

# Roadmap for Conventions

by

A. Fienga

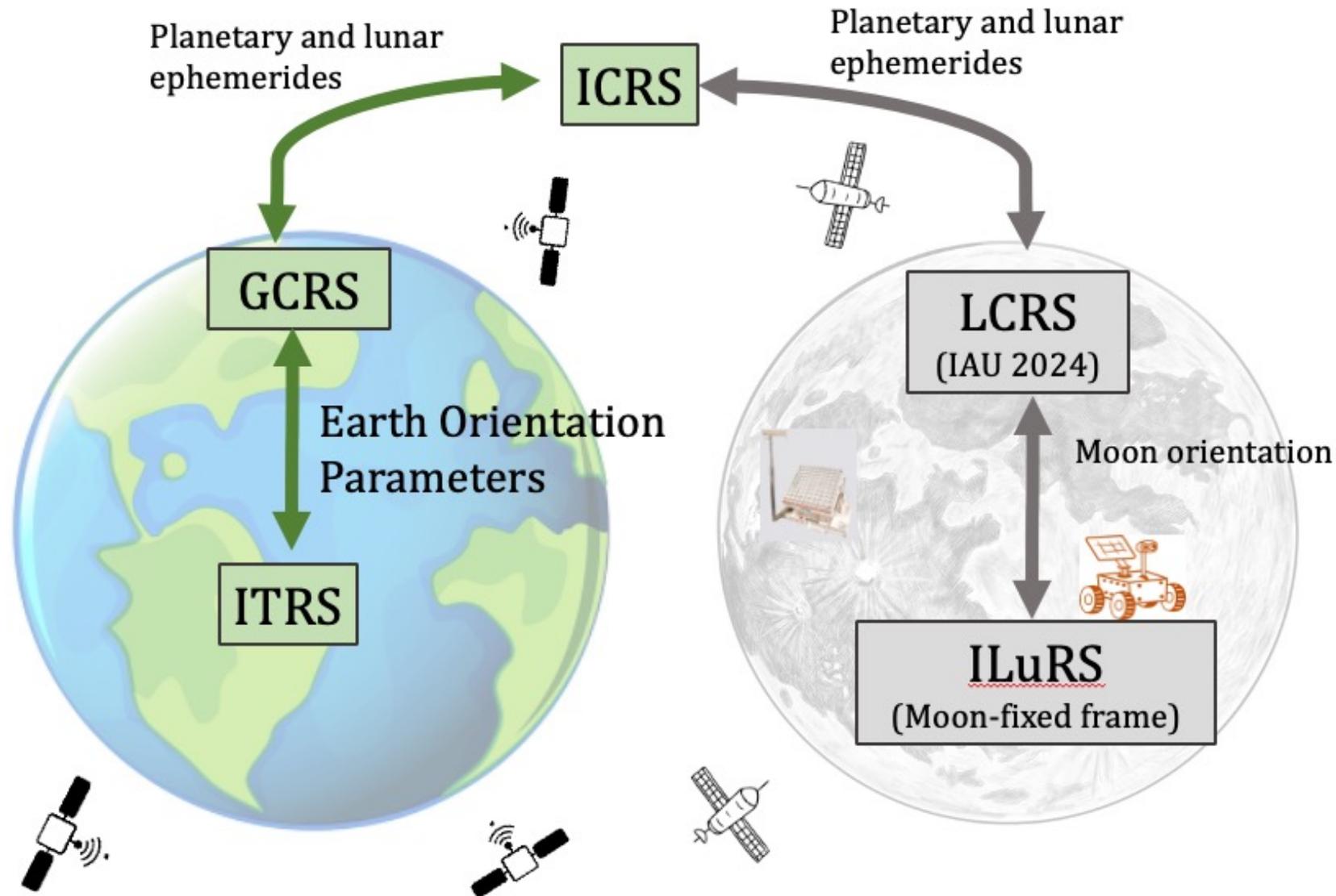
Observatoire de la Côte d'Azur,  
Chair of the IAG WG 1.1.3 Lunar Reference system and frames



