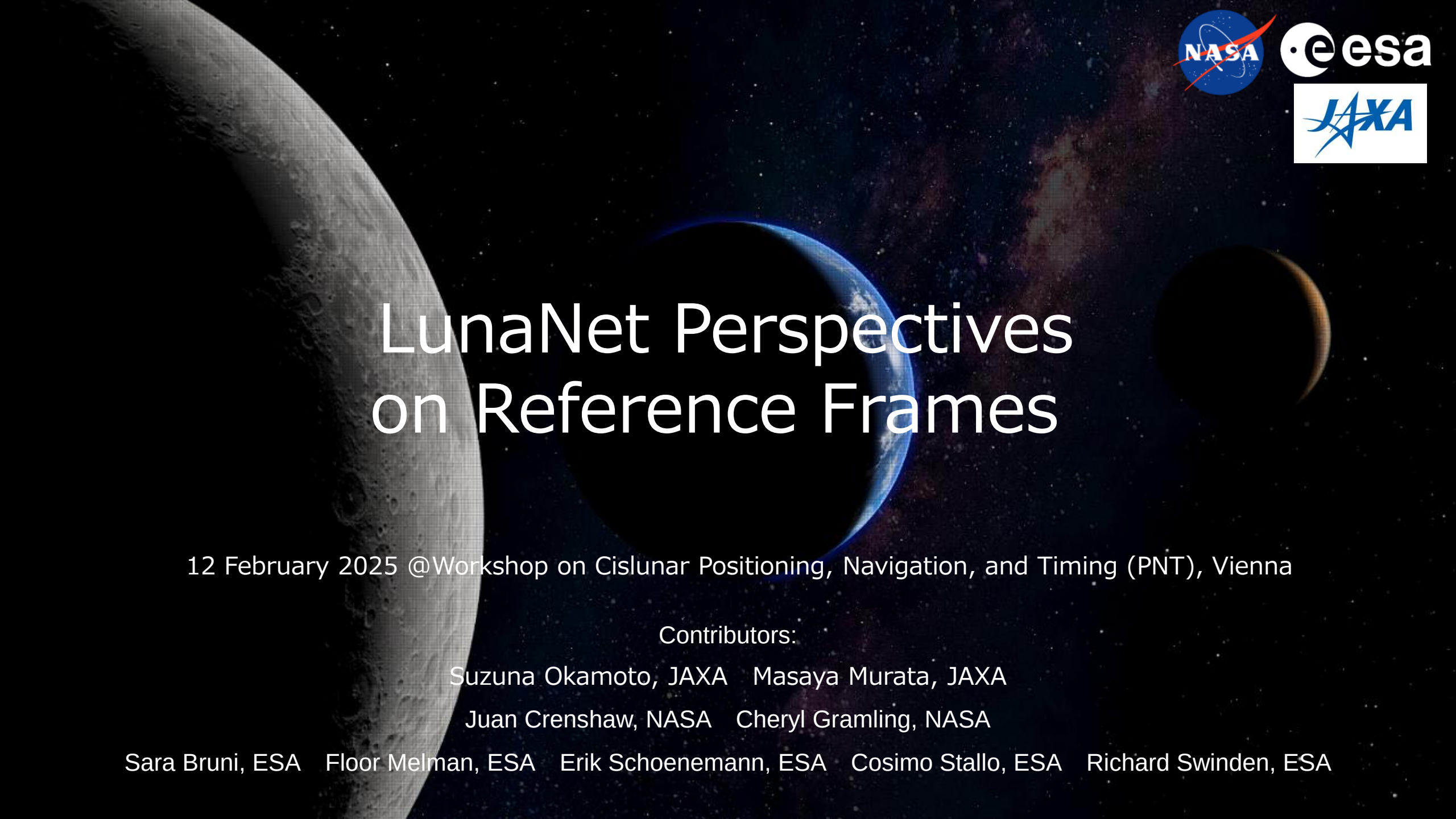

LunaNet Perspectives on Reference Frames

12 February 2025 @Workshop on Cislunar Positioning, Navigation, and Timing (PNT), Vienna

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Overview of LunaNet Perspectives; Time & Reference Systems Application

