Estimating the Lunar Core Equatorial Ellipticity using Lunar Laser Ranging

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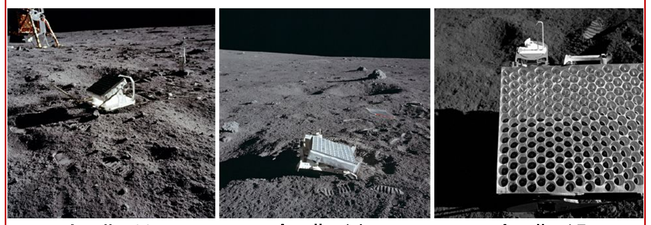
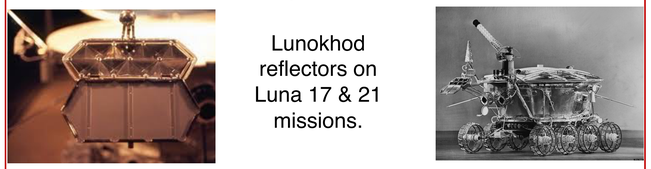
A. Introduction

Lunar Laser Ranging involves precise millimeter-level tracking of five retroreflectors on the near-side lunar surface.



Apollo 11 | Apollo 14 | Apollo 15



Lunokhod reflectors on Luna 17 & 21 missions.

Fig. 1: Lunar retroreflector arrays

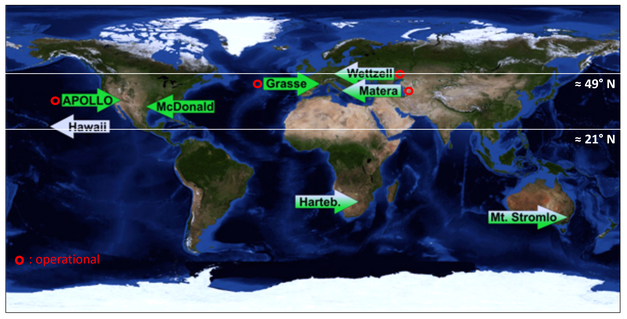


Fig. 2: Present and future LLR stations (ILRS)

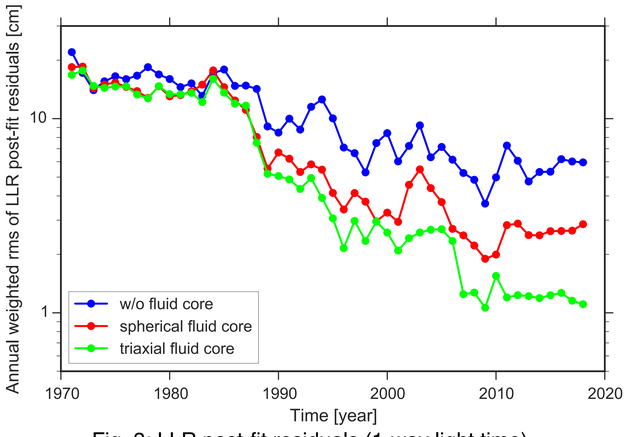


Fig. 3: LLR post-fit residuals (1-way light time).
Blue - Model without a fluid core;
Red - Model with a spherical fluid core;
Green - Model with a triaxial fluid core[5].

B. Methodology

How does tracking surface reflectors help understand interior structure?

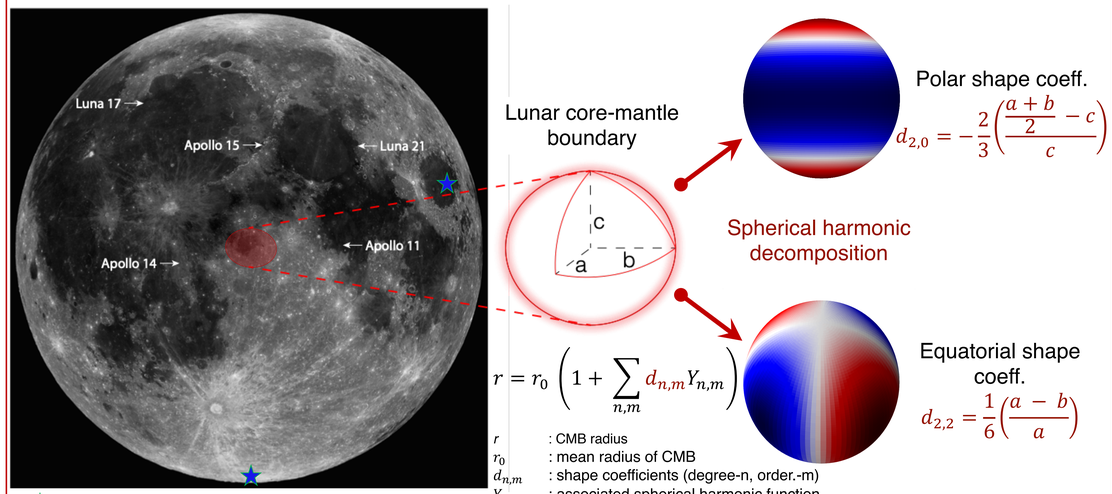
Monitoring the rotation of a body gives us clues to understanding its interior structure. i.e. a moon with a fluid core rotates differently from one with a solid core. Angular momentum is exchanged between the layers of the Moon as it rotates and orbits around the Earth.

