OBSERVATOIRE
DE LA CÔTE D'AZUR

UNIVERSITÉ CÔTE D'AZUR

Novamoon and the future of the Lunar reference system

by

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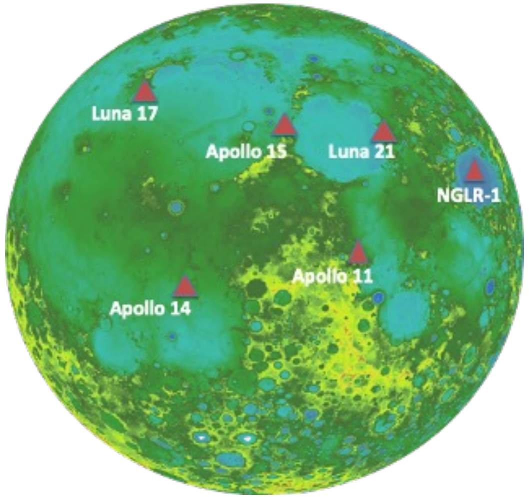
Observatoire de la Côte d'Azur (OCA)

10 - 13 February 2026

Challenges for Moon RF

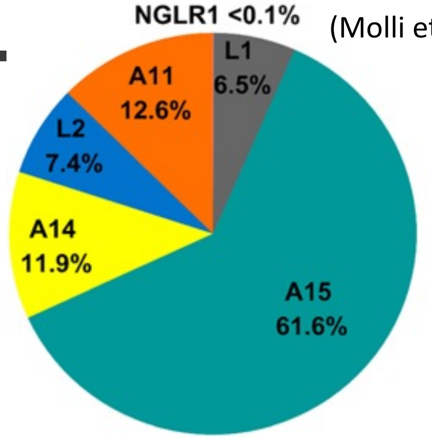
(Williams and Boggs 2021)

Only 6 control points



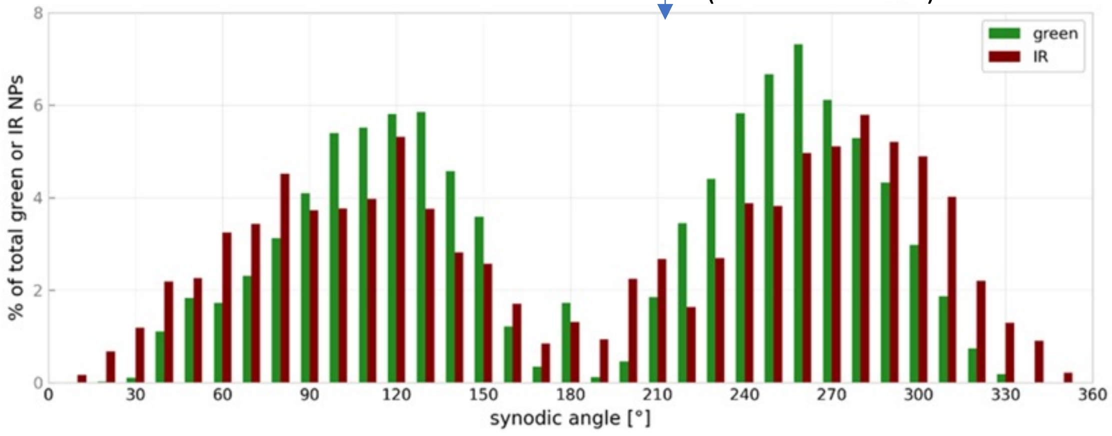
Non-homogeneous distribution of data in space and time

from 04.1970 to 05.2025



(Molli et al. 2026)

(Molli et al. 2026)



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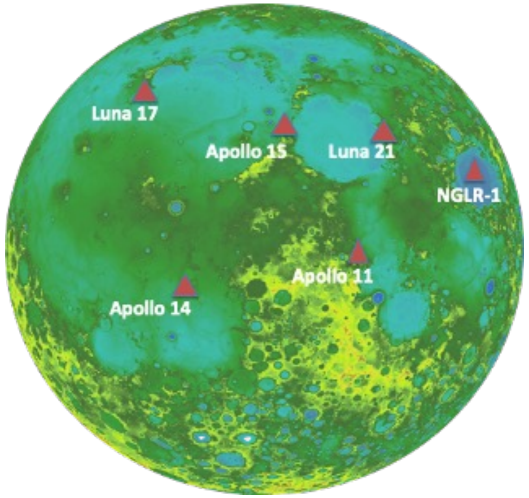

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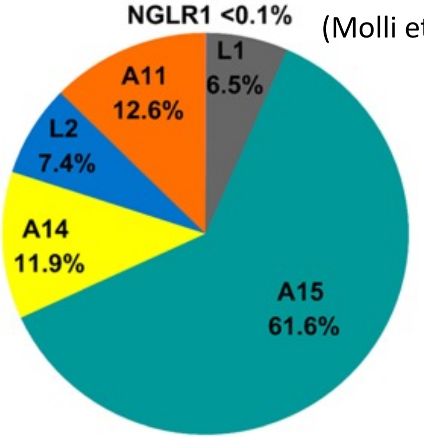
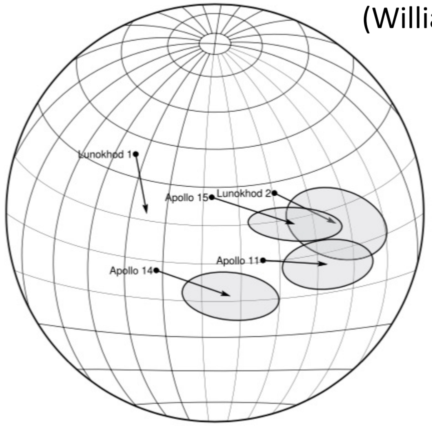


(Molli et al. 2026)



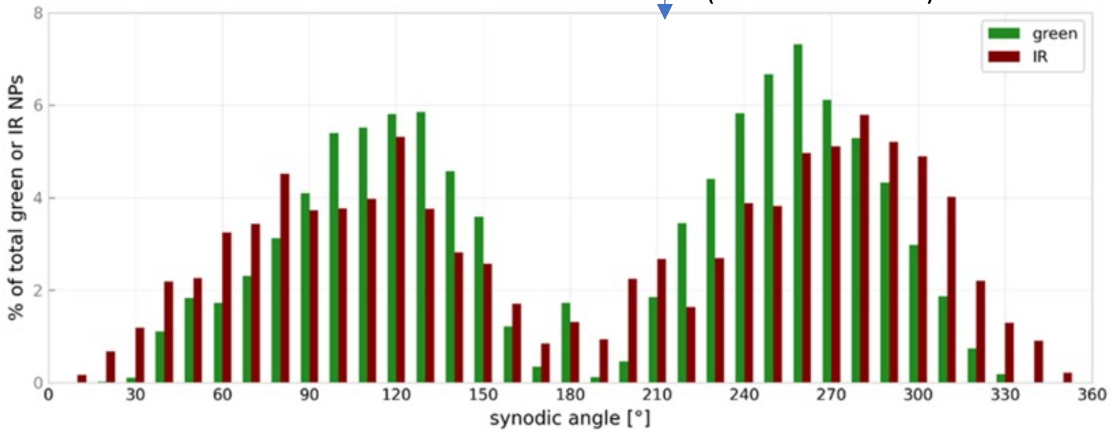
(Williams and Boggs 2021)

Displacements of LLRR (20 cm in 25 years)

Lacks in the rotational modeling

Inconsistent surface deformation / LRO and GF / GRAIL

(Molli et al. 2026)

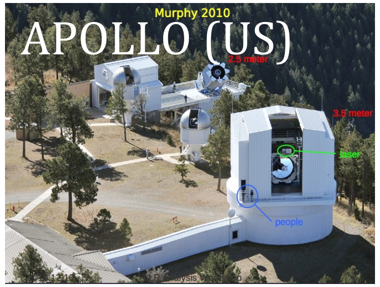


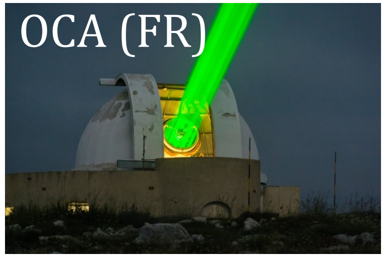
Empirical terms added in orientation angles

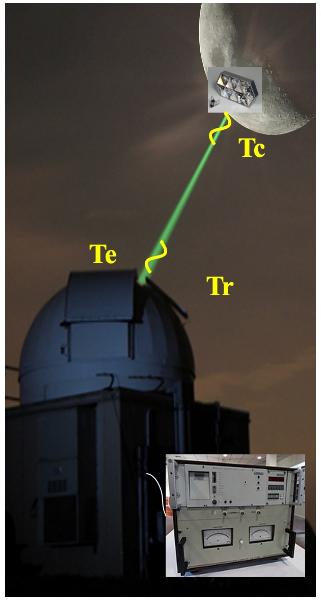
Periods in days	31	206	365	1095	1306	1643	2190
DE440	x	x	x	x	x	x	x
DE430		x	x	x			
INPOP19a		x	x	x			
EMP2021		x	x	x			

