A SIMULATION STUDY FOR EXTENDING LUNAR LASER RANGING SCIENCE.

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Introduction: Lunar Laser Ranging (LLR) is a scientific experiment that has been conducted since 1969. LLR-capable stations on Earth have since performed regular range measurements to 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.

The exchange of angular momentum between the Moon's interior layers leaves signatures on the orientation of the Moon, to which LLR is sensitive. The parameters to which LLR is sensitive include (but are not limited to): initial conditions of orbit state vectors and orientation of the Moon, geophysical parameters such as the gravitational mass of the Earth-Moon system, gravity fields, the lunar polar moment of inertia, moment differences, tidal displacement Love numbers, dissipation-related parameters, the shape of the lunar core-mantle boundary, and coordinates of the retroreflector arrays. Perturbations to these parameters can be sensed by LLR. Improvements to these parameters, and a decorrelation of them in the solutions can be improved via:

A) Wider distribution of retroreflector network; NASA's Commercial Lunar Payload Services (CLPS) initiative has several deliveries planned in upcoming years. Two providers were selected to deliver payloads to the lunar surface in 2022 (Intuitive Machines & Masten) and one in 2023 (Astrobotic). Two next-generation retroreflectors have been selected for delivery: one each to Mare Crisium and Reiner Gamma. The European Large Logistics Lander (EL3) offers another opportunity well-suited to deploy additional retroreflector(s) towards the end of the decade and into the 2030s. The New Frontiers-class Lunar Geophysical Network (LGN) proposed mission [1] will further extend this network and offer independent and complementary datasets for the investigation of the lunar interior.

B) New participating Earth-stations; LLR-participating stations on Earth are currently limited to a small band of stations in northern latitudes, such as Grasse (France), Wettzell (Germany), Matera (Italy) and Apache Point (USA). LLR operations can be extended to southern hemisphere stations to enable an improved, uniform coverage of the lunar declination. New stations such as Yunnan Observatory (China), Hartebeesthoek (South Africa), Altai (Russia) and Mt. Stromlo (Australia), TMO/JPL (USA) and GGAO/GSFC (USA) hold the potential to expand the LLR ground network. LLR operation in IR wavelength will improve detection capabilities [2] notably for smaller SLR station telescopes.

C) Independent parameter constraints; Some of the parameters such as the low-degree gravity field, Earth-station coordinates, Earth's Love numbers, are better constrained via independent measurements. The low-degree gravity field (up to degree and order 6 in spherical harmonic expansion) are part of the LLR parameterization, but a high-accuracy determination via the gravity field recovered from the GRAIL mission better constrain the LLR solution. GRAIL solutions were themselves obtained from a priori lunar orientation models (*e.g.*, DE421/DE430) fitted to LLR data and may contain systematic effects when reconciling the GRAIL-LLR principal axis frame. This is visible in the large variations on the non-zero coefficients C_{21}, S_{21} and S_{22} describing these frame differences between various independent GRAIL solutions [3]. While time-variations on these coefficients play a crucial role for gravitational signatures from a solid inner core structure [4], their non-zero constant values can be accommodated in LLR models using core-mantle boundary features that deviate from the mantle's principal axis frame. However, at present, LLR offers reduced sensitivity to a non-principal axis core-mantle boundary [5] and the C_{21}, S_{21} and S_{22} coefficients from GRAIL have relatively large uncertainties.

