Report on Activities of the ILRS Goddard Lunar Data (GLD) Analysis Center

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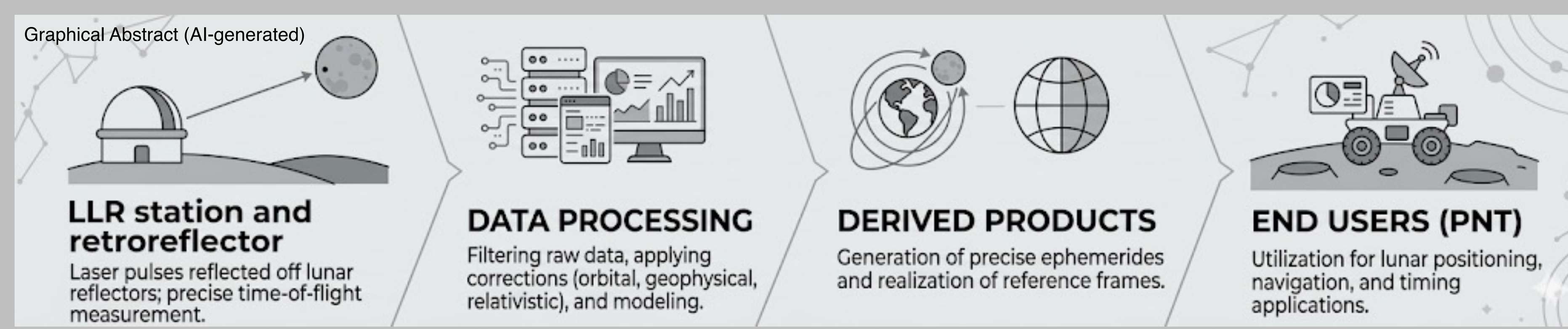

GOAL

To unify lunar laser ranging (LLR) instrumentation, observations, data processing and derived products within an operational framework that supports the objectives and needs of the lunar geodesy and PNT community.

ACTIVITIES

- Support Apache Point Observatory LLR (APOL) station operations, data archival and LLR scientific return.
- Support Artemis Lunar Laser Retroreflector (ALLR) design and pointing requirements.
- Support international lunar positioning, navigation and timing (PNT) efforts and knowledge sharing across the community.

1 APOL station enables lunar science and exploration

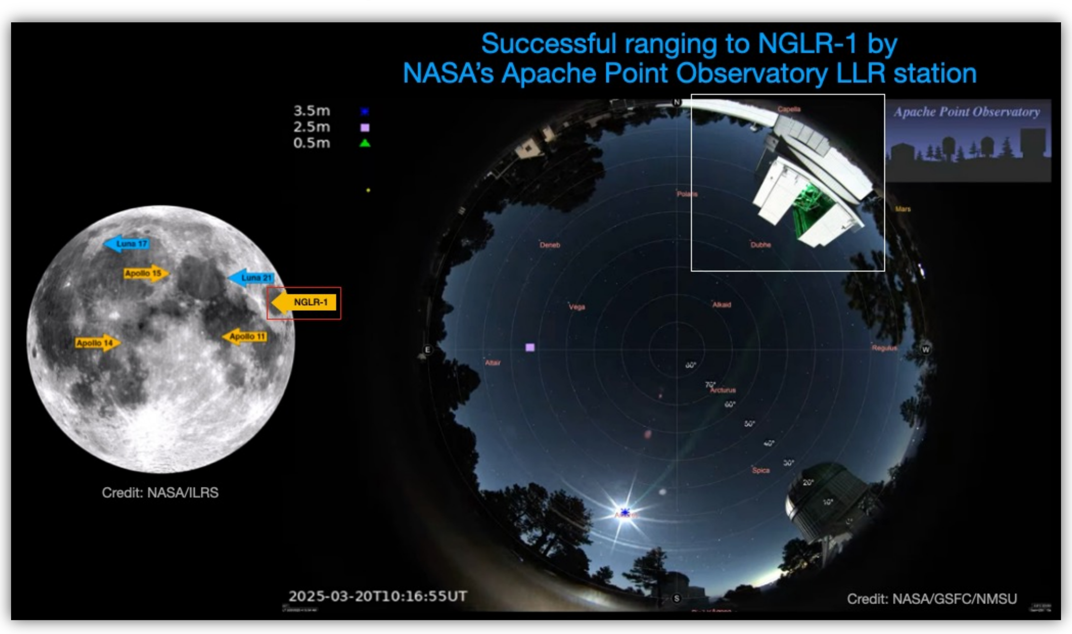

Figure 1: APOL's first observations to NGLR-1 on 20th March 2025, captured by its all-sky camera.

