Réflecteurs lunaires de nouvelle génération: Une application spatiale du Temps-Fréquence

AG-First-TF – Workshop "Application des technologies du Temps-Fréquence au domaine de la défense et du spatial" 2025

09/10/2025

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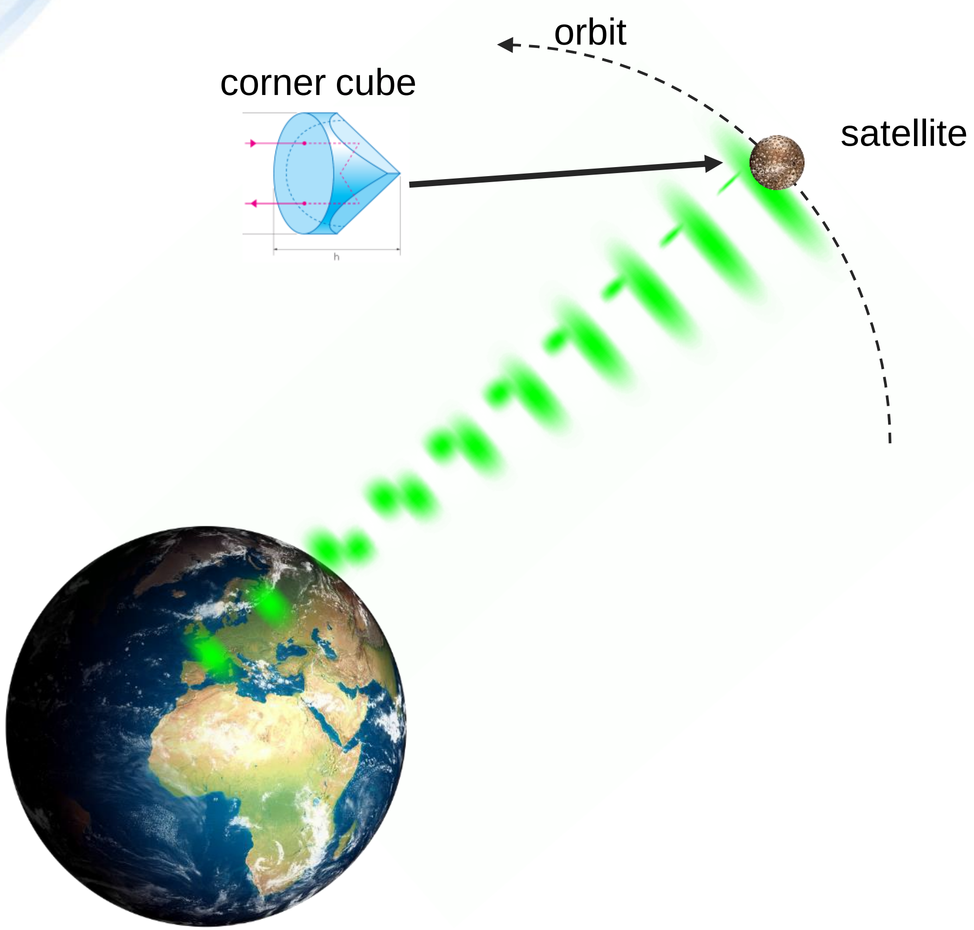
Outline

- Lunar laser Ranging & Applications
- Next Generation of Lunar Laser Reflectors: Moonlight
- Time transfer in Lunar Orbit

Satellite & Lunar Laser Ranging principle: ToF

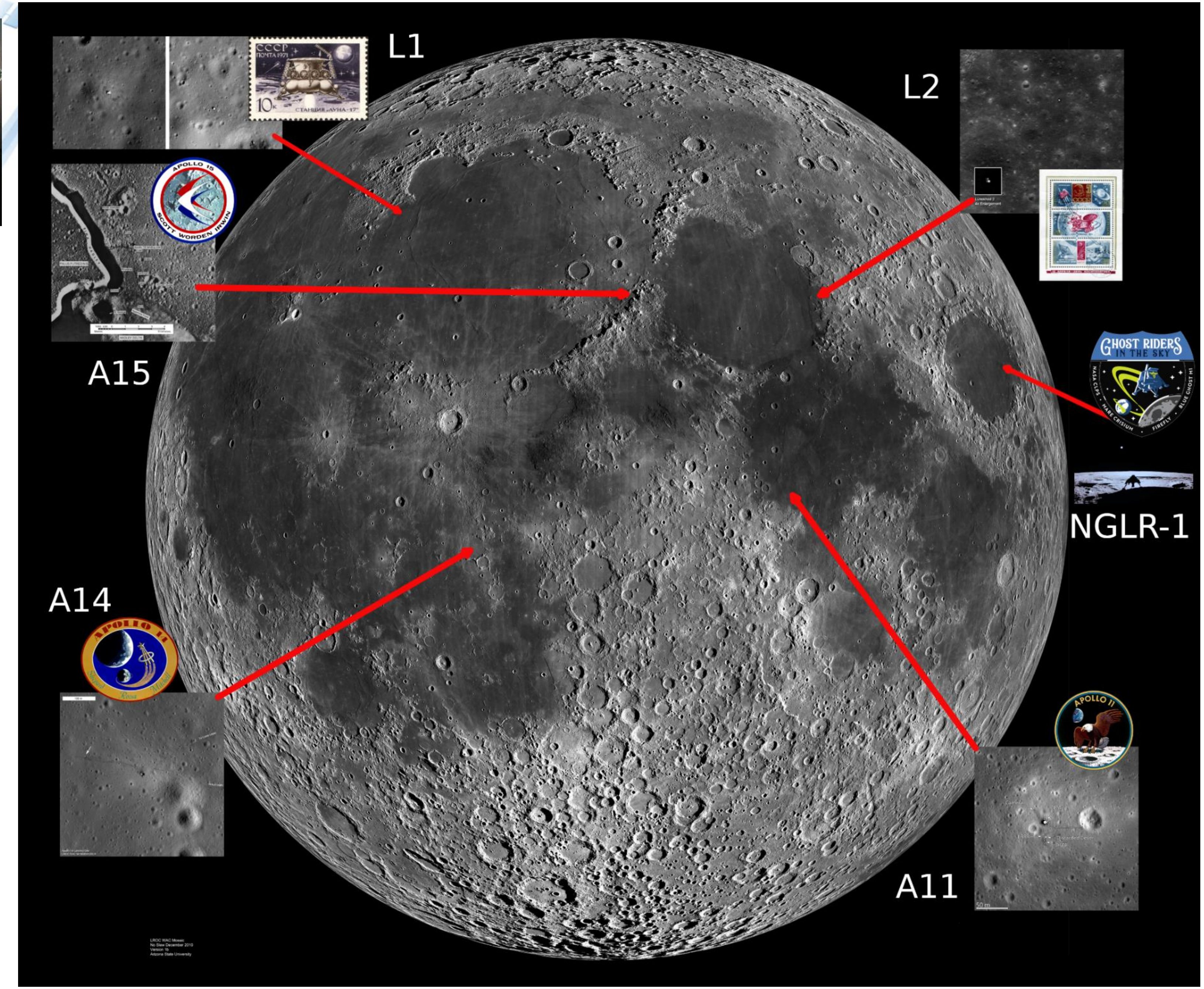


- Measurement of the time of flight of laser pulses:

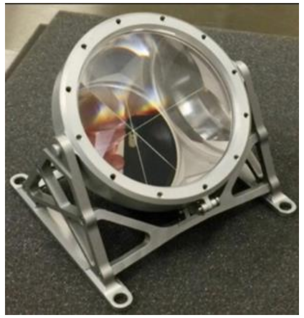
$$D = \frac{c.(t_{arrival} - t_{departure})}{2}$$

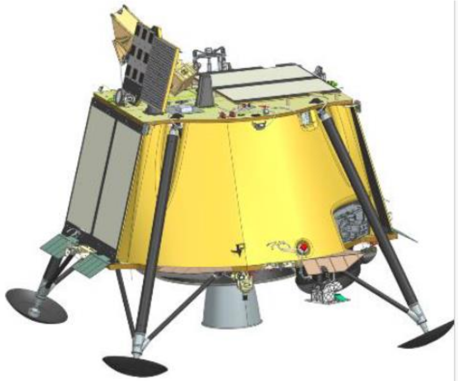
- Reference points:
  - Ground : the cross of the telescope axes
  - Space : the center of mass of the satellite

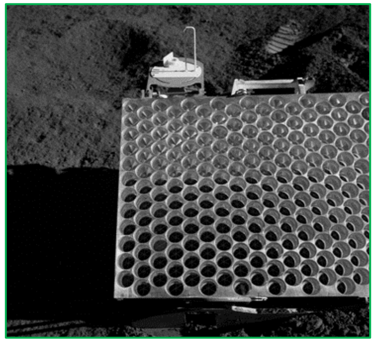
Measured distance: [300km – 380 000 km]
Accuracy < 10 mm
Precision ~ few mm