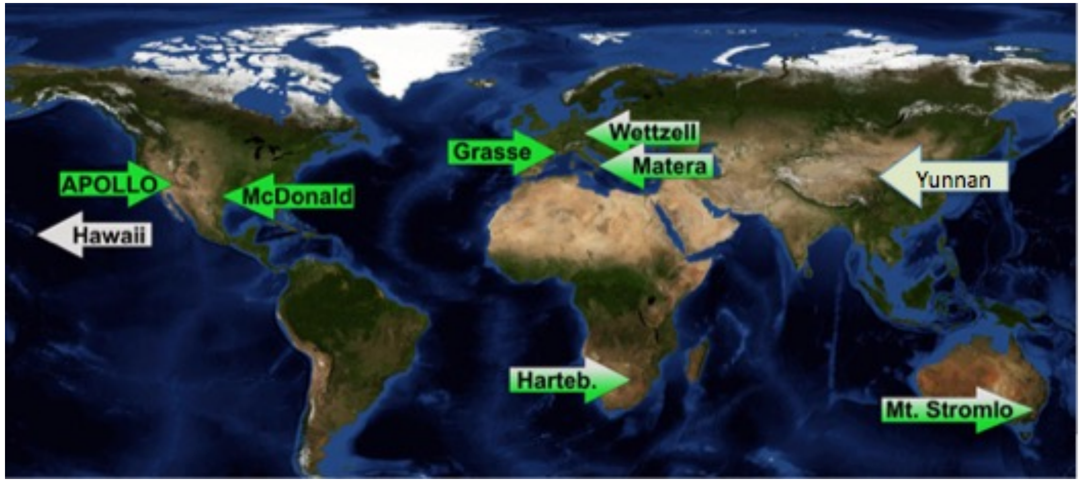
Challenges for Moon RF

Only distances are observed









Challenges for Moon RF

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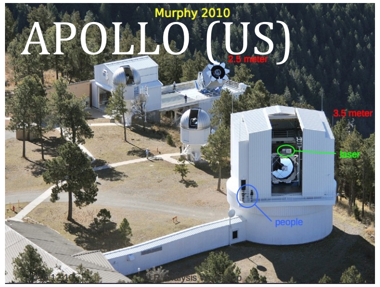
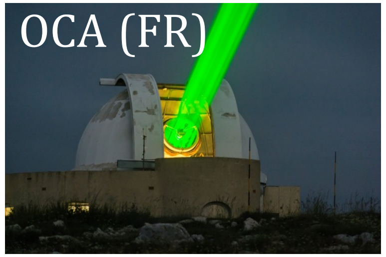
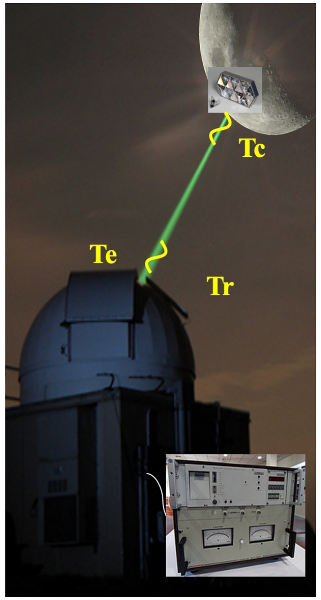






Lacks in the reference frame definition

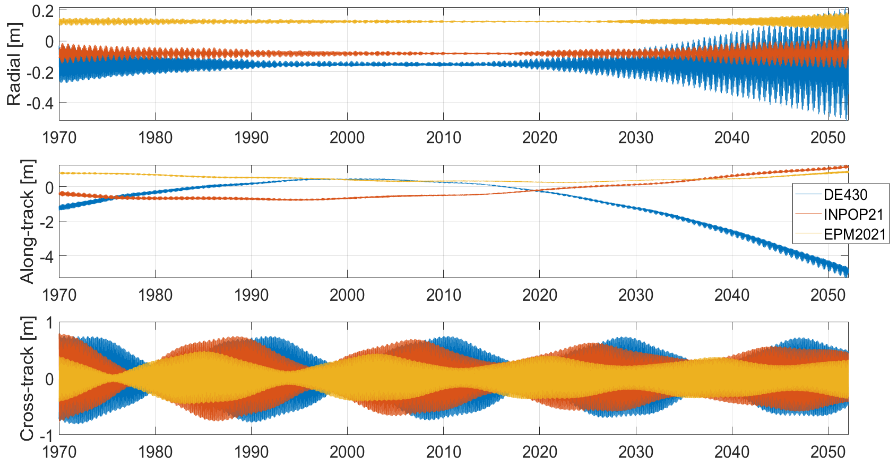
Correlation in S,Tx for Helmert RF definition

	Tx	Ty	Tz	Rx	Ry	Rz	s
Tx	1.00	0.09	-0.23	-0.01	0.76	0.10	-0.97
Ty	0.09	1.00	0.05	-0.65	-0.04	0.43	-0.13
Tz	-0.23	0.05	1.00	0.05	-0.58	0.20	0.08
Rx	-0.01	-0.65	0.05	1.00	0.01	-0.04	0.02
Ry	0.76	-0.04	-0.58	0.01	1.00	-0.15	-0.59
Rz	0.10	0.43	0.20	-0.04	-0.15	1.00	-0.19
s	-0.97	-0.13	0.08	0.02	-0.59	-0.19	1.00

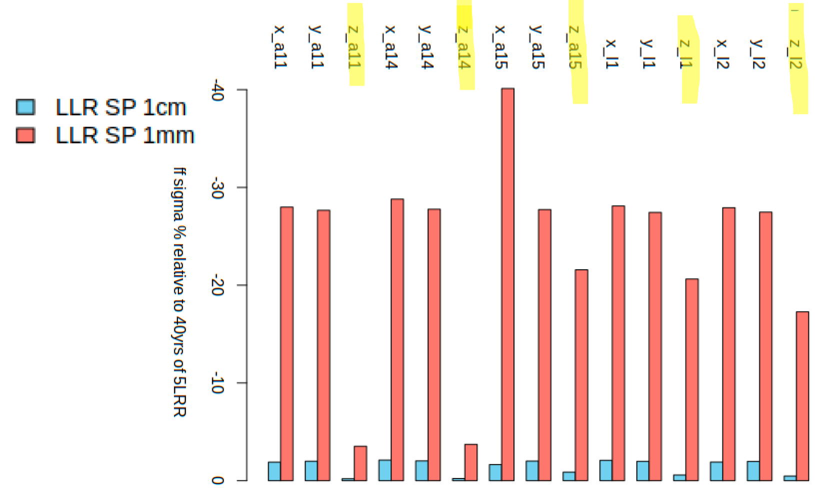
Correlation matrix (Sosnika et al. 2025)

Origin is only well constrained along the radial direction

(Sosnika et al. 2025)



