

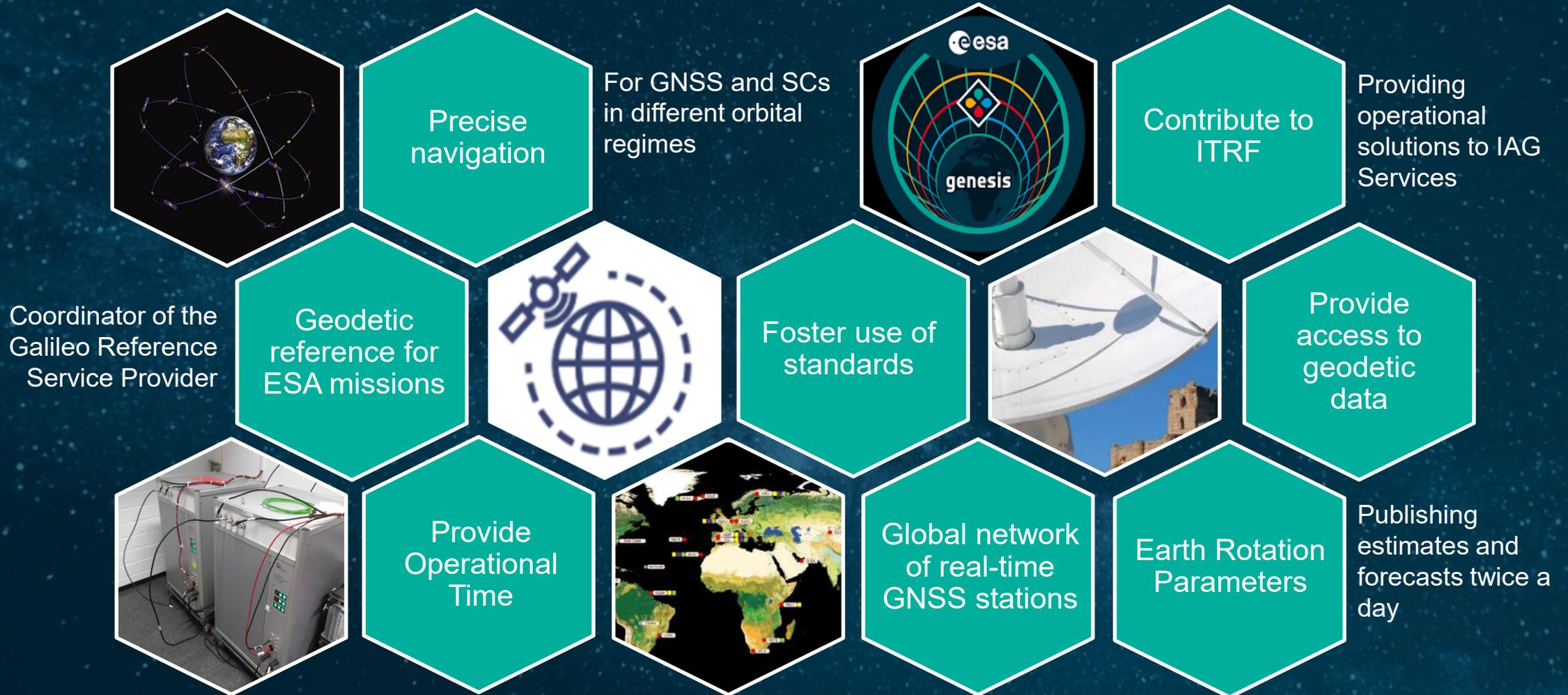
# ESA activities in support of lunar reference frames