L1
L2
APOLLO 15
SCOTT WORDEN IRWIN
A15
GHOST RIDERS IN THE SKY
NGLR-1
A14
A11

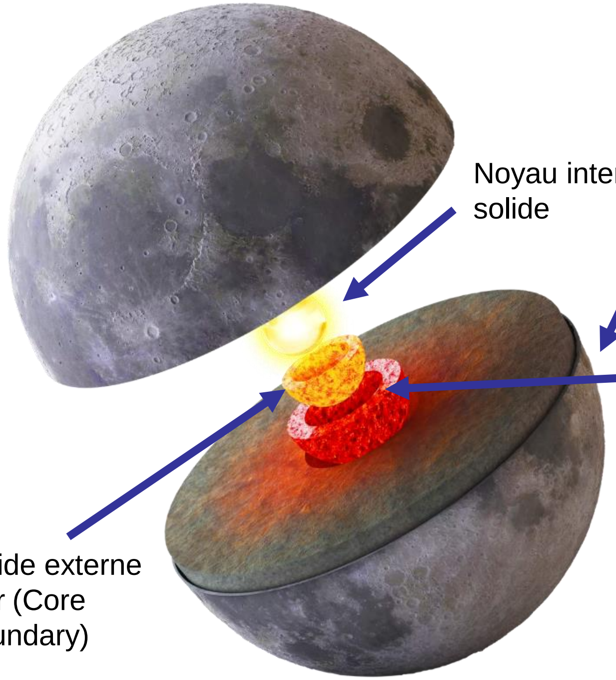






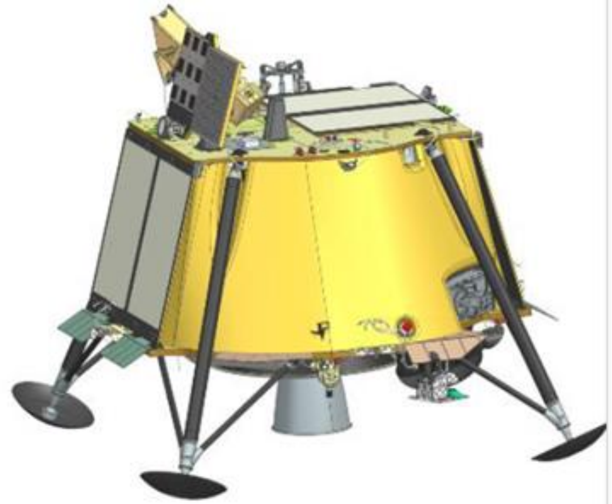
Most recent LLR scientific outcomes

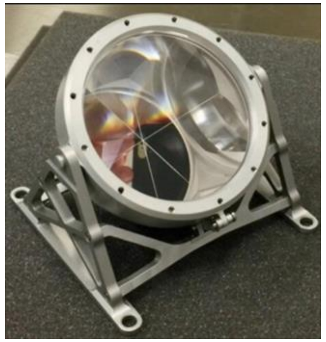
- Structure Lunaire:
  - **2019**: l'accumulation des données LLR depuis plus de 50 ans a permis en 2019 de trancher en faveur d'un **noyau liquide de 381±12 km** de rayon avec une précision inégalée par les autres méthodes géophysiques appliquées à la Lune (Viswanathan, V., Rambaux, N., Fienga, A., Laskar, J. & Gastineau, M. Observational constraint on the radius and oblateness of the lunar core-mantle boundary. ***Geophys. Res. Lett.*** **46, 7295–7303 (2019))**
  - **2021**: Les données montrent un **taux de rotation lunaire non synchrone supplémentaire de 1,0 ± 0,4 mas/an** qui est suspecté provenir d'effets non modélisés à très longue période de la libration physique en longitude. (Williams, J. G., & Boggs, D. H. (2021). Testing the motion of lunar retroreflectors. ***Journal of Geophysical Research: Planets*****, 126, e2021JE006920**)
  - **2023**: ***Mise en évidence d'un noyau solide d'environ 500 km de diamètre***, soit environ 15 % de la taille de la Lune. Il est composé d'un métal dont la densité est proche de celle du fer. L'existence de ce dernier a pu être prouvée en combinant des données provenant de différentes missions spatiales et celles de télémétrie laser-Lune. Briaud, A., Ganino, C., Fienga, A. *et al.* The lunar solid inner core and the mantle overturn. ***Nature*** **617, 743–746 (2023)**.
- Physique fondamentale: Relativité générale
  - **2017-2019** Invariance de Lorentz par le LLR: La qualité et la quantité de ces données offrent une précision de 100 supérieure à celle obtenue par d'autres méthodes (A. Bourgoin et al. Lorentz Symmetry Violations from Matter-Gravity Couplings with Lunar Laser Ranging, ***Physical Review Letters*** **(2017)** - Constraining velocity-dependent Lorentz and violations using lunar laser ranging A Bourgoin,S Bouquillon, A Hees, C Le Poncin-Lafitte, QG Bailey, ... **Physical Review D 103 (6), 0640552021**)
  - **2023** :**Nouveau test de la violation possible de l'équivalence des masses gravitationnelles passive et active (*malmp*),** pour l'aluminium (Al) et le fer (Fe), en utilisant les données LLR. Une nouvelle limite de $3{,}9\times10^{-14}$ est environ **100 fois meilleure que le dernier test** de ce type réalisé en 1986 (Vishwa Vijay Singh, Jürgen Müller, Liliane Biskupek, Eva Hackmann, and Claus Lämmerzahl **Phys. Rev. Lett. 131, 021401 2023**)
- Rotation de la Terre:
  - 2**022** Vishwa Vijay Singh, Liliane Biskupek, Jürgen Müller, Mingyue Zhang, Earth rotation parameter estimation from LLR, Advances in Space Research, Volume 70, Issue 8, 2022, Pages 2383-2398

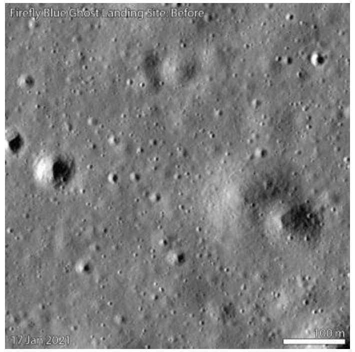


Next Generation of Lunar Laser Reflectors

NGLR-1 Blue Ghost March 02, 2025







- Most precise robotic landing
- Reflector NGLR-1: Collaboration INFN (Frascati, Italy), Maryland University (USA)
- Localisation depuis l’Observatoire de Calern de Blue Ghost NGLR le 03/03/2025 mars à 11h 38 minutes et 26 secondes TU à ~90 m de sa position attendue

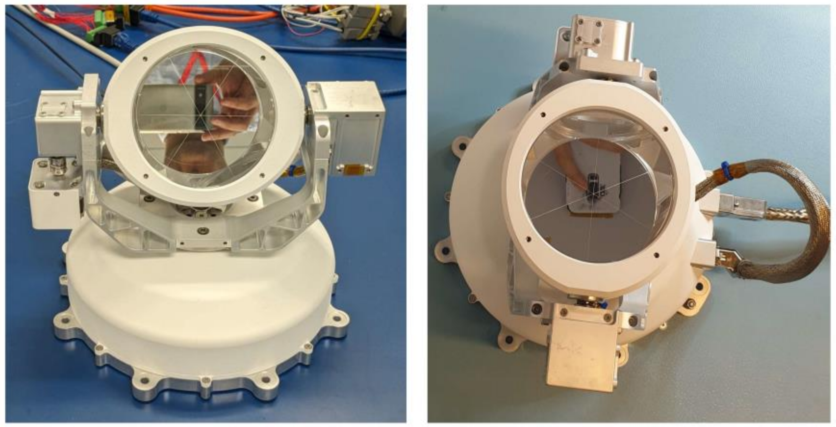
Moonlight: MoonLIGHT (Moon Laser Instrumentation for General relativity/geophysics High-accuracy Tests)

- Under the agency's "Moonlight" initiative, ESA is exploring with industry the necessary technical solutions along with delivery models for the provision of lunar telecommunication and navigation services.

