Activities of the IAG Working Group 1.1.3 on

Lunar reference systems and frames

by

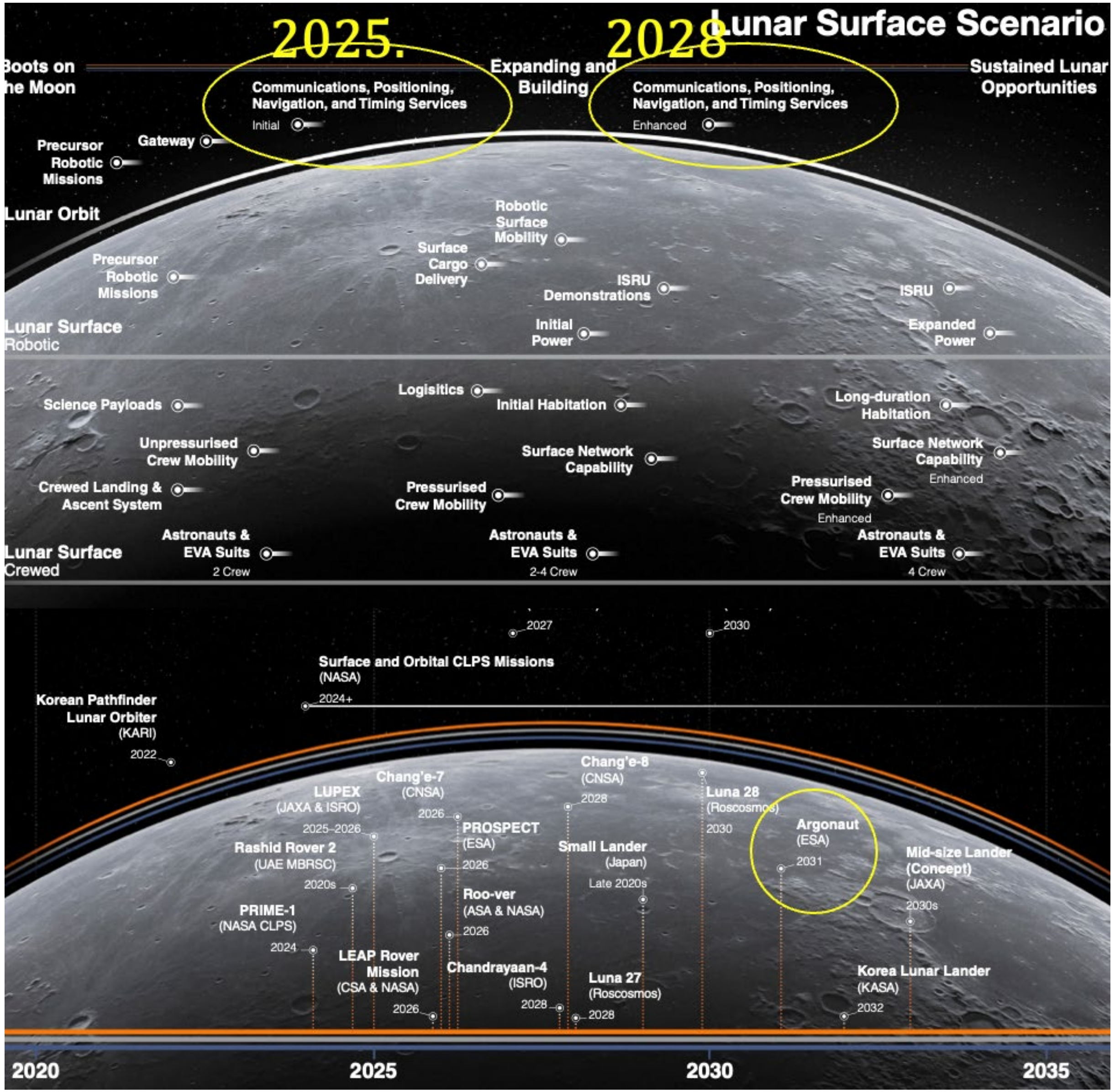
A. Fienga, **K. Sosnica**, K. J. Brinkley, P. Defraigne, C. Gramling, T. Garner, R. Heinkelmann, L. Iess, M. Karbon, S. Klioner, E. Mazarico, S. Merkowitz, M. Murata, J. Müller, F. Paganelli, D. Pavlov, J. Ping, N. Rambaux, S. Stewart, R. Swinden, P. Tavella, J. Ventura-Traveset

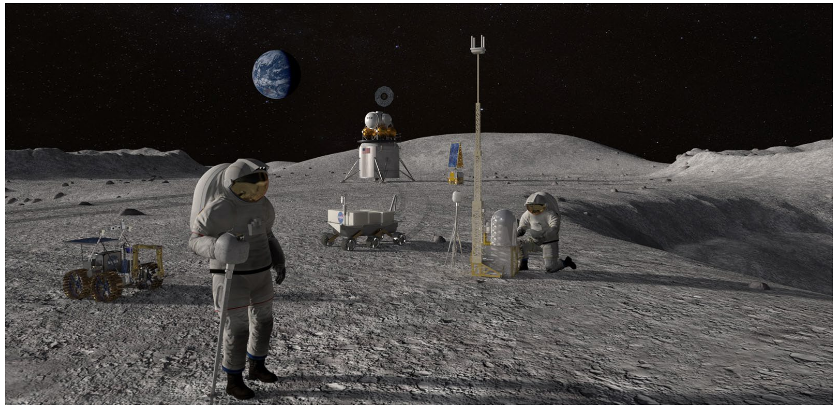
International Association of Geodesy

Context

Intense activities and developments around Moon and crewed Moon exploration

Global Exploration Roadmap (ISECG 2024)