D) Choice of parameterization; The choice of LLR solution parameters also impacts the degree of freedom for the LLR solutions. Notable differences between DE/EPM [6,5] vs. INPOP [8] lunar ephemeris solutions are: 1) the definition of the lunar moment of inertia. While DE/EPM use moment differences (β & γ) along with GRAIL's C_{20} as solution parameters (offering a greater degree of freedom to LLR), the INPOP solutions use the entire degree-2 gravity field and polar moment of inertia (C/MR^2) to tap into the high accuracy of GRAIL; 2) the core-mantle boundary of DE/EPM is an axisymmetric model (described using polar oblateness) while the INPOP model is triaxial [5] (both polar oblateness and equatorial ellipticity). The value of the lunar core-mantle boundary's equatorial ellipticity is expected to be small ($\sim 10^{-5}$; one order of magnitude smaller than its polar oblateness, $\sim 10^{-4}$), making its detection using LLR challenging. The core's equatorial ellipticity has the capacity to modify the free core nutation frequency of the Moon [9] as well as influence inertial instabilities in the lunar fluid core over geological timescales to power a short-lived lunar dynamo [10]. The detection of such small effects will be possible with added geometry and improved precision offered by the next generation of large (single) retroreflectors [11]. Moreover, understanding the resolution of inner core signatures will require consideration of potential topography at the lunar core (fluid)-mantle boundary. At present, the uncertainties in the lunar interior density profile, based on Apollo-seismic data analyses limit further constraints on the lunar core-mantle boundary structure from LLR.

E) Coupling with geodetic devices enabling a complementary geometry; LLR data provide the frame tie between the body-fixed principal axis frame to the inertial ICRF. An independent tie can be obtained using co-located radio beacons (preferably located at lunar limbs) and has the potential to also offer complementary geometry for the tidal deformation signals [12,13,14].

Simulation setup: A simulated environment with control on various factors influencing LLR operation and analysis were considered. These include (but are not limited to) observations per day per hour allotted by a typical LLR station, temporal separation between normal points, minimum elevation angle, accuracy of LLR observations based on station capabilities, accuracy of LLR observations based on retroreflector capabilities, year of deployment of new retroreflectors, potential degradation of present-day retroreflectors, non-uniformity based on historical LLR data, and extension of the LLR station network.

Typical LLR stations operate under time-sharing with other geodetic techniques, such as SLR. We set a similar station environment based on a prefixed number of hours per station, with observations spread over multiple retroreflectors and >10 degrees of local elevation angle. The accuracy of LLR observations also depends on several factors local to each LLR station. Each participating station has a demonstrated its level of precision. For a simple case, we consider LLR stations that provide observations with at least a ~7mm accuracy in 1-way range (1-sigma standard deviation). This range accuracy is reported to improve significantly with next-generation retroreflectors. Degradation of retroreflectors due to dust accumulation will impact the efficiency of the retroreflectors, which will result in an increase in the statistical centroid uncertainty. Since the extent of the degradation remains uncertain based on recent results that compared returns from surface retroreflectors arrays with pristine LRO retroreflector arrays [15], a degradation with time on the statistical uncertainty may not be warranted for simulation purposes covering less than 2-3 decades. The non-uniformity in LLR observations with the lunar phase is difficult to overcome with passive LLR targets. Since no active laser transponders are planned to date, this trend can be assumed into the future and thus into our simulated environment.

Conclusions: The extension of the current accuracy of a few mm observed by the present-day participating stations to all LLR data has an overall value for the maintenance of planetary and lunar ephemerides, improving the precision of fundamental physics tests and for the extraction of secular but subtle signatures in the rotation of the Moon that helps reveal information about its interior structure. Data accuracy is equally important as timespan. Extension of the simulation to three decades into the future shows that parameter uncertainties tend to gradually flatten, *i.e.*, with no considerable improvements to parameter recovery, if the accuracy of the data does not improve. New retroreflectors that support present-day accuracies or beyond, are valuable for extracting orientation-related signatures if they are more evenly distributed, away from the present-day network. Additionally, retroreflectors near the lunar poles and limbs are desired to offer complimentary geometry to the existing arrays, which will help reduce correlations among model parameters.

The expansion of the retroreflector network offers an opportunity to resolve shape features of the deep lunar interior. Ranges to Lunokhod and Apollo 14/11 arrays are preferable to A15 for constraining the lunar orientation. A15, is however the most abundant in the historical data, being easier to range onto. Its larger arrays actually cause more dispersed photon returns and thus contribute to less accurate measurements and lesser value for LLR science. Telescope and observer times are valuable, and their use needs to be optimized with the goal of maximizing science return.

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