gilvarry, 1970).

It can be seen from these examples that the gravimetry of the moon has provided some strong implications which in turn have had, and continue to have, considerable impact on proposed theories of lunar history and structure. The debate continues, with gravimetry one of the central observations,

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* Reference 3

and the thorn in the side of many theories previously considered established. Such is an appropriate setting for a gravity phenomenon, and another example of the mystery of gravitation.

<u>References</u>:

1. P. M. Muller and W. L. Sjogren, <u>Science</u>, 161, 680 (1968).

2. M. F. Kane, J. Geophys. Res., 74, 6579 (1969).

3. W. L. Sjogren, P. Gottlieb, P. M. Muller, and W. Wollenhaupt, <u>Science</u>, 175, 165, (1972).

<u>Brief Bibliography</u>:

William L. Sjogren is a Member of the Technical Staff of the Jet Propulsion Laboratory and Principal Investigator on two Apollo experiments. Paul M. Muller is a Group Supervisor (Earth-Lunar Physics) at the Jet Propulsion Laboratory, and a Co-Investigator on the lunar gravity science team. They received the NASA Exceptional Scientific Achievement award in 1969, and the Magellanic medal of the American Philosophical Society in 1971 for their discovery of the lunar mass concentrations.

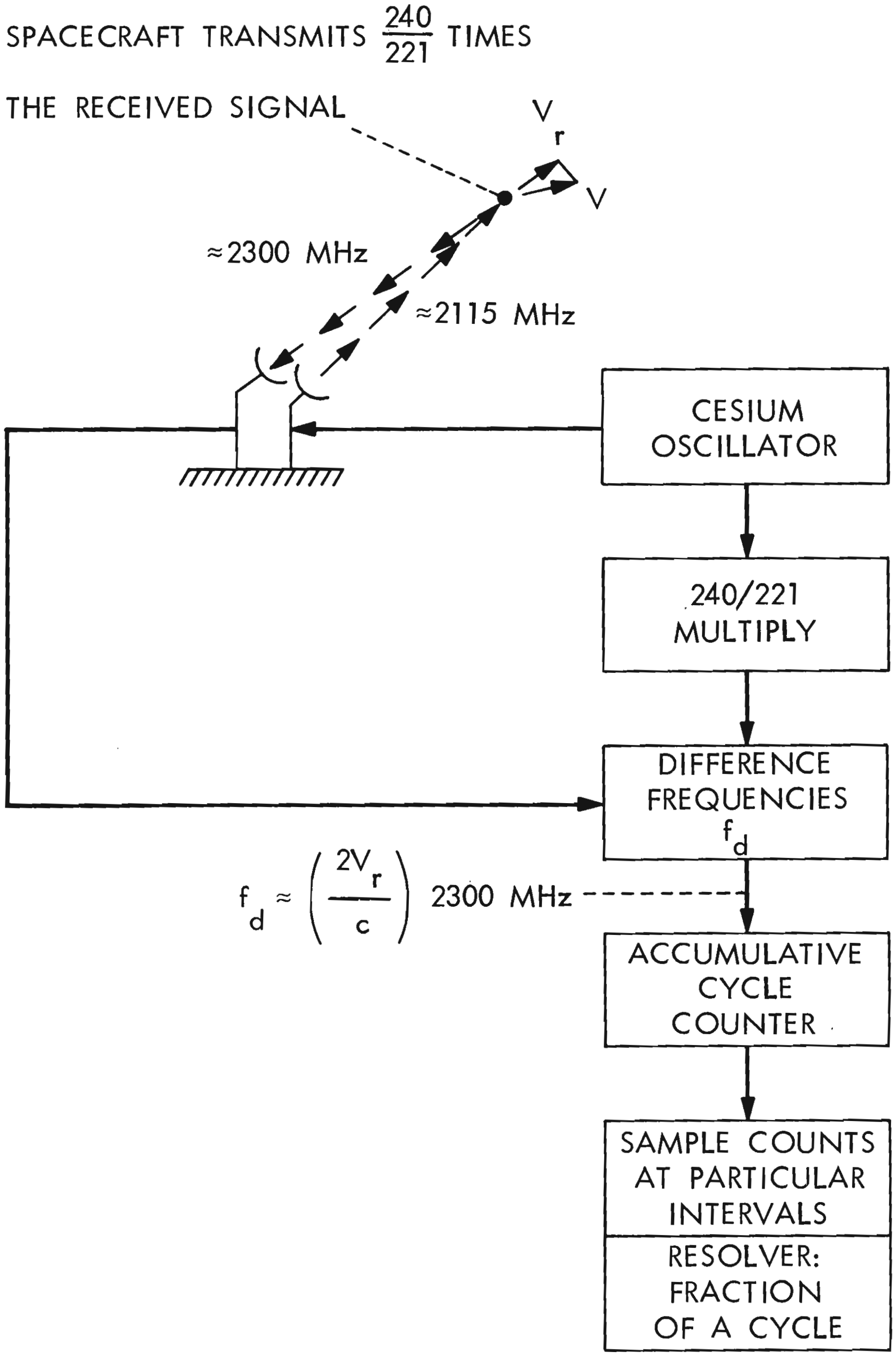
SPACECRAFT TRANSMITS $\frac{240}{221}$ TIMES THE RECEIVED SIGNAL
V_r
V
≈2300 MHz
≈2115 MHz
CESIUM OSCILLATOR
240/221 MULTIPLY
DIFFERENCE FREQUENCIES f_d
$f_d \approx \left(\frac{2V_r}{c}\right)$ 2300 MHz
ACCUMULATIVE CYCLE COUNTER
SAMPLE COUNTS AT PARTICULAR INTERVALS
RESOLVER: FRACTION OF A CYCLE

Fig 1