

## SCIENTIFIC EXPLORATION OF THE LUNAR SOUTH POLE WITH RETRO-REFLECTORS.

V. Viswanathan<sup>1,2</sup>, E. Mazarico<sup>1</sup>, D.R. Cremons<sup>1</sup>, S. Merkowitiz<sup>1</sup>, X. Sun<sup>1</sup>, D.E. Smith<sup>3</sup>; <sup>1</sup>NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA, <sup>2</sup>University of Maryland Baltimore County, Baltimore, MD 21250, USA, <sup>3</sup>EAPS, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

**Introduction:** Lunar retro-reflector arrays (LRAs) consisting of corner-cube reflectors (CCRs) placed on the nearside of the Moon from the Apollo-era missions have demonstrated their longevity, cost-effectiveness, ease of deployment, and most importantly their interdisciplinary scientific impact through the ongoing lunar laser ranging (LLR) experiment. Smaller LRAs, such as those built under NASA's Commercial Lunar Payload Service (CLPS) program and installed on recent lunar landers (Beresheet/SpaceIL and Vikram/ISRO), intend to demonstrate their science and exploration value, *e.g.*, as fiducial markers on the lunar surface to support navigation and geolocation [1]. The human exploration of the lunar south polar region provides a unique opportunity to build on this legacy and contribute to the scientific return of Artemis, for many decades to come.

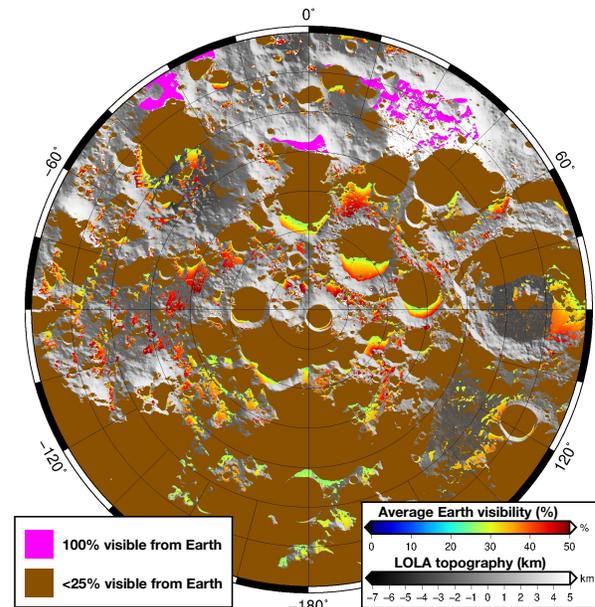
**Lunar Laser Ranging:** The large Apollo and Lunokhod LRAs develop thermal gradients near full Moon that reduce the optical return from the LRAs. This difficulty results in a deficit of LLR observations at full Moon phase, which has led to a non-uniform distribution of the LLR data vs. lunar phase, impacting the science derived from LLR (*e.g.*, extraction of lunar tidal deformation periods [3] and the search for equivalence principal violation signals [4]). Furthermore, the five surface LRAs currently cover a limited portion of the nearside (from 40°N to -3.6°S in latitude and -35°W to 31°E in longitude) which limits the sensitivity of LLR to lunar geophysical parameters.

Figure 1 shows a map of the south polar region and some metrics that can help assess landing sites from the LLR perspective. The locations in magenta are always in view of the Earth, and would straightforwardly extend the LRA network spatially. Another option, novel and possible only near the lunar poles, is to deploy new LRAs (or larger single retro-reflectors) in permanently shadowed regions (PSRs) and in cold regions (maximum temperature below 200K). Thermal variations are much smaller than typical over a diurnal cycle for the lunar surface, simplifying design requirements and improving the link margin by a factor of ~100. A large subset of these cold regions can still view the Earth (up to ~50% of the time; Figure 1).

For instance, smaller CCRs (~3.8 cm across and packed in an LRA configuration to obtain a given throughput) are favorable to reduce the thermal gradients in the typical lunar environment. Such LRAs employ a recessed packing of CCRs to limit direct thermal

exposure, resulting in a reduction of throughput by a factor of up to ~10 based on the off-axis angle of incidence ( Fig. 7-13 in [5]). A more efficient back reflective coating (typically using aluminum or silver) is often avoided, again due to the thermal constraints. On the contrary, larger single CCRs are favorable over an array configuration in order to reduce the pulse spreading induced by lunar librations (deviations from normal incidence) and thus increase measurement accuracy (LRAs requiring repeated measurements vs more consistent single-shot measurement to CCRs) [6,7]. Hollow cubes do not suffer from thermal changes in their index of refraction and do not introduce significant polarization effects like solid cubes, but geometric thermal stability remains critical [8].