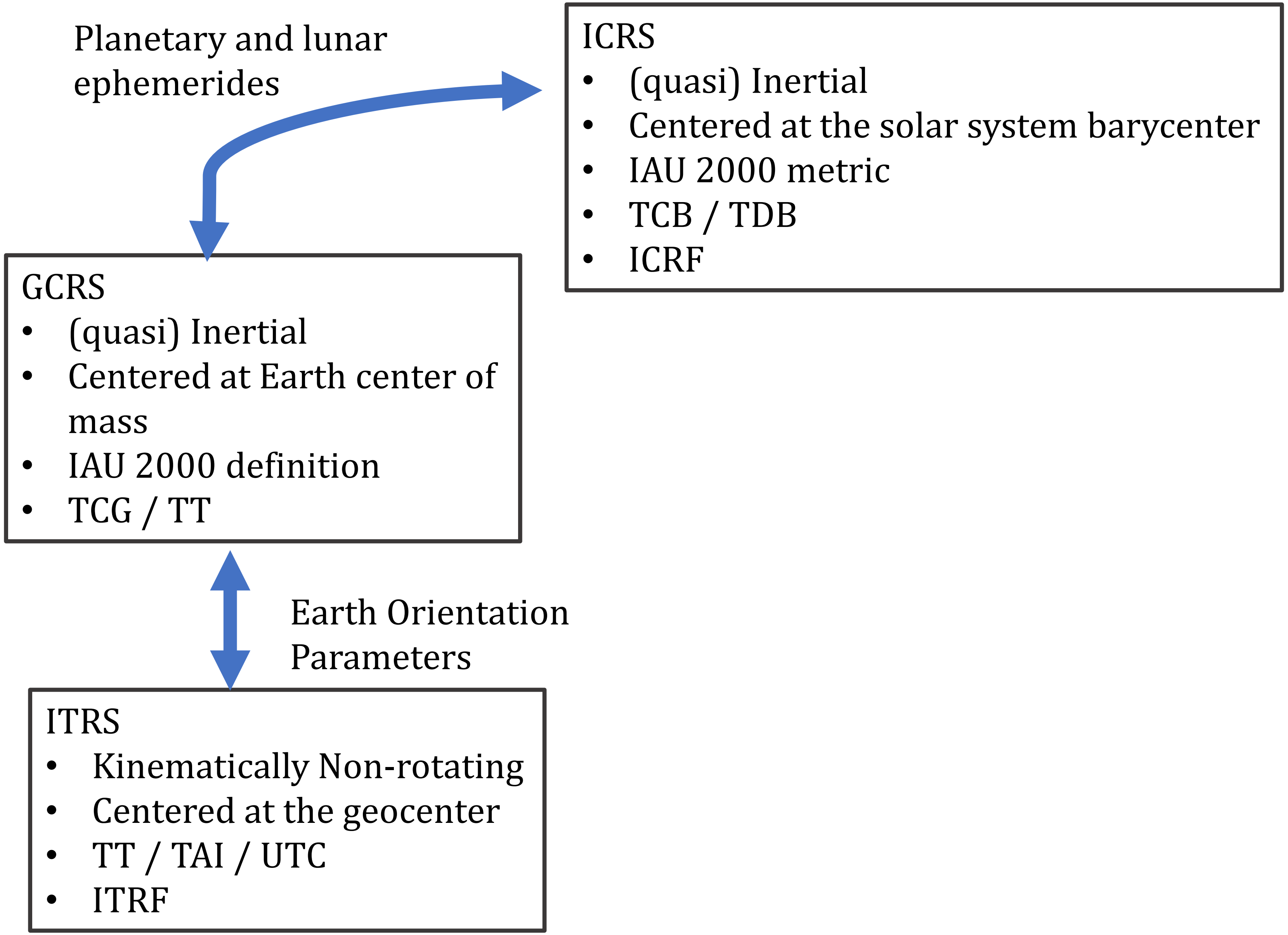


- Human and robotic activities on the Moon surface

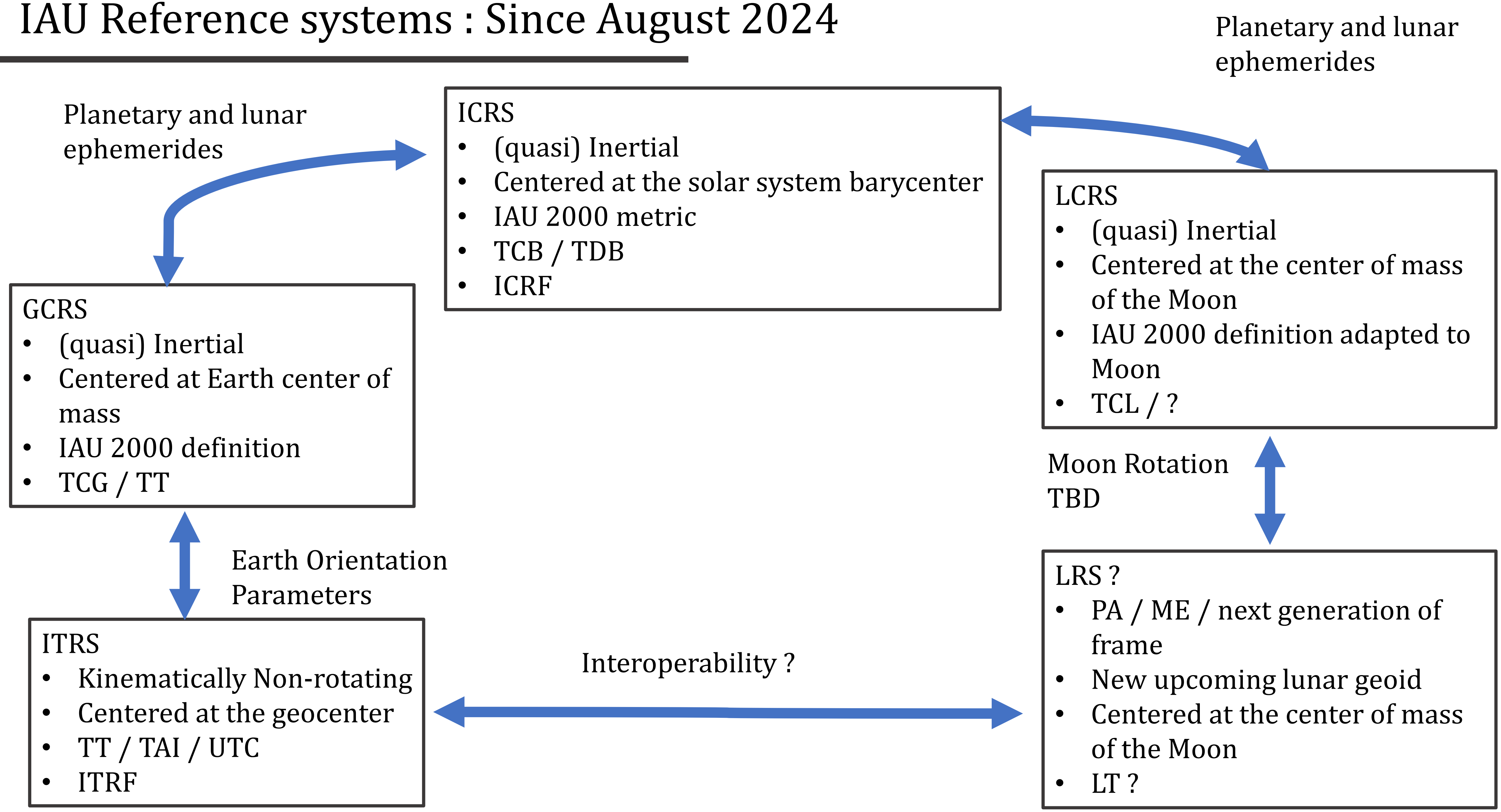
- Multiple public and private providers

→ Need of accurate localization for human activities on the Moon surface

IAU Reference systems : Before August 2024

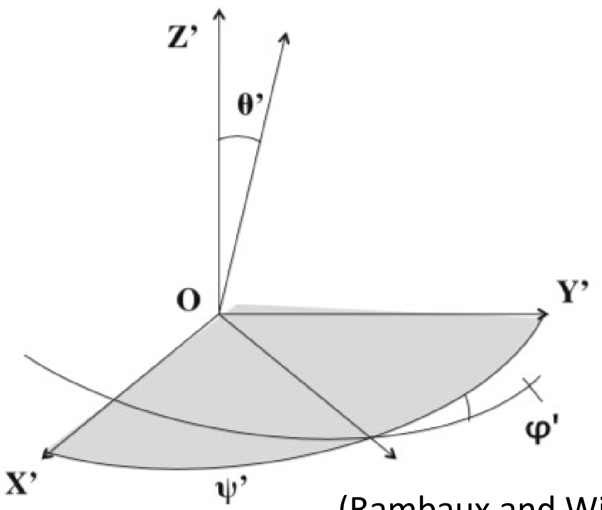


IAU Reference systems : Since August 2024



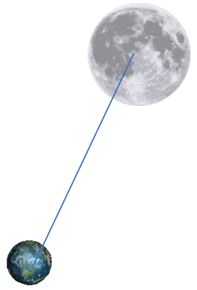
Principal axis (PA) frame / Mean Earth (ME) frame

