TIDAL TOMOGRAPHY TO PROBE THE MOON'S MANTLE STRUCTURE USING LUNAR SURFACE GRAVIMETRY.

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Introduction: The Moon's surface is dominated by an unexplained nearside/far-side dichotomy. The source of such a large-scale feature may be due to past processes within the lunar mantle. In order to explore this possibility, a better understanding of lunar mantle heterogeneity is highly desirable. Here we describe a proposed investigation to gain such an understanding: GLIMPSE (Gravimetry of the Lunar Interior through the Moon's PulSE) uses data collected from one or more gravimeters emplaced on the Moon's surface to measure temporally varying gravity changes, as the Moon deforms elastically in response to periodic tidal stresses.

Tidal Tomography: Just as the Sun and the Moon exert tidal forces on Earth, the Earth and the Sun exert tidal forces on the Moon. Tidal stresses in the Moon are proportional to the gravity gradient tensor field at the Moon's centre, multiplied by the distance from the Moon's centre. The gravity gradient at the Moon due to the Earth is on average 81x larger than the gravity gradient at the Earth due to the Moon. But the Moon is smaller than the Earth, so the maximum tidal force on the Moon's surface due to the Earth is ¼ of that, or about 20x larger than the maximum tidal force on the Earth's surface due to the Moon.

The tidal forces on the Moon due to the Earth vary with time. While the Moon is tide-locked to the Earth, and so the direction of the tidal force vector is (roughly) constant in the Moon-fixed frame, the Moon's orbit around Earth is elliptical (e=0.0549), and so the Moon's distance from Earth varies between about 357,000 km and 406,000 km, a variation of about +/-7%. Since gravity gradient varies with inverse cube of distance, the magnitude of tidal forces on the Moon vary by $1.07^3 = 1.22$, or a total of 45% due to this orbit-ellipticity effect. (There will also be further variations due to the Moon's libration, changing the direction of the Earth's gravity gradient field in the Moon's reference frame) A gravimeter on the Moon's equator will see a variation in apparent gravity of about 1 micro-g due to this effect, with a periodicity equal to that of the Moon's orbit around Earth (about one cycle per month).

Since the Moon is not a perfectly rigid body, these tidal forces cause the Moon to deform elastically, the first-order response being to stretch along the Earth/Moon axis, and compress about the two orthogonal axes—the well-known Body Tide effect, characterized by a planet's Love numbers. That elastic deformation will cause a point on the Moon's surface to change its distance from the Moon's center of mass (depending on its location on the surface), which will change the local apparent value of gravity by an additional amount over and above the change due to the tidal acceleration field due to the Earth. Because this will be a time-varying effect, it can potentially be detected by gravimeters on the Moon's surface. Because the magnitude of this effect will depend on the details of the Moon's internal distribution of elasticity and density, surface gravimetry measurements can be used to constrain models of the Moon's interior structure. Because nothing blocks gravity, this can be used to investigate the Moon's entire structure.

The same effect occurs on Earth. Tidal accelerations on Earth due to the Moon and the Sun change with time, with a period of about half a day, due to the Earth's rotation. In [Lau et al., 2015][Lau et al., 2017 a] we have derived expressions to predict the body tide response of a rotating, anelastic and laterally heterogeneous Earth model via a normal mode approach; this provides a highly efficient means of predicting the complicated response of Earth's shape to time-varying tidal forcing. This theory has been applied [Yuan et al., 2013] to GPS data where the deep mantle buoyancy structure of the Earth was estimated, and represented a first demonstration of the new and powerful technique now known as Tidal Tomography. A subsequent study [Lau et al., 2017], [Lau & Faul, 2019] explored how the observed anelastic effects on the tides compare with experimentally derived ideas of anelastic deformation of deep Earth rocks.

Lunar Tidal Tomography via Surface Gravimetry: While GPS measurements of the Moon's surface deformation are not available, variations in the height of the Moon's surface versus time due to tidal forcing can be detected by using gravimetric techniques. Zhong [6] proposed analyzing the GRAIL mission's global Lunar gravity measurements from orbit, in order to constrain models of Lunar mantle lateral inhomogeneity. Our GLIMPSE concept is instead to emplace highly accurate gravimeters at various locations on the surface of the Moon, to use them to monitor time-varying changes in the Moon's gravity over an extended duration (ideally, many months), and to use those measurements to constrain such models of the Moon's deep interior structure.

This technique requires a gravimeter instrument suitable for deployment on the Moon's surface, with high enough accuracy to detect the Moon's elastic response to tidal forcing. Gedex is developing a small (2.1 kg, <10x10x20 cm) instrument suitable for this purpose, the Vector Gravimeter/Accelerometer (VEGA), which is being developed for use on the surface of the Moon and other planets; VEGA is described in some detail in [7]. VEGA is an absolute gravimeter, with a stationary zero-mean measurement noise process, and with an expected RMS error of between 0.1 and 1 micro-g for each 15-minute measurement of the local gravity field magnitude, when used on the Moon. Initial study indicates that this will be sensitive enough to detect the signal from Lunar elastic response to tidal forcing, for measurement campaigns as short as 7 days.

References:

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