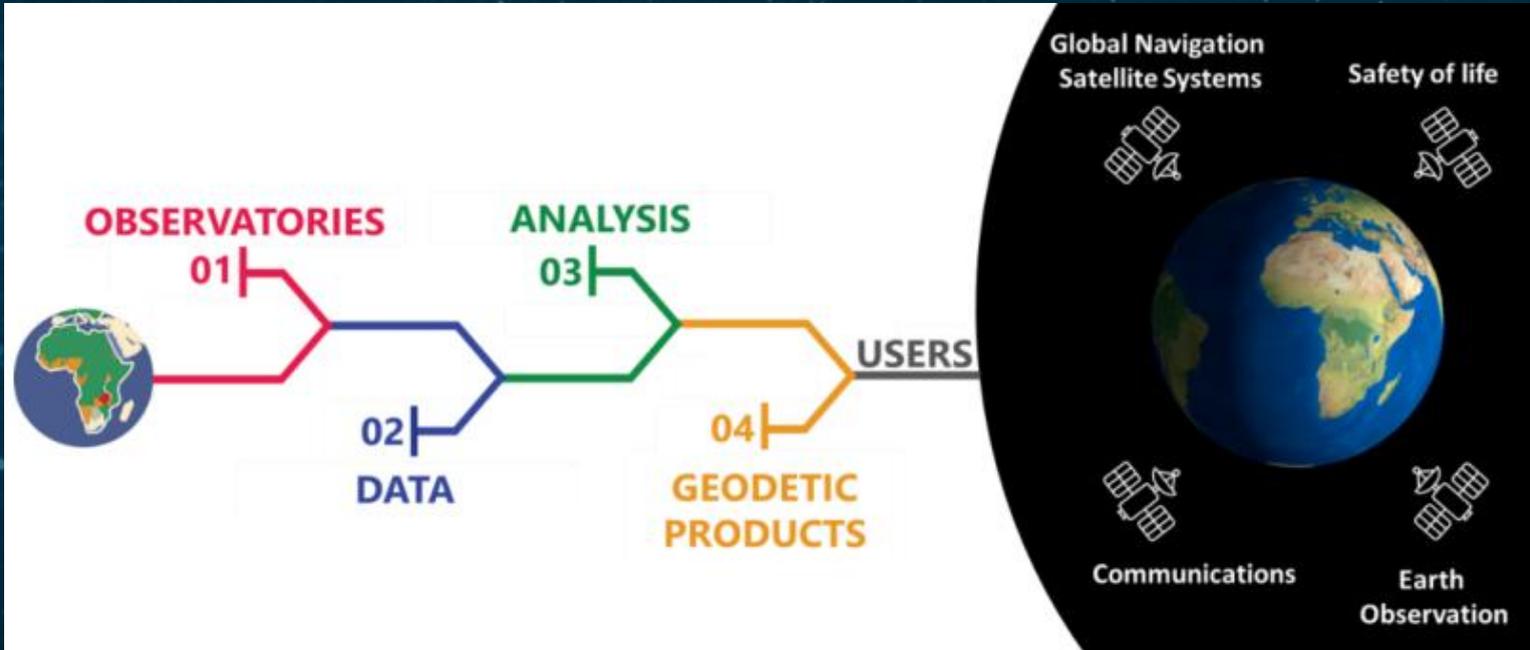
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Sara Bruni, Erik Schönemann, Eleonora Antonietti, Tim Springer,  
Cosimo Stallo, Monica Gotta, Richard Swinden, Floor Melman, Jörg Hahn

11/02/2026, Workshop on Cislunar Positioning, Navigation, and Timing (PNT), Vienna 10-13/02/2026

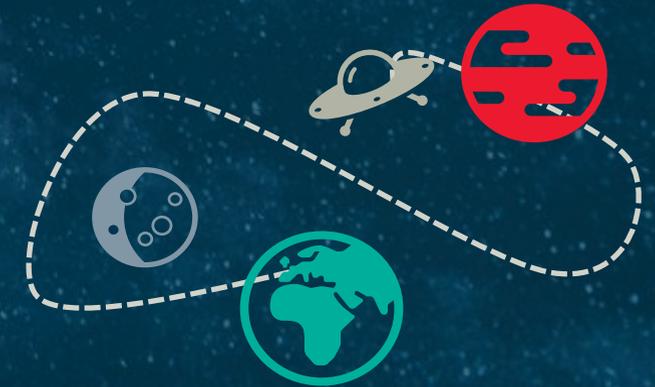
# Geodetic activities at the Navigation Support Office





