DETECTION OF THE LUNAR BODY TIDE BY THE LUNAR ORBITER LASER ALTIMETER.

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Introduction: After ~4.5 years of operation, the Lunar Orbiter Laser Altimeter (LOLA) aboard the Lunar Reconnaissance Orbiter (LRO) has collected ~6.3 billion measurements of surface height with a vertical precision of ~10 cm and an accuracy of ~1 m. The LOLA dataset contains ~10 million crossovers, instances when two altimetric ground-tracks intersect. Previous work has demonstrated the utility of altimetric crossovers in improving reconstructed spacecraft orbits [1]. For LRO/LOLA, these crossovers are especially useful because the 5-spot, 50 m wide footprint provides extra information in the cross-track direction [2]. In this contribution, we present results using the LOLA crossovers as a globally distributed set of measurements to detect the signature of tidal deformation. We derive a value of the radial Love number, h_2 = 0.0371 ± 0.0011, consistent with, but more precisely determined than, previous estimates.

Lunar tides: The Moon exhibits a tidal gravity field due to the difference in the gravitational force of the Earth (and to a lesser extent, the Sun) at the Moon's surface and its center of mass. This field was recently measured precisely using data from the GRAIL mission [3]. The solid body of the Moon responds elastically to the tidal field, which causes the Moon to be slightly squashed along the limb and bulged on the near and far sides with a maximum radial displacement of ~50 cm (with respect to a perfect sphere) near the sub-Earth point and its antipode. The detailed behavior of these deformations depends on the Moon's physical properties, such as the density distribution and bulk elastic properties, and they are often parameterized in terms of the degree-2 Love numbers, h_2, l_2, and k_2. Therefore, the Moon's tidal deformations have important consequences for topics such as lunar geodesy, the interior structure of the Moon, and the long-term evolution of the Earth-Moon system [4].

Although tidally locked, the lunar tidal potential not only varies with surface location, but with time as well. As the Moon revolves around the Earth it experiences variations in the gravitational force due to the orbital eccentricity and obliquity. These changes lead to periodic variations about the mean tidal bulge shape with a period of ~27.5 days and a surface amplitude as large as ~20 cm radially at each point. Consequently, it is possible to detect the signature of lunar tides with repeated accurate measurements of the surface height at many different locations.

Crossover Analysis: The method for processing each LOLA crossover is similar to that explained in [2]. In summary, each track forms a surface onto which the other track's points can be interpolated. For each crossover, we solve for the best-fit offsets in the X, Y, and Z directions of a local stereographic frame centered on the crossover. We use a downhill simplex algorithm to minimize the RMS radial residuals between the adjusted tracks. The algorithm is started from 50 random initial guesses to reduce the probability of finding a local minimum.

The analysis is restricted to those crossovers with valid profiles from all 5 spots and occurring during LRO's near-circular orbit (between July 2009 and Dec. 2011). We use an orbit reconstruction based on the GRAIL degree-420 gravity field of [5]. After excluding crossovers with poor fits, high radial errors (>1 m), large slopes (>20°), and large off-nadir (>5°) angles, the total sample size is ~350,000.

The RMS of the best-fit offsets (along-track/cross-track/radial) is 13.58/8.72/1.22 m while the median offset is 8.43/4.65/0.45 m. Before adjustment, the median RMS radial crossover residual is 1.78 m and after adjustment it is 0.56 m. The spatial distribution of the post-adjustment RMS radial residual (see Figure 1) is closely correlated with the surface roughness, indicating that the best-fit offsets are limited by interpolation errors and, hence, that there are no significant biases in the minimization procedure.

Deriving h_2: The best-fit radial crossover offsets are compared to the predicted values due to tides alone in Figure 2. The predicted values are calculated using JPL ephemeris DE421 [6], the SPICE library [7], and the expression $h_2V(t)/g$, where $V(t)$ is the degree-2 tidal potential due to the Earth and Sun, and g is the surface acceleration. The red line in Figure 2 is the one-to-one line, *not a fit*. Any deviation from a slope of unity could indicate an error in h_2, whose *a priori* value was 0.03786, used in DE421 from a constrained fit to lunar laser ranging (LLR) data [6].

Much of the vertical scatter in Figure 2 is due to orbit reconstruction errors, which are larger in magnitude than the tidal signal. To minimize the orbital errors, we modeled them as once-per-revolution perturbations superimposed on the tides. We solve for the global h_2 value and the amplitude and phase, slowly varying every orbit, by performing a least-squares inversion with weights given by the errors of the radial crossover offsets.

Figure 3 shows the result of subtracting the model orbital errors from the measured offsets. The red line is again the one-to-one line. Now, the RMS is reduced to 39 cm, a factor of three improvement over the original 1.22 m of Figure 2. The largest fit residuals occur near the poles where the predicted tidal signal is smallest but where fluctuations in instrument temperature cause the LOLA receiver telescope to rapidly move into and out of alignment.