Z-coordinates of LLRR badly estimated

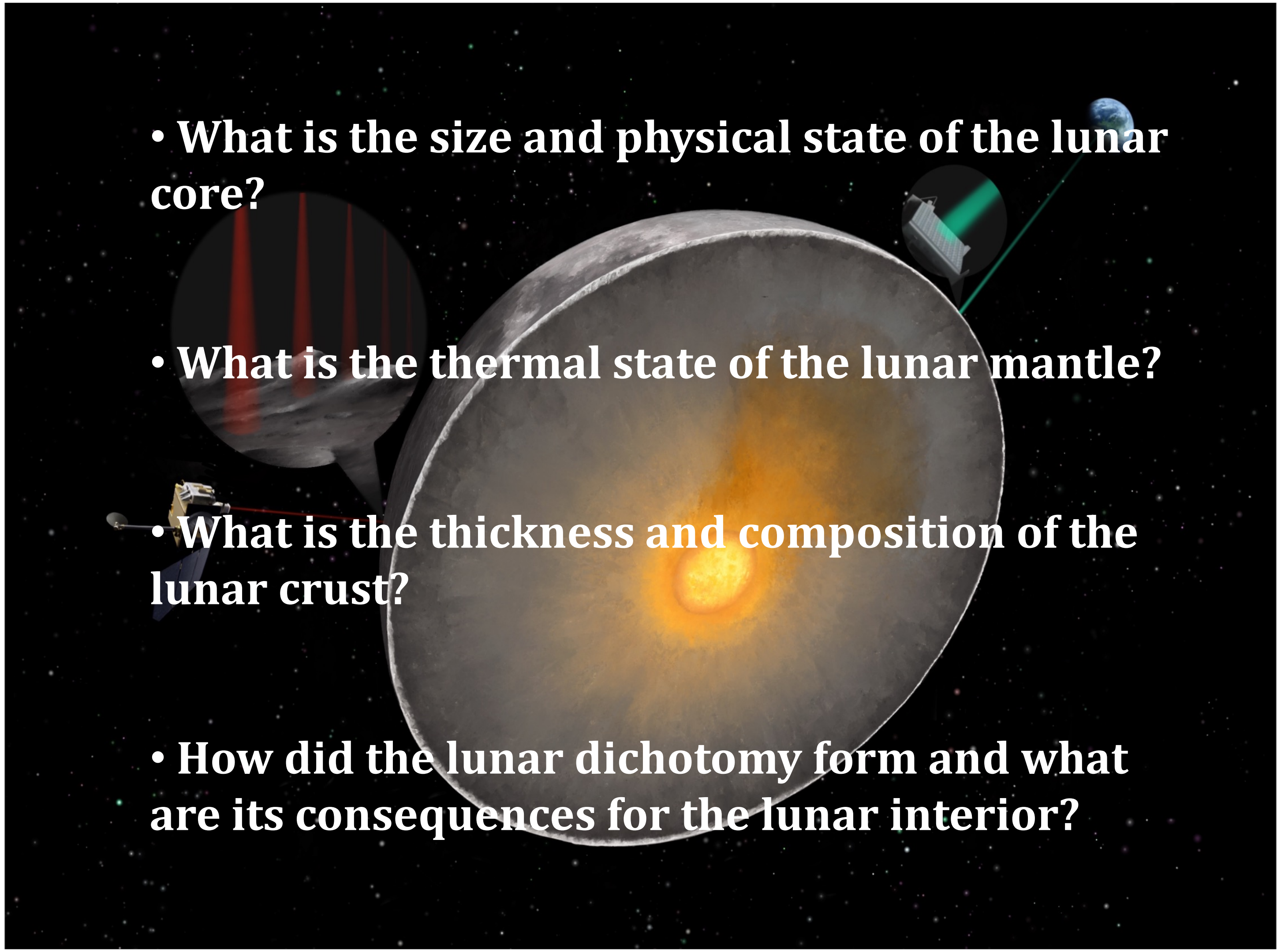


Present situation for Selenodesy

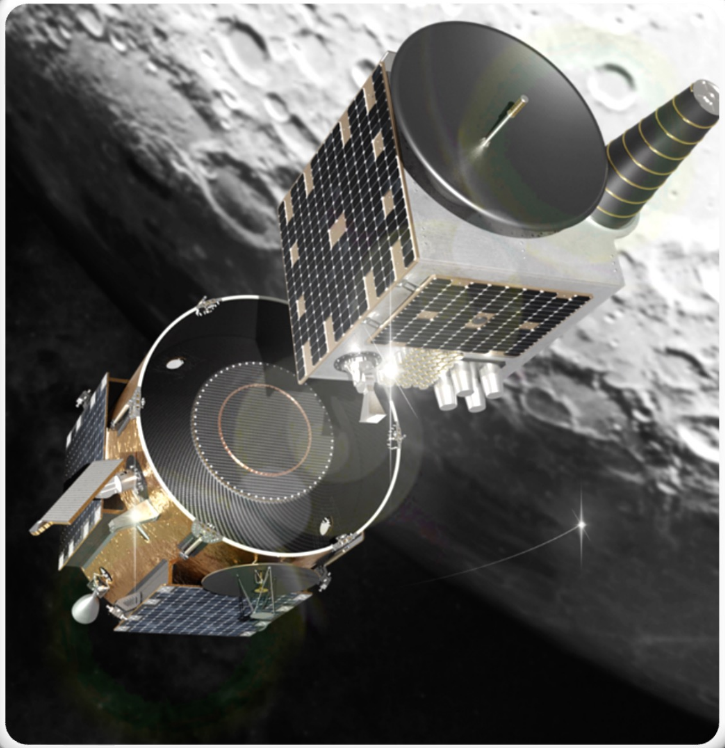
NovaMoon: A Strategic Lunar Reference Station for Positioning, Timing, and Largely Enhanced Science in the Earth–Moon System

Serena Molli[1], Agnès Fienga[2], Pascale Defraigne[3], Krzysztof Sośnica[4], Luigi Cacciapuoti[5], Luca Porcelli[6], Lotfi Massarweh[7], Sara Bruni[8], Riccardo Pozzobon[9†], Albert Roura[10], Francesco Vespe[11], Diego Blas[12], Ozgur Karatekin[3], Yoann Audet[13], Floor Melman[5], Richard Swinden[5], Javier Ventura-Traveset[14], Olivier Alibart[2], Marie-Christine Angonin[15], Daniel Arnold[16], Ruth Bamford[17], Emmanuele Battista[6], Marco Belloni[5], J.C. Berton[1], Orfeu Bertolami[18], Mathis Bloßfeld[19], Adrien Bourgoin[15], Giada Bargiacchi[6], Salvatore Buoninfante[20], Nicolò Burzillà[6], Roberto Campagnola[6], Paolo Cappuccio[21], Salvatore Capozziello[22], Giuseppe Cimò[23], Clément Courde[2], Rolf Dach[16], Mario Siciliani de Cumis[11], Simone Dell'Agnello[6], Fabrizio De Marchi[24], Valentina Galluzzi[20], Francesco Gini[1], Philipp Glaeser[25], Klaus Gwinner[10], Alex Guinard[2], Rüdiger Haas[26], Aurélien Hees[15], Hauke Hussmann[10], Luciano Iess[24], Alexander C. Jenkins[27], Siddarth K. Joshi[28], Maria Karbon[37], Sergei Klioner[29], Kaisa Laiho[10], Christophe Le Poncin-Lafitte[15], Marco Lucente[20], David Lucchesi[20], Riccardo March[30], Lucia McCallum[31], Jürgen Müller[32], Weijie Nie[28], Jillian Oduber[5], Roberto Peron[20], Francesco Picciariello[5], Théo Pichavant[33], Michael Plumaris[5], Eleonora Polini[2], Ana-Catalina Plesa[10], Dimitrios Psychas[5], Bernardino Quaranta[5], Nicolas Rambaux[15], Marc Rovira-Navarro[7], Francesco Santoli[20], Matthias Schartner[34], Florian Seitz[19], Ilaria Sesia[35], Yan Seyffert[36], Stefano Speretta[7], Tim Springer[8], Giuseppe Vallone[9], Paolo Villoresi[9], Sebastien Vincent-Bonnieu[5], Ben Wadsworth[5], Pierre Waller[5], Radosław Zajdel[4], Erik Schoenemann[1]

(Molli et al, 2026, Space Science Reviews, submitted)

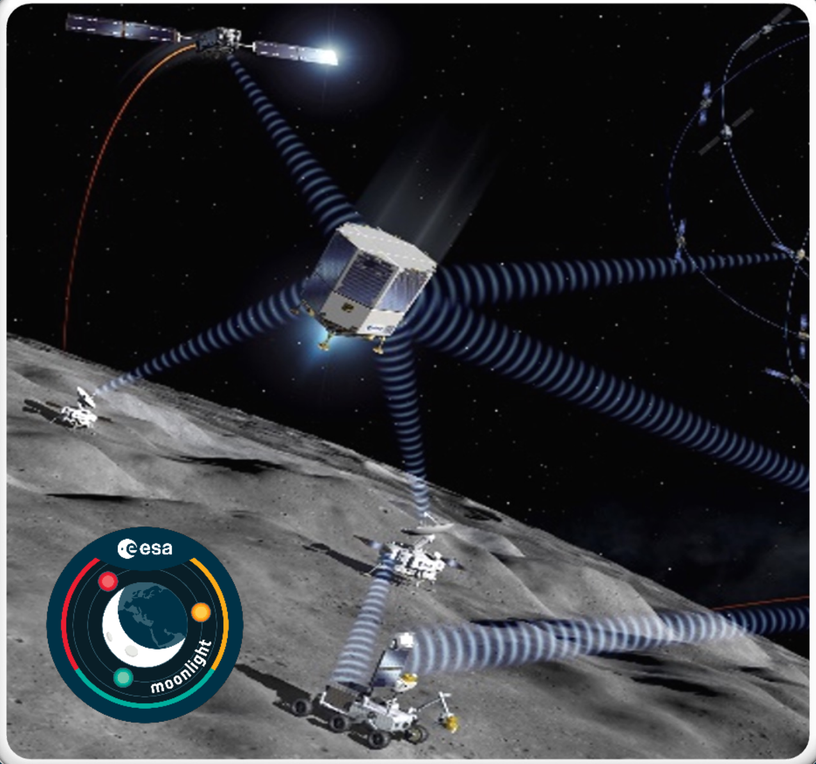


ESA Roadmap For Lunar COMM and PNT Services



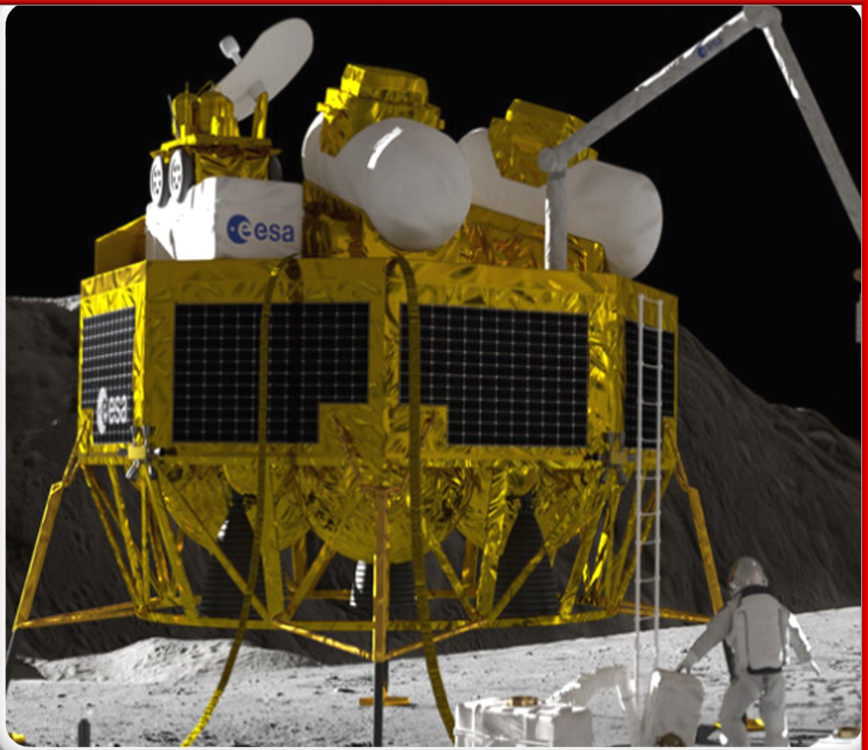
STEP 1:
LUNAR PATHFINDER

(LAUNCH in 2026 !)