- The “geo”-detic infrastructure is fundamental for any PNT system, independently on the reference body
- Lessons learned from Earth shall be recycled
- Fundamental role of international collaboration among agencies, scientific community and private sector
- Standardization is key

Image credits:  
UN GCCE hidden risk reports, [https://ggim.un.org/UNGGCE/documents/20240620-Hidden\\_Risk\\_Report.pdf](https://ggim.un.org/UNGGCE/documents/20240620-Hidden_Risk_Report.pdf)





The reference frames of Solar System bodies are a fundamental asset to support many upcoming ESA missions, collaborations and initiatives:

- LunaNet
- Lunar Missions
  - Lunar Pathfinder
  - Moonlight
  - NovaMoon
- Mars missions
  - Marconi
- SSI

# ESA's selenodetic activities

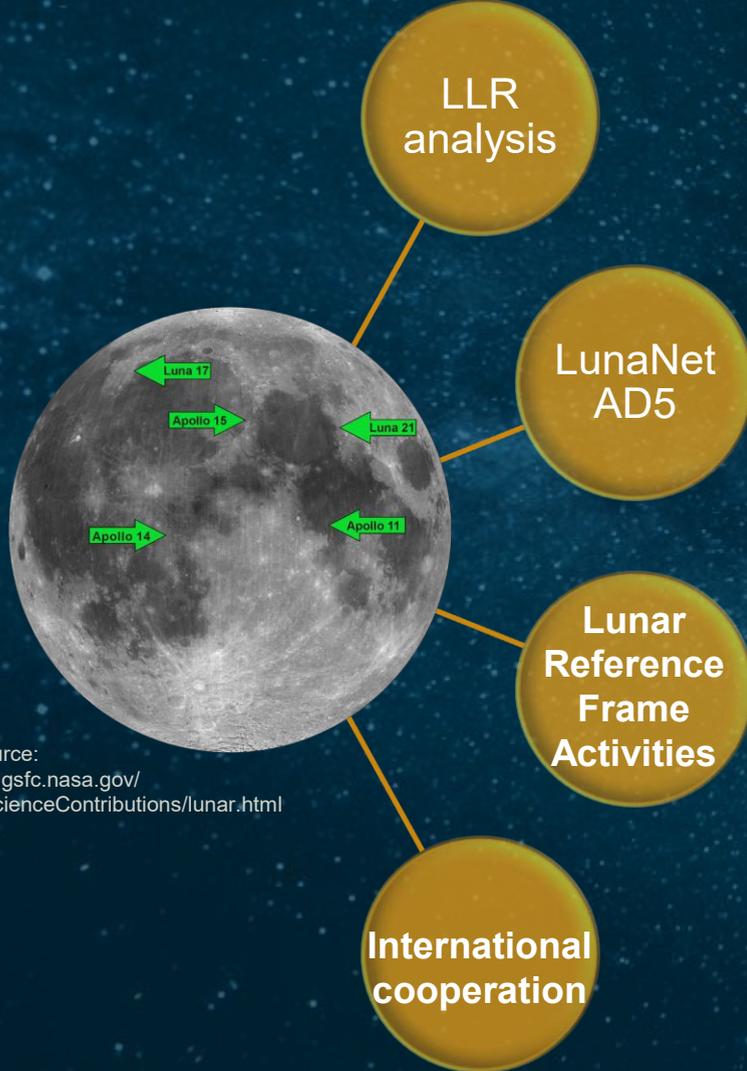
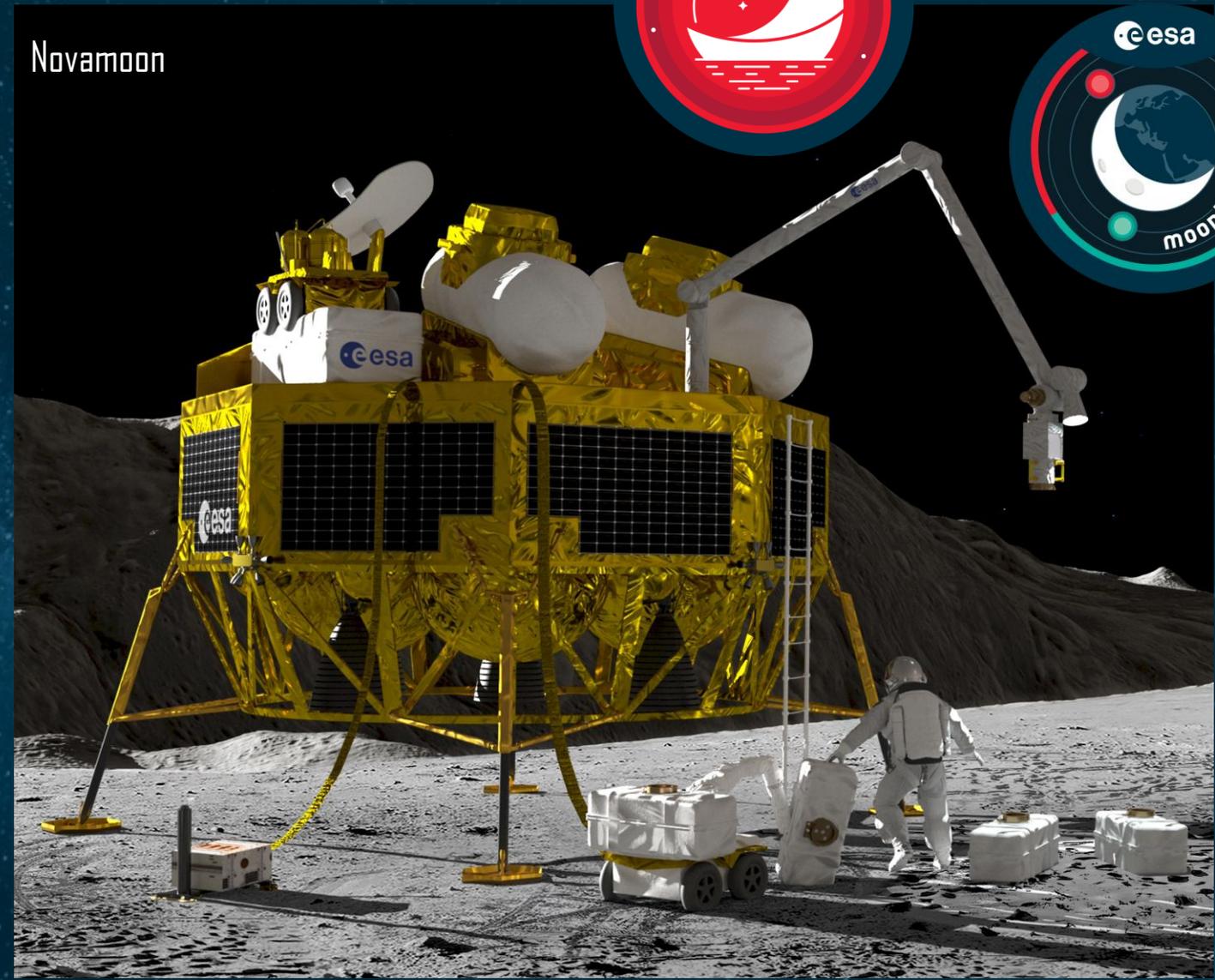


Image source:  
<https://ilrs.gsfc.nasa.gov/science/scienceContributions/lunar.html>