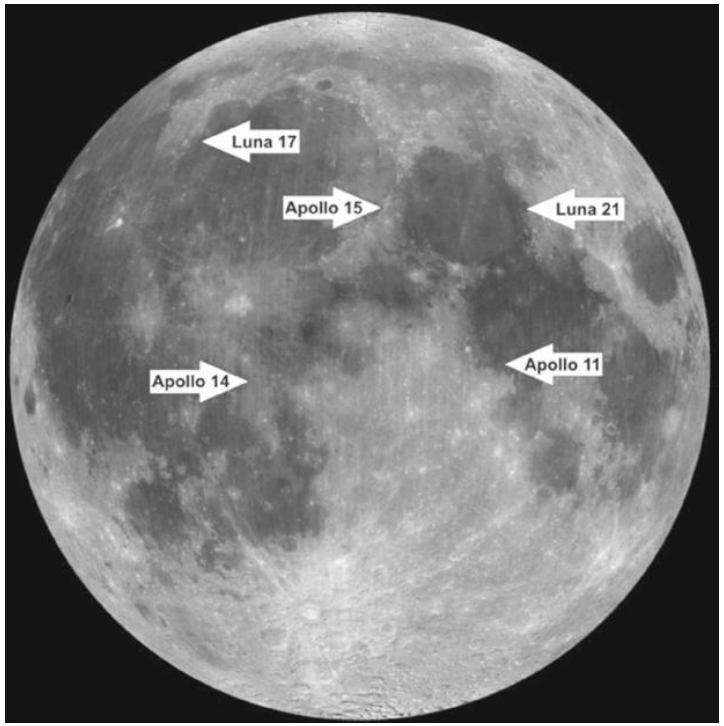
- LunaNet Perspectives on Reference Frames (given by JAXA)
- Towards an International Lunar Time Reference – LunaNet Reference Time (given by ESA)
- LunaNet Perspectives – How the International Standards Community Can Help (given by NASA)

Importance of Reference Frame

To ensure PNT on the Moon, developing standards is essential.

Currently, several reference frames are considered for the Moon, and 2 commonly used systems, which is PA (Principal Axis) and ME (Mean Earth), have a difference of about 860m.[3]

Location of the measurement devices on each mission [1]



Coordinate positions for each location in PA and ME [2]

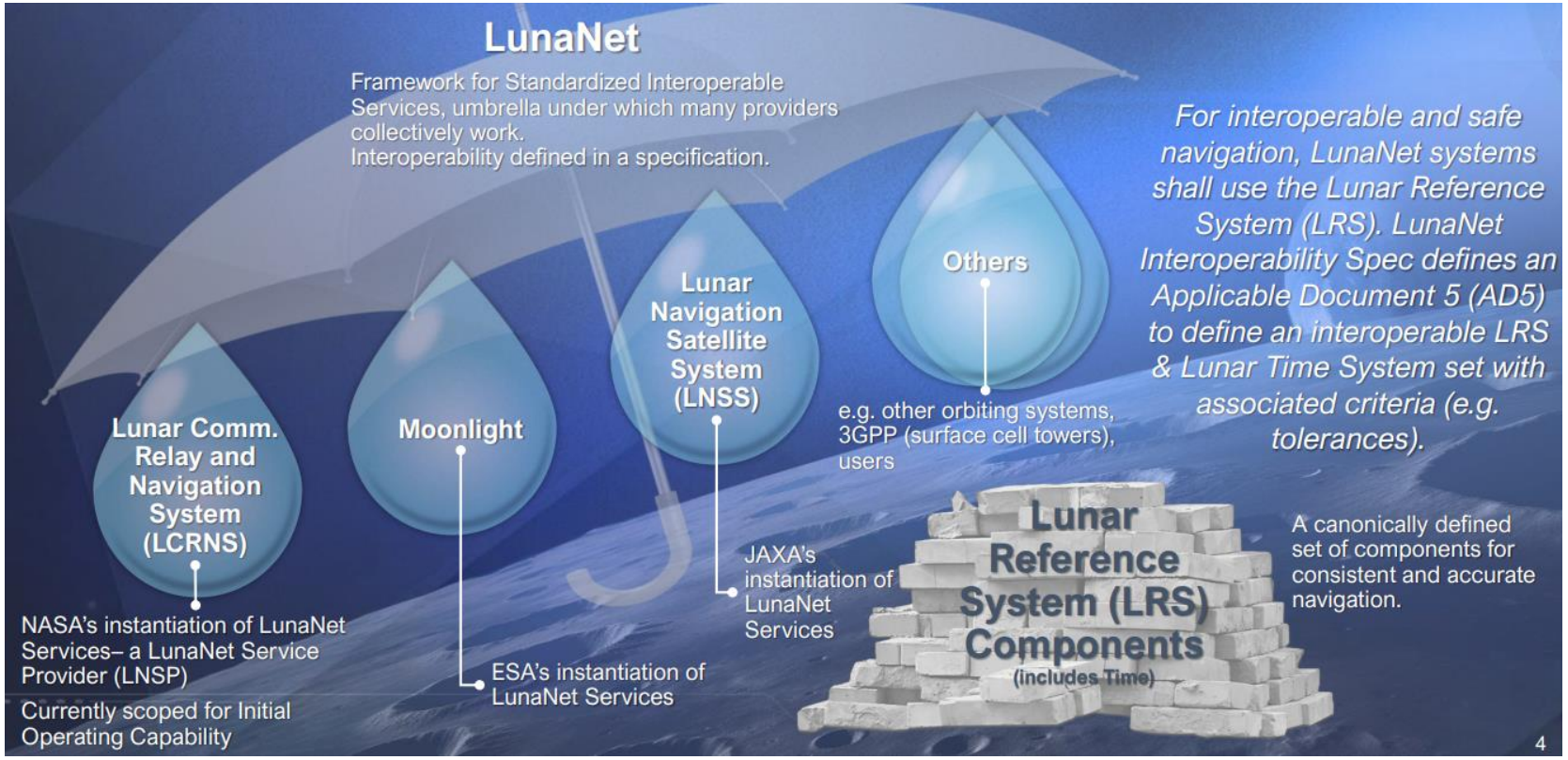
Retroreflectors	DE440 PA Frame (m)	DE421 MER Frame (m)
Apollo 11	1591967.049	1591747.649
	690698.573	691222.200
	21004.461	20398.110
Apollo 14	1652689.369	1652818.682
	−520998.431	−520454.587
	−109729.869	−110361.165
Apollo 15	1554678.104	1554937.504
	98094.498	98604.886
	765005.863	764412.810
Lunokhod 2	1339363.598	1339388.213
	801870.995	802310.527
	756359.260	755849.393
Lunokhod 1	1114291.452	1114958.865
	−781299.273	−780934.127
	1076059.049	1075632.692