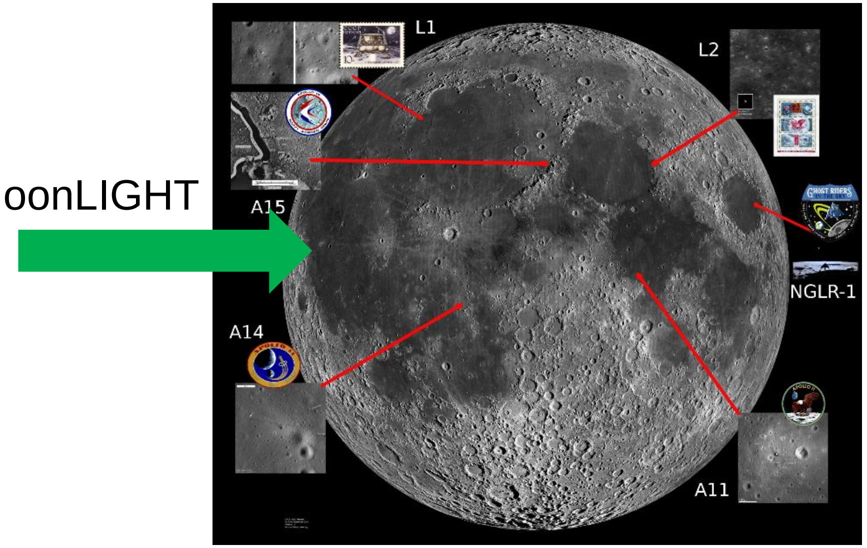
- Moonlight will be a constellation of five lunar satellites (one for high data rate communications and four for navigation), launched into space and carried by space tug from Earth’s orbit to the Moon’s. The constellation will connect to Earth via three dedicated ground stations, creating a data network spanning up to 400 000 km.

- The MoonLIGHT retroreflector can reduce Earth-Moon laser range error thanks to its next-generation compact design. The single, larger reflector with a front face 100 mm in diameter can improve accuracy to within millimeters.

MoonLIGHT + MPaC



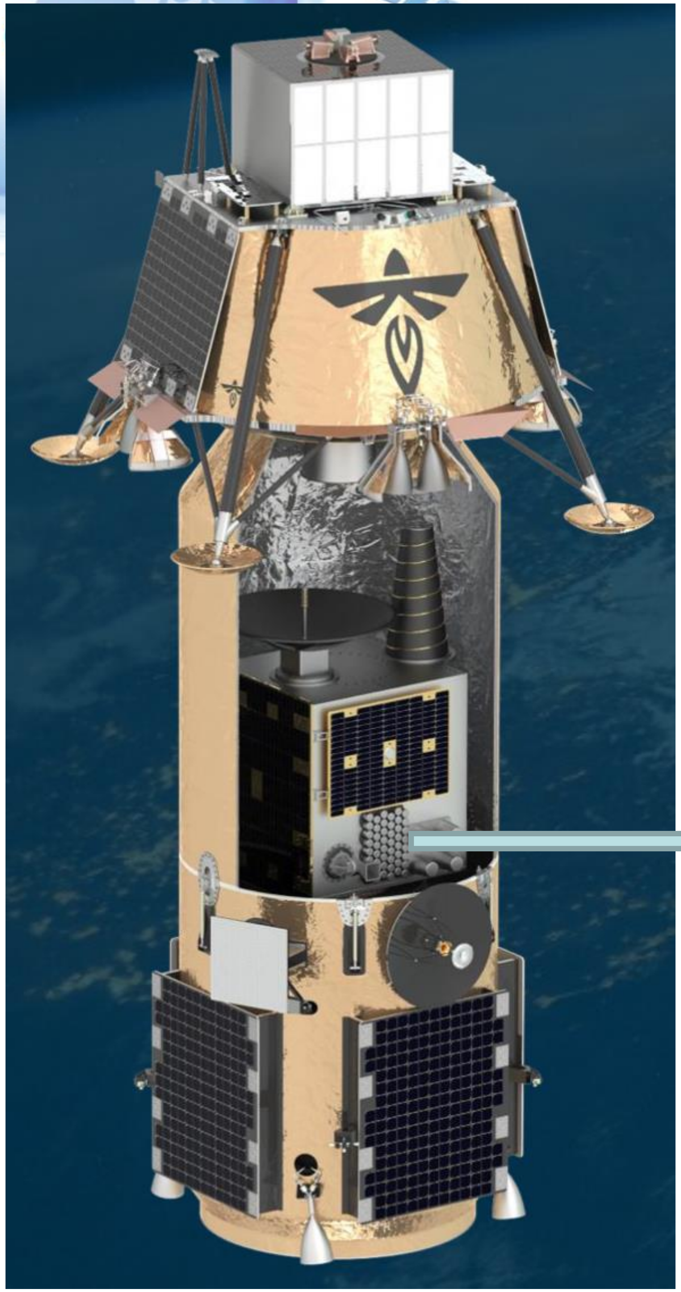
(a) (b)



- MoonLIGHT + MPaC:
  - NGLR Reflector
  - Pointing Actuator (MPAc) hardware

- To the Reiner Gamma swirl on the Moon, with a Commercial Lunar Payload Service (CLPS)
- NASA selected a Nova-C (Intuitive Machines) mission for CLPS
- The launch of IM-3 is expected to take place in first half 2026

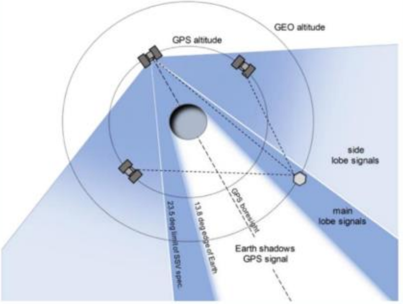
Muccino, M.; Montanari, M.; Lauretani, R.; Remujo Castro, A.; Rubino, L.; Denni, U.; Rodriquez, R.; Salvatori, L.; Tibuzzi, M.; Filomena, L.; et al. MoonLIGHT and MPAc: The European Space Agency's Next-Generation Lunar Laser Retroreflector for NASA's CLPS/PRISM1A (CP-11) Mission. *Remote Sens.* **2025**, *17*, 813. https://doi.org/10.3390/rs17050813



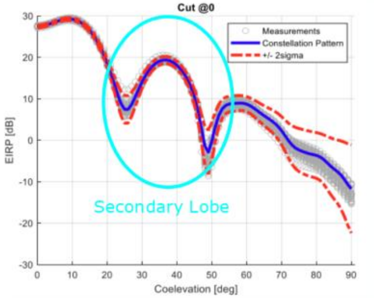
Lunar Pathfinder

- Commercial Lunar Communication Relay Satellite (part of Moonlight)
- Orbit delivery through NASA-led CLPS CS-3 program
- Will perform data relay operation for the first US lander on the far side (LuSEENight)

- Will host two hosted paylods:
  - A GNSS receiver
  - A radiation monitor
  - A Laser retroreflector



Courtesy: Donaldson, Jennifer E., et al. "Characterization of on-orbit GPS transmit antenna patterns for space users." *NAVIGATION: Journal of the Institute of Navigation* 67.2 (2020): 411-438.



Courtesy: EUSPA https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_Reference_Antenna_Pattern_v1.0.pdf

- Launch: Q4 2025
- Exploitation: Q1 2026 – Q3 2034

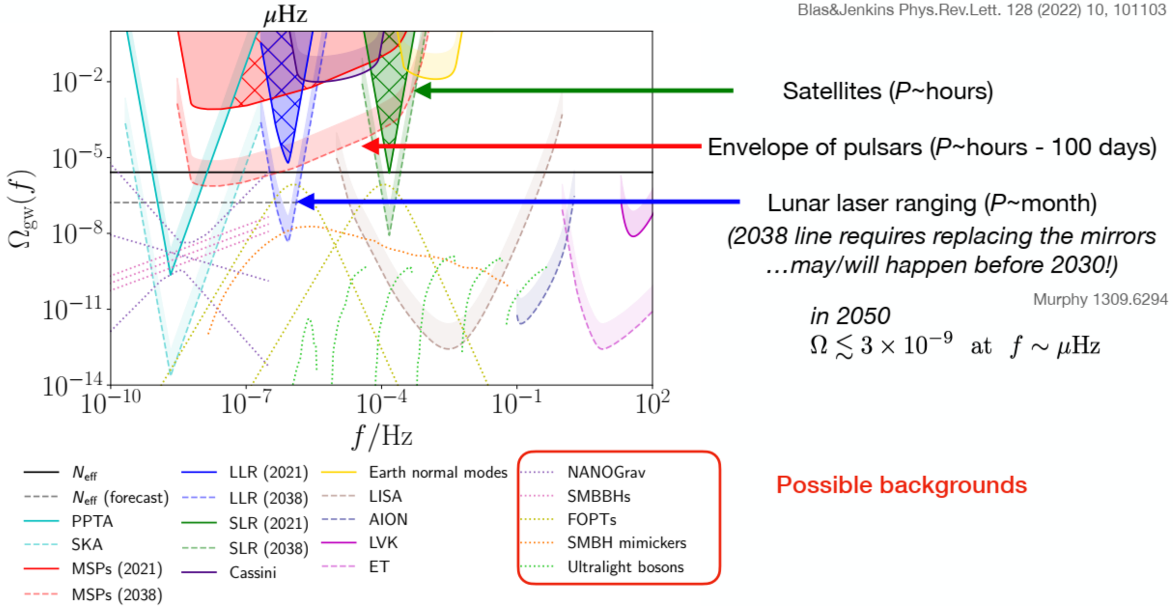
New Scientific Objectives of Lunar Laser Ranging