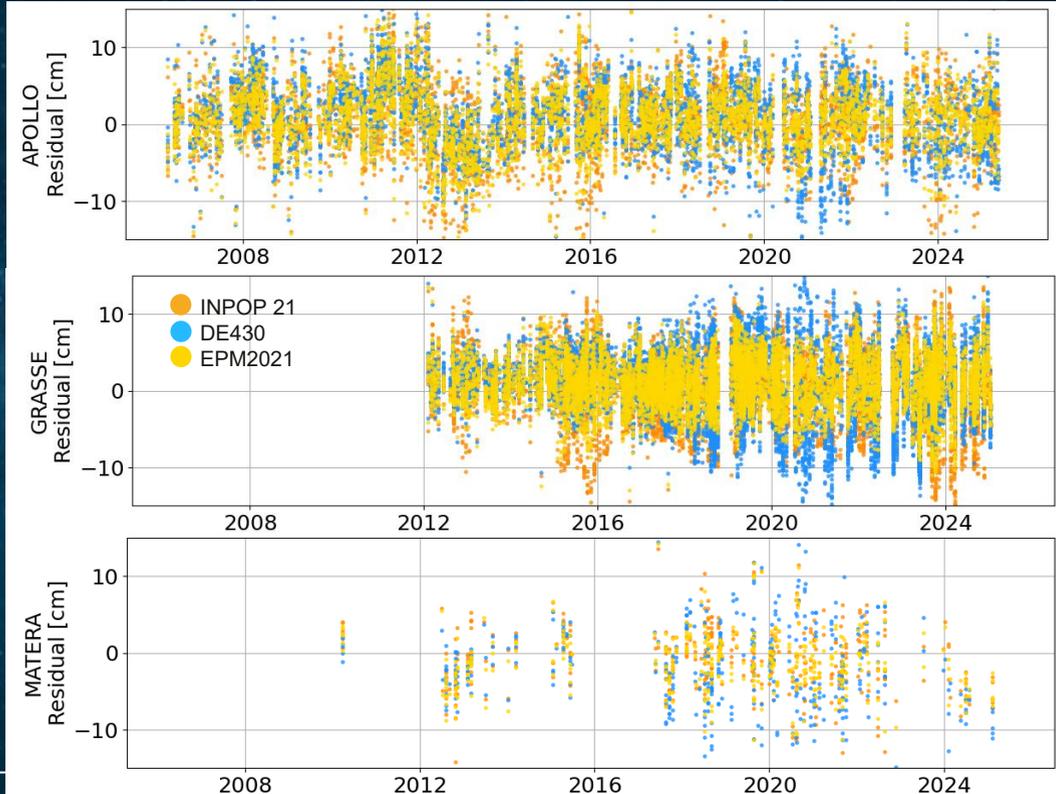
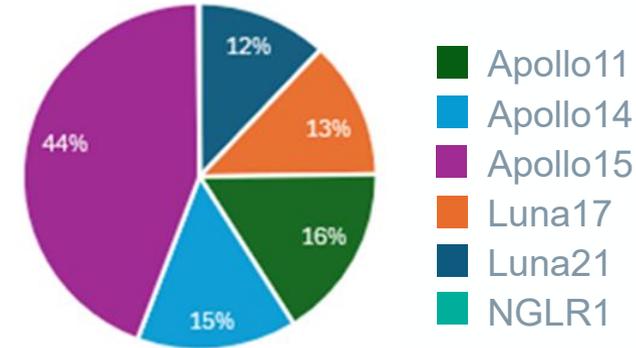
Novamoon