524m difference

LunaNet Perspectives on Reference Frames

LunaNet is working on a standardization document called LNIS (LunaNet Interoperability Specification).

The AD5 of LNIS will describe the interoperability of lunar reference frames that can be used in LunaNet.



LunaNet Overview [4]

Reference Systems and Reference Frames; Long term

The long-term perspective of LunaNet is to adopt reference systems/frames generated with the contribution of the whole scientific community under the auspices of official international organizations.

	Inertial System	Fixed System	Reference Frame
The Earth	GCRS (Geocentric Celestial Reference System)	ITRS (International Terrestrial Reference System)	ITRF (International Terrestrial Reference Frame)
The Moon	LCRS (Lunar Celestial Reference System)	ILRS (International Lunar Reference System)?	Short term: PA, ME Long term: ILRF (International Lunar Reference Frame)?

LunaNet Perspectives on Reference Frames; Short term

- To focus on the PNT perspective, LunaNet recommends PA in the short term for the LunaNet radio navigation systems.
- Reason 1: ME is derived from PA. [2]

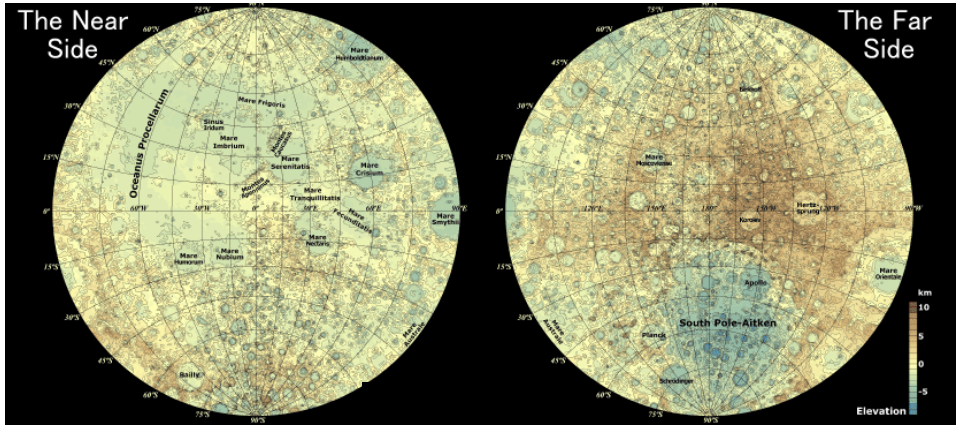
$$\begin{aligned} \boldsymbol{r}_{\mathrm{MER,DE421}} &= \mathcal{R}_x\left(-0\,''.2785\right)\mathcal{R}_y\left(-78\,''.6944\right) \\ &\quad \times \mathcal{R}_z\left(-67\,''.8526\right)\boldsymbol{r}_{\mathrm{PA,DE440}}. \end{aligned}$$

- Reason 2: PA is more easily applied to other celestial bodies.