Gravitational measurement	Apollo/Lunokhod LLR accuracy (~ few cm)	Next generation LLR accuracy (~1 mm)	Time scale	Ultimate goal LLR accuracy (~0.1 mm)
WEP	$\lvert\frac{\Delta a}{a}\rvert < 1.4 \times 10^{-13}$	10^{-14}	Few years	10^{-15}
SEP	$\lvert\eta\rvert < 4.4 \times 10^{-4}$	3×10^{-5}	Few years	3×10^{-6}
β	$\lvert\beta - 1\rvert < 1.1 \times 10^{-4}$	10^{-5}	Few years	10^{-6}
$\frac{\dot{G}}{G}$	$\lvert\frac{\dot{G}}{G}\rvert < 9 \times 10^{-13} yr^{-1}$	5×10^{-14}	$\sim$ 5 years	5×10^{-15}
Geodetic precession	6.4×10^{-3}	6.4×10^{-4}	Few years	6.4×10^{-5}
$1/r^2$ deviation	$\lvert\alpha\rvert < 3 \times 10^{-11}$	10^{-12}	$\sim$ 10 years	10^{-13}

- J. G. Williams et al. Phys. Rev. Lett. 93, 261101 (2004)
- M. Martini, S. Dell'Agnello, Springer, DOI 10.1007/978-3-319-20224-2_5 (2016)
- Currie, D. G. et al. (2013), Acta Astronautica 68, 667–680
- H. Haviland et al., The Lunar Geophysical Network Landing Sites Science Rationale (2021), arXiv:2107.06451
- Biskupek, L., Müller, J., and Torre, *"Benefit of New High-Precision LLR Data for the Determination of Relativistic Parameters"*, Universe, 7, 34 (2021)
- S. Turyshev et al., NASA BPS Division's *"Lunar Surface Science Workshop Fundamental and Applied Lunar Surface Research in Physical Sciences"*, August 2021

- All previous fundamental physics tests but 10 to 100 better !

Blas&Jenkins Phys.Rev.Lett. 128 (2022) 10, 101103



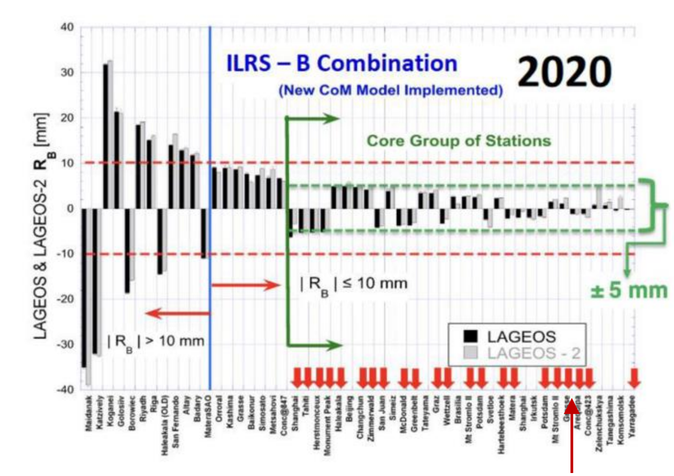
Murphy 1309.6294

in 2050

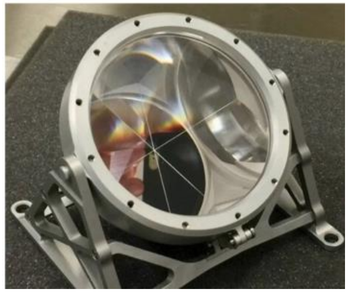
$\Omega \lesssim 3 \times 10^{-9}$ at $f \sim \mu\text{Hz}$

- Moon-Earth binary system is resonant to gravitational waves in the μHz regime

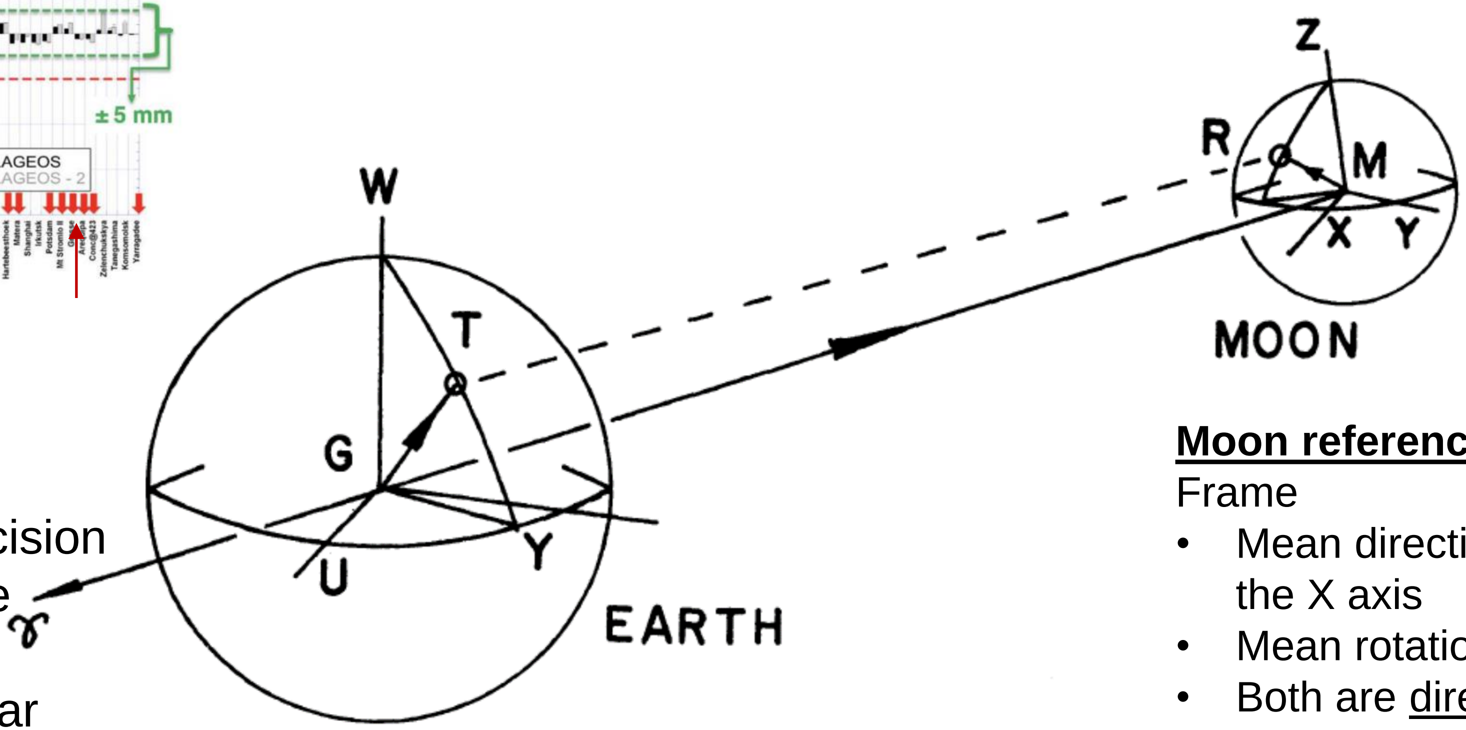
References frames

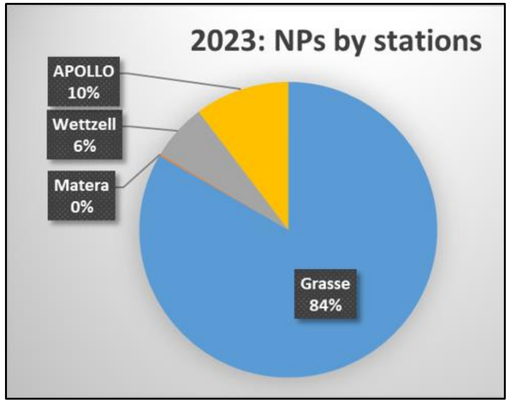


Next Generation Lunar Retroreflector (NGLR)



NGLR-1 en 2025
Millimetric performances





SLR for ITRF:

- Soon millimetric precision on LLR (laser update 2025)
- Stability < 2.5mm/year

Moon reference frame : ME Reference Frame

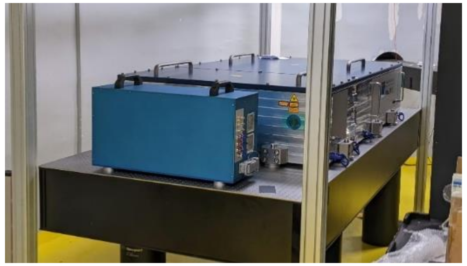
- Mean direction toward the Earth for the X axis
- Mean rotation direction for the Z axis
- Both are directly measured by LLR

Journal of Geodesy (2019) 93:2293–2313
https://doi.org/10.1007/s00190-019-01307-0