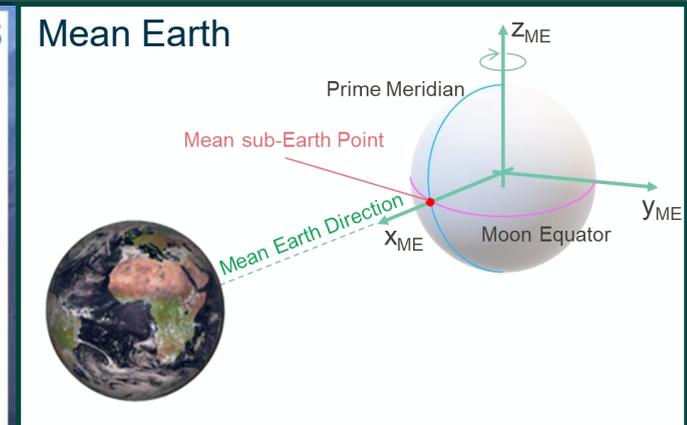
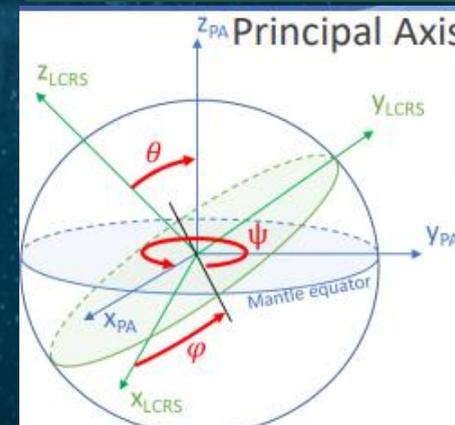
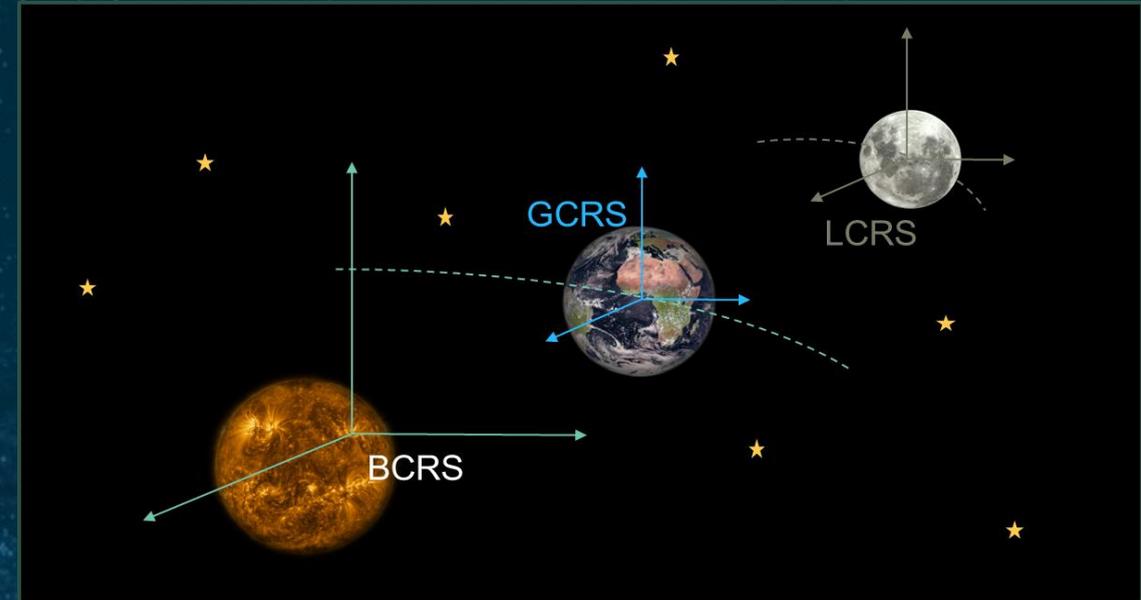
# LLR Analysis

- Motivation: LLR data are key for the estimation of the orbit and orientation of the Moon (see e.g. Folkner et al., The Planetary and Lunar Ephemerides DE430 and DE431, Section V)
- Fully integrated in the Esa Precise Navigation System (EPNS)
- Rigorous application of IERS Conventions
- All lunar LLR targets supported, including Blue Ghost
- Different ephemerides sources supported including DE, INPOP and EPM
- Estimation of Love numbers under development