International  
Association of  
Geodesy

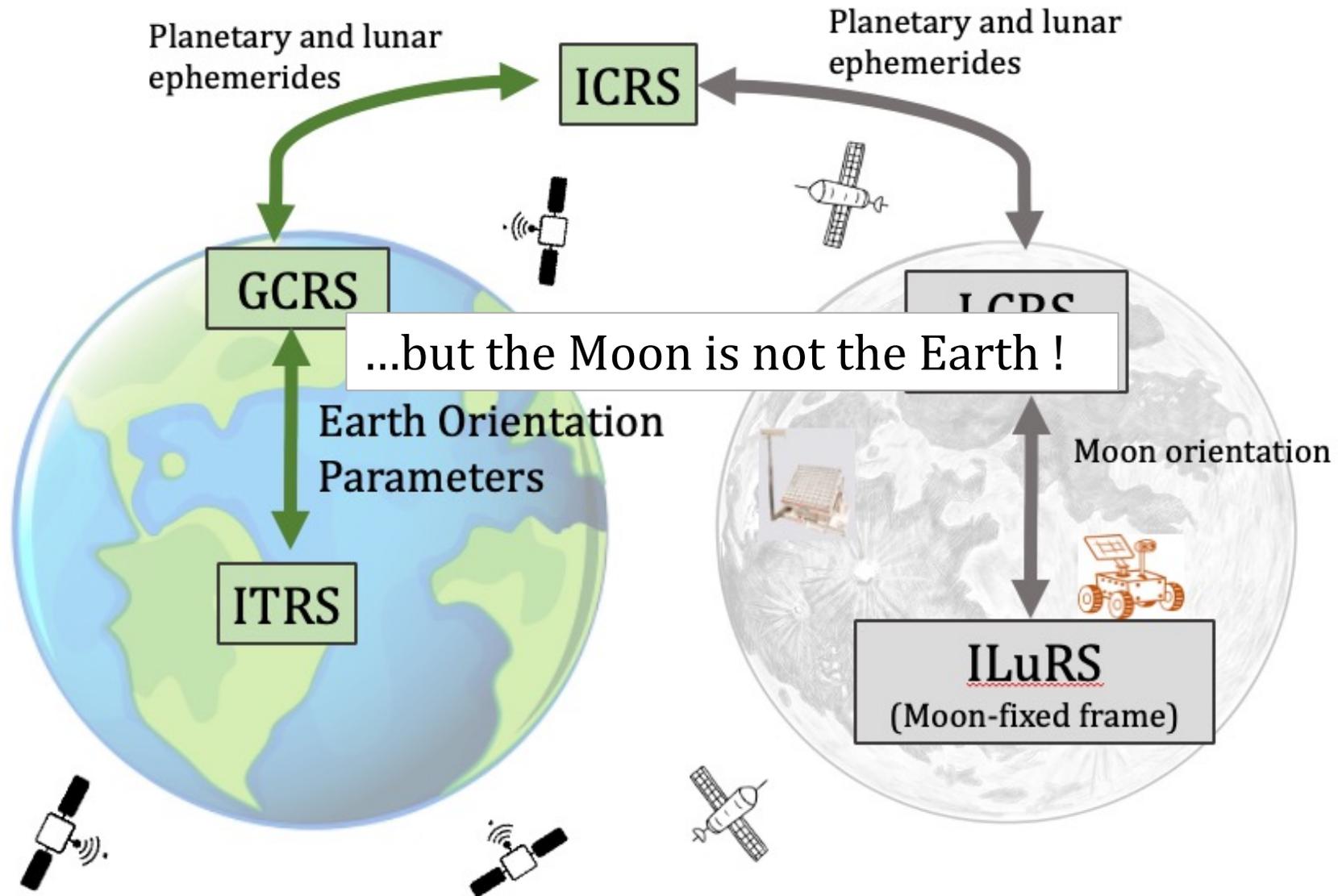
# The Moon context

The ideal case: Lunar Reference system, let's do as for Earth



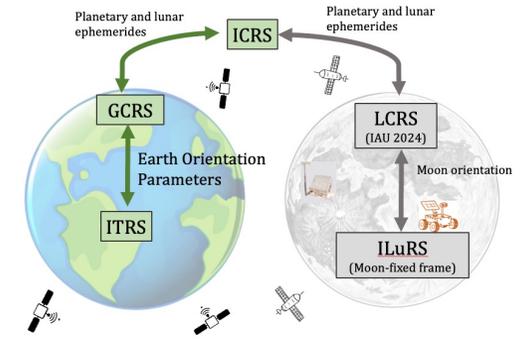
# The Moon context

The ideal case: Lunar Reference system, let's do as for Earth



# The Moon context

No superficial fluid layers	Pure deterministic rotation, simpler variable GF and layer interaction
No plate tectonics	No residual (physical) rotation
But still control points are moving !	Lack in the dynamical modeling (Empirical terms)
5 (+1) Control points (LLRR) and 1 (radial) technic (LLR)	Limitation in the modelisation of the reference frame
	Need of more control points and more technics (ie VLBI)
No atomic clock or poor time realization for the 5 coming years	No direct time realization



N. Rambaux's talk



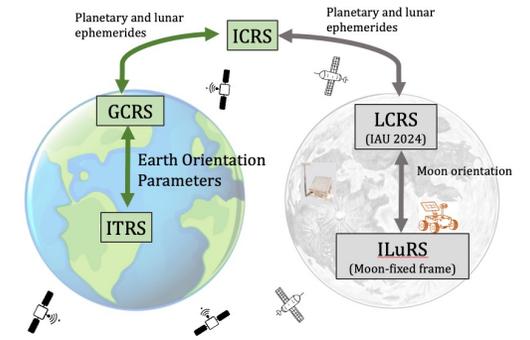
V. Viswanathan's talk  
K. Sosnika's talk



Merkovitz and Fienga talk

# The Moon context

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Merkovitz and Fienga's talk

IAG WG 1.1.3 recommendations for  
**ILuRS / ILuRF** and for **Geoid definition**

Makley's talk

	ICRS	ITRS	ILuRS IAG WG 1.1.3
Concept	Quasi-inertial	Non-rotating	Co-rotating with the Moon
Choice of structure	QSO	Stations	Undistorted Moon
Structure modeling	Masses, EOP → IERS conventions	GF, EOP, earth crust → IERS conventions	Lunar ephemerides, GRAIL GF
Materialization	ICRF	ITRF	LLRR coordinates
Extension	GAIA	WCS	New selenodesic stations

→ PA-based definition

## ILuRS

- its origin coincides with the center of mass of the Moon,
- its orientation is defined by the diagonal matrix of the lunar tensor of inertia, thus, co-rotates with the Moon,
- the scale of the time will be defined by BIPM.
- its GR framework is the IAU 2024 recommendation

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## The International Lunar Reference System ILuRS

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  - its orientation is defined by the diagonal matrix of the lunar tensor of inertia, thus, co-rotates with the Moon,
  - the scale of the time will be defined by BIPM.
  - its GR framework is the IAU 2024 recommendation
- we need to use planetary and lunar ephemerides

# Lunar Ephemerides (LE) present status

- LE require for defining the ILuRF (lunar tensor of inertia)
- ILuRF depends on dynamical modeling, GF, Moon internal structure, fit to LLR...
- LLRR coordinates = LE products
  
- DE / INPOP/ EPM ...
- cm-level internal accuracy LRR coordinates
- meter-level external accuracy LRR coordinates

Do we have to decide which LE to use ? Can each of the provider have its own definition ? We should also avoid relying on only one provider

## **The International Lunar Reference Frame (ILuRF)**

Moon Reference Frame (origin, orientation) based on **VCE-combination of LE** :