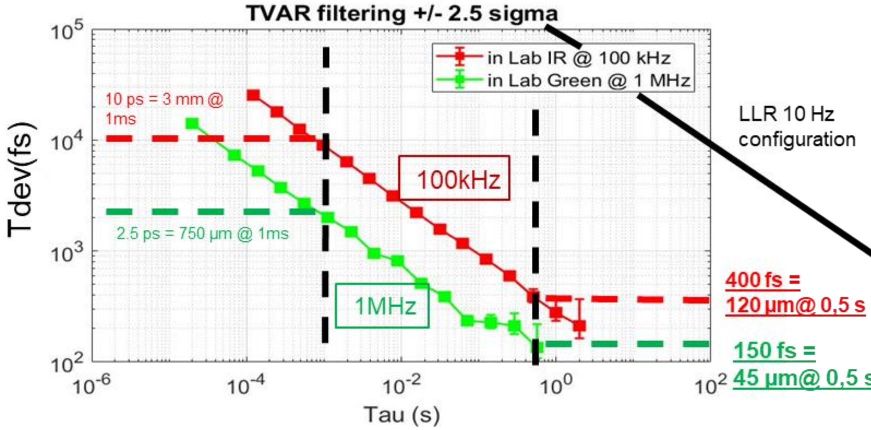
New Lunar targets = New Challenges @ Lunar Laser Ranging station

- Millimetric precision from target :
  - Millimetric precision from the laser: ~100ps laser pulse -> 10 ps + khz repetition rate
  - Time Base : New Hydrogen Maser for 2027
  - Event Timer: Mhz sub picosecond event timer

- Active R&D research:
  - Timing jitter free detection by parametric down conversion of single photon



MéO 2025: Laser 7ps kHz, 750k€



Time transfer in Lunar Orbit

Passive vs Active LRR

Measurement of the time of flight of laser pulses: 2 recorded dates

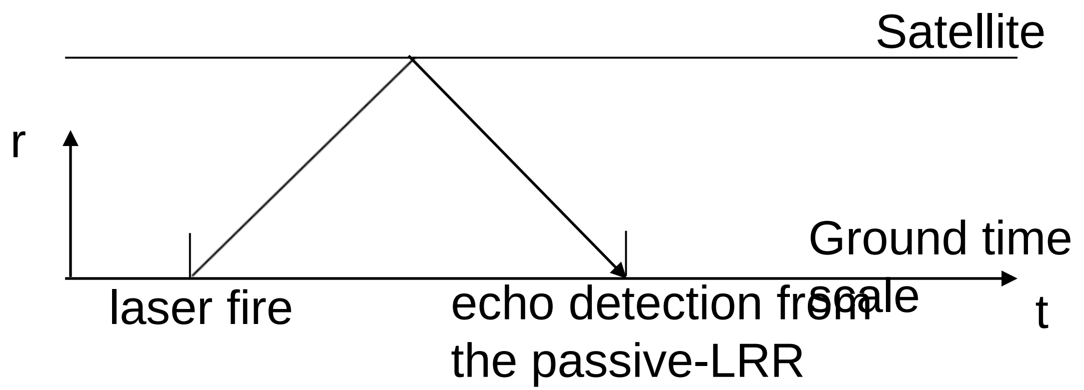
In space

$$D = \frac{c.\Delta T}{2}$$

Two-way measurement:
400km (ToF=2.7 ms) to 400 000 km (ToF=2.4s)

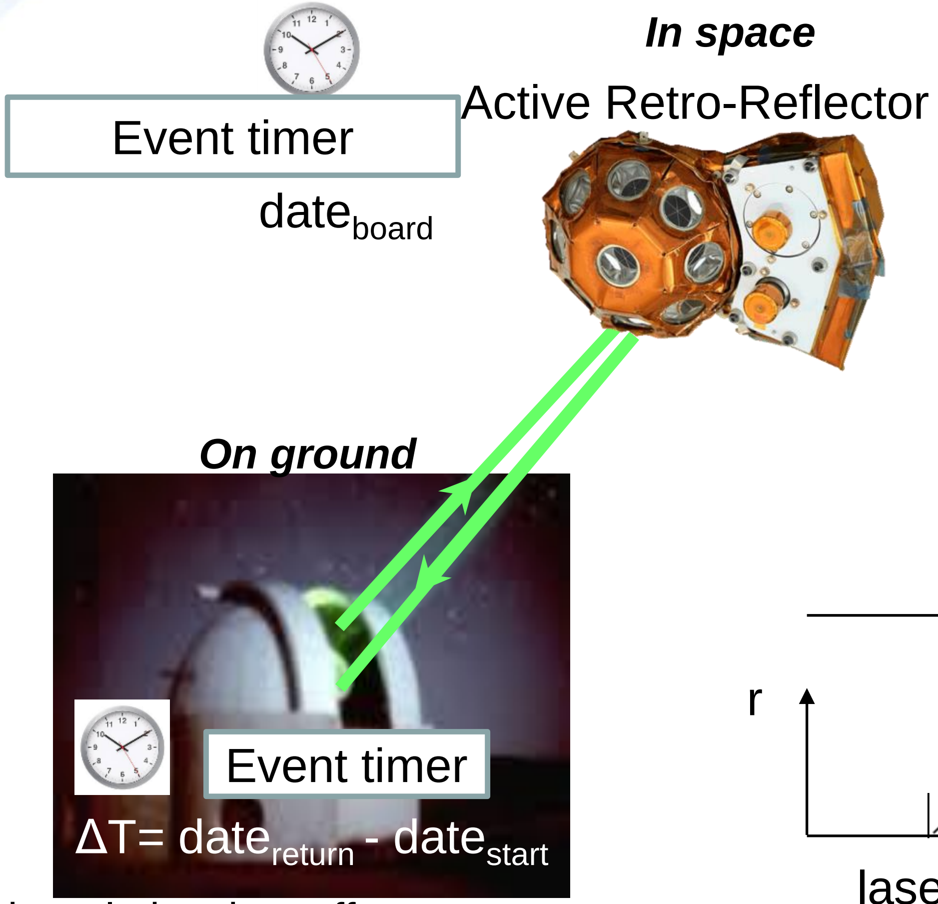
Accuracy < 10 mm
Precision ~ mm

Performances of the ground time scale required:
Accuracy on the date: better than 100 ns /UTC
Accuracy on the clock frequency: better than ~ 10^{-12}



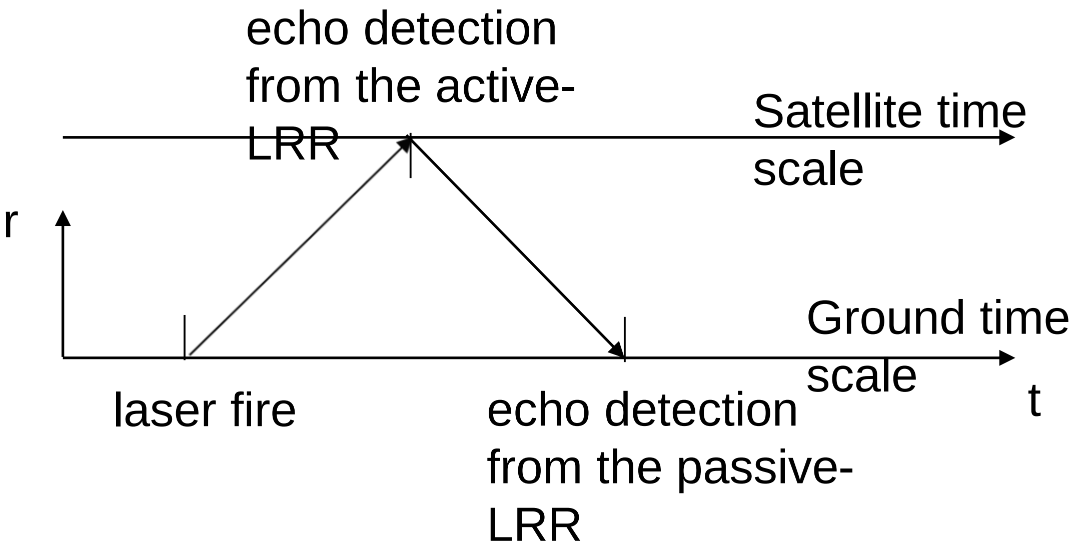
Passive vs Active LRR

Measurement of the time of flight of laser pulses: 3 recorded dates



A-LRR allows single-photon dating and then:

- Ground to space time-scale offset determination
- One-way measurement
- Ground to ground time transfer



the relative time offset
between on-board and ground time :

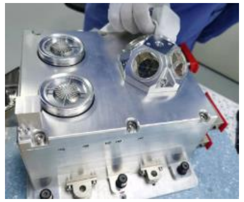
$$\chi = \frac{date_{start} + date_{return}}{2} - date_{board} + corr$$