LunaNet Perspectives on Reference Frames ; Short term

- In general, the most likely scenario is that users can employ either ME or PA with clarifying the frame in use.
- This is because ME has been widely employed in the past scientific studies and mappings and it is easy to ensure consistency and compatibility with historical data sets.
  - ➢The IAU/IAG WG recommended ME for cartographic applications.
- The experience of SLIM's operation demonstrated combined use of PA and ME.

Map of the Moon according to the ME system using DE421 [5]



SLIM landed on the Moon in 2024 [6]

Future Discussion

- Why do the current PA realizations show discrepancies at 1m-level on the Moon surface (DE vs INPOP)?

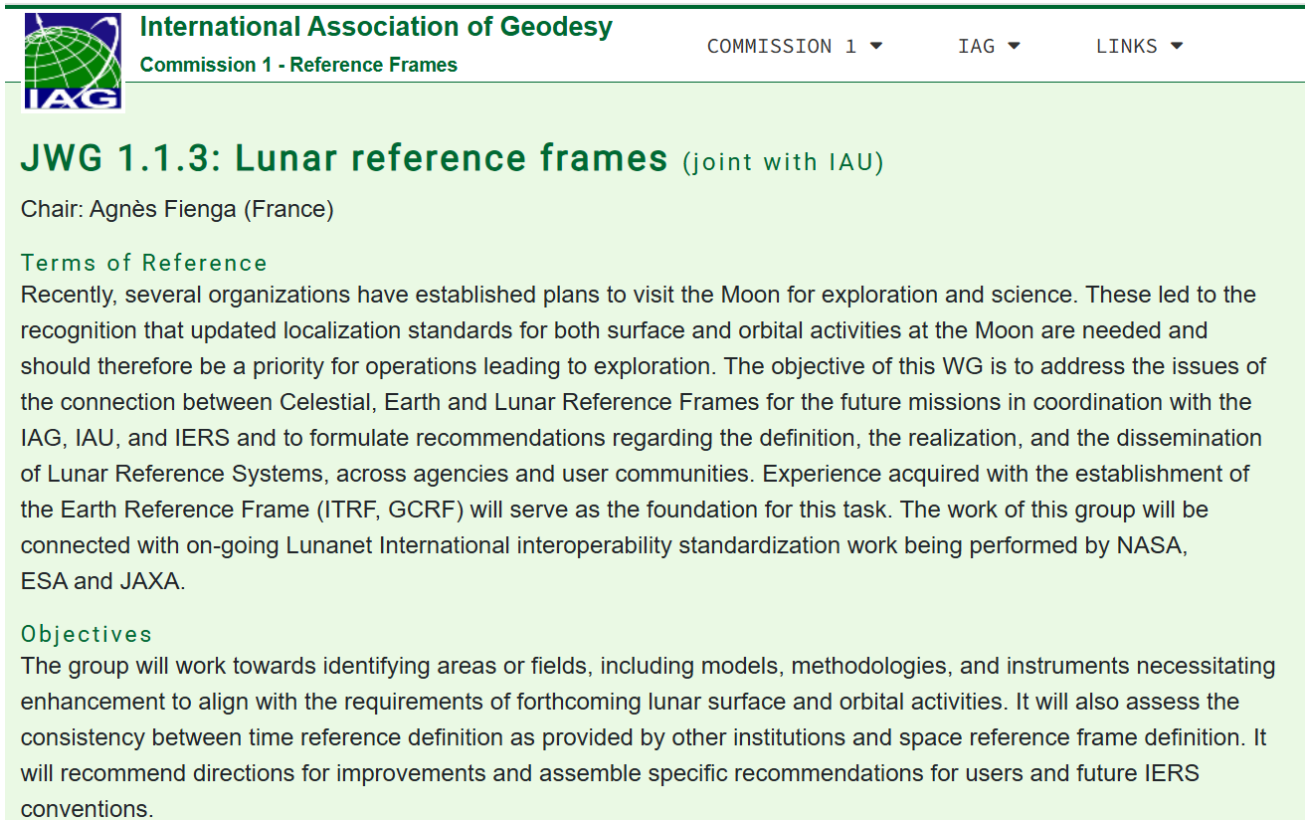
- How can we strengthen the international scientific collaboration?

