On the GRAIL-LLR low-degree gravity field inconsistencies

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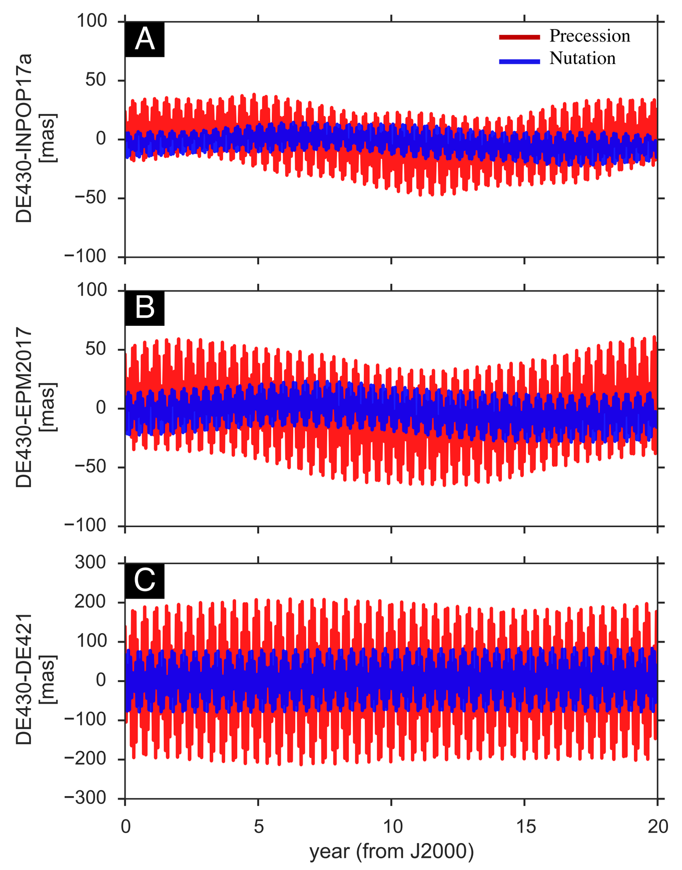
A. Introduction

The year 2019 marks the 50th year of science from the lunar laser ranging (LLR) experiment. The retroreflectors placed on the surface of the Moon from the Apollo and Luna missions continue to serve as reference markers for the accurate tracking of the Moon. Currently, LLR experiments measure the time of flight of photons to these reflectors at few tens of picosecond accuracy - i.e., an accuracy of a few mm on the position of the Moon with respect to Earth!

Such precise tracking data helps to monitor the changes in Moon's orientation along its orbit gives us insight into its deep interior – through the exchange of angular momentum between the internal layers of the Moon.



The three planetary and lunar ephemeris groups (JPL, IMCCE and IAA RAS) provide lunar orientation data through independent fits to LLR data.

Fig. 1: Differences in the orientation of the Moon obtained by comparison of DE430 with INPOP17a (**A**), EPM2017 (**B**), and DE421 (**C**) are shown here.

State-of-the-art models contain an elaborate description of the torques and other interactions acting on the Moon from the Sun and planetary bodies. Small changes in the lunar gravity affects the modeled torque equation that modifies the rate of change of this angular momentum.

A clean fit of the model parameters to the LLR data would give post-fit residuals close to the observational accuracy (see Fig. 2).

