HIGH-RESOLUTION ESTIMATES OF LUNAR CRUSTAL DENSITY AND POROSITY FROM THE GRAIL EXTENDED MISSION. Mark A. Wieczorek[1], Francis Nimmo[2], Walter S. Kiefer[3], Gregory A. Neumann[4], Katarina Miljkovic[1], H. Jay Melosh[5], Roger J. Phillips[6], Sean C. Solomon[7,8], James W. Head[9], Sami W. Asmar[10], Alexander S. Konopliv[10], Frank G. Lemoine[4], Michael M. Watkins[10], James G. William[10], Jason M. Soderblom[11], David E. Smith[11], Maria T. Zuber[11]. [1]Institut de Physique du Globe de Paris, 75013 Paris, France (wieczor@ipgp.fr); [2]Department of Earth and Planetary Sciences, University of California, Santa Cruz, Santa Cruz, CA 95064, USA; [3]Lunar and Planetary Institute, Houston, TX 77058, USA; [4]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; [5]Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907, USA; [6]Planetary Science Directorate, Southwest Research Institute, Boulder, CO 80302, USA; [7]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA; [8]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA; [9]Department of Geological Sciences, Brown University, Providence, RI 02912, USA; [10]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099, USA; [11]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

Introduction:

Gravity Recovery and Interior Laboratory (GRAIL) [1] is a dual spacecraft mission to map the gravity field of the Moon by inter-satellite ranging. Gravity models from the primary mapping phase of this mission [2] have determined the gravity field of Earth's natural satellite to unprecedented accuracy over both the near and farside hemispheres. From an average mapping altitude of about 55 km, a spherical harmonic model to degree and order 420 has been constructed, which corresponds to a spatial wavelength of about 25 km.

Analyses of these models, in combination with topography data from the Lunar Orbiter Laser Altimeter (LOLA) onboard NASA's Lunar Reconnaissance Orbiter, have led to several discoveries [3]. The density of the upper portion of the lunar crust was found to be 2550 kg m^{-3}, substantially less than generally assumed. Combined with independent estimates of crustal grain density [4], this bulk density implies average crustal porosities of about 12%. Lateral variations in crustal density were found to correlate with crustal composition. Lateral variations in porosity were found associated with the youngest large impact basins. From the GRAIL crustal densities, global crustal thickness maps were constructed and show that the average thickness is likely between 34 and 43 km, values up to 20 km thinner than previously inferred.

During GRAIL's extended mission, the average altitude of the spacecraft was lowered to 23 km, allowing for the construction of gravity models with spatial resolutions considerably higher than obtained during the primary mission. The first extended mission gravity model extends up to spherical harmonic degree and order 660 [5], corresponding to wavelengths of about 15 km, and models approaching degree and order 1000 will be attainable once all of the extended mission data have been processed.

Ultra-high-resolution gravity models will allow for substantial improvements in our understanding of how impact cratering has affected the lunar crust. These lessons will be directly applicable to other planetary bodies, on which impact craters are often in a less well-preserved state than those on the Moon.

In our continued analyses of the GRAIL data, we will report on two investigations: high-spatial-resolution estimates of crustal density and porosity, and improved constraints on how porosity varies with depth below the surface.

Lateral variations in density and porosity:

In our previous investigations [3], we constrained the density of the lunar crust with both spatial and spectral domain approaches. By constructing simulated

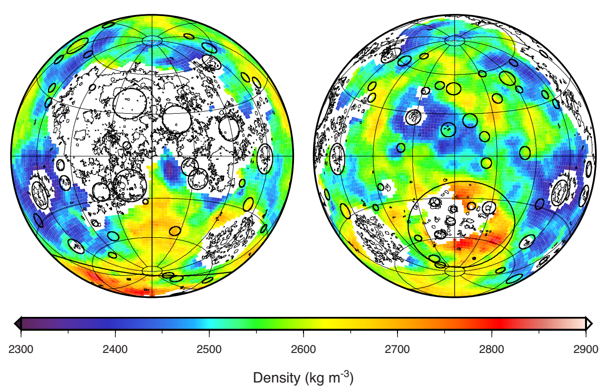

Figure 1. Density of the lunar crust obtained from GRAIL primary mapping data [3]. The bulk density was calculated within circles 360 km in diameter. Regions in white were not analyzed, thin lines outline the maria, and solid circles correspond to prominent impact basins, whose diameters are taken as the region of crustal thinning. The largest farside basin is the South Pole-Aitken basin. Data are presented in two Lambert azimuthal equal-area projections centered over the near- (left) and farside (right) hemispheres, with each image covering 75% of the lunar surface.

gravity models from the Moon's surface relief, the crustal density was found that best matched the GRAIL observations. Since the gravitational contribution resulting from flexure of the crust–mantle interface is negligible at high spherical-harmonic degrees, the modeling approach is very straightforward. With the primary mission mapping data, density estimates were obtained over regions with spatial scales of 360 km (or 12° of lunar latitude) and with uncertainties of a few tens of kg m^{-3} (see Figure 1).

With a 360 km resolution for our density estimates, it was possible to see the effects of large-scale compositional variations (such as those associated with the South Pole-Aitken basin) and the consequences of enhanced porosity surrounding the largest impact basins. Analyses using extended mission data will provide crustal density estimates with spatial scales appropriate for investigating simple and complex craters, impact melt pools interior to basins, and volcanic structures.

Depth dependence of porosity:

The GRAIL bulk density and porosity estimates represent an average over the entire crust that depends upon the magnitude of surface relief in the study region and the density profile of the underlying crust. If the density of the crust were constant at all depths below the deepest topographic excursion, our density estimates in Figure 1 would represent an average over the depth scales of the surface topography, which is on the order of about 4 km.

If the crustal density were instead a function of depth below the surface, the lateral variations in density along a spherical interface below the surface would give rise to an additional gravitational signal. Since these gravitational signals would be attenuated both with increasing depth and with increasing spherical harmonic degree, the highest spherical harmonic degrees will more effectively sample the density of the shallowest portions of the crust.

In Figure 2, we show the global effective density of the lunar crust for each spherical harmonic degree [3]. The effective densities are most representative of the farside crust since this is where the highest-amplitude short-wavelength gravity signals are found. This figure shows that whereas the effective density is close to 2550 kg m^{-3} for degrees near 200, the effective density decreases to about 2400 kg m^{-3} at degrees near 420. This observation implies that the density of the crust decreases as one approaches the surface. From these observations, it will be possible to place constraints on how density and porosity vary as functions of depth below the lunar surface.

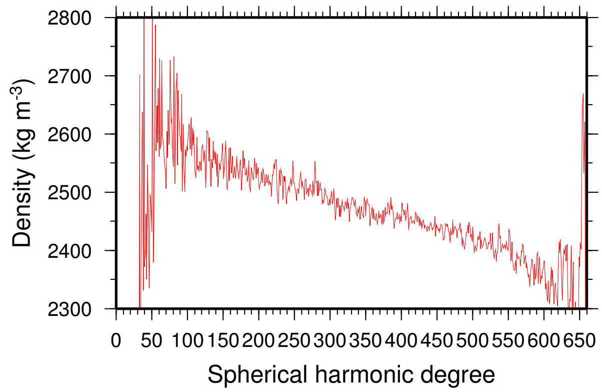

Figure 2. Effective density of the lunar crust as a function of spherical harmonic degree under the assumption that the surface topography is uncompensated. Lithospheric flexural signals are negligible beyond degree 150. For this preliminary extended mission gravity field, the spherical harmonic coefficients are valid globally to about degree and order 420.

References:

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