DE430 (0.17), INPOP21a (0.38), EPM21 (0.45) from 1970 to 2050



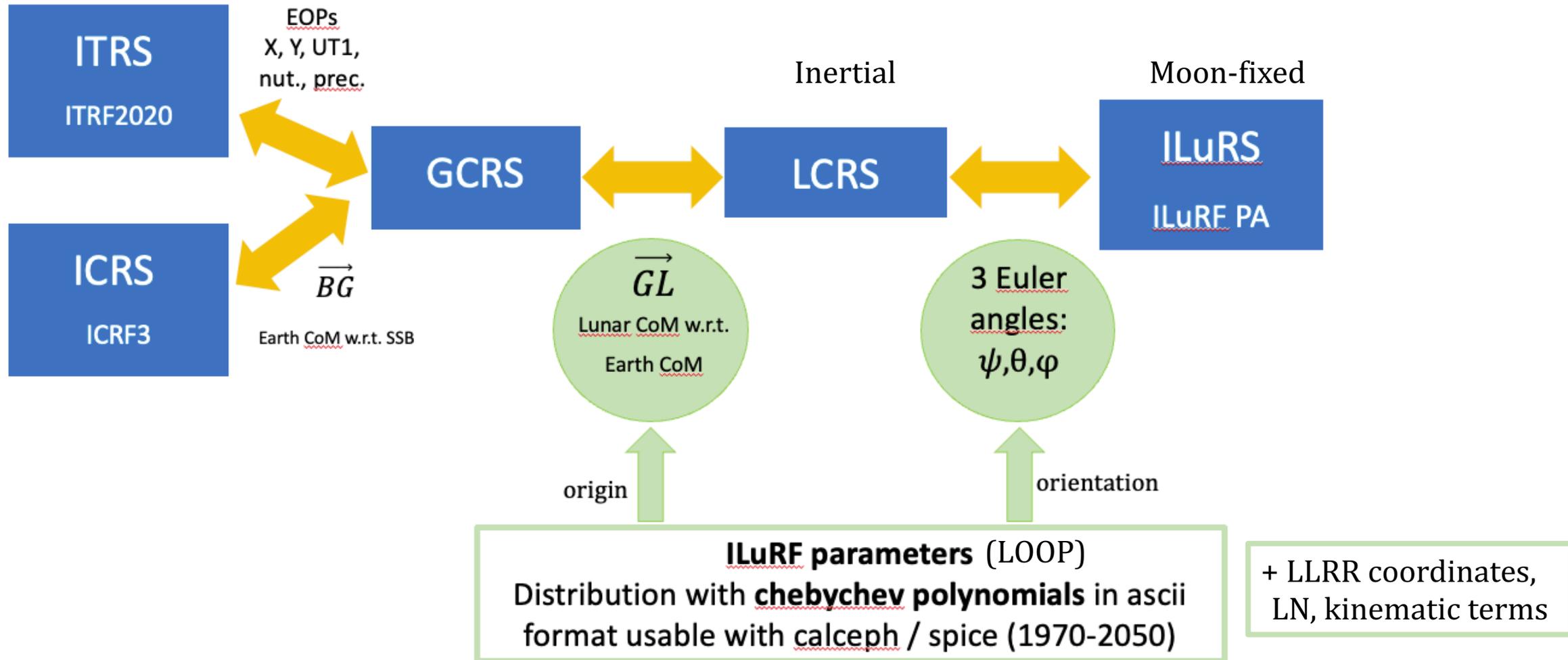
K. Sosnika's talk

# The International Lunar Reference Frame (ILuRF)

## The International Lunar Reference Frame (ILuRF)

Moon Reference Frame (origin, orientation) based on **VCE-combination of LE**

→ K. Sosnika's talk

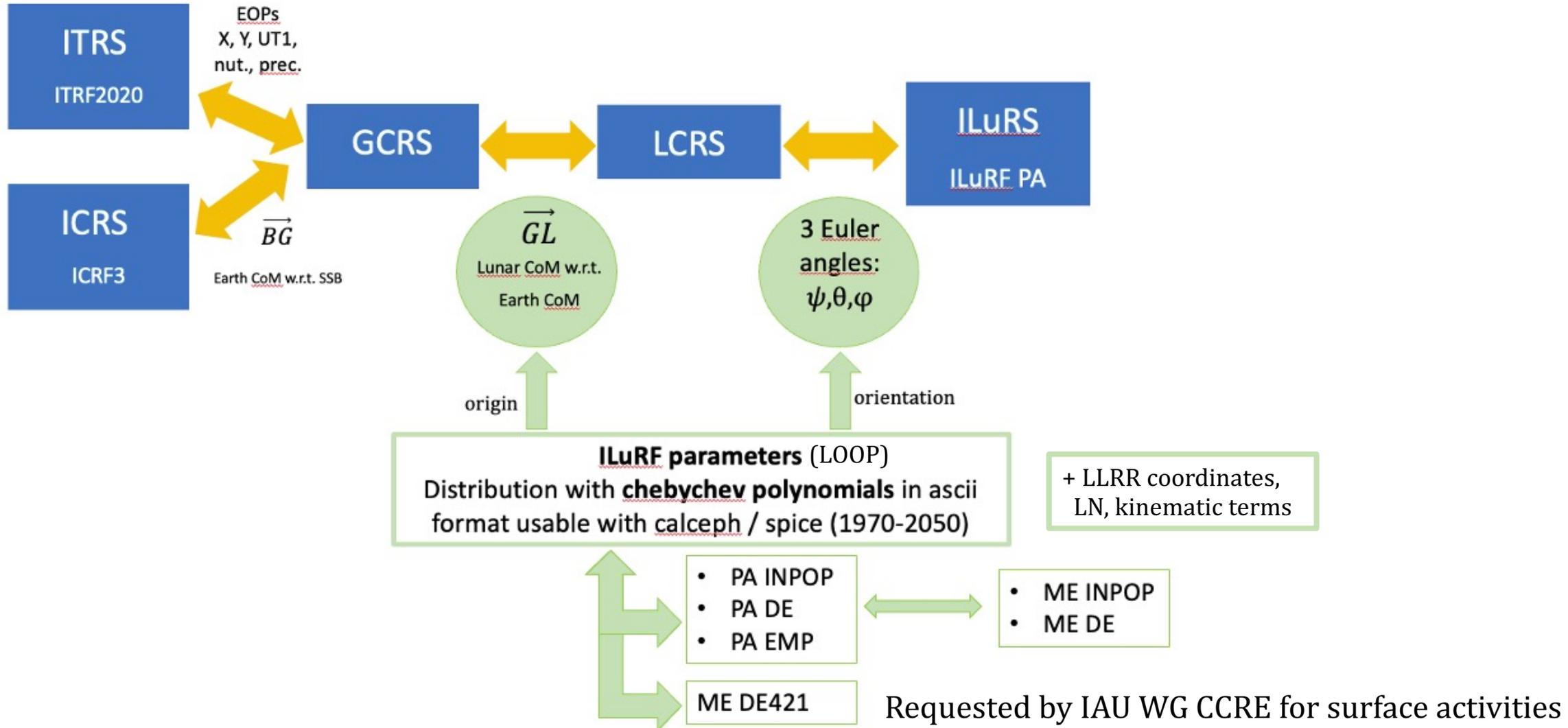


# The International Lunar Reference Frame (ILuRF)

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Moon Reference Frame (origin, orientation) based on **VCE-combination of LE**