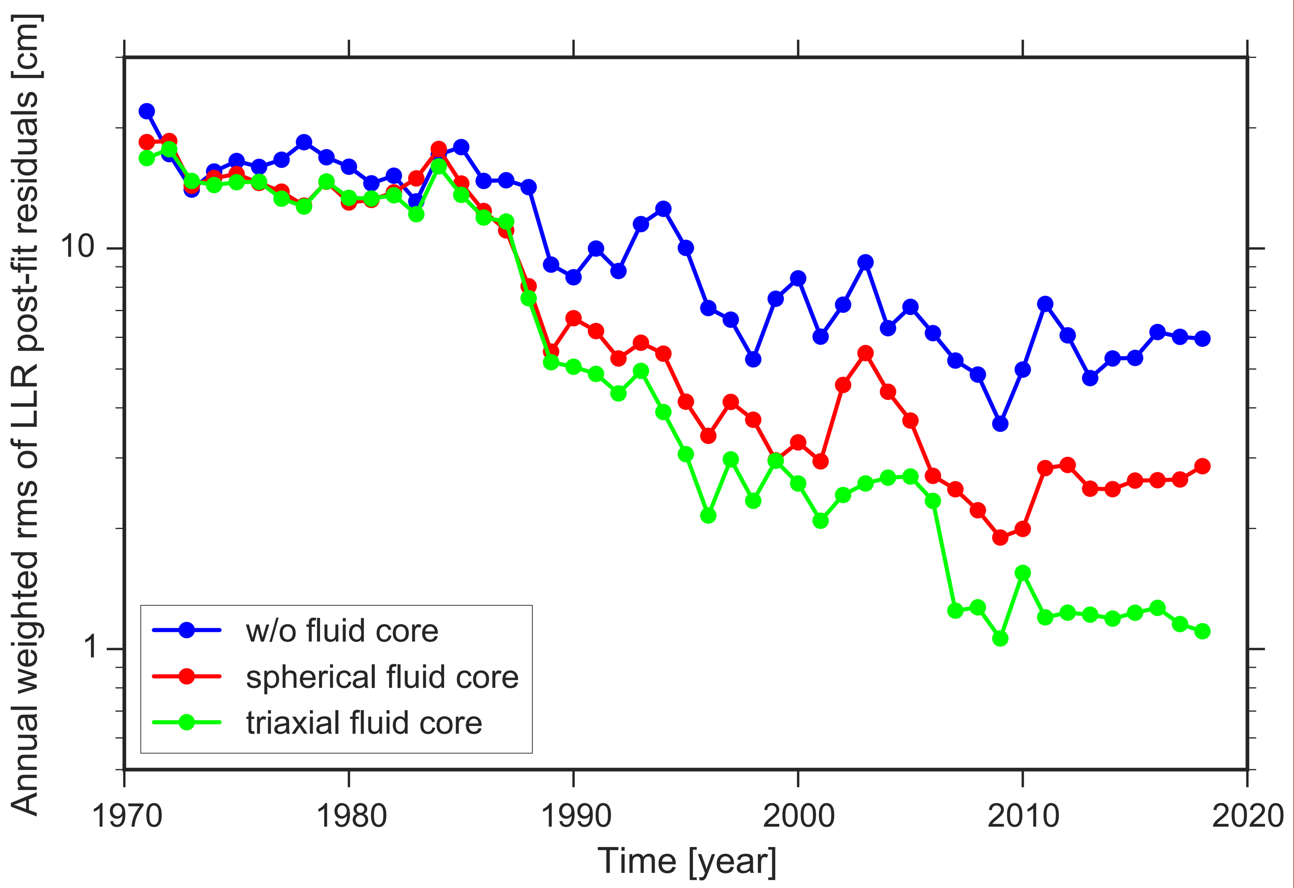


Fig. 2: LLR post-fit residuals with time. The fluid core and its triaxial shape play an important role in the dynamics of the Moon's orientation.

B. The problem

The gravity field of the Moon was recovered to a very high resolution from the analysis of the GRAIL spacecraft tracking data. GRAIL provides a strong constraint for LLR solutions, especially for computing torques originating from the Moon's aspherical gravity field.

However, imposing the gravity field from GRAIL during LLR analysis results in a strong signature in the LLR post-fit residuals. If some degree-3 gravity coefficients (C_{32}, S_{32} & C_{33}, especially) are allowed to be adjusted (well beyond their GRAIL-derived uncertainties), the LLR post-fit residual signature disappears. The underlying cause for this misfit is unknown.

This signature mimics a ~ 6-yr signal as seen from the Earth-Moon geometry (see Fig. 3). The opposite phases in the post-fit residuals arising from the reflector's position indicates a longitude libration signature.