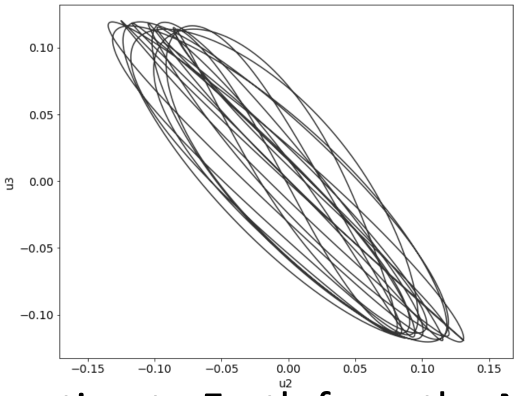
- The PA reference frame used to write and to compute the Moon rotation in the ephemerides
- PA reference frame is deduced from the fit of the model to the LLR observations. It is a lunar orientation ephemerides described through the rotation (Euler) angles (ψ, θ, φ).
- The lunar ephemerides **DExxx** (JPL) and **INPOPxx** (OCA/IMCCE) : similar in terms of LLR residuals.

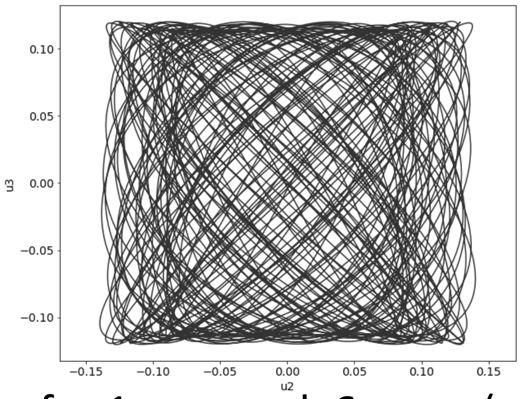


(Rambaux and Williams 2011)

- The ME reference frame is an idealization and depends on ephemerides and gravity solutions.
- The *z*-axis as the mean rotational pole
- The prime meridian (0° Longitude) is defined by the **mean** Earth direction.
- This point does not coincide with any prominent crater or other lunar surface feature.







Direction to Earth from the Moon for 1 year and 6 years (rd)

IAG JWG 1.1.3 : Lunar reference frame since 2024

Members :

Kayla.J.Brinkley (USA)
Pascale Defraigne (Belgium)
Agnès Fienga (France), *Chair*
Cheryl Gramling (USA)
Trevor Garner (USA)
Robert Heinkelmann (Germany)
Luciano Iess (Italy)
Maria Karbon (Spain)
Sergei Klioner (Germany)
Erwan Mazarico (USA)
Stephan Merkowitz (USA)

Masaya Murata (Japan)
Jürgen Müller (Germany)
Flora Paganelli (France)
Dmitry Pavlov (Russia)
Jinsong PING (China)
Nicolas Rambaux (France)
Krzysztof Sosnica (Poland)
Susan Stewart (USA)
Richard Swinden (ESA)
Patrizia Tavella (BIPM)
Javier Ventura-Traveset (ESA)

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

International Association of Geodesy
Commission 1 - Reference Frames
COMMISSION 1 ▾ IAG ▾ LINKS ▾

an Zus (Germany)

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.

IAG JWG 1.1.3 : 4 topics

Topic	Questions	Members/corresponding member
1. PA and ME statement	Definition, methodology, conversion, advantages	E. Mazarico, F. Paganelli, **N. Rambaux**, C. Gramling, L.Iess, M.Murata
2. Accuracy of the lunar reference frames	How do we build more accurate dynamical model of the Moon? Do we need to introduce empirical periodical corrections to better fit the model to LLR data?	E. Mazarico, F. Paganelli, J. Müller, S.Stewart, **D. Pavlov**, N. Rambaux, K. Sosnica, A. Fienga
3. Interoperability / compatibility between Lunar and Earth frames	How do we tie the new lunar frame to ITRF, lunar network versus GNSS ? With what accuracy?	D. Pavlov, C. Gramling, M.Murata, K. Sosnica, S. Stewart, **A. Fienga**, S. Klioner, F. Paganelli
4. Atomic clocks on the Moon surface and/or in the Moon vicinity	Consequences / requirement for the lunar reference system? For Time realization? Utilization of atomic clocks on Moon.	S.Klioner, J. Müller, J. Ping, P. Tavella/Meynadier, J. Ventura-Traveset, R. Swinden, , C. Gramling, L. Iess, M. Murata, **P. Defraigne**

IAG JWG 1.1.3 : PA / ME statement

Propositions

- PA for navigation and positionning
- ME for cartography and archiving

Open questions

- Need of clear definitions of PA and ME
- Need of clear definition of conversion procedure from PA/ME
- Assessment of accuracy for the conversion procedure
- Discussions about Moon ”geoid” definition based on future data

IAG JWG 1.1.3 : Accuracy of the lunar reference frames

Assessments

- Comparison between lunar ephemerides (LE) DE / INPOP/ EMP
- Libration angles / propagation of uncertainties / control point
- (Fienga et al. 2024, ArXiv)

  -Uncertainties in LRR position is **40 cm** for DE (IOM-DE), formal uncertainties about **3 cm** INPOP

  -External accuracy is about **2 meters** for EPM vs DE, INPOP and **1 meter** for INPOP vs DE440

Propositions

- Work on better introducing dynamical effects not included in the present LE (i.e. visco-elastic contribution of the energy dissipation at the core-mantle boundary) → Improvement of the model of tidal deformation and its impact of Moon rotation

IAG JWG 1.1.3 : Interoperability between Lunar and Earth frames

Propositions

- Multi-technique lander such as NASA/ASI LuGre (technical demonstrator) or ESA Argonaut/NovaMoon
- Need of simulation for assessing the improvements

NASA/ASI LuGRe

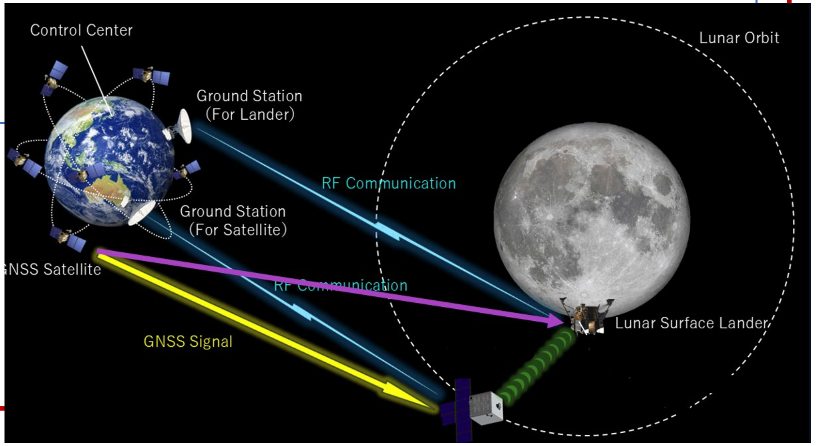
a weak-signal GNSS receiver, a high-gain L-band antenna, a low-noise amplifier, and an RF filter,
launch 15th Jan 2025