Active Laser Retro-Reflector & Transponder

Past :
- LASSO (1989-1992) 2way asynchronous
- Messenger (2005) 2x1way asynchronous
- MOLA-MGS (2005) 1way
- LRO (2009-2014) 1way
- T2L2 (2008-2018) 2way asynchronous
- Hayabusa2 (2015;2020) 1way ; 2x 1way synchronous

On-going :
- CSS-LTT (2022, underway) 2way asynchronous
- ACES-ELT (2025) 2way asynchronous
- DRO-A (2025)

Up-coming:
- GALA-JUICE (2026)
- NovaMoon-Argonaut (2031)



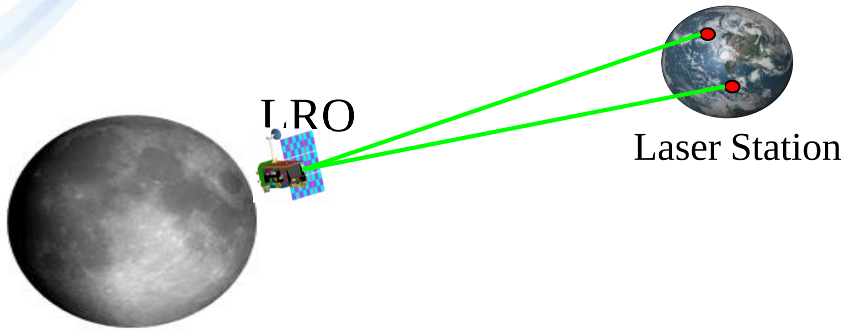
- Science and application with A-LRR
- Time & frequency transfer and clock synchronization between ground & space
- Interplanetary laser ranging
- Fundamental physics (Einstein’s gravitational redshift, Time variations of fundamental constants,Dark matter searches)
- Chronometric geodesy
- Laser communication and Quantum communication
- Navigation

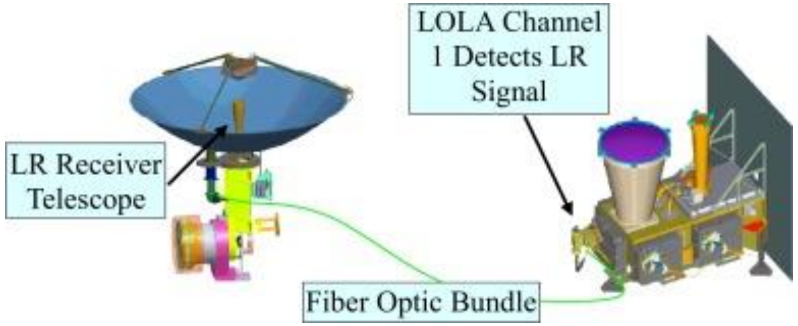
Outputs from past experience: CNES-T2L2

Performances obtained:

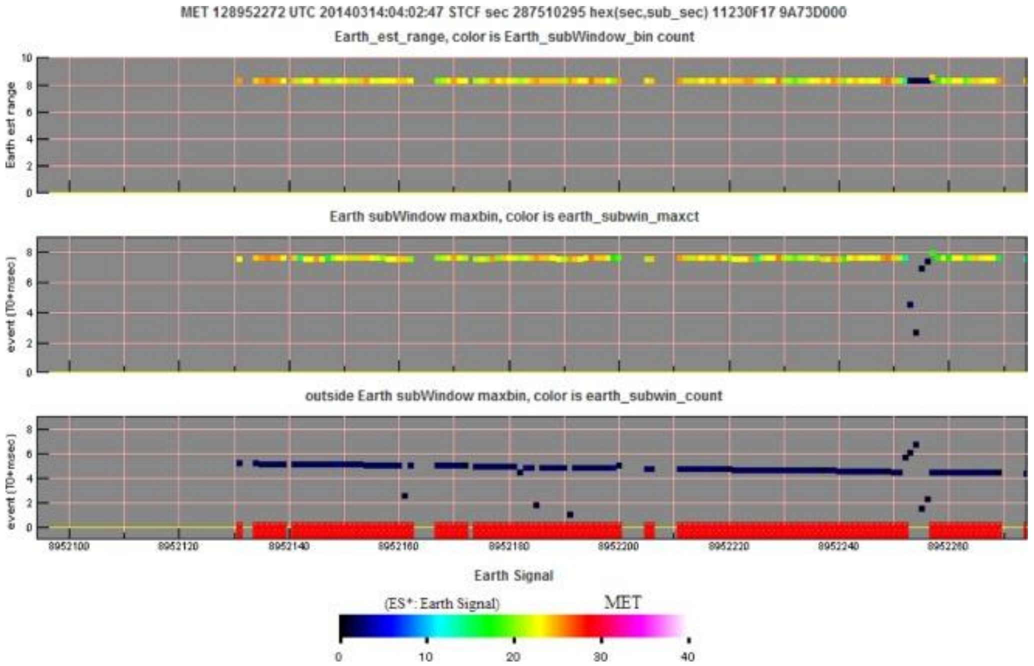
- 10 ps stability @ 1000 s for Ground-Space & Ground-Ground time transfer
- Uncertainty below 150 ps [E. Samain et al., 2015, Metrologia]
- Agreement between T2L2 and GPS-CV better than 240 ps [P. Exertier et al. 2016, Metrologia]
- Agreement between T2L2 and IPPP in cv with a standard deviation below 100 ps [J. Leute et al. 2018]
- Agreement between T2L2 and GPS PPP in non cv at 1 ns level [E. Samain et al., 2018]
- Impact of the radiation (SAA) on the USO frequency behaviour [A. Belli et al., Advanced in spaces research, 2015]

NASA-LRO description





Active-LRR:
The Earth uplink signal is detected by the LR telescope mounted on the HGA, and sent to LOLA channel 1 for processing via the fiber optic bundle



Real-time LOLA receive signal count website seen at the ground station during operation.

Outputs from the A-LRR of the NASA-LRO mission

Two-way laser ranging from Earth on the passive-LRR:

- Only the Grasse station has succeeded in infrared [Mazarico et al., 2020] => the passive-LRR is too small to allow a good link budget.

Active-LRR for time transfer [Bauer et al., 2016] [Mao et al., 2016]

- Ground to space time transfer at a precision of 256 ns over all mission phases.
- Ground to ground time transfer:
  - Relative offsets ranging from 33 to 560 ns
  - Relative rates ranging from 2×10^{-13} to 6×10^{-12} between the ground station clocks during selected mission phases.

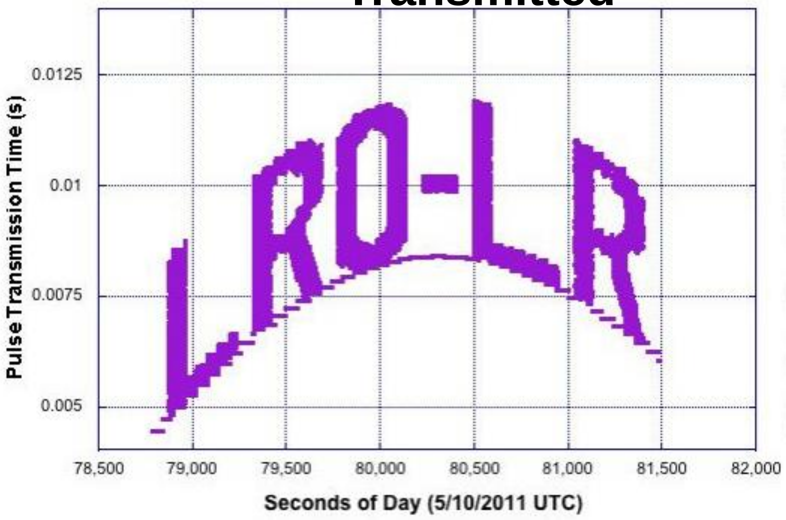
Active-LRR for One-way laser ranging [Bauer et al., 2016]:

- Laser ranging measurement precision of 12.3 cm in case of the Full Rate data which surpasses the LOLA timestamp precision of 15 cm. The averaging to Normal Point data further reduces the measurement precision to 5.6 cm.