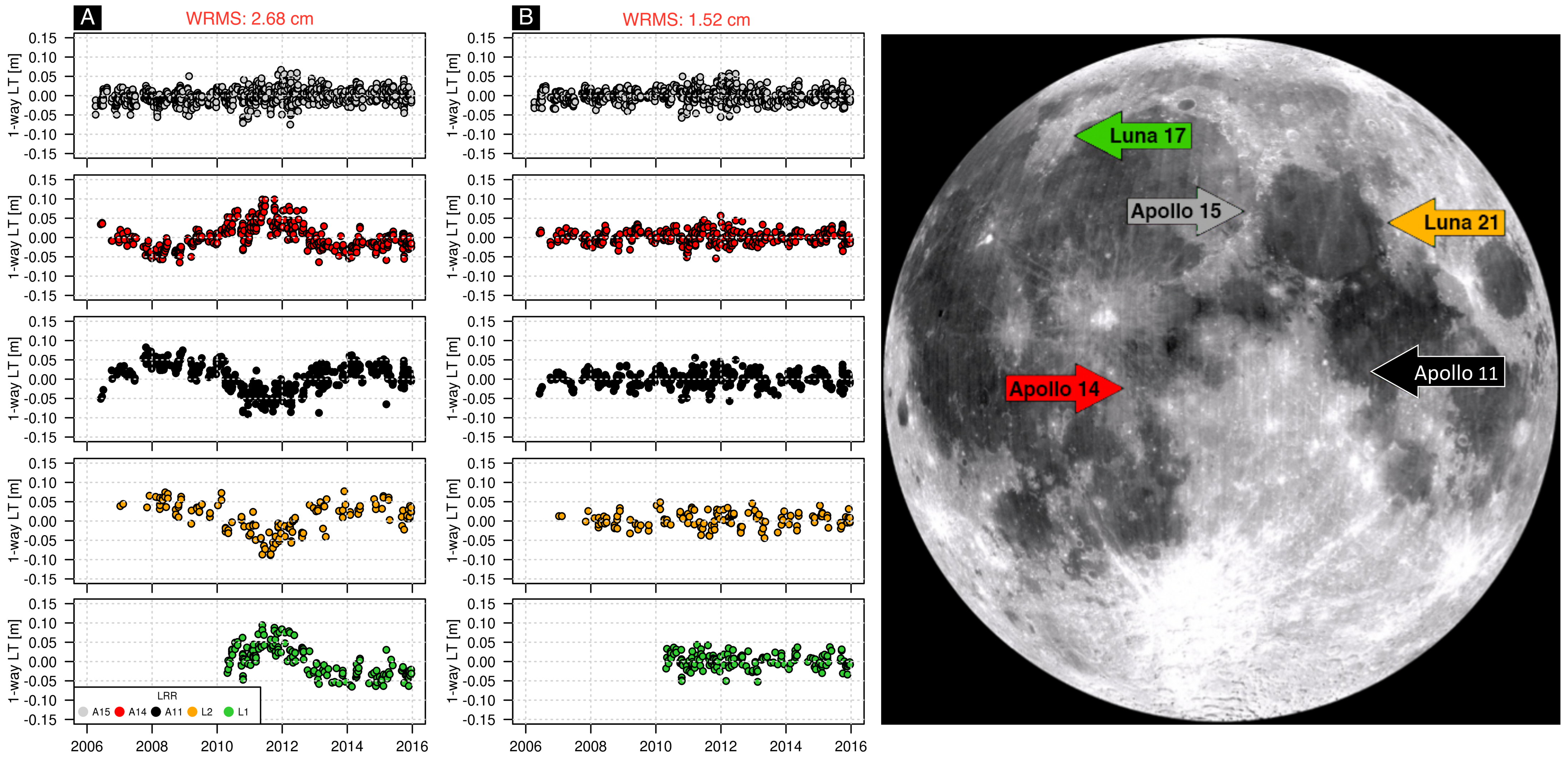


Fig. 3: Impact of deg-3 gravity field on LLR solutions.
A: Solution fixed to GRAIL, **B**: Some degree-3 gravity coefficients allowed to be adjusted.
Adjusting some gravity field coefficients (at 1%) through LLR fits, absorbs this longitude libration signature.

C. Finer details about the GRAIL-LLR system

- **Non-gravitational force modeling**

The GRAIL analyses require a complex non-gravitational force model to account for *all* the observed signal (mostly from KBRR). A compromise is made by introducing empirical accelerations terms (cosine, sine and constant term ~4 times per orbit) to absorb the remaining signal with an upper bound on its uncertainty (~10^{-9} m/s^2 here). Comparing phases of *quiet* periods (see Fig. 5) can help understand their significance on the gravity field solutions.

- **Moon's orientation from lunar ephemeris**

The LLR fits to lunar ephemerides provide the orientation parameters for processing the GRAIL tracking data. Small differences in the lunar orientation can lead to differences in the frame of the gravity field. This would also introduce some differences in the gravity field solutions. Lunar orientation is known from LLR fits at the level of few mas (see Fig. 1).

- **Lunar dissipation**

LLR solutions are sensitive to dissipative effects, such as viscous friction at core-mantle boundary (CMB), lagged response of the Moon to tide raising, rheology, etc. The LLR model for dissipation fits well for near-monthly periods and needs improvement for longer periods. Frequency analysis from LLR solutions and lunar theory are currently used as input for GRAIL's dissipation model and can benefit from a more self-consistent model.

D. Preliminary results

The GRAIL-LLR system was jointly inverted using the variance component estimation (VCE) method. The study was limited to a degree 270 gravity field with apriori GRAIL orbits obtained from a 1200 field. Preliminary results show that this inversion gives a low-degree gravity field solution closer to GRAIL than an LLR only solution (see Fig. 4).