Share of LLR observations to each Moon target (2006-2025):



- Interoperability is key to providing better user-level capabilities than would be achieved by relying exclusively on one provider
- PNT Services rely on definition, adoption and maintenance of common reference frames and time systems
- It is paramount to establish international standards for the realization of
  - Quasi-inertial selenocentric reference frames
  - Moon-fixed reference frames
  - Lunar time scales
- Please refer to the contribution by Gramling et al. for further details



- The first combined lunar reference frame emerged from the IAG–IAU JWG 1.1.3 on Lunar Reference Frames as a coordinated effort to address the operational requirements of operators and users working in the lunar environment.
- Its development created a unique platform for comparing independent ephemerides, yielding new insights into their consistency and performance.
- The initiative plays a key role in broadening awareness and understanding of lunar reference frame standards, ensuring that knowledge extends beyond specialist communities.

## Definition and Realization of the International Lunar Reference Frame

K. Sośnica<sup>1</sup>, A. Fienga<sup>2</sup>, D. Pavlov<sup>3</sup>, N. Rambaux<sup>4</sup>, and R. Zajdel<sup>1,5</sup>

### ABSTRACT

*Context.* All future lunar missions require a definition of the lunar reference system and a realization in the form of the lunar reference frame to ensure consistent products for positioning, navigation, cartography, and timing.

*Aims.* This paper defines the origin, orientation, and scale of the Lunar Reference System (LRS), as well as provides numerical solutions for the first realization of the International Lunar Reference Frame (ILRF). ILRF is defined as the Principal Axis (PA) system, attached to the surface and co-rotating with the Moon, with its origin in the lunar center of mass (lunocenter).

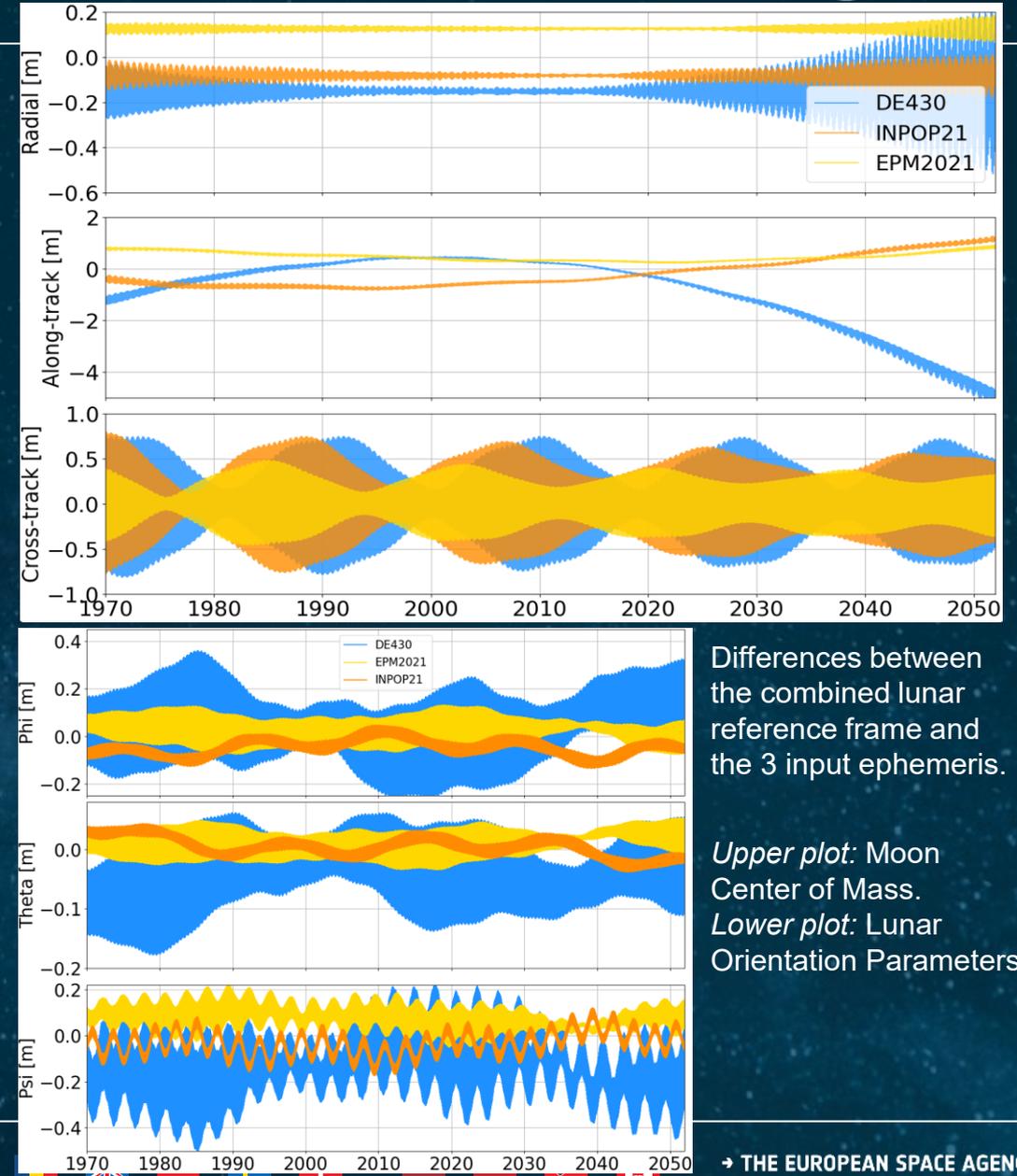
*Methods.* The ILRF realization is based on variance component estimation of the three lunar ephemeris solutions: INPOP21a, DE430, and EPM2021 for the series of the position of the lunar center of mass and rotation Euler angles – precession, nutation, and proper rotation. The solution is valid starting with the period covered by Lunar Laser Ranging (LLR) data in 1970 and ending with extrapolated ILRF realizations in 2052 for future lunar missions.

