ESTIMATING THE LUNAR CORE EQUATORIAL ELLIPTICITY USING LUNAR LASER RANGING.

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Introduction: Lunar Laser Ranging (LLR) is an on-going scientific experiment since 1969. LLR-capable stations [1,2] on Earth continue to perform range measurements to the five optical passive retro-reflector arrays on the near-side of the Moon's surface. The analysis of LLR data has contributed to a variety of scientific disciplines such as lunar geophysics, Earth rotation and orientation, planetary ephemerides and precision tests of fundamental physics (see [3] for a recent review).

Here we suggest that the lunar core equatorial ellipticity (which can inform us on the origin and evolution of the Moon) has the potential to be measured using extended LLR data, and we assess the accuracy of the estimation through an extension of the historical LLR data into the following decades.

State-of-the-art: The lunar interior models (with co-estimation of ephemerides) consist of three layers: lunar crust, mantle, and fluid core. The shape of the interface between the mantle and the fluid core (among other model parameters) affects the rotational dynamics of the Moon, which itself is observable through the analysis of LLR data. A recent estimation of the degree-2, order-0 shape (or polar oblateness) of the lunar fluid core-mantle interface gives a fractional uncertainty ($\partial x/|x|$) of ~0.27 [4].

Relevance. From assuming a hydrostatic interface (within a non-hydrostatic lunar lithosphere) it is shown that the degree-2, order-2 core shape (called equatorial ellipticity here) is an order of magnitude smaller than the polar oblateness, and it lacks a confident detection using the 50 years of LLR data [4]. However, the equatorial ellipticity of the fluid core-mantle boundary (CMB), even at these faint magnitudes, is shown to be sufficient to excite inertial instabilities in the fluid core (over geological timescales) and may have powered a short-lived lunar dynamo in the past [5]. Hence, we design this study to evaluate the prospects of resolving the CMB equatorial ellipticity using real and simulated LLR data.

Simulation setup: We consider the LLR covariance matrix (with 150 parameters, describing the Earth-Moon system such as the lunar interior shape; external gravity fields of the Earth and the Moon; orbital, rotational and tidal parameters; station and reflector coordinates) containing 50 years (1969-2019) of historical LLR data and estimate the fractional uncertainty of the lunar CMB equatorial ellipticity using four simulated scenarios for the upcoming decades of observations.

The fractional uncertainty herein is obtained from a calibrated error-covariance matrix (the Variance Component Estimation iterative method, or VCE, used in [6]) for a realistic recovery of parameter uncertainties. Currently, two LLR stations have provided routine millimeter-level (range accuracy) LLR data extending over a decade: Grasse, France (1999-2019) and Apache Point, New Mexico, USA (2006-2016).

Simulated cases. Case 1: We consider that Grasse and Apache Point stations continue to range to the existing five lunar retro-reflector arrays (LRAs) well into the future. Case 2: We introduce an additional LLR station on Earth, operating from the southern hemisphere (HartRAO, South Africa [7]) in the year 2020. Case 3: We introduce a new LRA near the lunar south pole in 2021, increasing the total number of LLR targets from five to six and extending their current spatial distribution. Case 4: Another LRA is placed near the lunar eastern limb, giving a total of seven possible LLR targets on the Moon.

Assumptions. A maximum of 1 hour per day (Moon in line-of-sight and above 10° local elevation) is allotted to each simulated station data – assumed as a lower bound for participating observatories. The duration of each simulated normal point is set as 10 minutes (typical LLR session) with an average weight of ~7 mm (in 1-way range, considering uncertainties scaled from bootstrap resampling [8]). LLR data accuracy is assumed to remain at millimetric-levels and the choice of range targets follow a uniform random distribution. We assume the instantaneous angular velocity of the fluid core (ω_c) with respect to the mantle's rotation to be known at a fixed uncertainty ($\partial\omega_{c,x}=10^{-5}$, $\partial\omega_{c,y}=10^{-6}$ and $\partial\omega_{c,z}=10^{-6}$ rad/day) to avoid unrealistic solution values in the VCE iterations (usually constrained during LLR fits [9]). The setup assumes the degree-2, order-2 shape of the CMB to be 5 times larger than a pure hydrostatic case [4,5].

Results: The results of this study are summarized in Figure 1. a) Using the available LLR data (1969-2019), we find that the CMB equatorial ellipticity cannot be well-determined ($\partial x/|x|$~2), serving as the reference case. b) Case 1 indicates that this may require another ~15 years of data accumulation. c) Case 2 shows that a new southern-hemisphere LLR station is beneficial and reduces the required data accumulation time by ~2.5 years. However, this would require a decade of millimetric-level operation along with Grasse and Apache Point stations. d) Case 3 indicates that a new LRA near the lunar south pole (considering a lunar lander mission in 2021) reduces this time by ~5 years. e) Case 4 with two new LRAs from future lander missions (one near the south pole and another near to the lunar eastern limb, in 2021), reduces this by almost a decade!

The results suggest that the desired accuracy on the CMB equatorial ellipticity can be achieved relatively soon, considering the relative cost-effective nature of the LLR experiment and the growing number of lunar manned (and commercial lander) missions, currently in development.

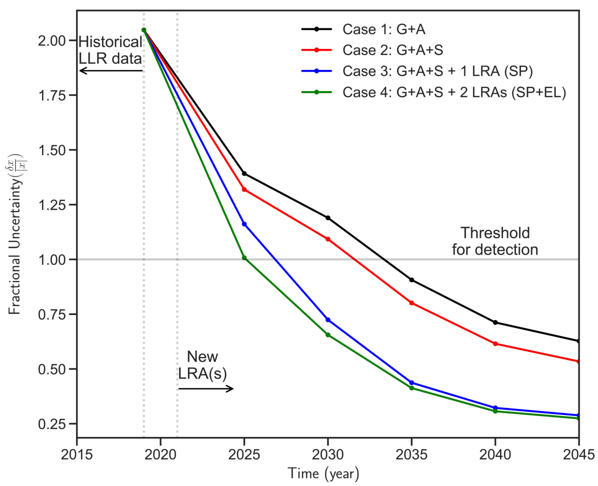

Figure 1: Fractional uncertainty (∂x/|x|) of the degree-2, order-2 CMB shape with accumulated LLR observations (time in years).
G - Grasse, France; A - Apache Point, NM, USA;
S - HartRAO, South Africa;
SP - lunar South Pole; EL - lunar Eastern Limb.

Summary: This study shows that new LRAs (and millimetric data collected from them) provide a better geometry to reduce parameter correlations, thereby allowing an estimation of the degree-2, order-2 lunar CMB shape. Knowledge of this shape would directly impact our understanding of lunar formation and evolution mechanisms.

The selenocentric positions of the current LRAs are well-known to few centimeters. The position of a new retro-reflector can be determined to this level of accuracy within a few months of LLR observations from a single LLR station (e.g. Lunokhod 1 by Apache Point [10]) and will contribute to improving and extending this lunar geophysical network [11] serving as precise control points for future lander missions. The growing interest in the LLR community is evident with newer participating and developing stations in Wetzell-Germany [12], HartRAO-South Africa [10] and Yunnan-China [13].

Currently, LLR is the only observation that allows an estimation of the shape of the lunar core. The impact of new improved observation techniques may shorten the data time-span requirement as shown through this simulation.

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