Blue Ghost

LuGRe + LRR + ...
Launched 15 Jan, 2025 and next in mid-2025

ESA Argonaut/NovaMoon

VLBI transmitter; mm ranging laser ranging accuracy;
Moonlight/LunaNet GNSS-like ranging/PNT & Direct-to-Earth ranging
alongside with lunar-based atomic clock ensemble and
real time communication access via Moonlight and Directo-to-Earth
Launch date: 2031



IAG JWG 1.1.3 : Atomic clocks on the Moon surface and/or in the Moon vicinity

Context

- On-board atomic clocks on ESA MoonLight
- Atomic clock on ESA Argonaut lander
- RF on NASA Blue Ghost

Propositions

The need for requirements on the lunar time scale and on the time transfer between the Cislunar environment and the Earth environment, from the geodetic point of view, for the definition and realization of the lunar reference frame.

Conclusions 1: Propositions

Propositions (2024)

- Use of PA for navigation and positionning
- Use of ME for cartography and archiving

- Work requested in improving the modeling of tidal deformations and its impact of Moon rotation

- Multi-technique lander such as NASA/ASI LuGre (technical demonstrator) or ESA Argonaut

Conclusions 2: Work for 2025

- Need a clear definition of conversion procedure from PA/ME (Rambaux et al. 2025)
- Assessment of accuracy for the conversion procedure
- Discussions about Moon ”geoid” definition based on future data

- Work requested in improving the modeling of tidal formations and its impact on Moon rotation

- 2025 : Start simulations for assessing the improvements induced by interlink between Moon orbiters-Landers-GNSS-Earth stations for the definition of the spatial and time reference frame (CRAS/OCA)

Thank you for your attention!

krzysztof.sosnica@upwr.edu.pl

fienga@geoazur.unice.fr

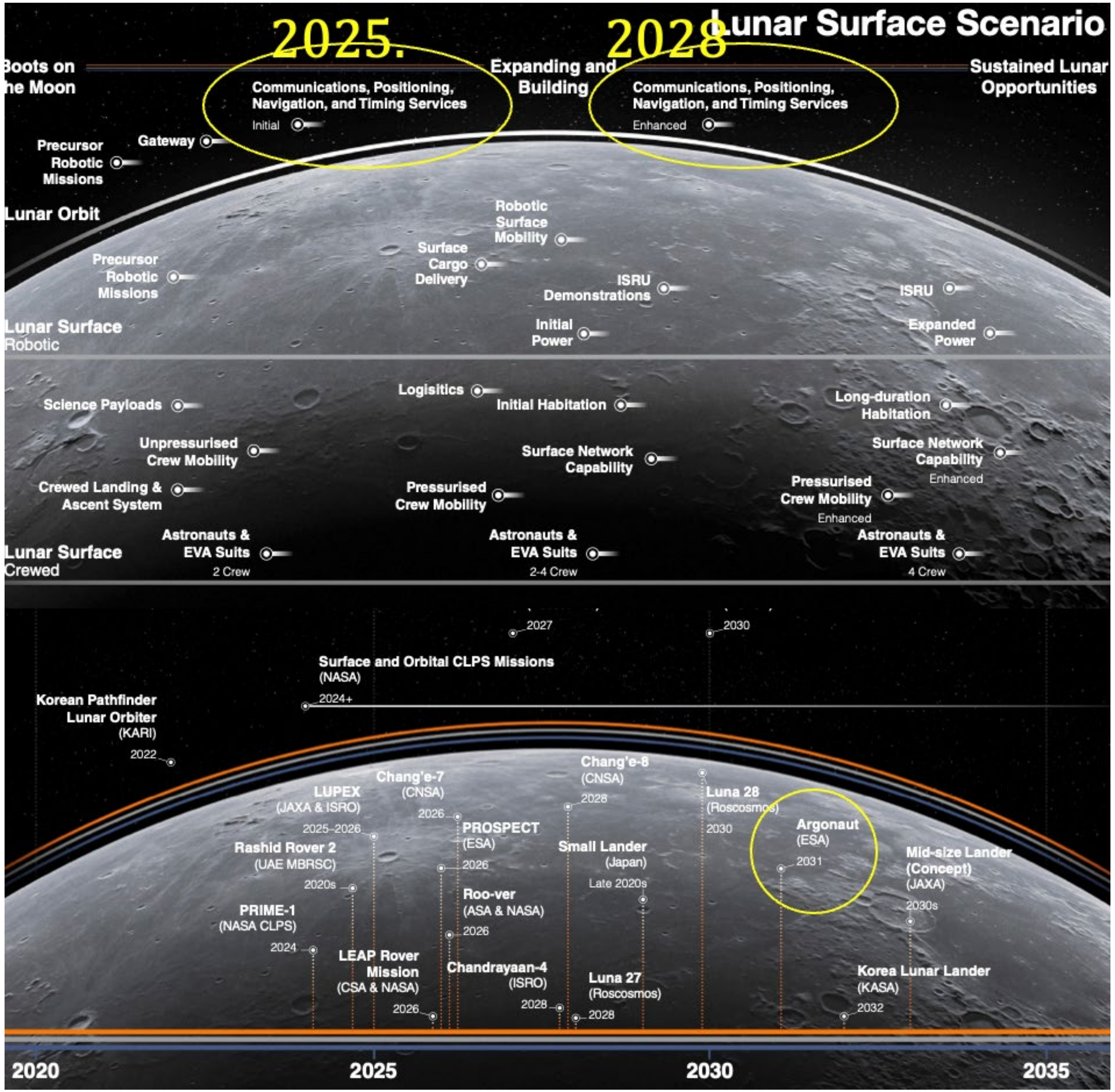
International Association of Geodesy

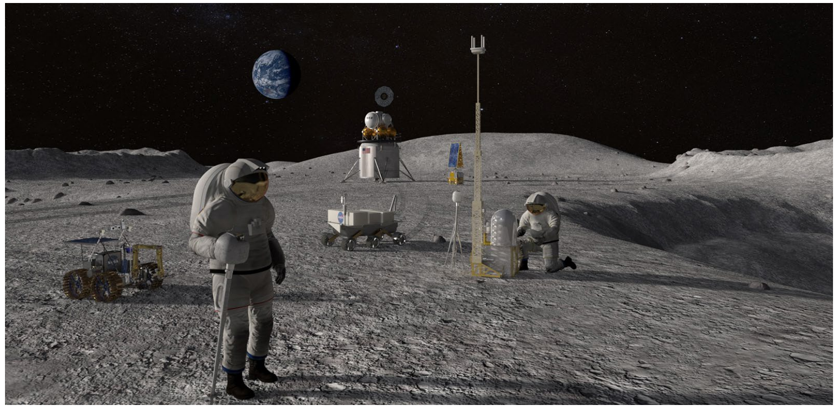
- Backup slides

Context

Intense activities and developments around Moon and crewed Moon exploration

Global Exploration Roadmap (ISECG 2024)