STEP 2:
MOONLIGHT System

(Initial: 2028; Final: 2030)



STEP 3:
NOVAMOON @ Argonaut :
Local PNT Differential Station
(2029-2032 in 3 steps)

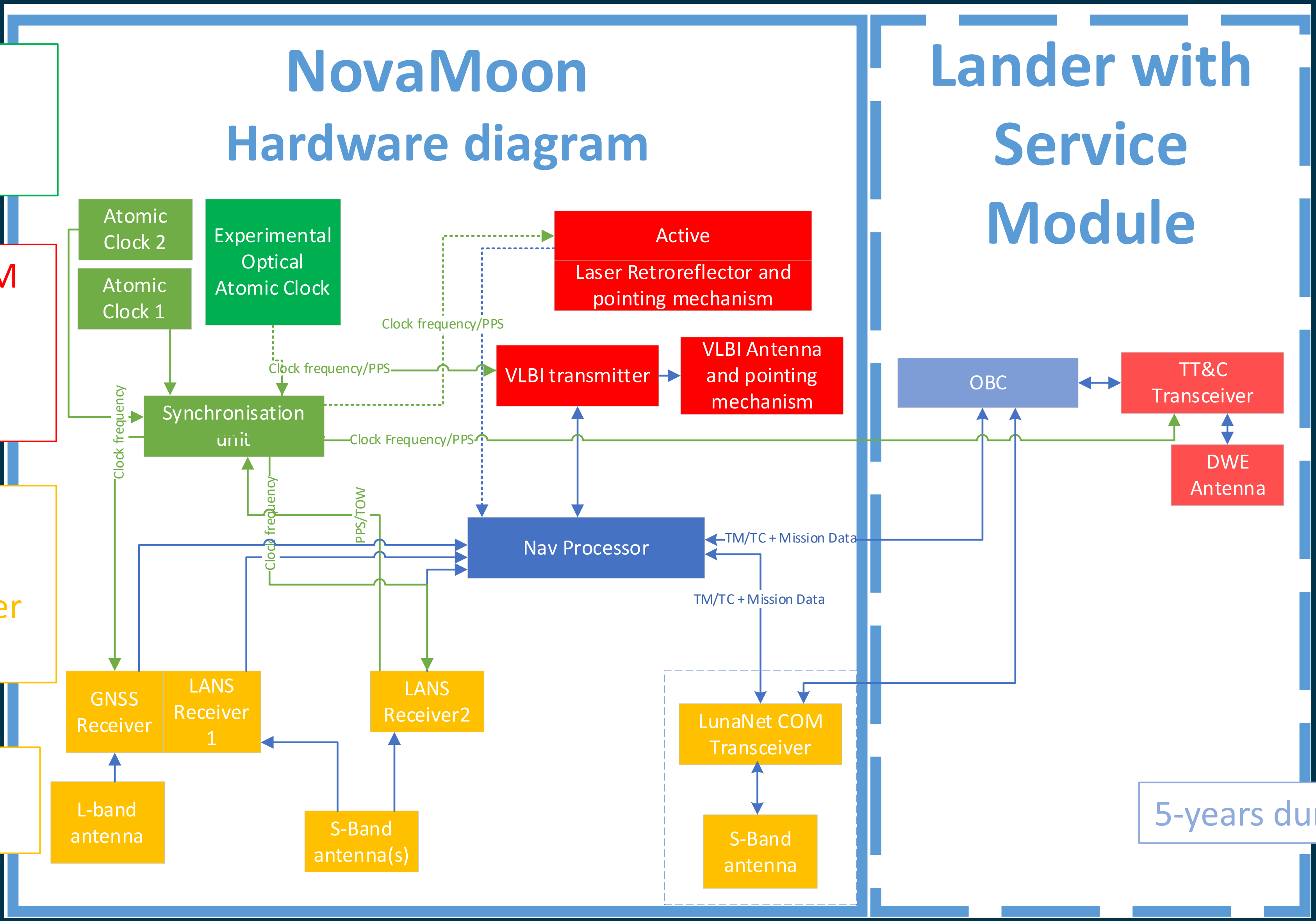
NovaMoon Full configuration - QAR in 2031

1) 2x MiniRAFS clock
2) Sync unit
3) Experimental Optical Clock

4) Laser Retroflector with APM plus INRRI
5) VLBI Transmitter
6) Active Laser Ranging

7) Combined GNSS+Moonlight/LunaNet Rx
8) Additional LunaNet Receiver
9) Navigation Processor

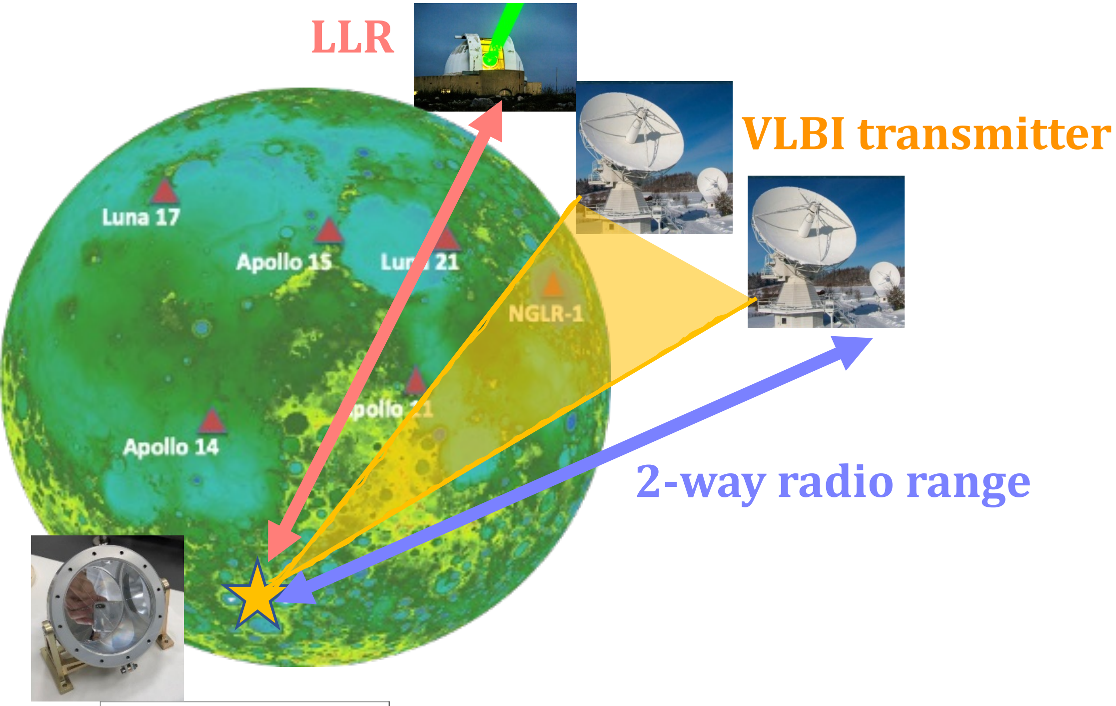
10) LunaNet/Moonlight/LPF Comms (S-band)

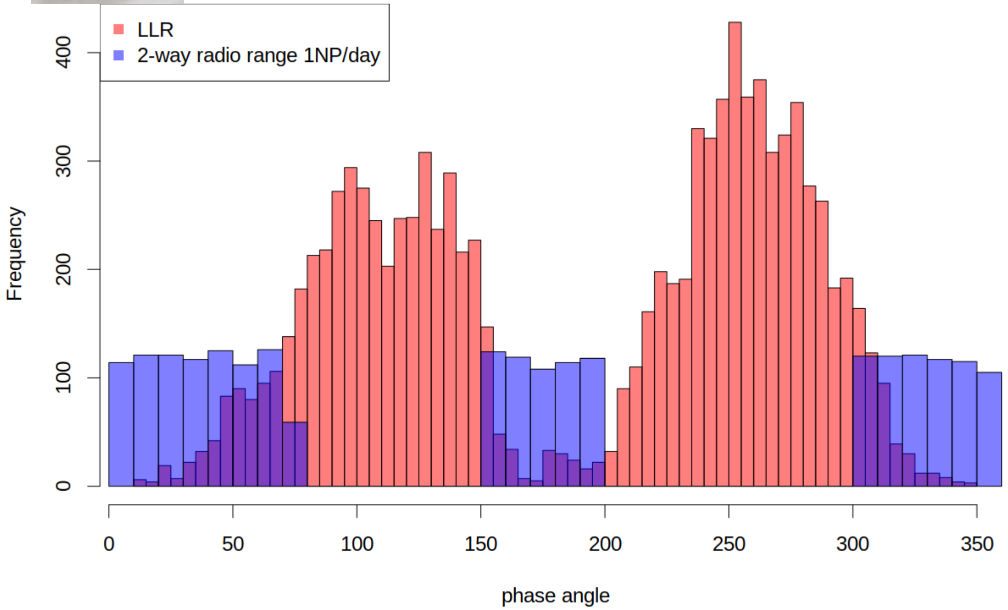


5-years duration

NovaMoon Build#3 baseline for Argonaut-2 .