In 2021, the APOL station in Sunspot, New Mexico, which uses the Astrophysical Research Consortium 3.5-meter telescope, became part of the NASA Space Geodesy Network. The APOL station continues to provide routine, high-precision range measurements to lunar retroreflectors, and the center performs regular data validation, quality control, and support for APOL data releases. In addition, the center facilitates APOL ranging to new LLR retroreflectors by providing target coordinate estimates that improve predictive range windows, as demonstrated by APOL's first return to NGLR-1 on March 20, 2025, and in subsequent ranging efforts.

2 High-precision APOL data are made publicly available, including NGLR-1 data.

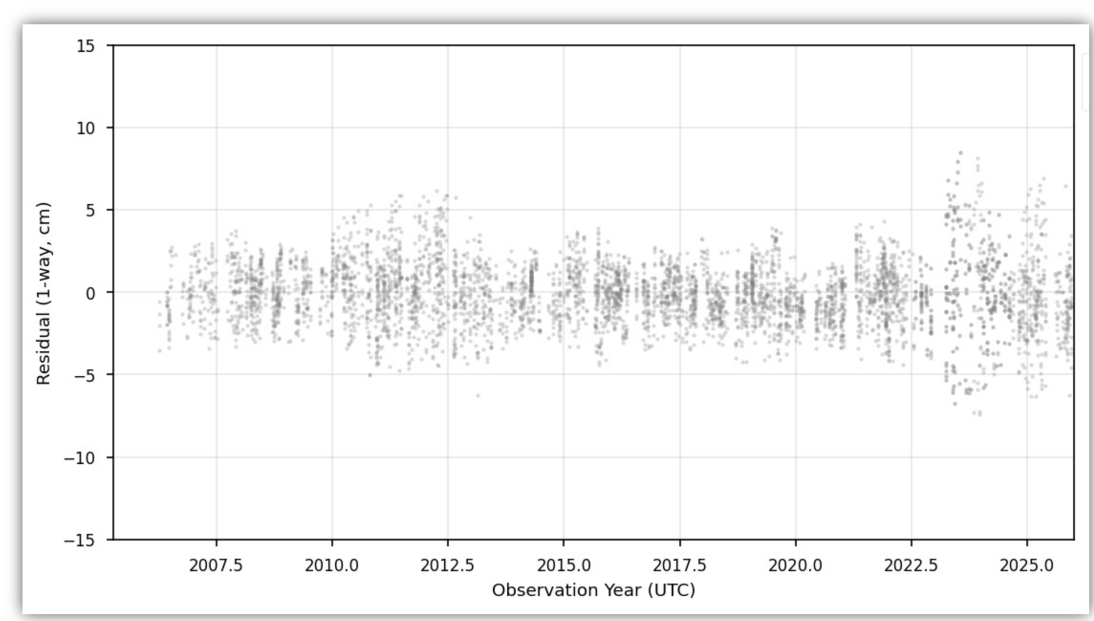

Figure 2: LLR model residuals using data from Apache Point

LLR data from APOL are made available in a timely manner, after initial vetting, through the CDDIS repositories: https://cddis.nasa.gov/archive/.

Although APOL LLR data are precise to a few millimeters, model residuals remain elevated because of limitations in the realism of current LLR models. The post-fit RMS of the LLR residuals is 1–2 cm. Small divergences in more recent years arise from the use of pre-fit models that degrade over extrapolated intervals outside the fit, demonstrating the need to maintain lunar ephemerides. LLR data quality assessment is provided as a service available upon request.