- Human and robotic activities on the Moon surface
- Multiple public and private providers

Context

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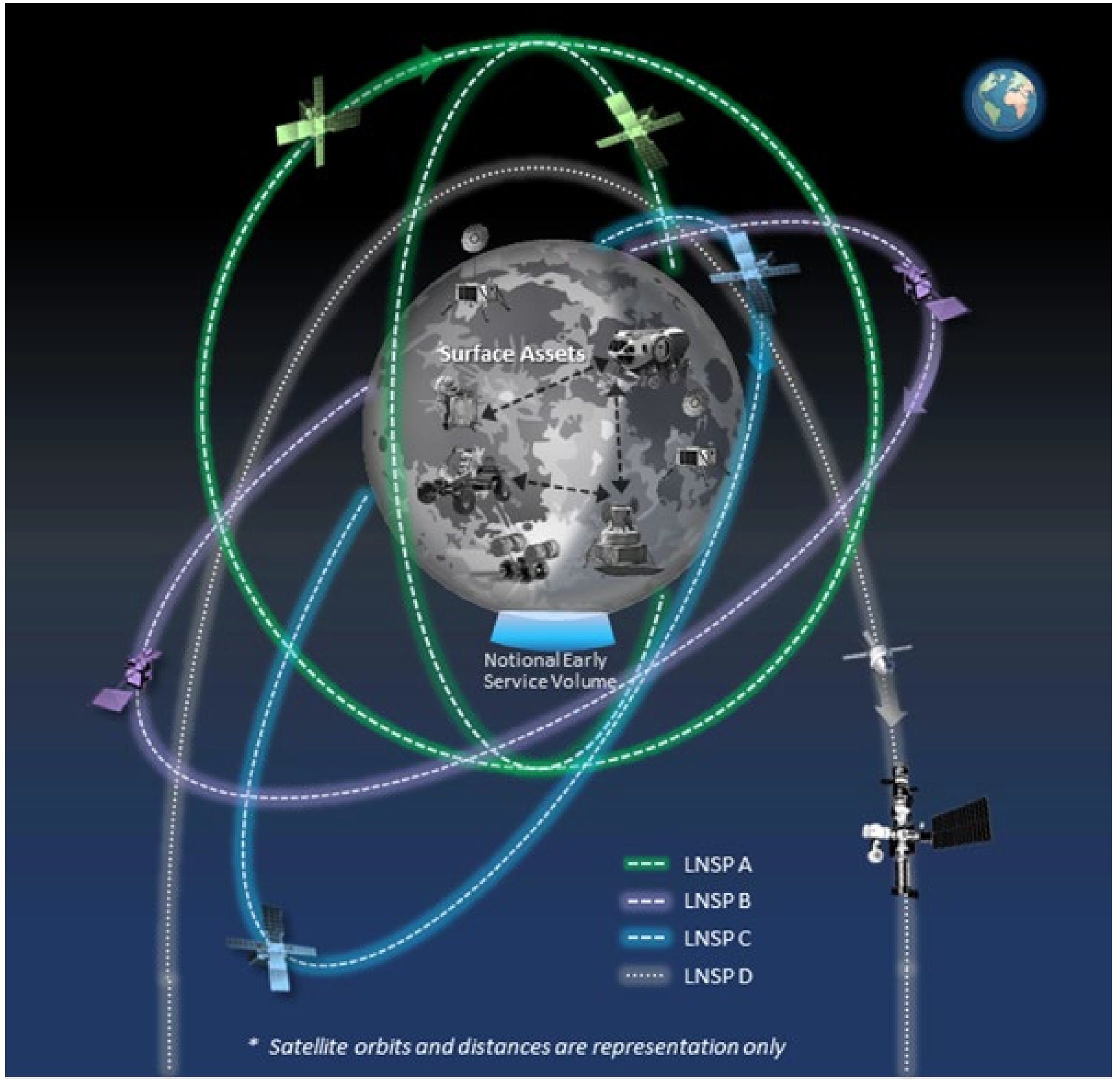
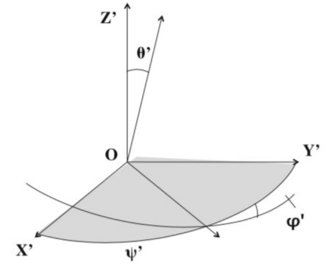


- Need of meter-level accurate localization for human activities on the Moon surface
- Multiple public and private providers

→ LunaNet
→ Moon reference system

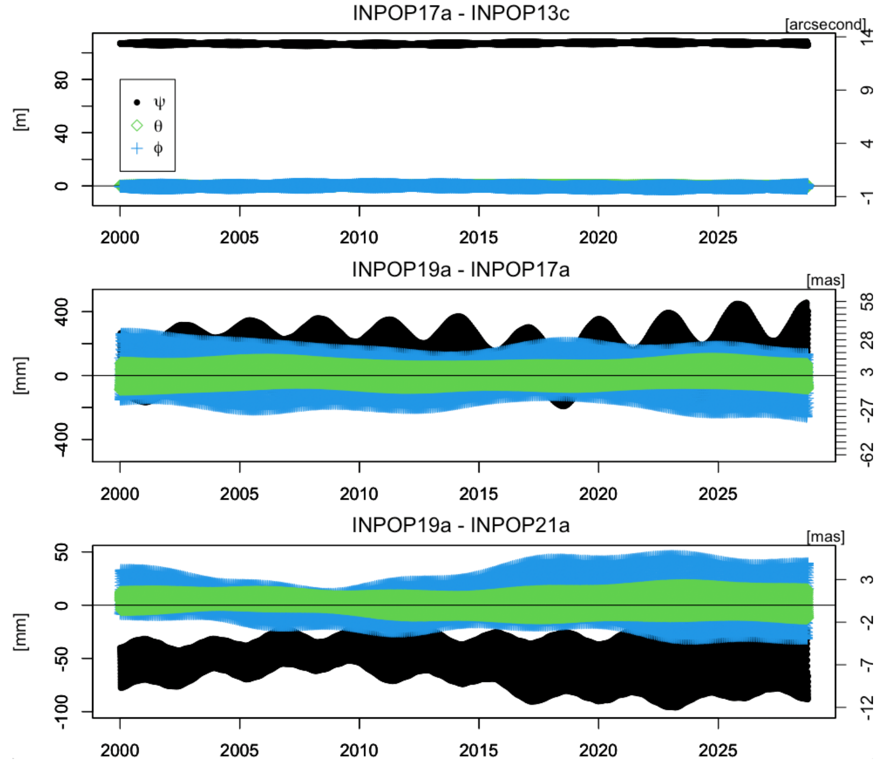
Libration accuracy assessments : internal accuracy



2000-2030	I17a-I13c	I19a -I17a	I19a-I21a	I19a-DE421
$\Delta\,\phi$	3 m	40 cm	6 cm	3 m
$\Delta\,\theta$	1.5 m	15 cm	3 cm	50 cm
$\Delta\,\psi$	3 m	50 cm	10 cm	1.6 m
Offset in ψ	100 m		5 cm	
	core-mantle interaction + 4 yrs LLR	core-mantle shape + 2 yrs LLR	2 yrs LLR	core-mantle interaction, shape + 11 yrs LLR