Novamoon set-up





Full Lunar ephemeris simulation based on 50 years of LLR data +

- **5 years of simulation**

- **LLR** with 2 scenario with A15 σ and A15 $\sigma/10$
- **VLBI transmitter →** angular measures with 0.1 mas accuracy versus ICRF3, 2x24h / week
- **2-way radio range** from a SH station with 1 cm accuracy and 1 NP/day, <u>complementing LLR</u>

Parameters considered in the simulation:

- Moon PV relative to Earth, orientation angles (Euler)
- LLRR coordinates
- 16 parameters related to Moon shape, internal structure and surface deformation

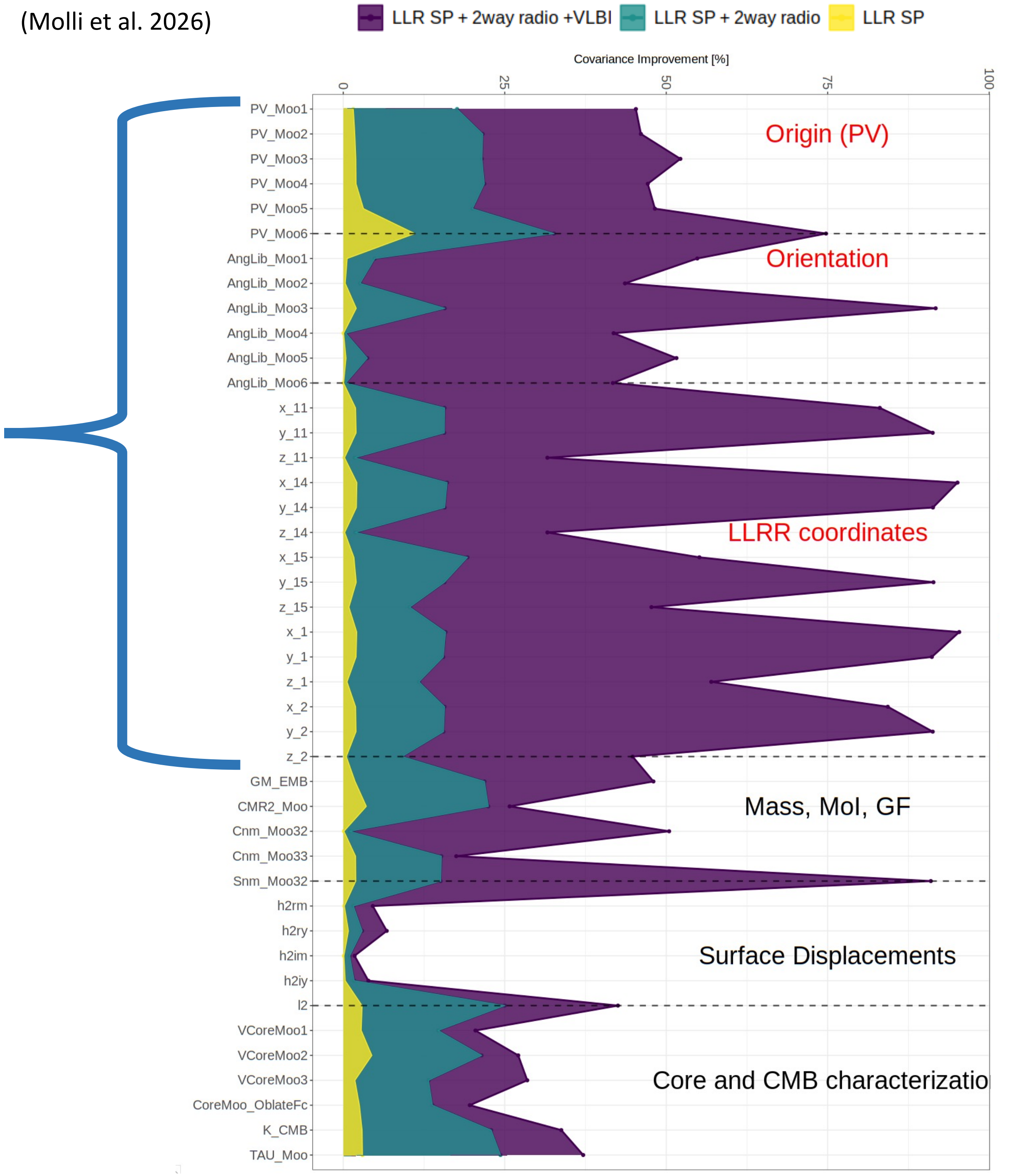
- Covariance analysis

Results for Moon RF definition

(Molli et al. 2026)

Improvement in RF definition

- **VLBI** : Up to 75% for Origin, orientation, LLRR coordinates
- **2-way range**: Up to 25% for Origin, orientation, LLRR coordinates



Results

(Molli et al. 2026)

Improvement in RF definition

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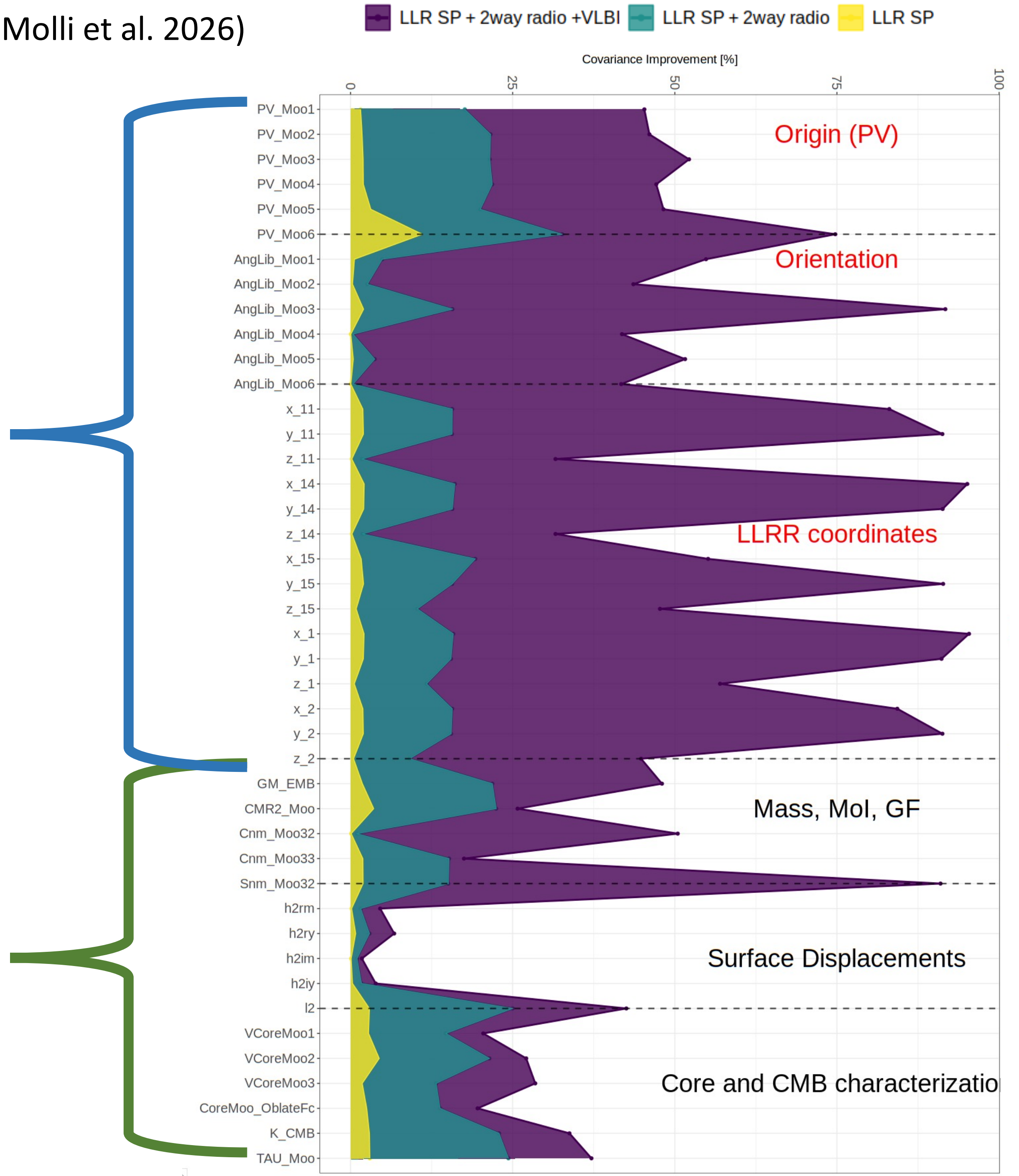
Improvement in Selenodesy