K. Sosnika's talk



# IAG JWG 1.1.3 : 3 recommendations

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- 1) LCRS definition : the WG endorses the IAU 2024 definition of the LCRS for its space and time metric
- 2) **ILuRS (PA-based definition) and its realization ILuRF based on VCE combined orientation and origin + other terms (LN, LLRR coordinates, empirical corrections, time-scale...).**  
*A version is already available with publication soon (Sosnika et al. in review)\**
- 3) **New definition of the lunar geoid based on GRAIL measurements**

 Makley's talk

Important dates:

- **16 July 2027 - 22 July 2027** : 29<sup>th</sup> IUGG General Assembly
- **10 August 2027 – 19 August 2027**: XXXIII<sup>th</sup> IAU General Assembly

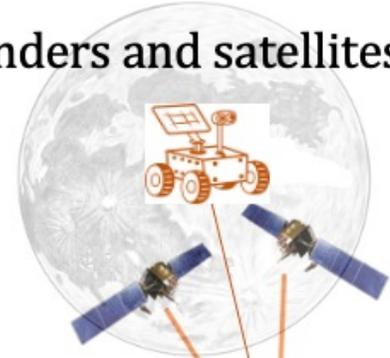
\* <https://arxiv.org/abs/2510.15484>

# IAG JWG 1.1.3 : next steps (short term)

1) ILuRS proposed as an IERS Product Center (IERS DB in May 2026)

- ILuRF LOOP
- distribution
- upgrade
- maintenance

landers and satellites



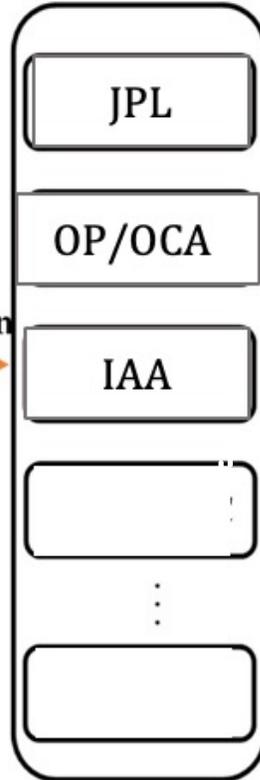
Observation



Observation

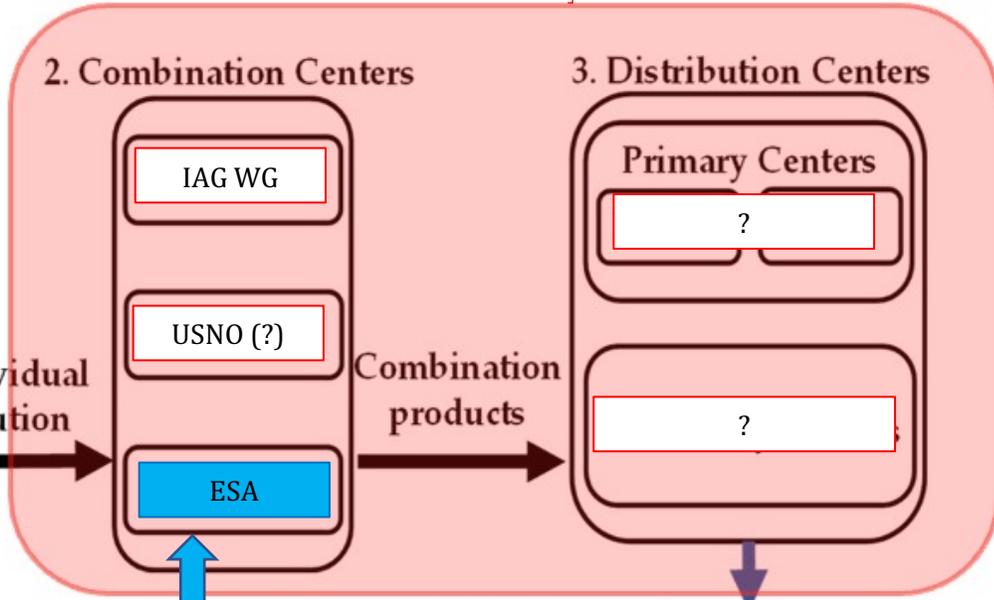
ILRS, VLBI, ESTRACK, DNS...

1. Analysis Centers



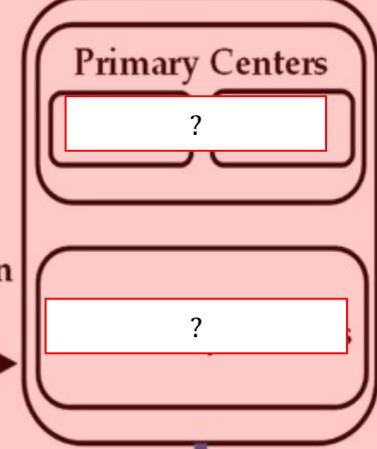
Individual solution

2. Combination Centers



Combination products

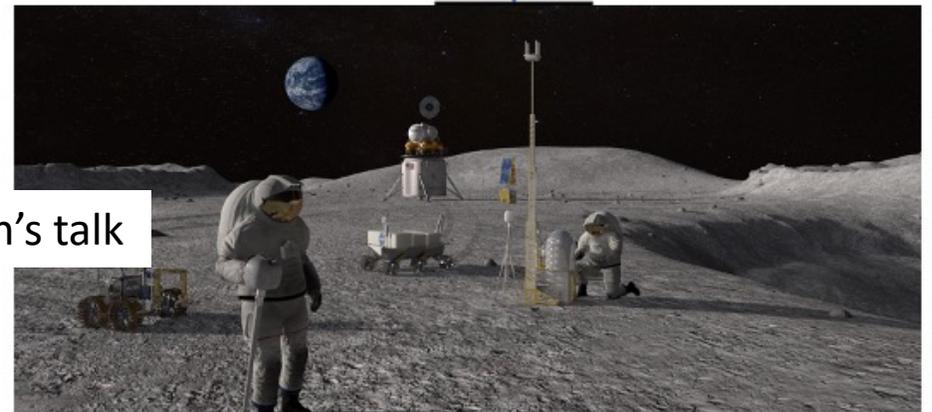
3. Distribution Centers



2) ILuRS in TDB → ILuRS in TCL

3) ILuRS extension to SSB ?