3 Velocity aberration for pointing lunar retroreflector(s)

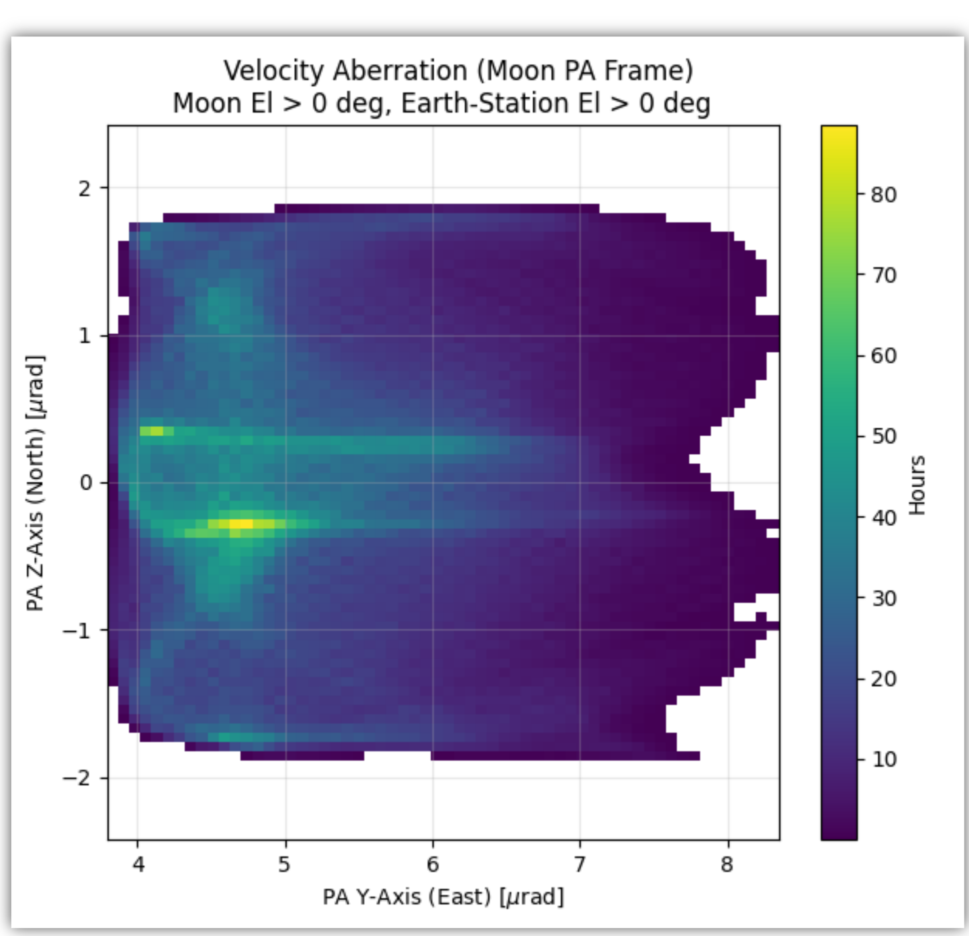

Figure 3: Histogram of velocity aberrations with color scale representing time spent in hours.

Velocity aberration is the angular shift in the return path of a laser beam caused by the relative motion between the transmitter and the reflector during the light-travel time between them. Here, we use data points sampled every 3 minutes over approximately 18.6 years, beginning in 2026, to show the velocity aberration from a south polar site with axes aligned to the Moon's principal axes. Two constraints were applied: a line-of-sight constraint to the retroreflector and an elevation angle greater than 0° from APOL. These show the full range of velocity aberration and the time spent across that range of values. Typical values remain around 4–5 μrad in +y and about 0.5 μrad south of the lunar equator in -z.