- **VLBI** : Up to 75% for GF, 50% mass, 50% for l_2 , 30% core characterization
- **2-way range**: Up to 20% for mass, MOI, 20% GF but complementary to VLBI, 20% for core characterization, few % $\Im$ (Love Numbers)
- Tidal tomography → constraints on deeper layers and their interactions (Briaud et al 2023)



Conclusions

- VLBI is the 1st key factor for the RF improvement
- 2-way radio range is a good complement to LLR
- The long duration (5 years) is the 2nd key factor

- Improvement on Earth RF (UT1-TUC)
- Constraints on deep layers (IC, FC, CMB), complementary to seismometers

Objectives	Instrumentation						
	LLR [cm]		VLBI [mas]		2-way link with Earth SH tracking	1-way/2-way link to MoonLight	Atomic clock
	1	0.1	1	0.1	1 cm		
consolidate and improve the realization of the lunar reference frame.							
Improve the links (i.e., rotation and transformations) between lunar, Earth terrestrial and celestial reference frames							
contribute to the generation of precise lunar ephemeris.							
improve the precise determination of the lunar rotation parameters.							
improve the precise determination of the lunar tidal deformation parameters							

Objectives	Instrumentation						
	LLR [cm]		VLBI [mas]		2-way link with Earth SH tracking	1-way/2-way link to MoonLight	Atomic clock
	1	0.1	1	0.1	1 cm		
What is the size and physical state of the lunar core?							
What is the thermal state of the lunar mantle?							
What is the thickness and composition of the lunar crust?							
How did the lunar dichotomy form and what are its consequences for the lunar interior?							

Conclusions

- VLBI is the 1st key factor for the RF improvement
- 2-way radio range is a good complement to LLR
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- Improvement on Earth RF (UT1-TUC)
- Constraints on deep layers complementary to seismometers
- NovaMoon White paper 2025
- Molli et al, 2026, Space Science Reviews (submitted, ArXiv)

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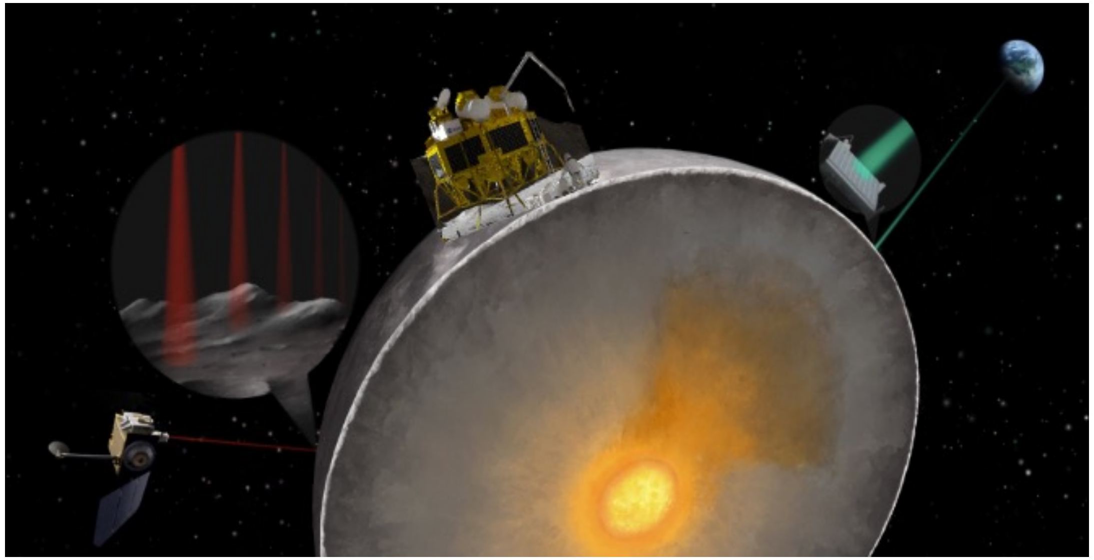

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Thank you

Results for Earth RF definition

- EOP parameters : UT1 and nutation parameters
- Current UT1 real-time uncertainties (0.8 ms) → 15m on Moon surface

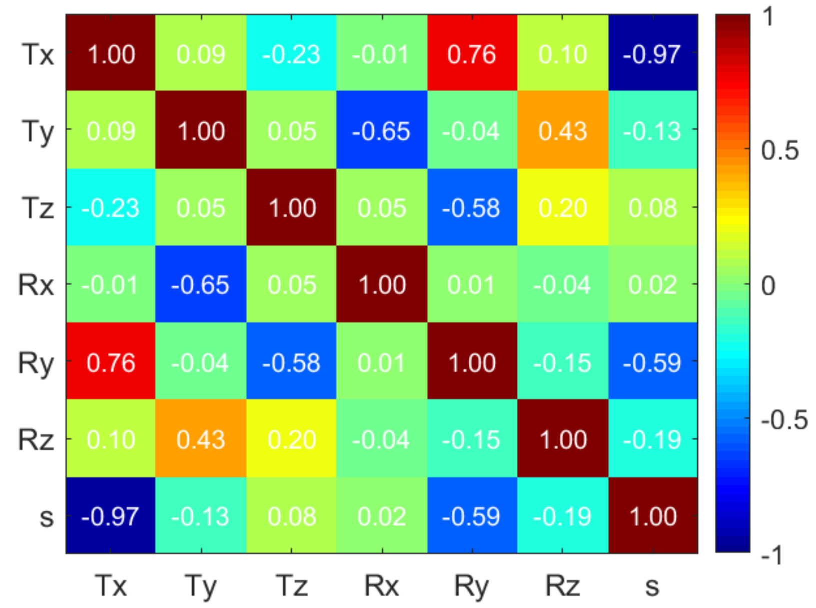
(Molli et al. 2026)

	VLBI	**NovaMoon** continuous tracking	**LLR**
Accuracy	**High (lateral)**	**High**	**High (radial)**
Continuity	No, e.g. 2*24h sessions per week (depending on ground segment availability)	**YES (~70%)**	No LLR observations during full and new Moon
Latency	Around 2 weeks	**near real-time**	Several days

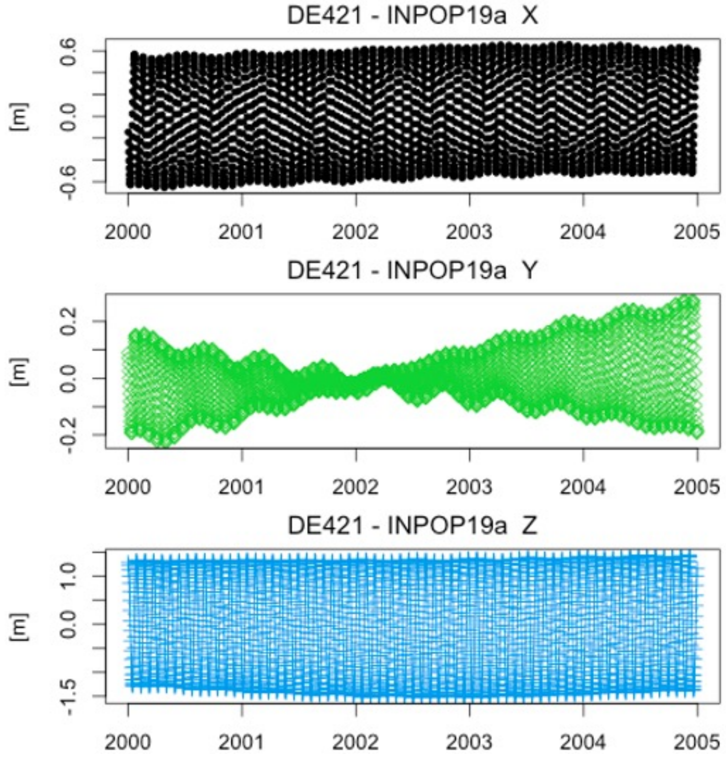
Present situation

- Only 5/6 control points
  - → Lack in the rotational modeling
    - → Empirical corrections (kinematic terms)
    - → LN disagreement with altimetry (?)
  - → Displacements of LLRR (20 cm in 25 years)

- Only GL distances ||GL|| is observed
  - → Correlated signature in RFP estimations
  - → Lunar CoM relative to earth differs from about 1 m between ephemerides