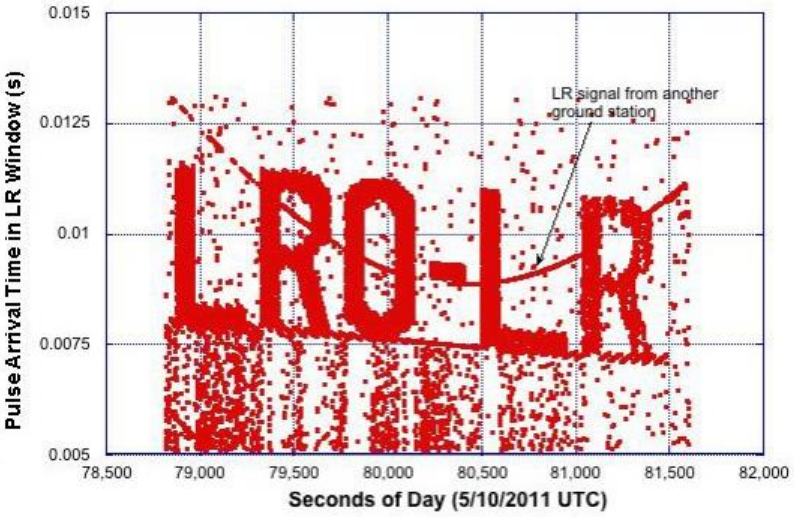
Outputs from the A-LRR of the NASA-LRO mission

- **Optical telecommunication with the A-LRR and pulse position modulation [Sun et al., 2013]**

Transmitted



Received



- **Two-way laser ranging from LRO**

The first laser retroreflector on the Lunar far side oboard China's Chang'E-6 lander had softly landed in the Apollo basin within the South Pole-Aitken basin. The LRO's LOLA altimeter has succesfully track the Instrument for landing-Roving Laser Retroreflector Investigations (INRRI) deployed on the lander top panel. Future observations by laser ranging from lunar orbiters will refine its positional data, and may contribute to advancing our understanding of Earth-Moon dynamics and lunar physics. (Hu H. et al. (2024) Aerosp. CN. 7,7–13.)

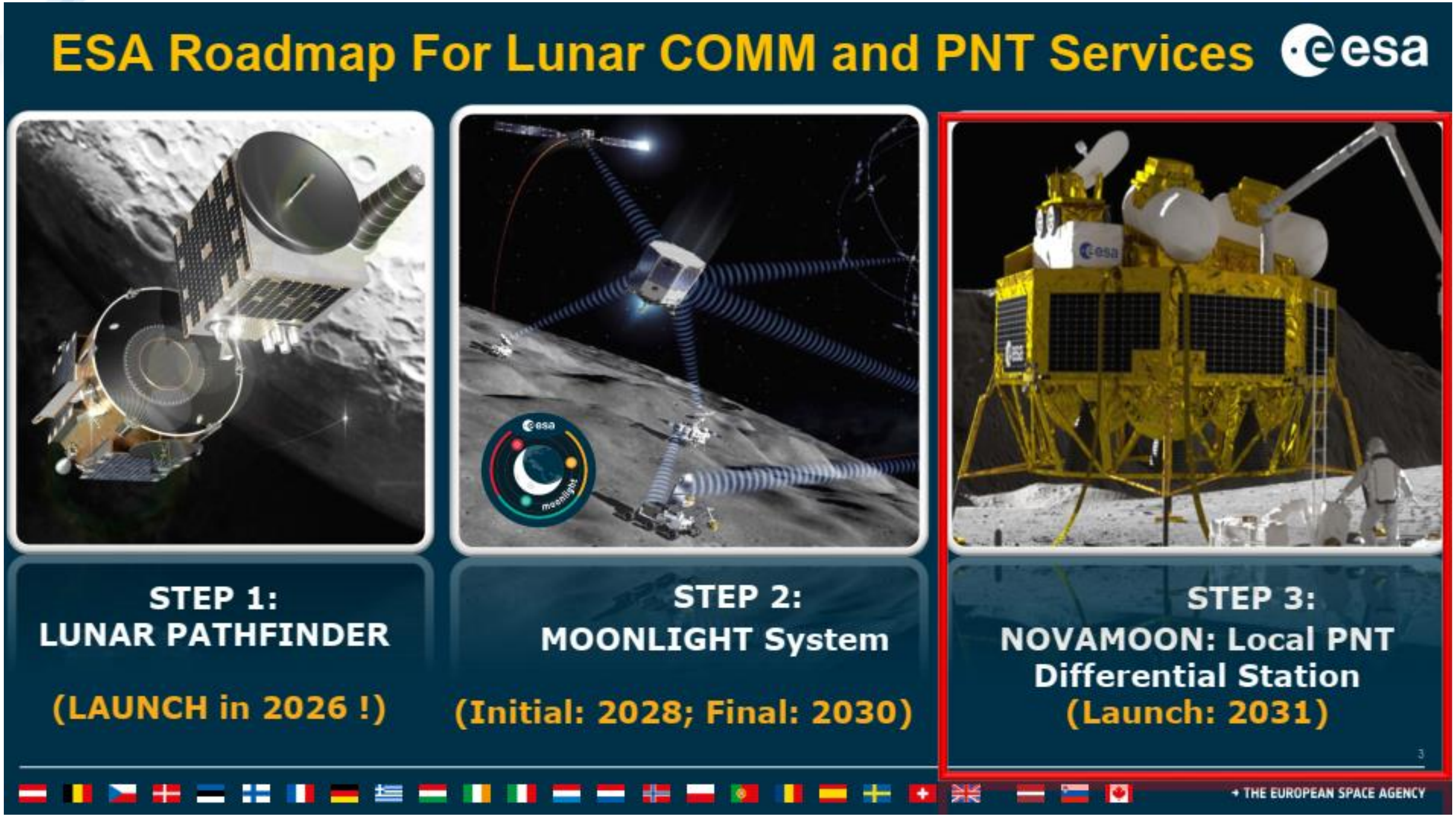
T2L2 vs ELT vs LRO-LR

Table 3. Performance comparison of the T2L2, the ELT and the LRO laser ranging time transfer experiment taken from Exertier et al., 2006, Schlicht et al., 2012 and the results of this work respectively. The performance is compared for ground to space and ground to ground time transfer in common view (CV) and non-common view (NCV).

Experiment	Setup	Ground to	Accuracy	Averaging period τ
T2L2	Two-way	Space	< 10 ps	1000 s
		Ground CV	≈ 10 ps	1000 s
		Ground NCV	150 ps	300 s
ELT	Two-way	Space	4 ps	300 s
		Ground CV	6 ps	300 s
		Ground NCV	7 ps	≈ 5400 s*
LRO LR	One-way	Space	166 ns**	56 days
		Ground CV	500 ps	≈ 2000 s***
		Ground NCV	–	–

[Bauer et al. 2016]

ESA ROADMAP


ESA Roadmap For Lunar COMM and PNT Services
esa
STEP 1:
LUNAR PATHFINDER
(LAUNCH in 2026 !)
STEP 2:
MOONLIGHT System
(Initial: 2028; Final: 2030)
STEP 3:
NOVAMOON: Local PNT Differential Station
(Launch: 2031)
→ THE EUROPEAN SPACE AGENCY