E.Schoenemann's talk



# Preliminary conclusions

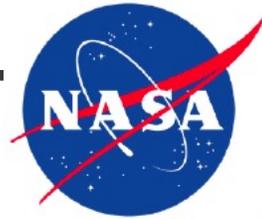
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- 1) LCRS definition : the WG endorses the IAU 2024 definition of the LCRS for its space and time metric
- 2) ILuRS (PA-based definition) and its realization ILuRF proposed as a future IERS product
- 3) New definition of the lunar geoid based on GRAIL measurements
- 4) Letter of consensus in discussion between IAG WG 1.1.3 and IAU WG CCRE for future IAU recommendation

## Important dates:

- **IERS DB May 2026** : ILuRS as an IERS Product Center ?
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Thank you



- IAU WG CCRE : ME-frame as defined by JPL DE ephemerides
- IAG WG 1.1.3: PA combined ephemeris based ILuRF
- AD5 LunaNet WG supports ILuRF
- ESA supports ILuRF
- Consensus letter for future IAU recommendation in discussion between IAG WG 1.1.3 and IAU WG CCRE

In 2024, NASA established a working group to begin developing an agency approach to lunar reference frames that could meet the needs of the Artemis campaign and future lunar exploration. **Based on the considerations outlined above, the working group recommended that NASA develop a flexible lunar exploration architecture that supports the use of more than one frame.**

**The working group endorsed the Mean Earth lunar reference frame as the standard for initial surface operations, including planning and user location data exchange.** Mean Earth meets identified needs at the lunar surface with minimum impact to current mission planning with minimal need to change heritage data products. **The working group did not endorse a corresponding orbital standard, understanding the need for mission-driven flexibility.**

# Roadmap for consensus

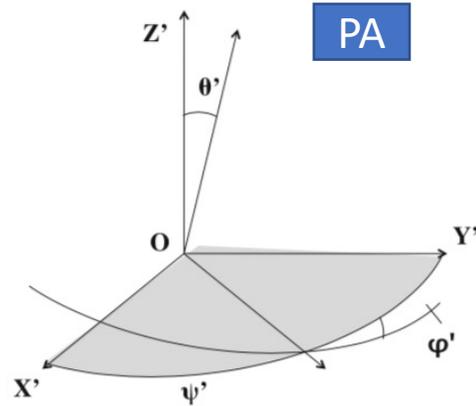
	ICRS	ITRS	ILuRS IAG WG 1.1.3	IAU WG CCRE
Concept	Quasi-inertial	Non-rotating	Co-rotating with the Moon PA-axis	Mean Earth direction
Choice of structure	QSO	Stations	Undistorted Moon	Gravity field, dissipative moon
Structure modeling	Masses, EOP → IERS conventions	GF, EOP, earth crust → IERS conventions	Lunar ephemerides, GRAIL GF	Lunar ephemerides, GRAIL GF
Materialization	ICRF	ITRF	LLRR coordinates	LLRR coordinates
Extension	GAIA	WCS	New selenodesic stations	Craters

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

# LRF definition for navigation data

ICRF,  
ecliptic of  
date

Lunar orientation  
Ephemerides  
( $\psi, \theta, \varphi$ ) =  
rotation Angles

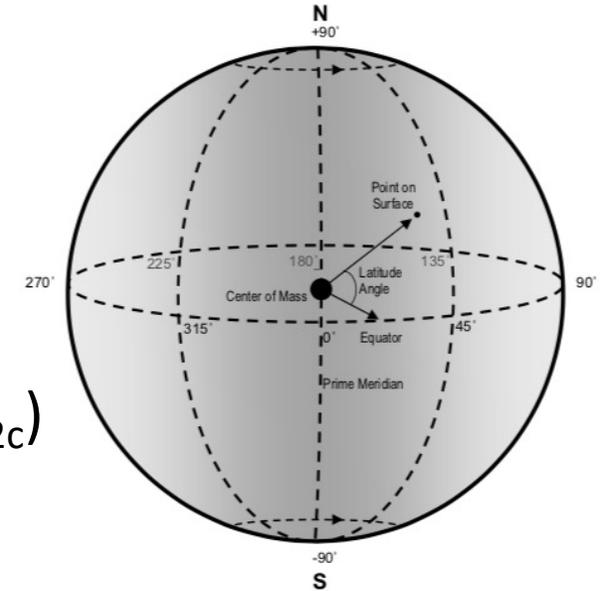


PA

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



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



ME

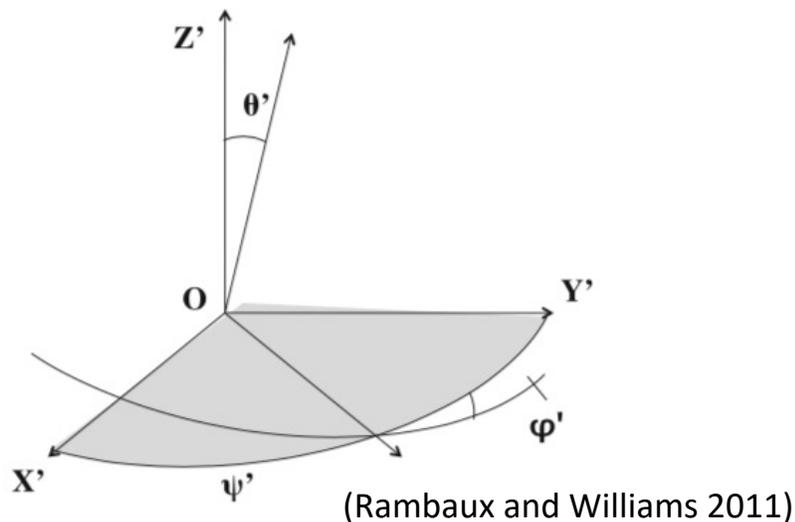
$$PA = R_Z(\psi) R_X(\theta) R_Z(\varphi) ICRF$$

