**LUNAR TIDAL DISTORTION FROM GRAIL AND LLR.** J. G. Williams[1], A. S. Konopliv[1], R. S. Park[1], D. H. Boggs[1], S. W. Asmar[1], D.-N. Yuan[1], M. M. Watkins[2], D. E. Smith[3], and M. T. Zuber[3], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA (e-mail James.G.Williams@jpl.nasa.gov); [2]Center for Space Research, University of Texas, Austin, TX, 78759, USA; [3]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

**Introduction:** Gravity from a body external to the Moon causes a two-lobed (degree-2) tide raising potential. The resulting tidal distortion of the Moon is quantified with three degree-2 Love numbers: $h_2$ for vertical distortion, $l_2$ for horizontal distortion, and $k_2$ for the distortion of the gravity field and moments of inertia.

The analysis of Doppler data from the Gravity Recovery and Interior Laboratory (GRAIL) mission [1] has determined a gravity field of the Moon to degree and order 1500. With data from the primary and extended missions, the new results include lunar tidal Love number $k_2$ and associated tidal dissipation quality factor $Q$, both at a 1-month period.

In parallel, the analysis of Lunar Laser Ranging (LLR) data provides information on $h_2$ at a 1-month period and tidal $k_2/Q$ at several periods.

These results from tidal deformation have implications for lunar structure.

**Love Numbers:** The tide raising potential causes the Moon to distort, and the distortion causes a change in its gravity field and moment of inertia. The distortion varies with time and these effects are sensed by GRAIL and LLR. The GRAIL analysis provides an accurate value for $k_2$ plus $k_2/Q$ and the LLR analysis provides tidal $k_2/Q$ and $h_2$.

**Degree-1500 Solution:** The GRAIL mission gathered accurate tracking data between two Moon-orbiting spacecraft [1]. The Primary Mission was 89 days long, from 1 March 2013 to 29 May 2013. The Extended Mission was 106 days long, from 30 August 2013 to 14 December 2013, with spacecraft altitudes as low as a few kilometers above the lunar surface. The Extended Mission Ka-band spacecraft-spacecraft range-rate data have a precision near 0.05 micron/second.

The highest resolution lunar gravity field to date has been generated by analyzing GRAIL data from the Primary and Extended Missions. Previous gravity fields of degree 660 [2,3] and 900 [4,5] have been described. Lunar Love numbers were published in [2,3,6] and the moment of inertia was published in [6]. In addition to a gravity field of degree and order 1500, new solutions include parameters for lunar $GM$, degree-2 and 3 Love numbers, degree-2 tidal dissipation, inner core periodic signals [7], orbit states, solar radiation pressure, and periodic non-gravitational accelerations. The final half-wavelength resolution is 3.7 km at the best locations and 6.1 km globally.

**LLR Solution:** The analysis of Lunar Laser Ranging (LLR) data uses 20,218 ranges extending from March 1970 to September 2015. Ranges are measured by firing a laser pulse from an observatory on the Earth that bounces off of retroreflectors on the Moon and returns back to the Earth. The accuracy has improved with time. On the Earth, McDonald Observatory, Texas, Observatoire de la Côte d'Azur, France, Haleakala Observatory, Hawaii, Apache Point Observatory, New Mexico, and Matera, Italy have provided data sets extending over years. Ranges to 5 retroreflectors at different lunar sites provide information on the Moon's orientation vs. time.

**Results for Love Numbers and Tidal Dissipation:** The degree-1500 solution finds a potential Love number $k_2$ of 0.024216±0.00012. This value is compatible with, but more accurate than, previously published values from GRAIL [2,3,6]. Solutions also determine the tidal phase shift. A degree 1200 solution gave $k_2/Q = (5.8\pm0.6)\times10^{-4}$ or $Q = 41\pm4$ at 1 month [8], where $Q$ is the quality factor that arises from dissipation.

The monthly $k_2/Q$ value derived from lunar laser range analysis was $k_2/Q = (6.4\pm0.6)\times10^{-4}$ and $Q = 38\pm4$ at 1 month [9]. The new LLR analysis is compatible and determines an annual value of $k_2/Q = (5.9\pm1.1)\times10^{-4}$ or $Q = 43\pm7$.

The LLR analysis gives $h_2 = 0.044\pm0.005$ at 1 month period. A model value based on the GRAIL $k_2$ is $h_2 = 0.0423$ [6,9]. The model uncertainty should be <1%. Based on height measurements by the Lunar Orbiting Laser Altimeter, [10] derives $h_2 = 0.0371\pm0.0033$. LLR data analysis attempted to determine $l_2$, but it was below the noise level. The model values of $h_2 = 0.0423$ and horizontal $l_2 = 0.0107$ [6,9] are recommended for $R$=1738 km.

**Structure:** Models of lunar structure have been fit to the GRAIL/LLR moment of inertia [11], tidal Love number $k_2$, and dissipation [6,9,12,13]. A small core is indicated.

Fits of several curves for $k_2/Q$ vs. period were presented in [9]. The two most successful had a single relaxation time and an absorption band of relaxation times; they peaked near 3 months. Figure 1 shows an example based on the dissipation results. A hot zone [13] of low viscosity is inferred by [6,9,12,14]. Both

[9] and [12] find that the lower mantle high attenuation low velocity zone extends from the core to the bottom of the moonquake zone or possibly higher.

**Summary:** A degree and order 1500 solution provides a higher resolution gravity field and an improved fit to the GRAIL data. The Love number is $k_2$ = 0.024216±0.00012. LLR data analysis determines a phase shift associated with tidal dissipation that gives a tidal $Q$ of 38±7 at a one-month period. The LLR determination of $h_2$ has improved. Models of lunar structure must be compatible with the tidal Love number and dissipation. LLR data analysis also determines terrestrial tidal dissipation [15].

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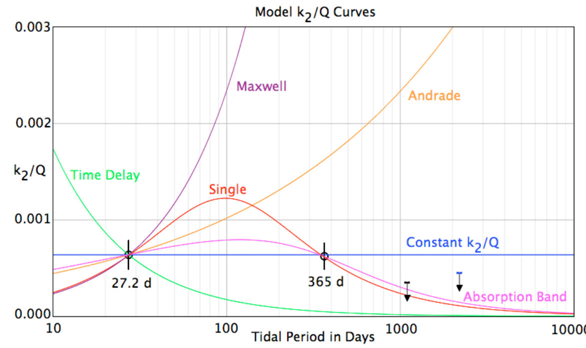


Figure 1. Six model curves show the dependence of $k_2/Q$ on tidal period. The two circles indicate monthly and annual determinations from LLR data analysis. Upper limits are shown at 3 and 6 years. The single relaxation time and absorption band curves with peaks near 100 d are successful fits. Time delay, Maxwell, and Andrade models are poor fits.