4 Deflection of the vertical at the Moon's south pole

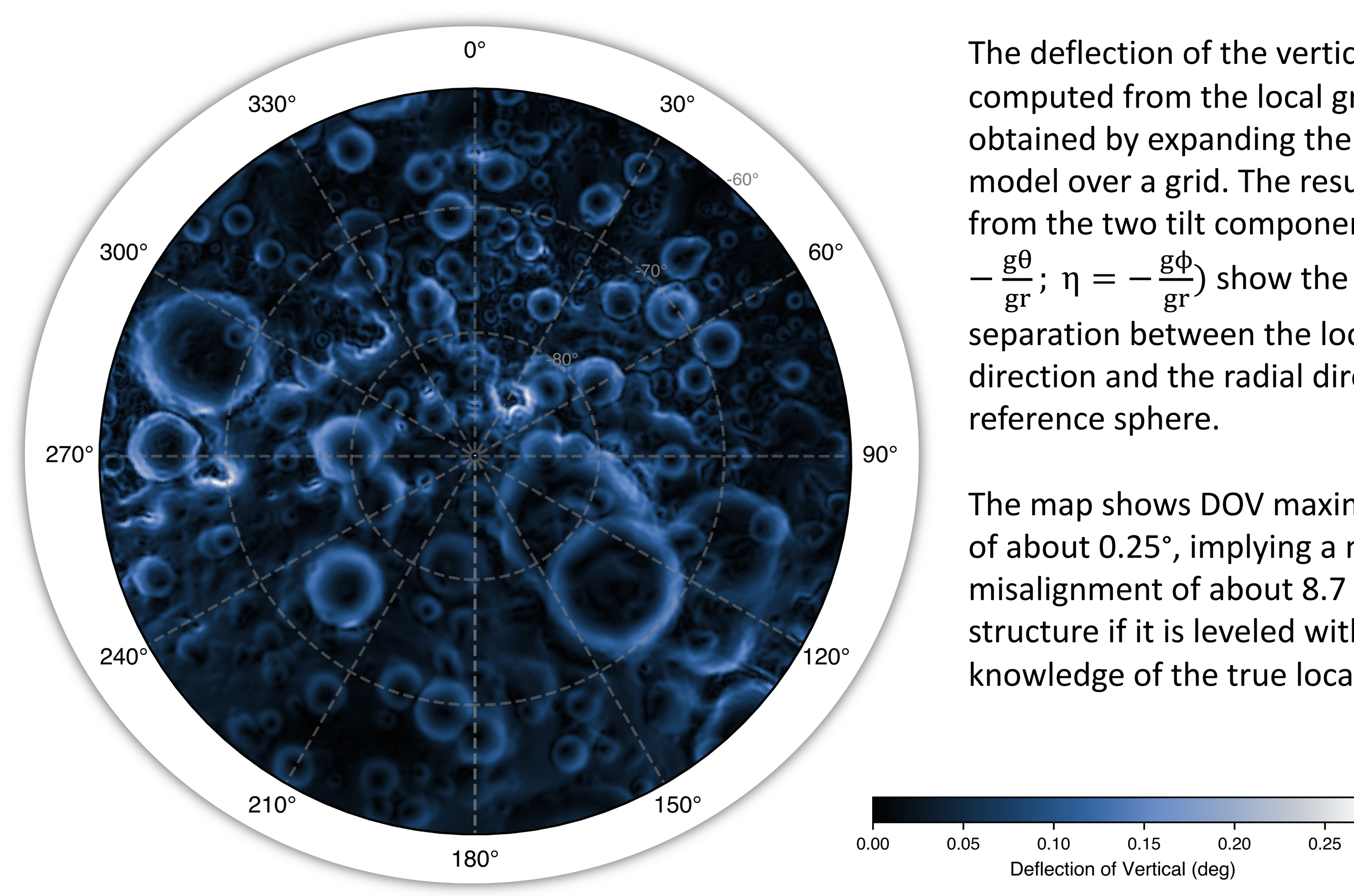

Figure 4: Deflection of the vertical from GRAIL gravity field [14], shown in south polar stereographic projection (extents to 60°S).

The deflection of the vertical (DOV) is computed from the local gravity vector obtained by expanding the lunar gravity model over a grid. The resultant magnitude from the two tilt components ($\xi = -\frac{g\theta}{gr}$; $\eta = -\frac{g\phi}{gr}$) show the angular separation between the local gravity direction and the radial direction from the reference sphere.

The map shows DOV maximum magnitudes of about 0.25°, implying a maximum lateral misalignment of about 8.7 mm over a 2 m structure if it is leveled without the knowledge of the true local gravity direction.

SUMMARY

The Goddard Lunar Data Analysis Center was established via the International Laser Ranging Service (ILRS) to support and extend the scientific return of lunar laser ranging (LLR) data. The LLR experiment has accumulated over five decades of range data with improving accuracy from ground stations to the laser retroreflectors on the lunar surface. The current LLR data accuracy obtained from select LLR observatories falls in the millimetric regime, while the fits of the state-of-the-art models [1-4] to the data are, at best, at the level of a centimeter (in weighted rms).

As data precision improves through the deployment of next-generation lunar retroreflectors (via collaborations across space agencies, academia, and commercial providers), model development efforts and independent analyses currently lag despite their vital role to support and extend the multi-disciplinary science returns from LLR data. Here we report on some activities of the center since its inception in early 2022. Contributions from the center are provided within references [4-13].

References: [1] Fienga *et al.* (2021). *NSTIM*, 110. [2] Folkner *et al.* (2014). *INPR*, 42–196, 1–81. [3] Williams *et al.* (2023). *Pla. Sci. J.*, 4(5), 89. [4] Viswanathan *et al.* (2021). *Bulletin of the AAS*, *53*(4) [5] Smith *et al.* (2022). *Pla. Sci. J.*, *3*(9), 217 [6] Briaud *et al.* (2023). *Icar.*, *394*, 115426 [7] Colmenares *et al.* (2023). *Pub. of the Astron. Soc. of the Pacific*, *135*(1052) [8] Blase *et al.* (2023). *LEAG*, LPI Contribution No. 2887, id.2917 [9] Sabhlok *et al.* (2024). *Icar.*, 417 [10] Ray *et al.* (2025). *Sci. Rep.*, *15*(1), 14466 [11] Cascioli *et al.* (2025). *Pla. Sci. J.*, *6*(10) [12] Chanover *et al.* (2025) *LPSC*, LPI Contribution No. 3090, id.2608 [13] Fienga *et al. Proc. of IAU S401* [14] Goossens *et al.* (2021). *Earth Space Sci.*, 8(11), e2021EA001695.

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