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

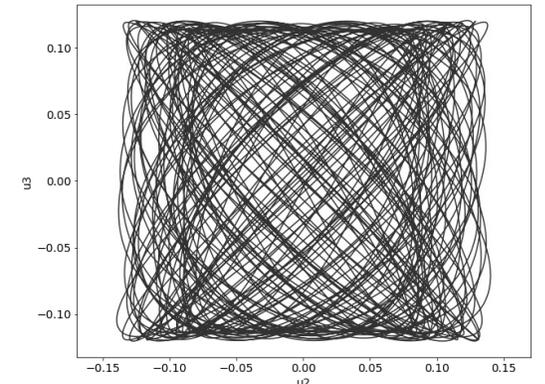
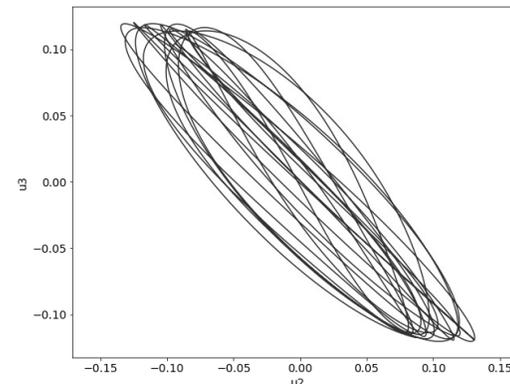
- ( $p_{1c}, p_{2c}$ ) are components of the normal to the ecliptic in the PA reference system,
- $\tau_c, \sigma_c$  are libration angles and
- $I$ , inclination of the equator of the Moon to the ecliptic of date.

# 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  $(\psi, \theta, \varphi)$ .
- The lunar ephemerides **DExxx** (JPL) and **INPOPxx** (OCA/IMCCE) : similar in terms of LLR residuals.



- 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 ( $0^\circ$  Longitude) is defined by the **mean** Earth direction.
- This point does not coincide with any prominent crater or other lunar surface feature.



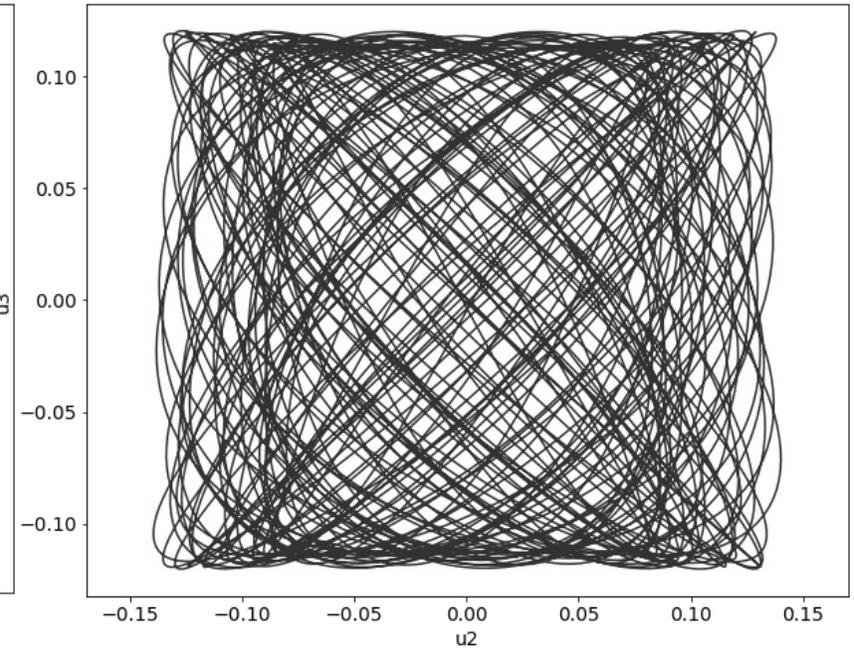
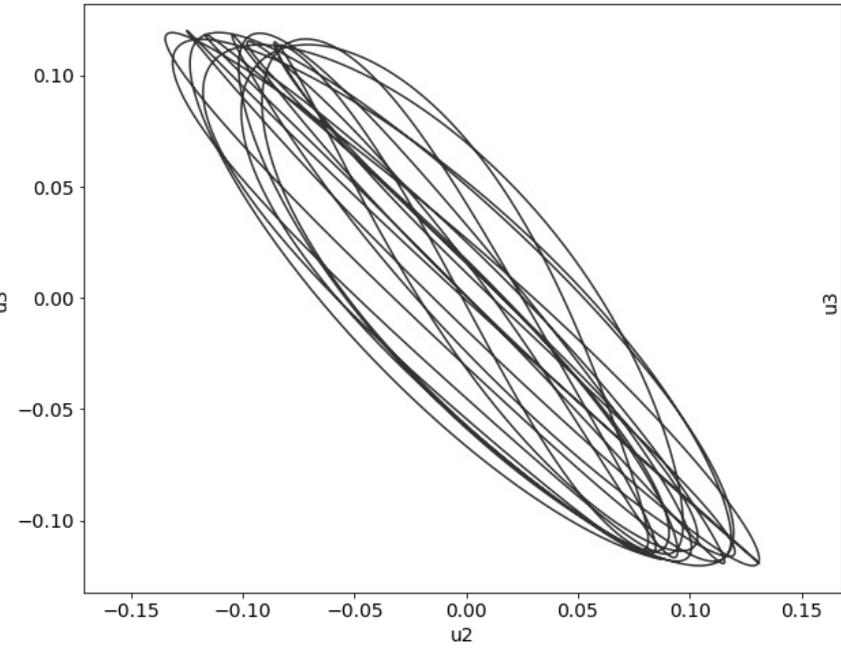
Direction to Earth from the Moon for 1 year and 6 years (rd)