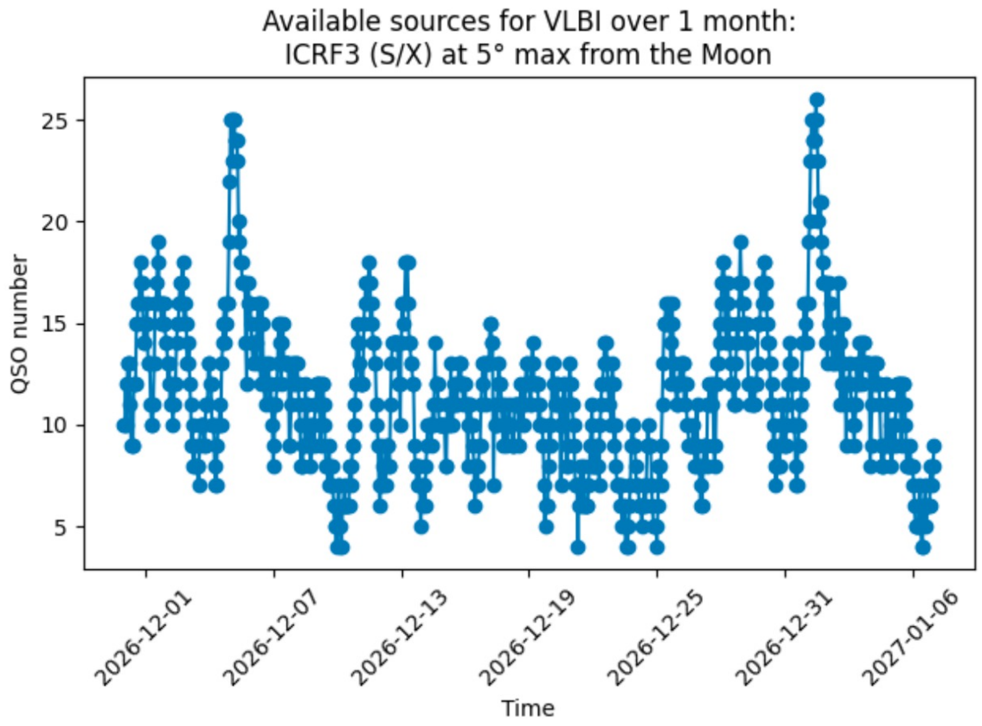
Correlation matrix

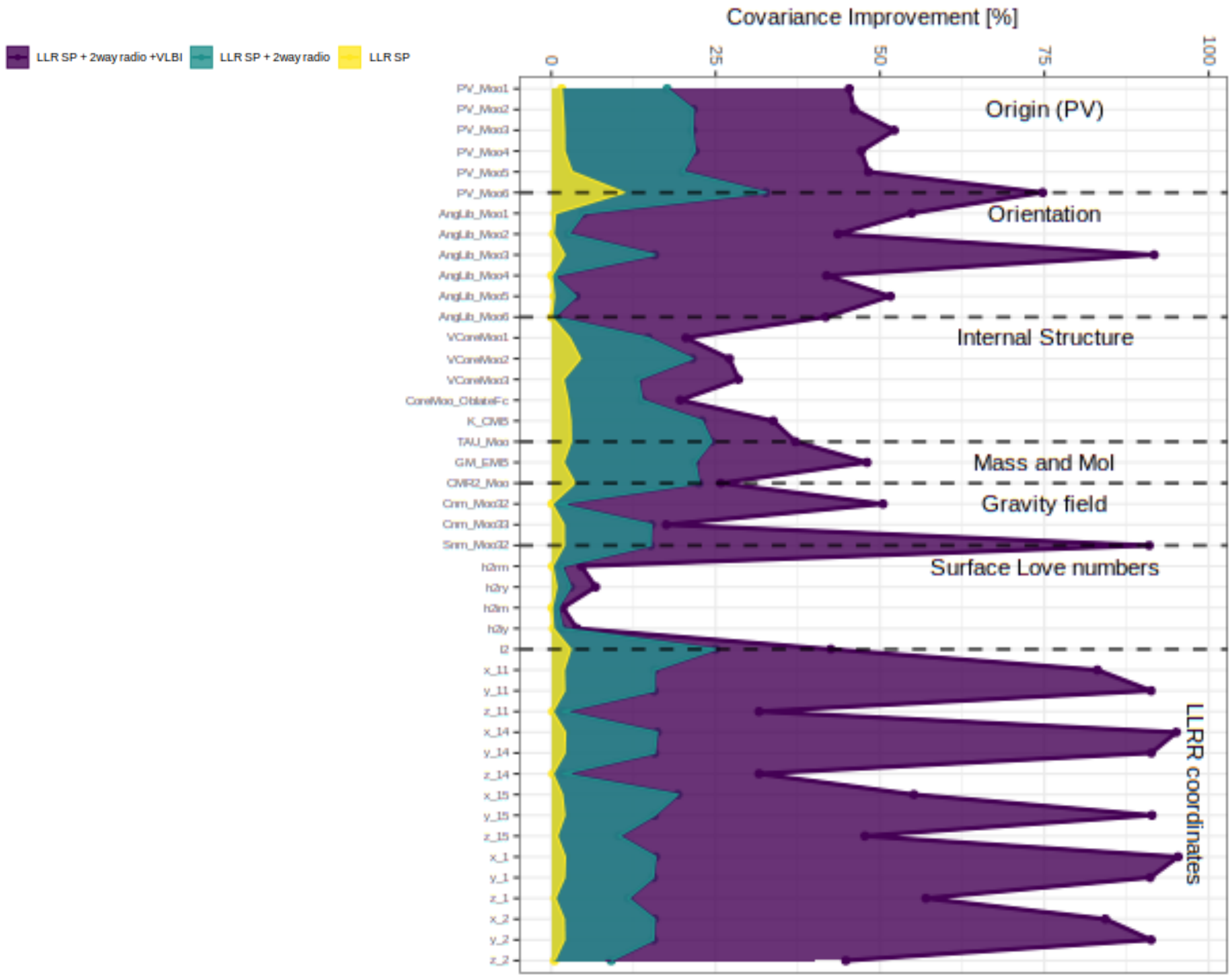


Instrumental Set-up : VLBI @ South-Pole

- Simulation topocentric SP (α, δ) with godot including :
  - Implemented: tidal surface deformation at the moon surface at the monthly and yearly periods,
  - From godot: topocentric vector
  - From inpop: moon PV and Euler angles from inpop21a and partials

- Differences between topocentric SP spherical coordinates (α, δ) and ICRF3 source coordinates. The observable is then $(\Delta\alpha \ \cos\delta , \Delta\delta)$
- Visibility of the ICRF sources at 5° (2° was also tested) away from SP and with a minimum of 10° elevation
  - with 5°, we have at least 5 QSO in the fov
  - with 2°, we have a minimum of 2 QSO
- 3 stations considered (i.e New_Norcia, Madrid_63, Goldstone_14) with at least visibility for 2 stations
- 2 accuracies : 1 mas (S3), 0.1 mas (S4)
- Time sampling: 2 continuous (24h) session per week for 5 years




Covariance Improvement [%]
LLR SP + 2way radio +VLBI
LLR SP + 2way radio
LLR SP
0
25
50
75
100
Origin (PV)
Orientation
Internal Structure
Mass and MoI
Gravity field
Surface Love numbers
LLRR coordinates
PV_Moo1
PV_Moo2
PV_Moo3
PV_Moo4
PV_Moo5
PV_Moo6
AngLib_Moo1
AngLib_Moo2
AngLib_Moo3
AngLib_Moo4
AngLib_Moo5
AngLib_Moo6
VCoreMoo1
VCoreMoo2
VCoreMoo3
CoreMoo_OblateFc
K_CMB
TAU_Moo
GM_EMB
CMR2_Moo
Cnm_Moo32
Cnm_Moo33
Snm_Moo32
h2rm
h2ry
h3m
h3y
l2
x_11
y_11
z_11
x_14
y_14
z_14
x_15
y_15
z_15
x_1
y_1
z_1
x_2
y_2
z_2

	VLBI	NovaMoon	LLR
Accuracy	**High (lateral)**	**High**	**High (radial)**
Continuity	No, e.g. 2*24h sessions per week (depending on ground segment availability)	**YES (~70%)**	No LLR observations during full and new Moon
Latency	Around 2 weeks	**near real-time**	Several days

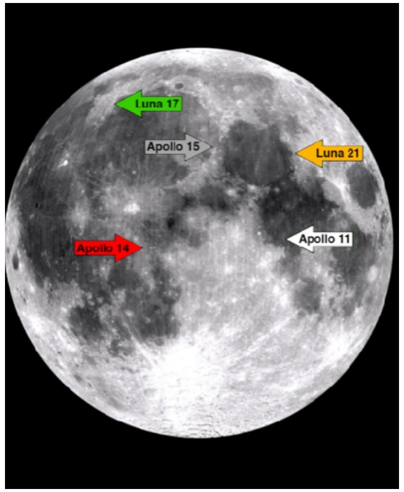
Table 3: Impact of VLBI, LLR, NovaMoon continuous tracking for EOP determinations

	Budget error - ITRF - ILRF	**Real-Time**	**Post-processing**
1	ITRF realization	2 cm (real-time accessibility by GNSS)	0.5 cm
2	Polar motion (x, y) - ITRF-ICRF	0.2 mas (0.6 cm Earth, 37 cm at lunar distance)	0.03 mas (0.1cm Earth, 6 cm at lunar distance)
3	**dUT1 - ITRF-ICRF**	**0.8 ms (37 cm Earth surf., 15 m at lunar distance)**	**0.01 ms (0.5 cm Earth, 19 cm at lunar distance)**
4	Sub-daily Earth rotation	0.007 mas (0.03 cm Earth, 1.3 cm lunar distance)	0.007 mas (0.03 cm Earth, 1.3 cm lunar distance)
5	Nutation - ITRF-ICRF	0.1 mas (0.3 cm Earth, 19 cm at lunar distance)	0.06 mas (0.2cm Earth, 11 cm lunar distance)
6	ICRF – LCRS (lunocenter)	15 cm (surface, ~1.2 m orbiter)	15 cm (surface, ~1.2 m orbiter)
7	LCRS – ILRF (Euler angles)	9 cm (surface, ~0.7 m orbiter)	9 cm (surface, ~0.7 m orbiter)
	Total: 1+2+3+4+5+6+7	**~15 m at lunar distance**	**~27 cm at lunar distance**

