THE ISOSTATIC STATE OF THE LUNAR HIGHLANDS FROM SPATIO-SPECTRAL LOCALIZATION OF GLOBAL GRAVITY, TOPOGRAPHY, AND SURFACE CHEMISTRY;

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Introduction. The nature of isostatic support of topography in the lunar highlands provides important clues to the processes of crustal formation and early crustal evolution. The chemistry of a crust formed by crystallization in a lunar magma ocean could be either heterogeneous or nearly homogeneous in density, depending on the horizontal length scales for convection in the cooling magma ocean and the mixing processes (e.g., impact mixing, remelting, serial magmatism) during crustal cooling [e.g., 1]. In a crust that is compositionally homogeneous on lateral scales of tens of kilometers and greater, elevation differences would be supported by an Airy compensation mechanism (i.e., variations in crustal thickness), whereas lateral variations in crustal composition and therefore crustal density at such length scales would contribute to isostatic support of elevation differences through a Pratt mechanism. Even if the earliest lunar crust varied only radially in density, lateral variations might now be present if a layered crust has been differentially excavated by large impacts [2] or if the earliest crust was variously intruded by later mantle-derived magmas [e.g., 3]. The total volume of the lunar crust, a quantity of importance for constraining models of large-scale differentiation and bulk composition, is sensitive to the assumed mechanism of highland isostasy.

Correlations of surface elemental chemical abundances mapped by Apollo subsatellites with lunar elevation prompted the first consideration of Pratt compensation models for the lunar highlands. For those limited areas for which Al/Si and Mg/Si ratios were measured by X-ray fluorescence and Fe and Mg concentrations were also measured by γ-ray spectrometry [4], densities calculated from normative mineralogies (and assumed to be representative of the underlying crustal column) show a negative correlation with elevation and a best-fitting slope consistent with a significant Pratt component to compensation [5]. For a larger set of regions including many for which Fe concentrations were estimated but X-ray fluorescence data were not obtained, the slope of density (estimated from a simpler algorithm) versus elevation is less and suggests a smaller Pratt component to isostasy [6].

It is worth reexamining this issue, for two reasons. First, important new data relevant to this topic have recently been obtained by the Clementine mission. New lunar topography and gravity fields [7] have extended earlier measurements to higher latitudes and to much of the backside. Analysis of multispectral images from the Clementine mission has yielded a new global map of surface Fe concentration [8]. Second, we have been developing new spatio-spectral localization methods [9] which permit a rigorous examination of the trade-off between spatial and wavenumber resolution to be explored on a regional basis using spherical harmonic representations of gravity and topography for bodies (such as the Moon) on which the gravity-topography relation displays strong regional or geological variations. Such a method is critical for extracting the full information content of the latest global gravity and topography fields (as well as for demonstrating what information cannot yet be resolved).

Localization Method. We perform our localization first in the spatial domain, by windowing the given harmonic field. This spatial windowing can be viewed either as spectral convolution of the given scaling window with the data or as a projection of the data onto a set of basis functions formed as products of a single harmonic and the scaling window [9]. If a window (e.g., a smoothed spherical cap centered at a given position, or a mare-highland function) is expanded into spherical harmonics, it is straightforward to calculate the coefficients of the windowed field. Further, if the window can be expressed in terms of a finite number of coefficients with a maximum degree L_{win} and if the data are of maximum degree L_{obs}, then there is an effective Nyquist degree for the windowed field equal to $L_{nyq} = L_{obs} - L_{win}$. This simple but powerful relation provides a basis for evaluating the trade off between increasing spatial localization (increasing L_{win}) and maximizing the spectral resolution of the localized field (maximizing L_{nyq}). Transfer functions between fields (e.g., admittance) are calculated from localized (windowed) fields and thus vary both spatially and with wavenumber. To compare such transfer functions with those for forward models, it is important to subject the models to the same operations as the data.

Results. Our first step has been to characterize the spectral information contents of the new gravity and topography fields and their dependence on position on the Moon. The rms free-air gravity anomaly S_l (the rms magnitude of the product of the global field at that harmonic and a wavenumber-dependent, azimuthally isotropic window centered at that location) for selected harmonic degrees l are shown in Fig. 1 (0° longitude center). A global mean value has been subtracted from each figure. Thus positive (solid lines) and negative (dashed lines) values denote rough (high lateral gradients) and smooth (small lateral gradients) areas of the field at the indicated wavelengths. At the lowest degrees ($l \leq 6$), the highest rms anomalies are over the southern farside, approximately