# Why « mean » Earth ?

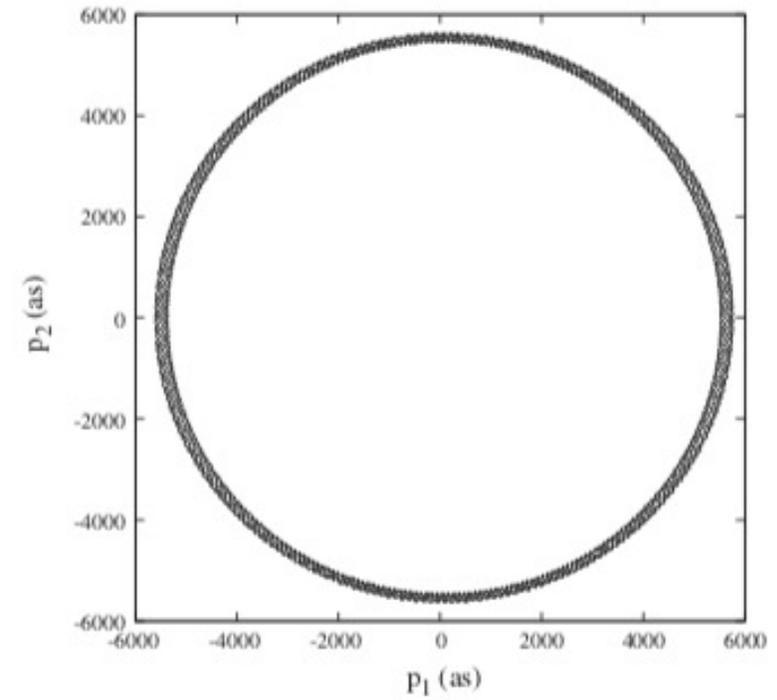


*Variations with time of Earth direction as seen from the Moon*

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



Ecliptic pole motion  
(Rambaux and Williams 2011)

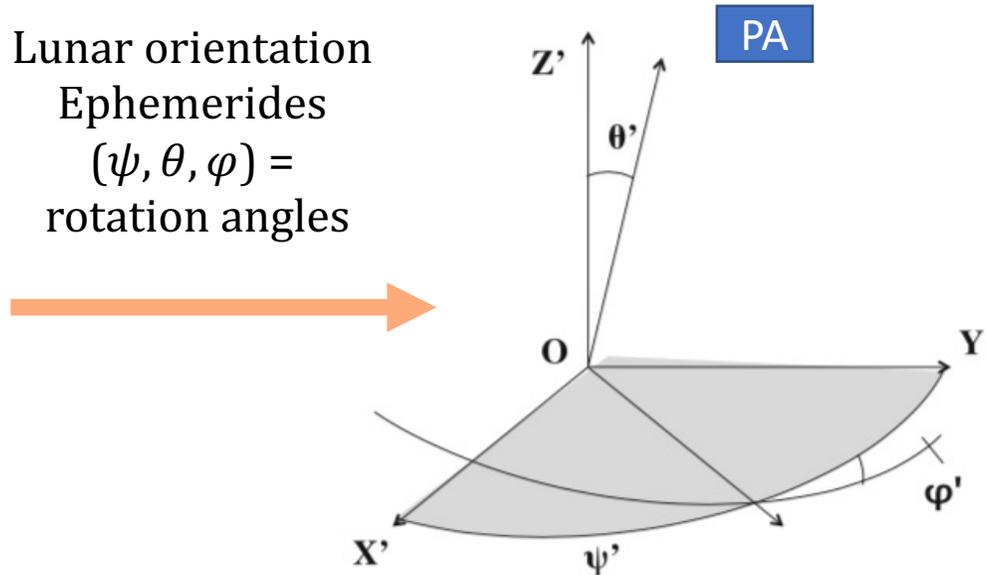


**→ Average (mean) direction in x-axis = ME frame**

# Lunar reference Frame (LRF) definition for navigation data

ICRF,  
ecliptic of  
date

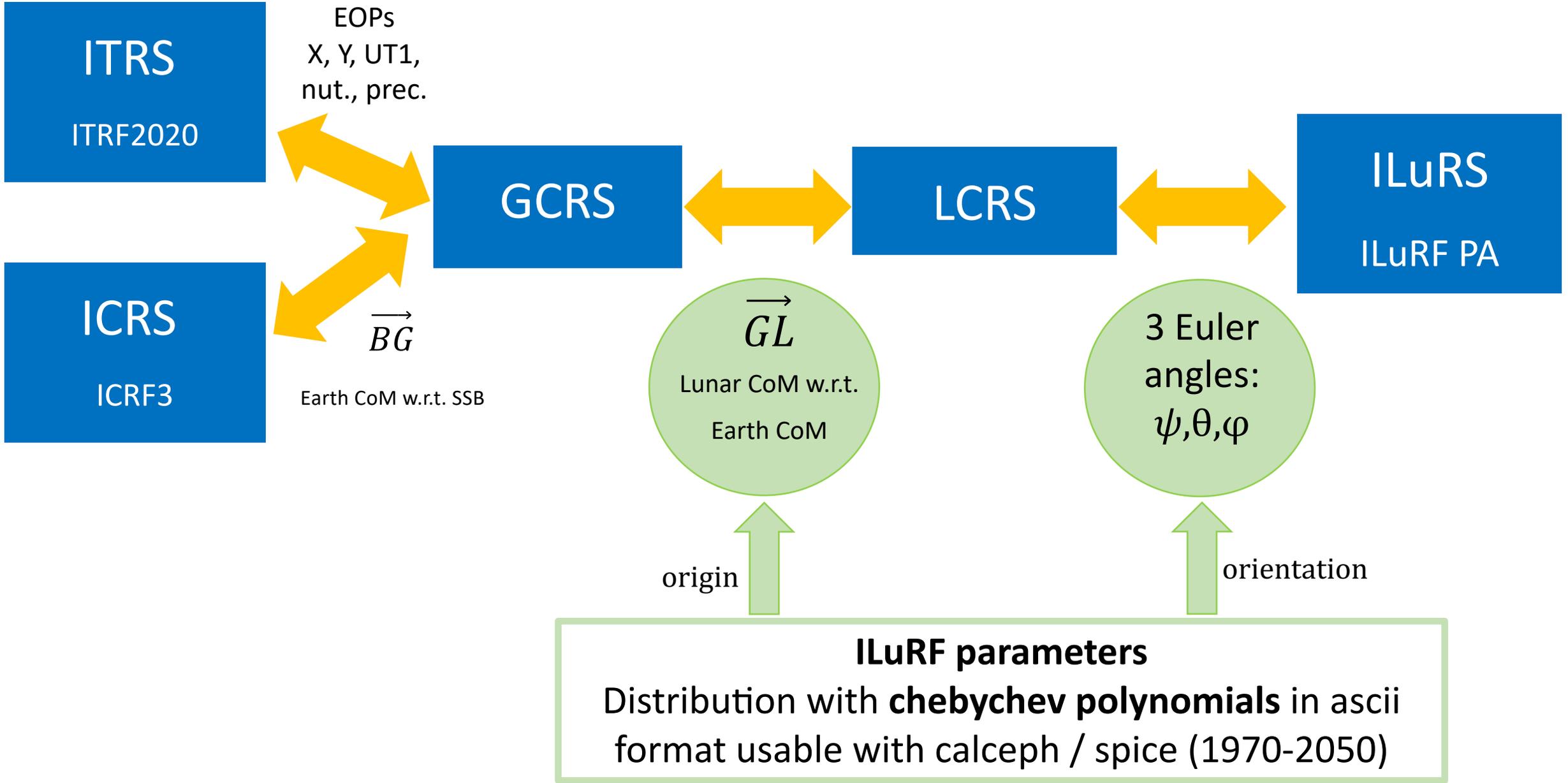
Lunar orientation  
Ephemerides  
 $(\psi, \theta, \varphi) =$   
rotation angles