A large single hollow CCR placed in cold regions at the lunar south pole (shown in Figure 1) would be resilient to these thermal limitations and would benefit from the resulting throughput gain. Such large reflectors placed at these Earth-visible lunar south pole PSRs would mean that the LLR detection capability of returned photons would no longer be limited to a select few LLR observing stations on Earth (currently 4 LLR



**Figure 1:** Stereographic map of the lunar South Pole region (83-90°) highlighting areas of full (magenta) and poor (<25%, brown) Earth visibility. The other colored regions are cold ( $T_{\max} < 200\text{K}$ ) with sufficient Earth visibility (25-50%) to support LLR objectives. Background is shaded relief of LOLA topography.

stations are in operation, all in a small band of latitude in the northern hemisphere), but potentially open to the wider SLR network (45+ stations distributed globally).

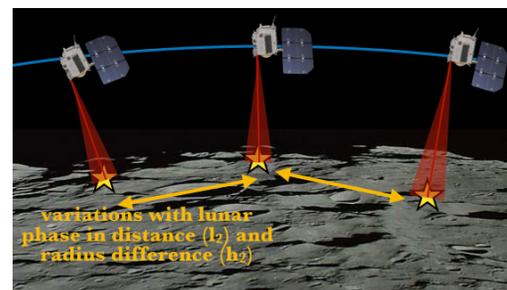
LLR-derived lunar interior and core shape parameters improve our understanding of the lunar formation and evolution. While the degree-2 order-0 shape of the lunar core-mantle boundary is accessible using LLR analysis, the degree-2 order-2 shape remains unresolved and holds importance to lunar dynamo mechanisms through tidal instabilities [9]. A recent study [10] shows that a new retro-reflector at the south pole would help resolve this parameter through its improved geometry. Currently, lunar ephemeris fitted to LLR data provides the link that connects the lunar principal axes frame to the solar system barycentric frame. A well-known lunar frame attached to the lunar crust has potential to confirm the existence of a solid inner core through resonances [11] and contributes to the maintenance of precise solar system ephemerides [12,13] that aid high-precision navigation. A new LRA/CCR placed at a PSR near the lunar south pole would have a significant positive impact on LLR-derived science that span lunar science [3], Earth orientation and rotation, reference frames [14] and precision tests of fundamental physics [4,15].

**Smaller Retro-reflectors:** Another class of LRAs are those presented in [16]. These contain smaller CCRs ( $\sim 1/3$  the size of Apollo CCRs) that have potential to act as fiducial surface markers which in turn help in trajectory determination, follow-on lander operation as well as for the determination of orientation/rotation axis of the target body (such as asteroids). Their array configuration (eight 1.27-cm-diameter CCRs) also provides a wider range of acceptance angles (any direction above  $30^\circ$  from horizon) for ease of spacecraft slew/pointing operations. Their small size also help to reduce thermal gradients, enabling improved sun-lit observations.

Presently, both LLR analysis and LRO laser altimeter data analysis have independently provided estimates of the lunar vertical tidal-displacement love number ( $h_2$ ) to a certain degree of agreement [4,17]. However, the current sensitivity provided by LLR for the independent estimation of the lunar horizontal tidal-displacement love number ( $l_2$ ) is insufficient due to a) the present geometry allowed by the LLR-enabled LRAs, and b) its limited sensitivity to the rotational dynamics of the deep interior [18]. Thus, lunar  $l_2$  determinations from LLR analysis remain model-dependent. An estimation of the lunar  $l_2$  using LRO's LOLA data analysis is also limited. This situation can be improved if smaller retroreflectors are placed at known location(s) in the spacecraft lidar's field of view.

For example, a single small-LRA placed at one lunar rotational pole would serve as an important surface

marker seen every orbit by a typical polar-orbiting lidar-enabled spacecraft (e.g., LRO-LOLA). This novel technique, would help improve the orbital errors near poles which are home to small tidal displacement signals [17]. This would also enable: a) an LLR-independent direct tracking of the lunar axial precession angle ( $\sim 1.543^\circ$  between the Moon's symmetry axis and the ecliptic normal), with improved estimates informing on the state of the lunar inner core [11]; and b) a physical marker for the dynamically determined principal axis reference frame for the Moon, to complement the current LLR model-dependent determination and its long-term monitoring. Two such retro-reflectors, one at the pole and the other sufficiently separated (up to a few minutes of orbital path, or a few hundred kilometers) would provide unexplored sensitivity to the lunar  $l_2$  determination. Such sensitivity can be enhanced or tailored to match specific degree-order components of the lunar horizontal tidal-displacement love number based on the chosen location/interdistance of this surface LRA network.



**Figure 2:** Co-estimation of lunar love numbers  $h_2$  and  $l_2$  with lunar laser altimetry.

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