Euler-Liouville equation for (a) the Moon and (b) the fluid core :

$$\frac{\mathrm{d}}{\mathrm{d}t}(\mathcal{I}\Omega + \mathcal{I}_c\omega_c) + \Omega \times (\mathcal{I}\Omega + \mathcal{I}_c\omega_c) = \Gamma^{\text{external}} \quad \text{(a)}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathcal{I}_c(\Omega + \omega_c) + \Omega \times \mathcal{I}_c(\Omega + \omega_c) = \Gamma_c^{\text{friction}} + \Gamma_c^{\text{inertial}} \quad \text{(b)}$$

$\mathcal{I}$, $\mathcal{I}_c$: Moment of inertia of the Moon, Moon's core
Ω, ω_c : Angular velocity of the Moon, fluid core (relative)
Γ^{external} : Torques (external) acting on the Moon
Γ^{friction} : Torques from viscous friction at CMB
Γ^{inertial} : Torques from flow along non-spherical boundary



★ Tentative locations for new retroreflectors

Q1: What do we currently know about the lunar core from the LLR data ?

- Viscous friction from relative motion at the core-mantle boundary (CMB) – spherical core model [1]
- Polar oblateness for a given core moment – axisymmetric core model [2,3,4]
- Polar oblateness and radius for a relaxed lunar core with plausible non-principal axis tilt – triaxial core model [5]

Q2: Can we detect the CMB equatorial ellipticity from LLR data ?

- Yes, LLR is sensitive to this parameter. But, presently remains unresolved.
- Extended high-precision data will enable detection.
- The next generation of lunar retroreflectors flown by commercial lander(s) and the Artemis program will strengthen detection and reduce data span requirements by almost a decade! See Fig. 6.

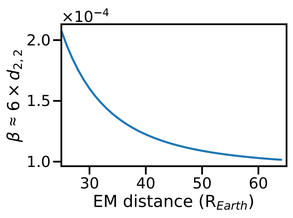


Fig. 4: Core ellipticity with EM distance[6,9]

Q3: What can we learn from the CMB equatorial ellipticity ?

- **Lunar evolution**: At first order, CMB equatorial ellipticity and Ekman number would help determine the threshold for the development of elliptical instabilities in the lunar core. The former particularly influences the growth rate of such instabilities – a mechanism to power lunar dynamos in the past[6].
- **Lunar rotational dynamics and interior structure**: The CMB equatorial ellipticity will modify the lunar free core nutation (FCN) and induce a new proper mode (analogous to the Chandler Wobble). It would also help confirm the current relaxed state of the lunar core[5].

C. Simulations

- LLR covariance matrix with 150 parameters.
- Fractional uncertainty from calibrated error-covariance (VCE)[7]
- Simulated data from Grasse (G), Apache Point (A) and HartRAO (S) with 1 hour per day (~10 min per normal point) with a precision of ~7 mm in 1-way range.
- Two new retroreflectors – near Crisium crater (upcoming CLPS lander) and South Pole (Artemis lander).
- Degree-2 order-2 shape of the lunar CMB is assumed to be 5 times larger than a relaxed core within a non-hydrostatic lithosphere [5,6].

Fig. 5: Sensitivity of lunar rotation to lunar core equatorial ellipticity.

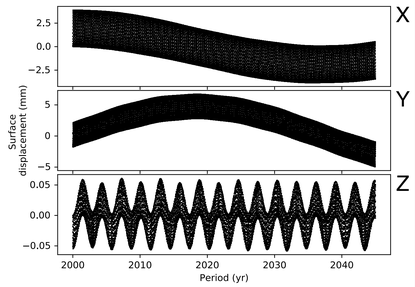
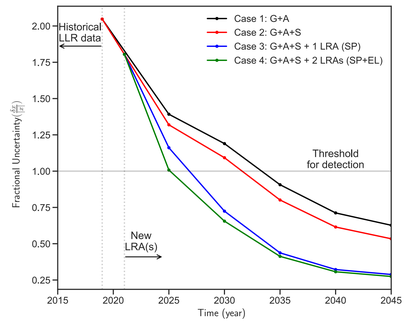


Fig. 6: Recovering the lunar core equatorial ellipticity



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[1] Williams *et al. JGR:Pla.* **106**, 27933–27968 (2001). [2] Folkner *et al. IPNR.* **42-196** (2014). [3] Pavlov, *et al. CMDA.* **126**, 61–88 (2016). [4] Viswanathan, *et al. MNRAS.* **476**, 1877–1888 (2018). [5] Viswanathan, *et al. GRL.* **46**, 7295–7303 (2019). [6] Le Bars, *et al. Nat.* **479**, 215–218 (2011). [7] Lemoine *et al. JGR:Pla.* **118**, 1676–1698 (2013). [8] Fienga *et al. NSTIM.* **109** (2019). [9] Wieczorek, *et al. JGR:Pla.* **124**, 1410–1432 (2019). [10] Wieczorek & Meschede, GGG. **19**, 2574–2592 (2018).

Acknowledgment

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