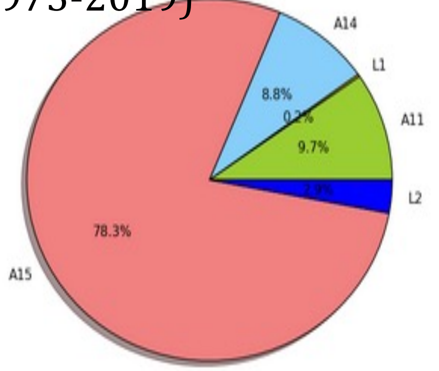
Table 4: Error budget for the transformation between terrestrial and lunar reference frames

Present situation

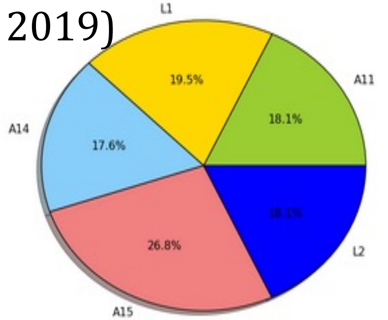
- Only 5/6 control points
  - → Lack in the rotational modeling
    - → Empirical corrections (kinematic terms)
    - → LN disagreement with altimetry (?)
    - → Disagreement with GRAIL GF
  - → Displacements of LLRR (20 cm in 25 years)



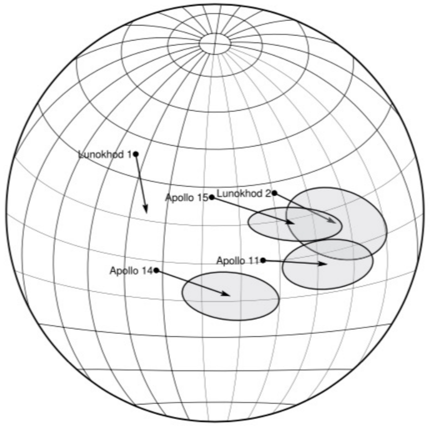
G (from 1973-2019)

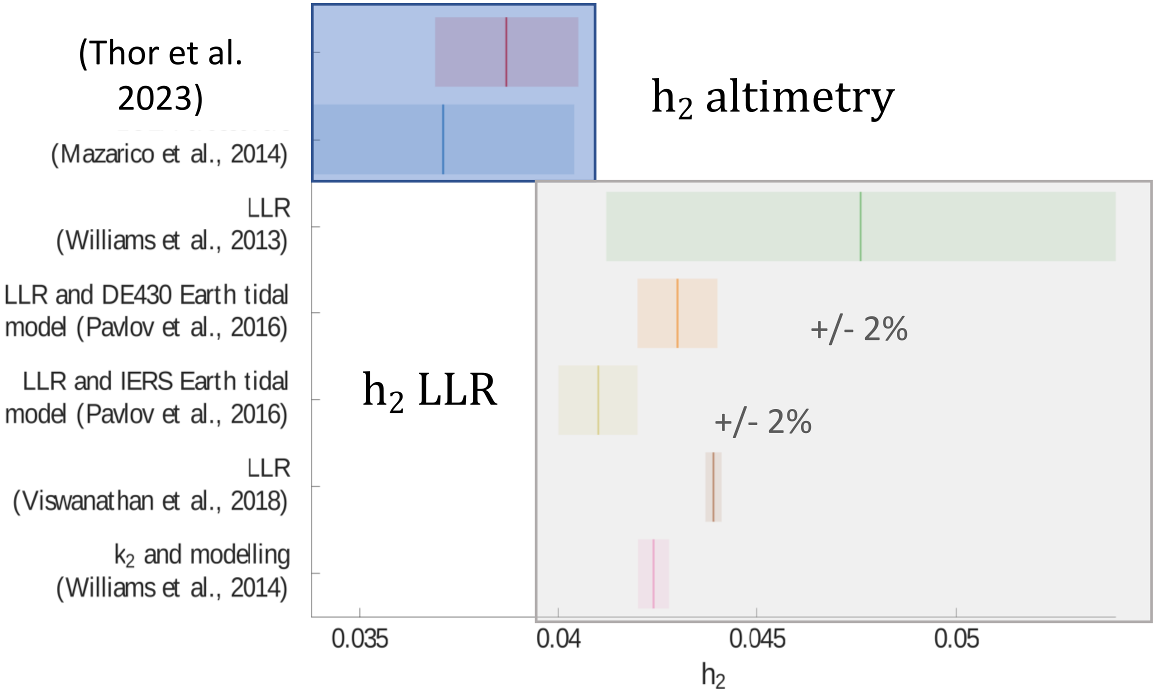


IR (since 2019)

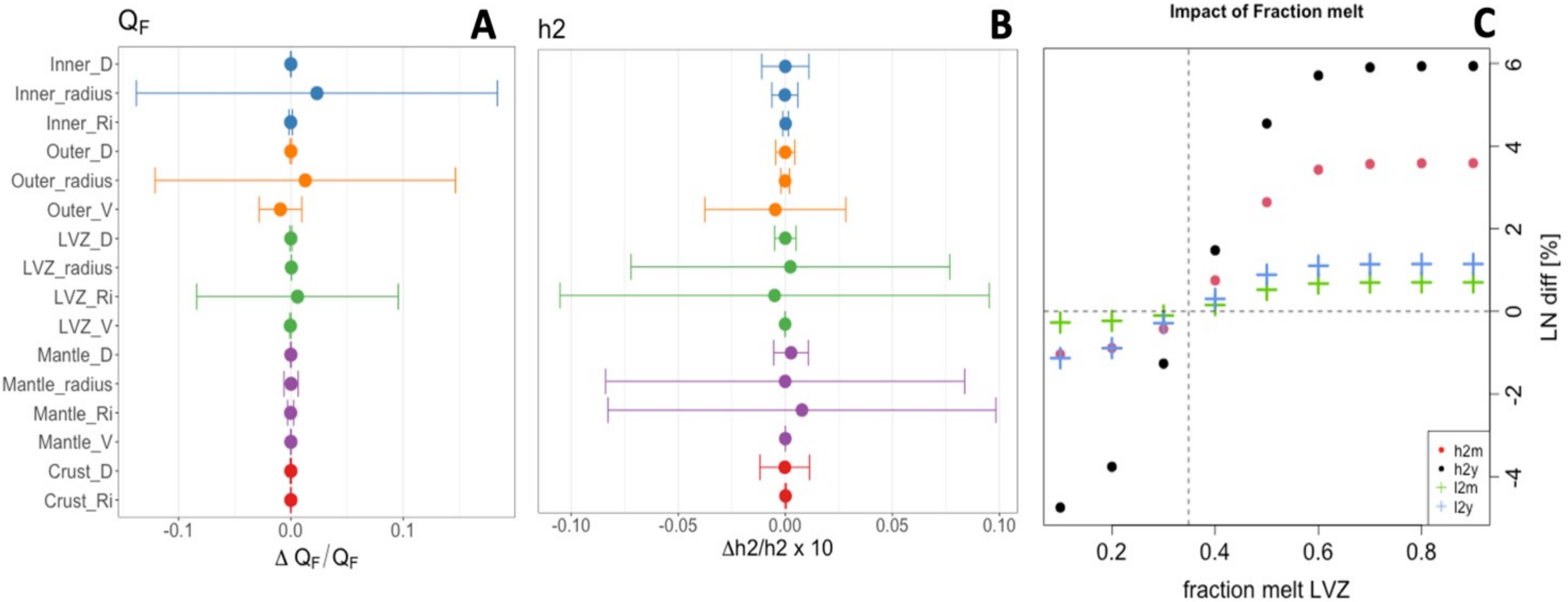


(Williams and Boggs 2021)





days	31	206	365	1095	1306	1643	2190
DE440*	x	x	x	x	x	x	x
DE430		x	x	x			
INPOP19a		x	x	x			
EMP2021		x	x	x			



QF
A
Inner_D
Inner_radius
Inner_Ri
Outer_D
Outer_radius
Outer_V
LVZ_D
LVZ_radius
LVZ_Ri
LVZ_V
Mantle_D
Mantle_radius
Mantle_Ri
Mantle_V
Crust_D
Crust_Ri
-0.1
0.0
0.1
Δ QF/QF
h2
B
-0.10
-0.05
0.00
0.05
0.10
Δh2/h2 x 10
Impact of Fraction melt
C
h2m
h2y
l2m
l2y
0.2
0.4
0.6
0.8
fraction melt LVZ
6
4
2
0
-2
-4
LN diff [%]