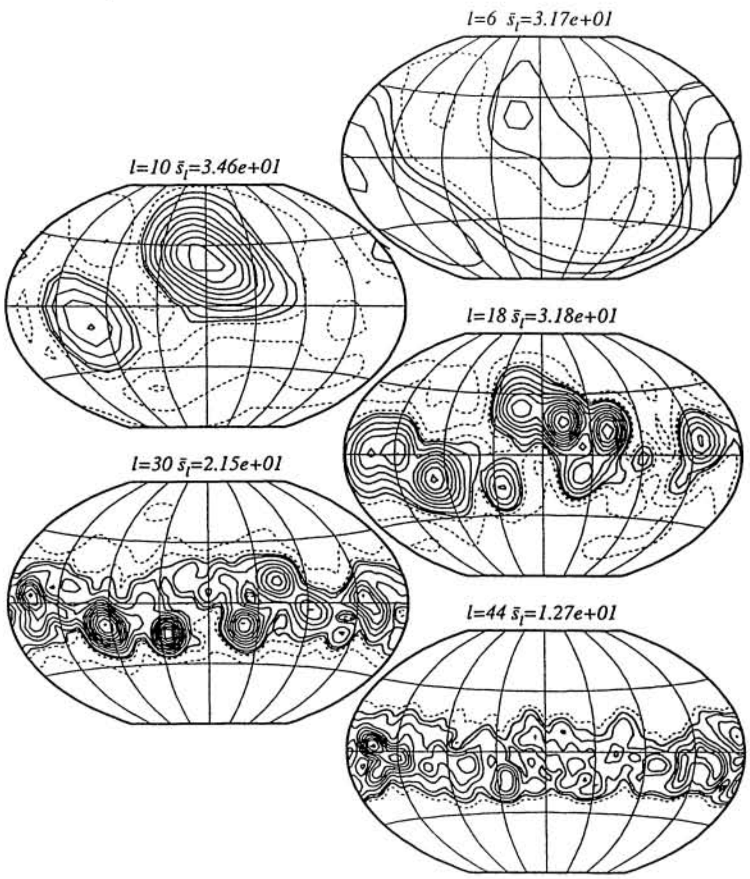

Fig. 1. Rms lunar gravity anomaly for selected harmonic degrees.

centered on the South Pole-Aitken basin. At intermediate degrees (l = 10 and 18), high rms anomalies are evident over both positive free air gravity features, including the nearside mascon maria, and predominantly negative anomaly features, including the Orientale basin and several basin-centered anomalies on the farside. At still higher degrees (l = 30 and 44), what is most obvious is that gravity information at these wavelengths is confined to low latitudes, less than about ± 30° at l = 30 and even more localized to the equator at l = 44. Clearly no analysis of this harmonic gravity field at such wavelengths should be attempted at higher latitudes. Finally, the Nyquist condition limits the spectral resolution of this harmonic field (for the adopted window) to $l \leq 44$. The equivalent maps of rms amplitude for the harmonic topography field are broadly similar at $l \leq 4$, but the solutions for gravity and topography at higher wavelengths look quite different. In particular, the topography field has energy at most latitudes and most $l \leq 44$.

Armed with such information, we have calculated the wavenumber-dependent admittance and mapped that quantity at each angular order [e.g., 10]. Obviously, the admittance for a region that includes both highlands and maria - particularly mascon maria - will be largely indecipherable, because of the pronounced difference in gravity-topography relations between highlands and maria, so careful attention to spatial localization and to the spectral bands in which such localization excludes mare contributions from highland areas is necessary. We have generated isostatic anomalies, for both Airy and Pratt models of isostatic compensation, as functions of harmonic degree. Areas where those anomalies are small to zero are those where the assumed isostatic model is a permissible solution, whereas areas with large anomalies either require a different form of isostasy or depart from complete compensation. The mascon maria will clearly fall in this latter group, but undercompensated impact basins with insignificant volumes of younger mare basalt deposits may also stand out with this procedure.

The question of Pratt versus Airy isostasy for the highlands requires the analysis of surface chemical information as well as gravity and topography. With the advent of global digital data sets for surface chemistry, such as the Fe concentration map [8] and presumably the data to be acquired by Lunar Prospector, the chemical data can be expanded readily into spherical harmonics for direct analysis with the harmonic gravity and topography fields. Wavenumber-dependent transfer functions among chemistry and geophysical fields are then straightforward, both for all highlands and on a regional basis. In regions where there is a local Pratt component to isostasy, the chemistry (e.g., Fe and Al contents) should be directly (negatively and positively, respectively) correlated with elevation. On the other hand, where there is an apparent Pratt component only because the lunar crust is layered and lower crust has been variably excavated by large impacts, then the topography-chemistry relation is both spatially variable and dependent on wavenumber in a manner that varies with basin size.

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