Covariances for INPOP21a

$\sigma(\psi)_{I21a}$ = 6 mas (~ 50 mm)
$\sigma(\phi)_{I21a}$ = 0.3 mas (~ 3 mm)
$\sigma(\theta)_{I21a}$ = 0.1 mas (~ 1 mm)

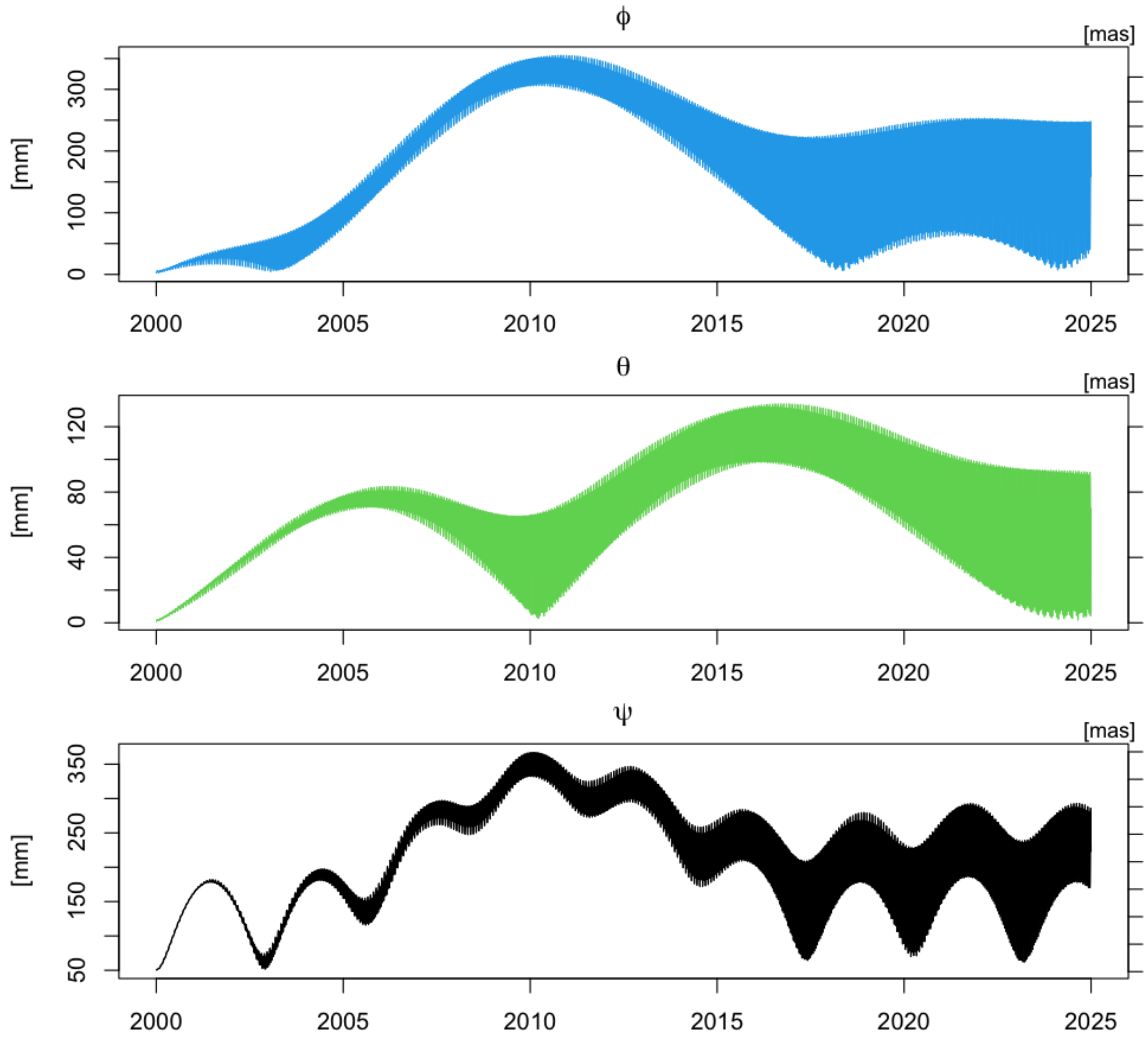


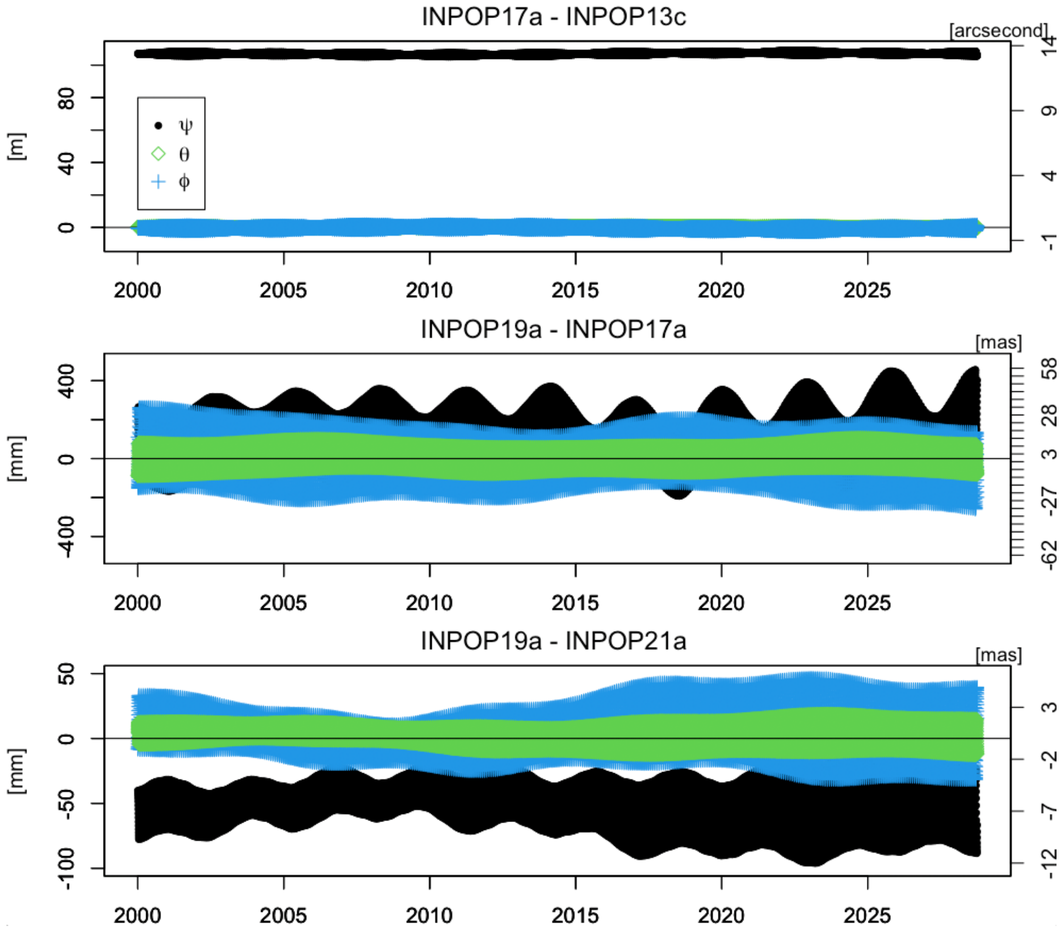
Differences in Euler angles defining PA are in average less than **30 cm over 5 yrs**