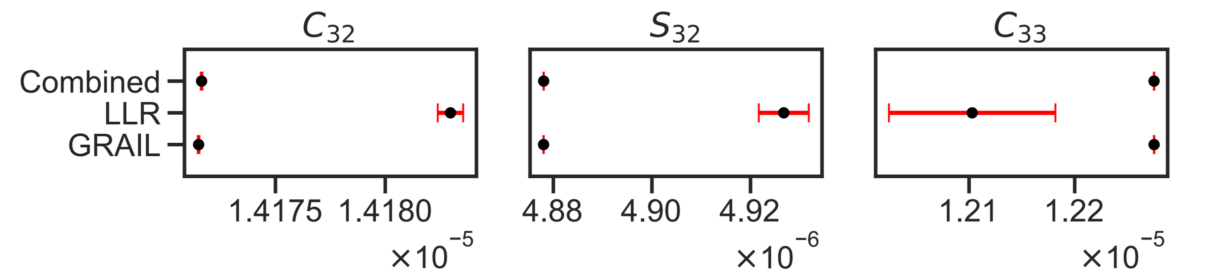


Fig. 4: Comparison of degree-3 gravity coefficients

Empirical accelerations estimated in this joint inversion are close to the GRAIL-only solution. Comparison of pre-VCE (light) and post-VCE (dark) weighted solutions (see Fig. 5) show a decrease in the amplitude of the empirical accelerations during the *quieter* phase of the GRAIL mission.

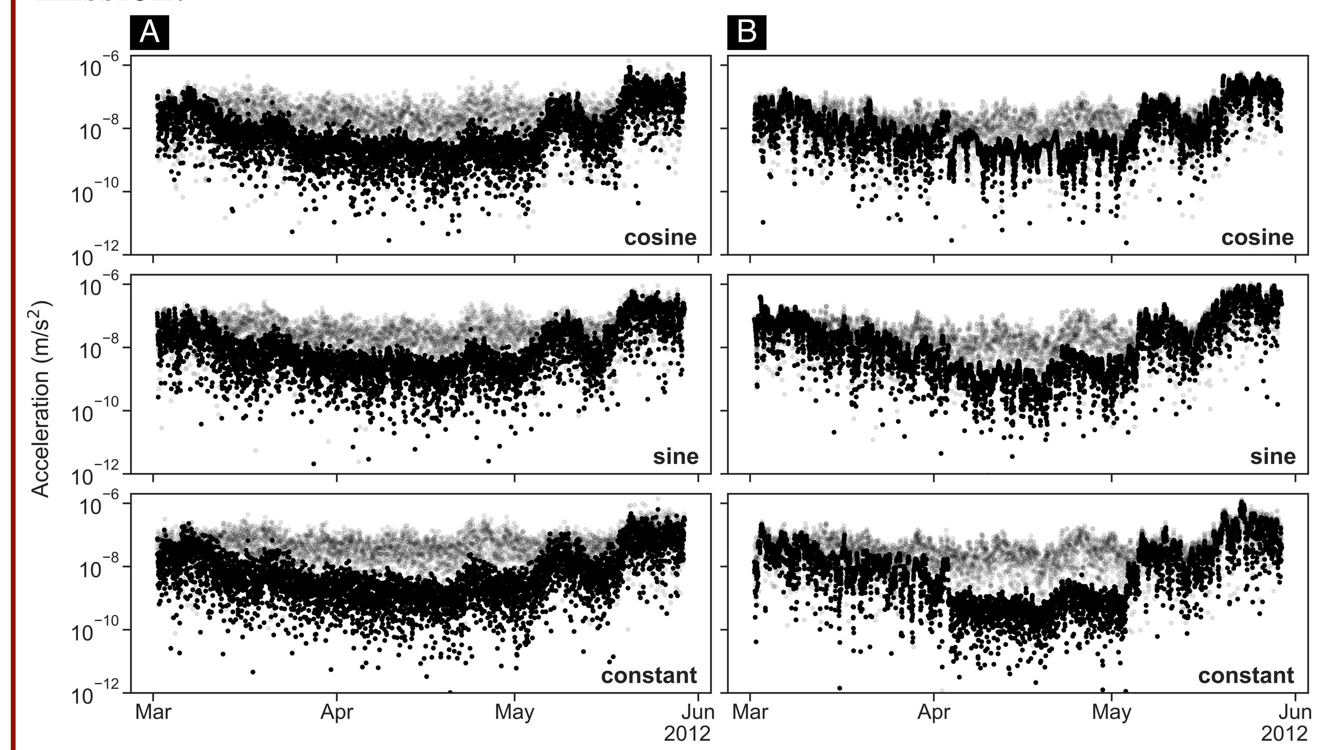


Fig. 5: Empirical accelerations from joint solution.
A: Along-track, **B**: Cross-track

E. Take home message

- GRAIL-LLR joint solution gives a preliminary gravity field solution closer to a GRAIL-only than an LLR-only solution.
- The non-gravitational empirical accelerations in the joint inversion of the GRAIL-LLR system were found to be stable for fields up to 270.
- The answer to this inconsistency is likely to be among the other "finer details" (or improved interior models).

Acknowledgements

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