- Would it be possible for the established working groups (e.g. IAG 1.1.3) to provide an endorsement for a given PA realization (as the IERS selects the official terrestrial reference frame among 3 available realizations)?

Future Initiatives

International communities like IAG (International Association of Geodesy) and IAU (International Astronomical Union) are going to work on standardization.

WG for several topics initiated their activities in IAG.



International Association of Geodesy
Commission 1 - Reference Frames

COMMISSION 1 ▾ IAG ▾ LINKS ▾

JWG 1.1.3: Lunar reference frames (joint with IAU)

Chair: Agnès Fienga (France)

Terms of Reference

Recently, several organizations have established plans to visit the Moon for exploration and science. These led to the recognition that updated localization standards for both surface and orbital activities at the Moon are needed and should therefore be a priority for operations leading to exploration. The objective of this WG is to address the issues of the connection between Celestial, Earth and Lunar Reference Frames for the future missions in coordination with the IAG, IAU, and IERS and to formulate recommendations regarding the definition, the realization, and the dissemination of Lunar Reference Systems, across agencies and user communities. Experience acquired with the establishment of the Earth Reference Frame (ITRF, GCRF) will serve as the foundation for this task. The work of this group will be connected with on-going Lunanet International interoperability standardization work being performed by NASA, ESA and JAXA.

Objectives

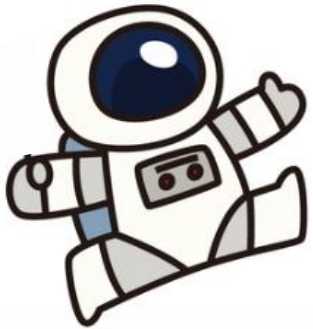
The group will work towards identifying areas or fields, including models, methodologies, and instruments necessitating enhancement to align with the requirements of forthcoming lunar surface and orbital activities. It will also assess the consistency between time reference definition as provided by other institutions and space reference frame definition. It will recommend directions for improvements and assemble specific recommendations for users and future IERS conventions.

1. PA and ME statement
2. Accuracy of the lunar reference frames
3. Interoperability / compatibility between Lunar and Earth frames

Summary

- To ensure PNT on the Moon, developing standards is essential.
- Currently, several reference frames are considered.
- LunaNet is working on AD5 of LNIS and it will describe the interoperability of lunar reference frames that can be used in LunaNet.
- To focus on the PNT perspective, LunaNet recommends PA in the short term for radio navigation.
- In general, the most likely scenario is that users can employ either ME or PA with clarifying the frame in use.
- The long-term perspective of LunaNet is to adopt reference systems/frames generated with the whole scientific community under international organizations.

Thank you for your attention.



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[1] Jürgen Müller, Thomas W. Murphy Jr., Ulrich Schreiber, Peter J. Shelus, Jean-Marie Torre, James G. Williams, Dale H. Boggs, Sebastien Bouquillon, Adrien Bourgoin, Franz Hofmann, 2019, “Lunar Laser Ranging: a tool for general relativity, lunar geophysics and Earth science”

[2] Park, R.S; Folkner, W.M.; Williams, J.G.; Boggs, D.H., 2021, “The JPL Planetary and Lunar Ephemerides DE440 and DE441”

[3] B. A. Archinal, C. H. Acton, M. F. A’Hearn, A. Conrad, G. J. Consolmagno, T. Duxbury, D. Hestroffer, J. L. Hilton, R. L. Kirk, S. A. Klioner, D. McCarthy, K. Meech, J. Oberst, J. Ping, P. K. Seidelmann, D. J. Tholen, P. C. Thomas, I. P. Williams,2018, “Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2015”

[4] Cheryl Gramling/NASA, Juan Crenshaw/NASA, Pietro Giordano/ESA, Richard Swinden/ESA, Erik Schoenemann/ESA, Sara Bruni/ESA. 2023, International Committee on GNSS, Madrid, “LunaNet: Interoperability for Lunar PNT”

[5] https://www.gsi.go.jp/chirijoho/chirijoho41003.html

[6] https://jda.jaxa.jp/

[7] https://com1.iag-aig.org/sub-commission-11

[8] https://www.ac-illust.com/


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