Libration accuracy assessments : accuracy propagation

$$cov\ H(t,P) = J_H(t)\ covP\ {}^tJ_H(t)$$

Propagation covariance INPOP21a (1-sigma)



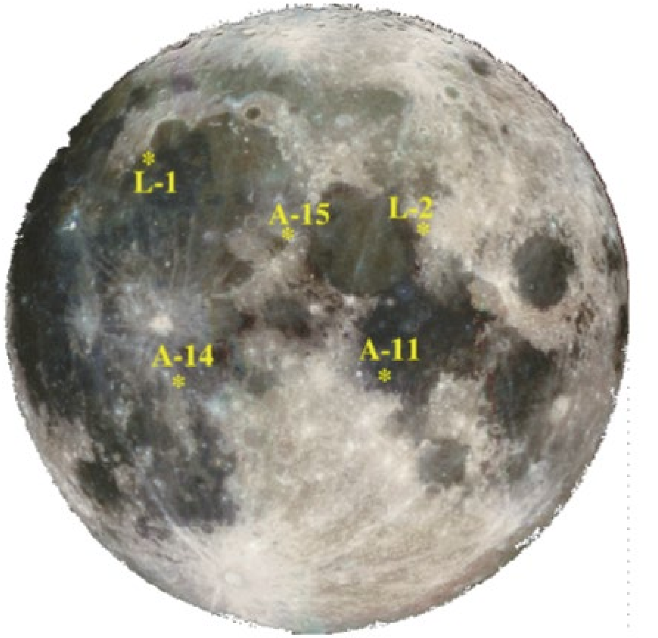


$\sigma(\psi)_{I21a}$ = 6 mas ; $\sigma(\phi)_{I21a}$ = 0.3 mas; $\sigma(\theta)_{I21a}$ = 0.1 mas

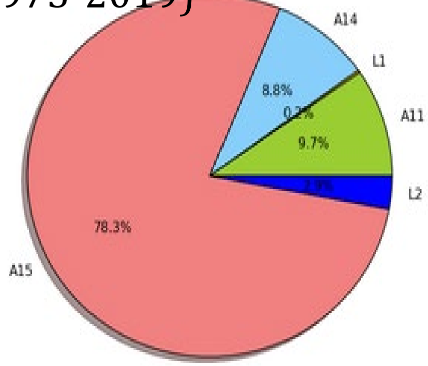
@ 2000.0

LRF accuracy assessments : LRR positions

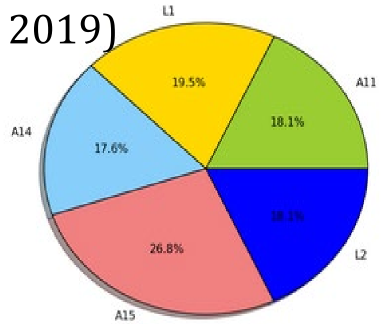
- Favored control points are the five LRR
- Uncertainties in LRR position is **40 cm** for DE (IOM-DE), formal uncertainties about **3 cm** INPOP
- External accuracy is about **2 meters** for EPM vs DE, INPOP and **1 meter** for INPOP and DE440



G (from 1973-2019)



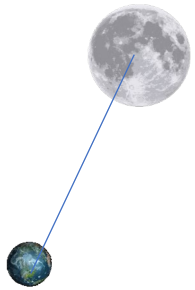
IR (since 2019)



LRRRR	EPM -I17a	I21a-DE421	I21a-DE440	I19a-I21a	I17a-I19a
A11	2.3 m	1.4 m	0.9 m	7.8 cm	0.1 m
A15	2.2 m	1.6 m	0.8 m	5.1 cm	0.1 m
A14	2.2 m	1.4 m	1.0 m	9.1 cm	0.15 m
L1	2.2 m		0.8 m	8.3 cm	0.25 m
L5	1.9 m	1.15 m	0.95 m	6.1cm	0.2 m

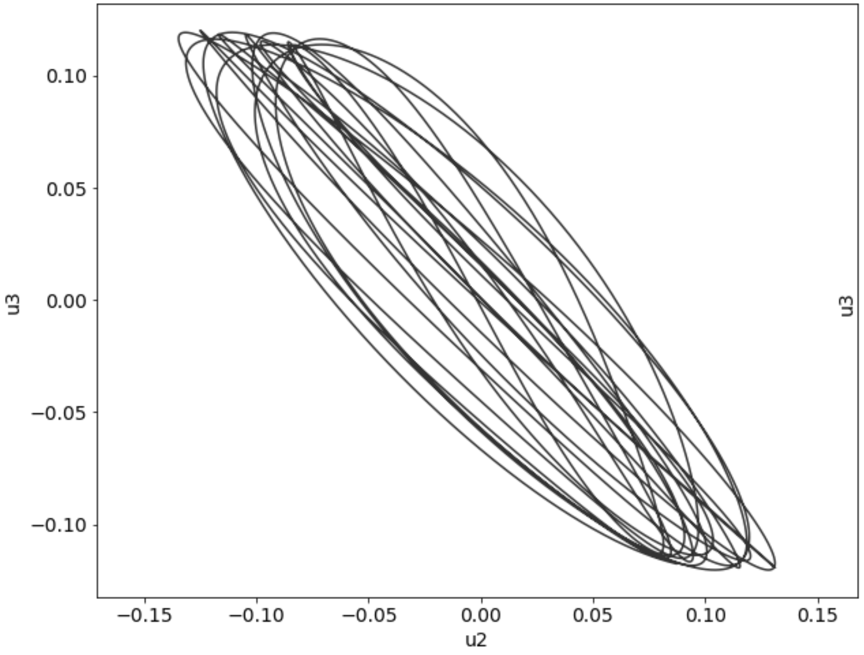
(EPM, Pavlov 2020; DE Folkner et al. 2014, Park et al. 2021; INPOP, Fienga et al. 2021)

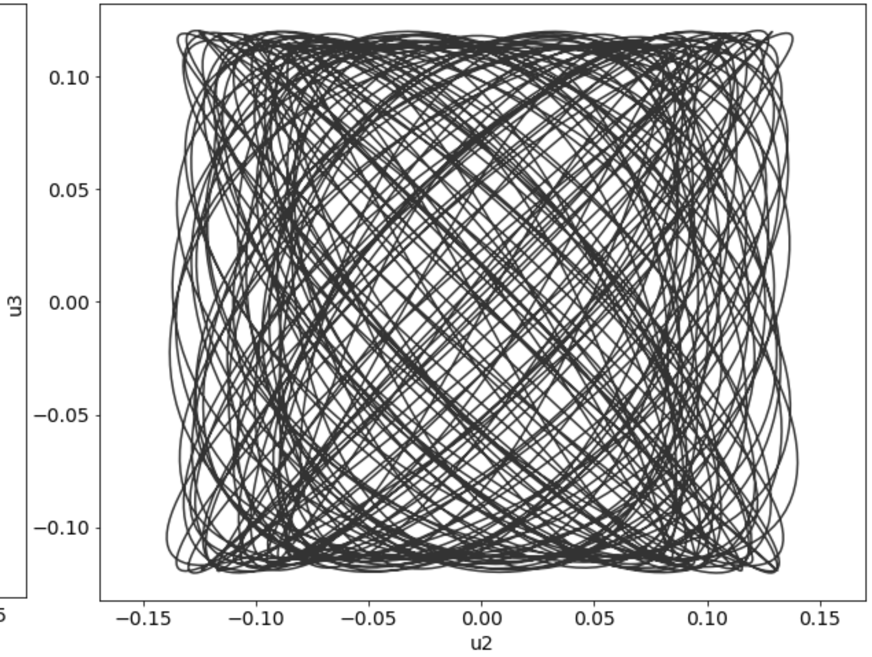
Why « mean » Earth ?