The best-fit h_2 value is 0.0371 ± 0.0011, about 2% smaller than the *a priori* value. The uncertainty comes from the covariance matrix. The correlation of h_2 with the other parameters is small, with an RMS of 0.05 and a maximum absolute value of 0.14. The variance inflation factor, a measure of multi-collinearity, is low (2.9) indicating the determination of h_2 is robust with respect to the other parameters. The best-fit h_2 is consistent with the most recent estimate based on LLR data: 0.0476 ± 0.0064 [8]. But, our estimate does not depend on assumptions about the Moon's interior structure, and it comes from a globally distributed set of measurements.

Future work will incorporate the horizontal crossover offsets, taking into account their correlations with the radial offsets, and performing the inversion of a larger system consisting of the time series of the full 3-D orbital errors, LOLA boresight corrections, and h_2.

References: [1] Neumann, G. A. et al. (2001) *JGR, 106,* 23753-23768. [2] Mazarico, E. et al. (2010) *Jour. of Geodesy, 84*, 343-354. [3] Lemoine, F. et al. (2013) *JGRE*, 118, 1676-1698. [4] Sagitov, M. U. ed. (1986) *Lunar Gravimetry*, London: Acad. Pr.. [5] Zuber, M. T. et al. (2013) *Sci*, 339, 668. [6] Williams, J. G. et al. (2008) JPL IOM 335-JW,DB,WF-20080314-001. [7] Acton, C. H. (1996) *Planetary and Space Science*, 44, 65-70. [8] Williams, J. G. et al. (2013) JPL IOM 335-JW,DB,WF-20130722-016.

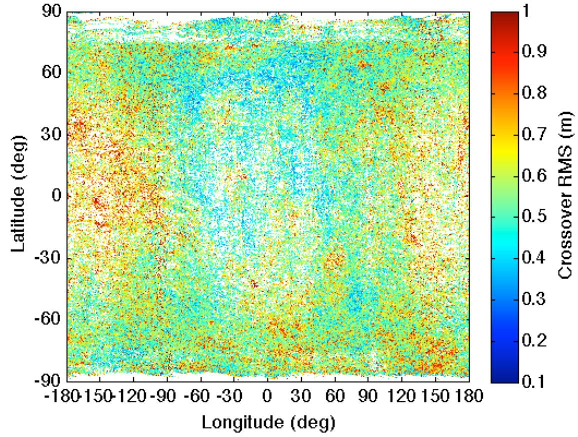

Figure 1 - Spatial distribution of crossover RMS residuals after applying best-fit adjustments.

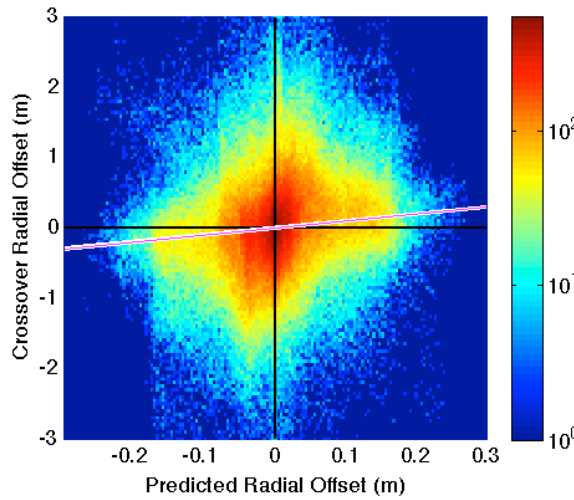

Figure 2 - 2-D histogram of measured crossover radial offsets and the predicted offsets due to tidal deformations alone. The line has a slope of unity.

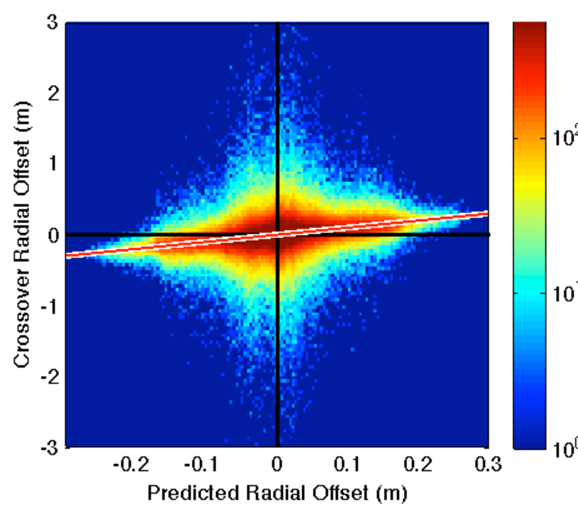

Figure 3 - Same as Figure 2, but the model orbital errors were subtracted from the measured offsets.