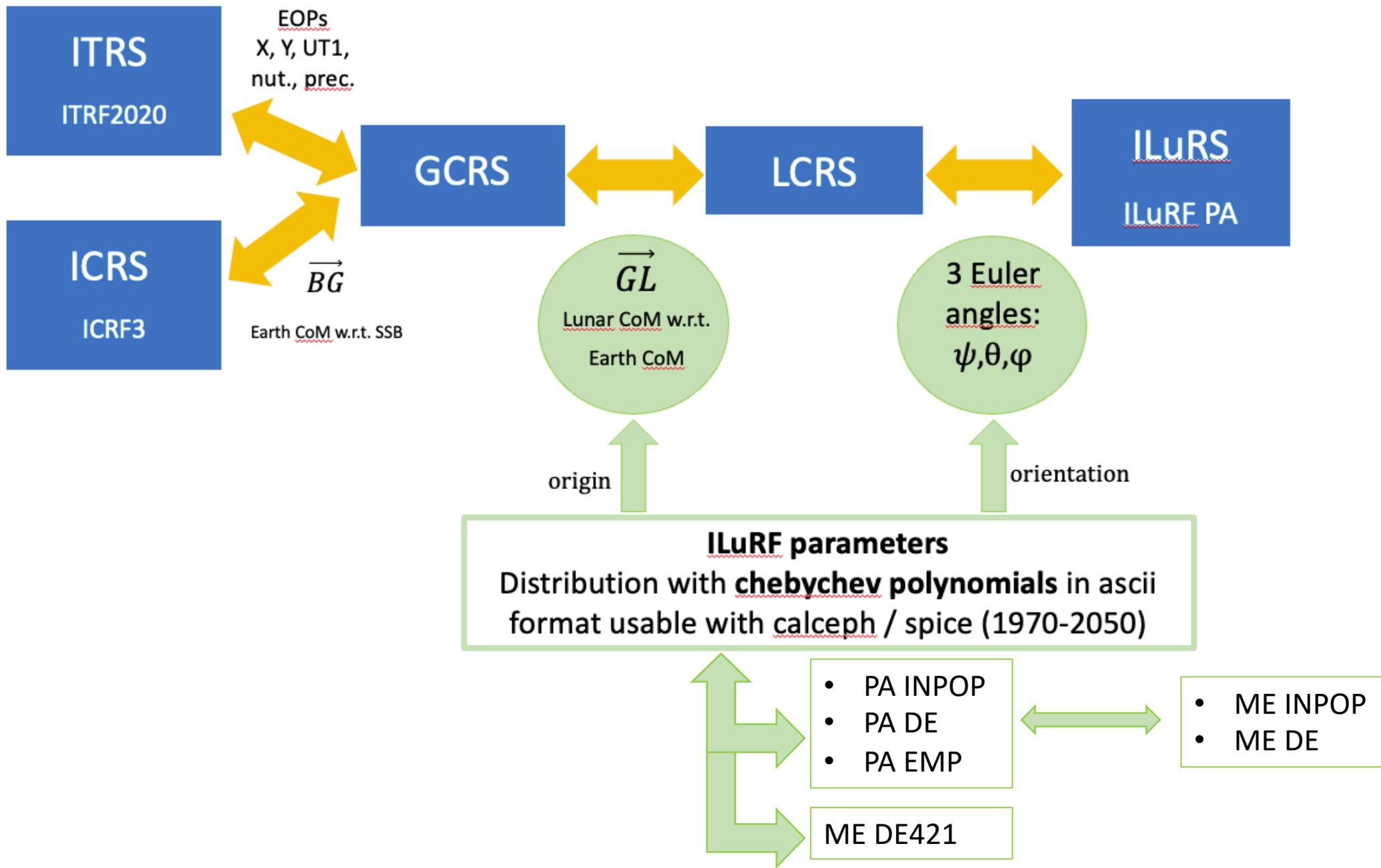


$$PA = R_Z(\psi) R_X(\theta) R_Z(\varphi) ICRF$$

- $(\psi, \theta, \varphi) =$  Libration (Euler, rotation) Angles
- defined by lunar and planetary ephemerides (PLE)
- Numerically integrated
- Adjusted to LLR

- Supplementary material





# IAU Reference systems