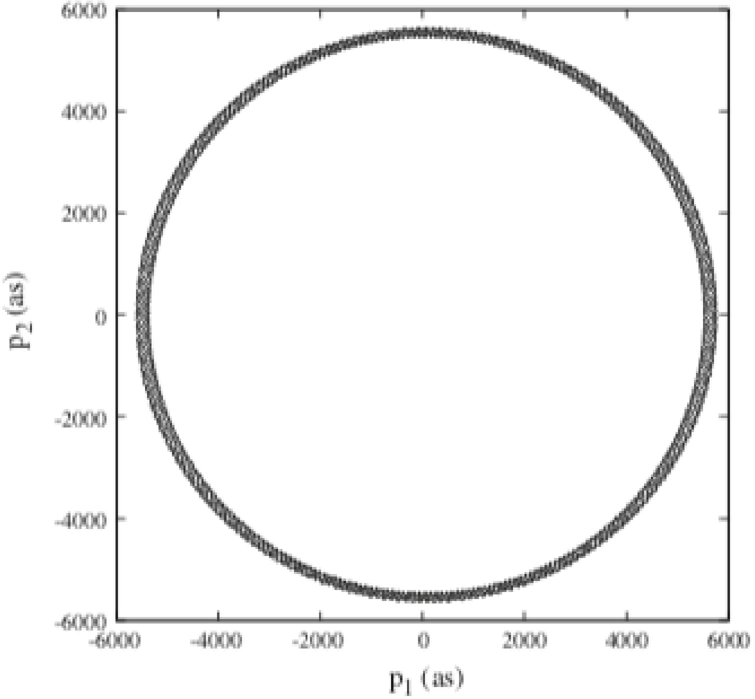
Variations with time of Earth direction as seen from the Moon

Direction to Earth from the Moon for 1 year and 6 years (rd)





Ecliptic pole motion
(Rambaux and Williams 2011)

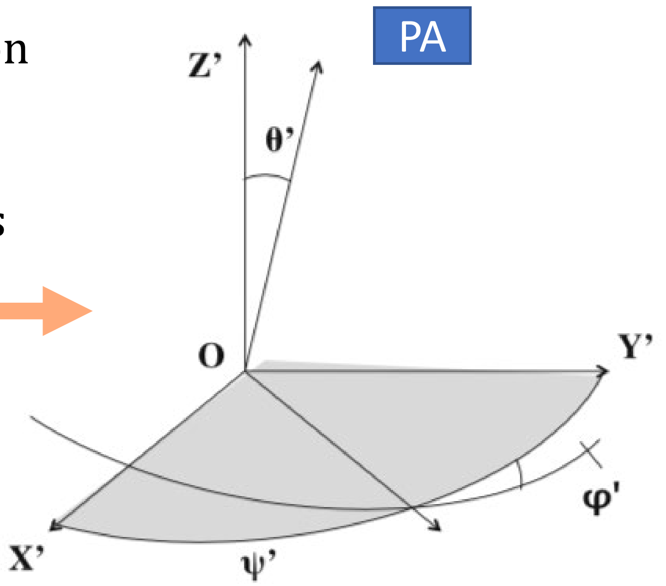


→ Average (mean) direction in x-axis = ME frame

Lunar reference Frame (LRF) definition for navigation data

ICRF, ecliptic of date

Lunar orientation Ephemerides
(ψ, θ, φ) =
rotation angles



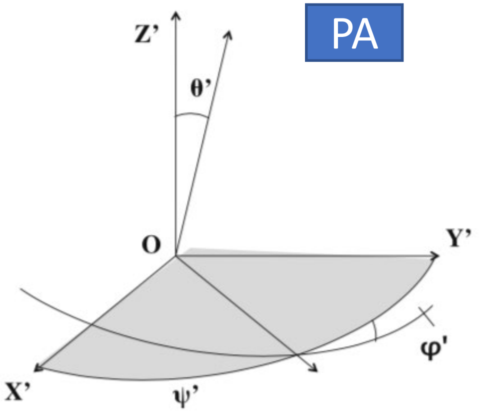
$$PA = R_Z(\psi) R_X(\theta) R_Z(\varphi)\ ICRF$$

- (ψ, θ, φ) = Libration (Euler, rotation) Angles
- defined by lunar and planetary ephemerides (PLE)
- Numerically integrated
- Adjusted to LLR

LRF definition for navigation data

ICRF, ecliptic of date

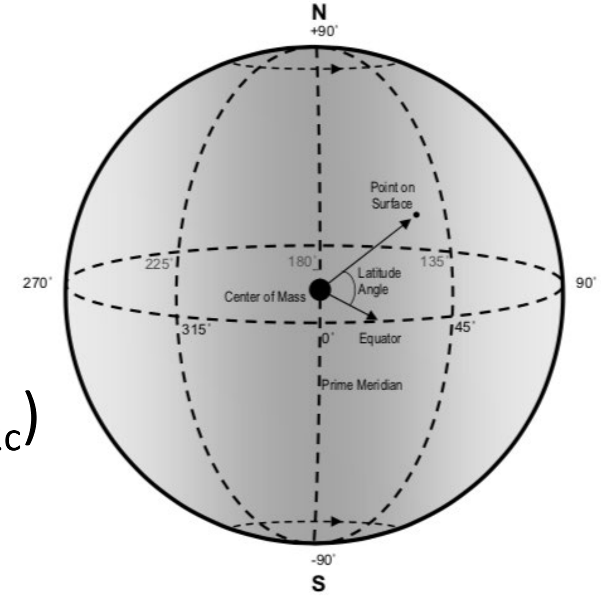
Lunar orientation Ephemerides (ψ, θ, φ) = rotation Angles



PA

$X_{PA} - X_{ME} \sim 860$ meters

$(\tau_c, \sigma_c, I, p_{1c}, p_{2c})$



ME

$$PA = R_Z(\psi) R_X(\theta) R_Z(\varphi)\, ICRF$$

$$ME = R_X(-p_{2c}) R_Y(p_{1c}) R_Z\left(-\tau_c + \frac{I^2 \sigma_c}{2}\right) PA$$

- (p_{1c}, p_{2c}) are components of the normal to the ecliptic in the PA reference system,
- τ_c, σ_c are libration angles and
- I, inclination of the equator of the Moon to the ecliptic of date.