*Results.* The combined ILRF is characterized by the mean error of 17.6 cm for 2010–2030, where 15.3 cm comes from the origin and 8.6 cm from the orientation realization. The error in the realization of the origin is mainly caused by a poor geometry of the retroreflector network, resulting in a high correlation between the scale and the X component of the lunocenter in PA. The LLR post-fit residuals in ILRF are at the level of 2–3 cm in terms of the standard deviations of one-way ranges for best-performing LLR stations. The mean errors of the transformation between ILRF and other reference frame realizations in PA are at the level of 3 cm, whereas the mean transformation error to the DE421 Mean Earth frame equals 5 cm.

<https://arxiv.org/abs/2510.15484v1>

# Lunar Reference Frame activities @ ESA/ESOC

- ESA is willing to contribute to the long-term generation of a combined lunar reference frame:
  - produced in alignment with the guidelines issued by the scientific community
  - maintained as an accessible resource for interested users.
- As a first step toward this goal, ESA has undertaken an initial replication of the combination approach proposed by Sosnica et al. to generate the first prototype I LuRF.
- Although the system is not yet fully operational, early comparisons are promising, showing high consistency between ESA's preliminary solution and the reference product generated by Sosnica and colleagues.



- ESA is taking steps towards
  - development of in-house state-of-the-art LLR analysis capabilities
  - lunar reference frame combination
  - involvement in the activities of the IAG-IAU WG
- ESA fully supports international cooperation and the establishment of permanent frameworks and forums dedicated to advancing research on lunar reference frames, as well as the generation, validation, and long-term maintenance of products that meet global operational needs.
- ESA intends to participate actively in such organisations, should the international consensus welcome our involvement, while fully respecting the scientific community's leadership in this domain.

**Thank you for your attention**