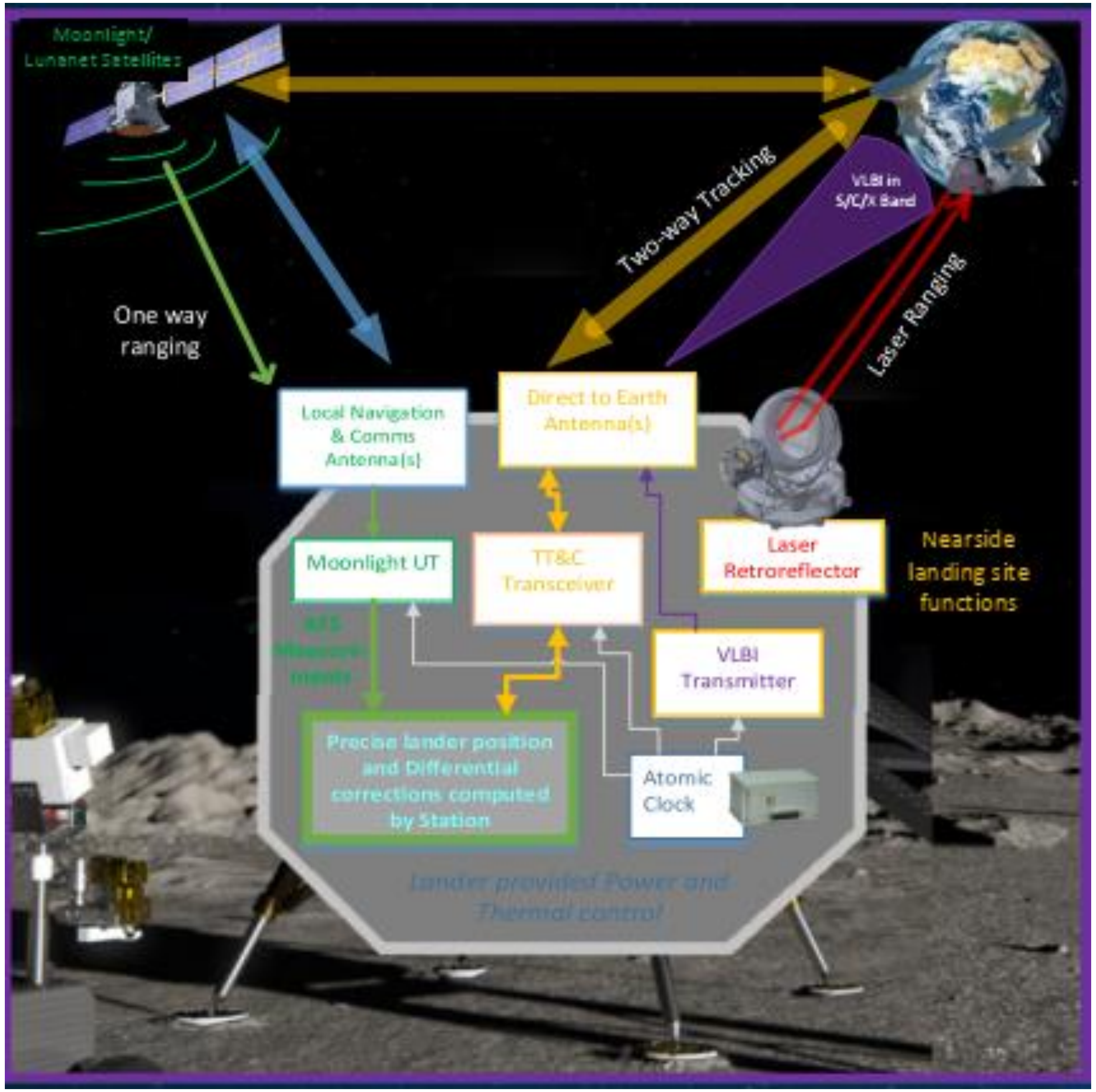
ARGONAUT-1: NOVAMOON

- ESA Argonaut: A familly of lunar landers to deliver infrastructure, scientific instruments, rovers , technology demonstrator

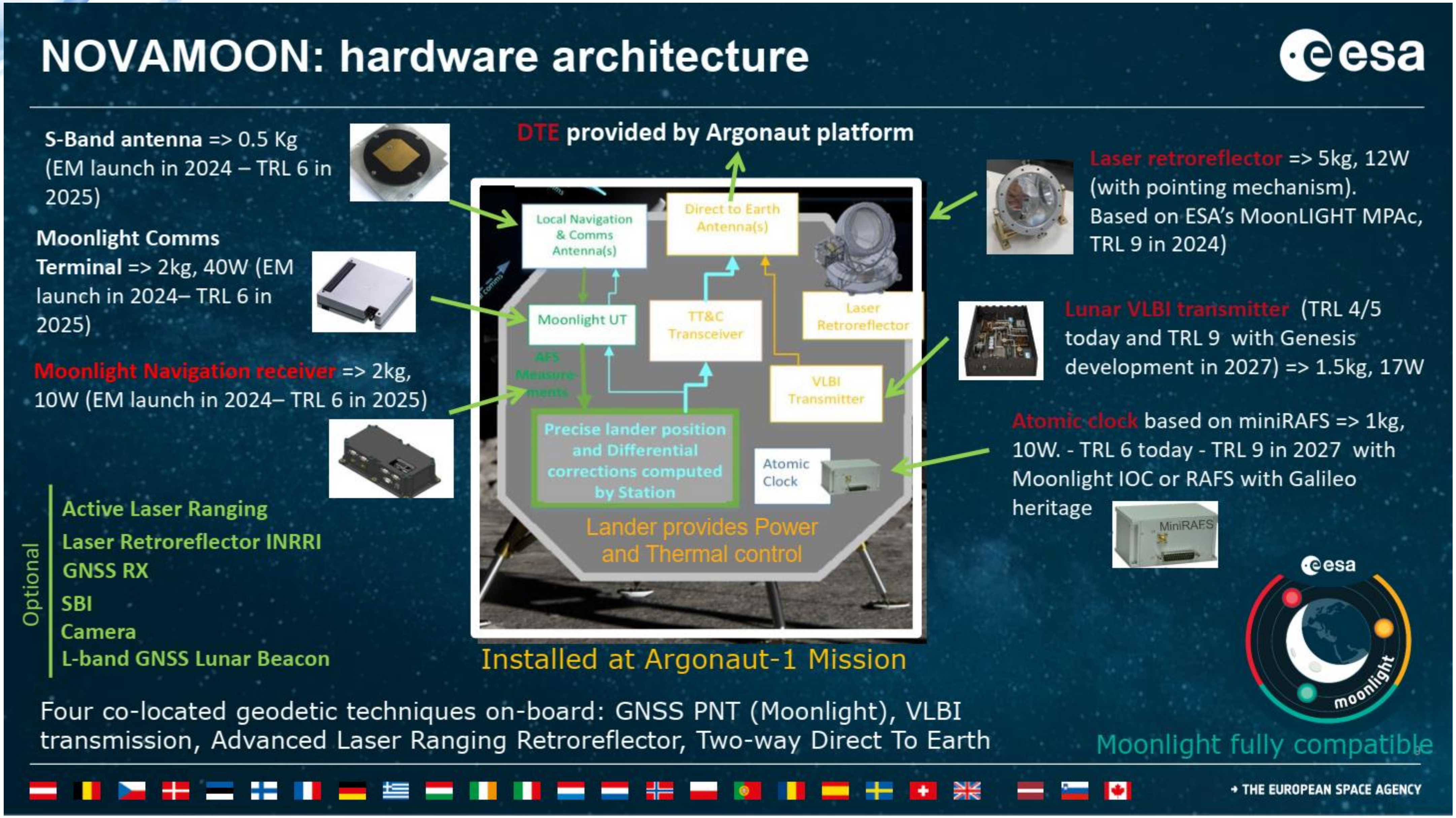
- ARGONAUT-1 with NovaMoon payload in 2031 to South pole region

NOVAMOON Lunar differential & Selenodetic Station

1. Install Reference local differentiel station on lunar surface
   1. Compute Moonlight Nav satellite pseudo range error correction @ decimeter level
2. Install international « geodetic » reference station
   1. Moonlight RX – VLBI TX
   2. LLR
   3. Two way DTE ranging @ cm level
3. First ever Time laboratory: supporting lunar time scale @ ns level



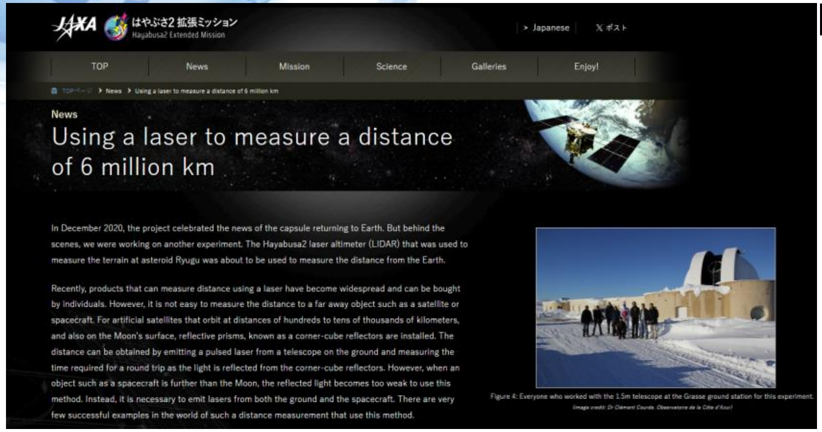
NOVAMOON Lunar differential & Selenodetic Station

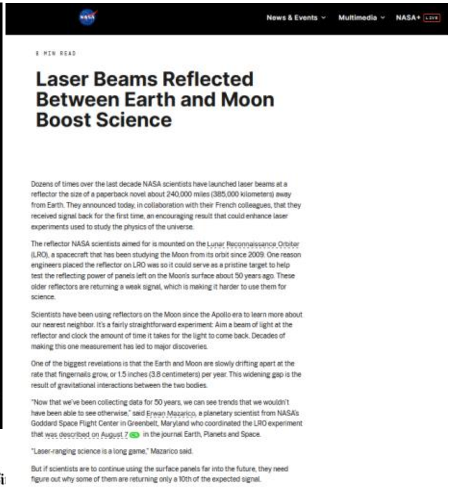


Conclusion

- New era for Lunar Laser Ranging:
  - New targets with large upgrade of the metrological performances
  - New scientific objectives (Gravitational waves)
  - Geodetic points for Navigation on the Moon
  - Linking Lunar Reference Frame Terrestrial Frame
- Direct Time & frequency applications on the Moon with Novamoon
  - GNSS, VLBI
  - Active Laser Time Transfer :
    - Increase the number of laser stations which can participate to the projects
    - First definition and production of a lunar time scale !
    - open the path to large scale quantum experiment

Merci de votre attention





[Et si le Terre était unique ?](#) :
Un film écrit par Bruno Bucher, Laurent Lichtenstein et Serge Brunier. (90').
Avec la participation de l' Observatoire Géodésique MéO

Je. 24 septembre 2020 (début 21'20)
Réalisation : Laurent Linchtenstein
Production : Igor Ochronowicz

[Un laser de la Terre à la Lune](#) :
Une interview de Clément Courde (IR CNRS) pour le CNRS.

Ve. 19 juillet 2019
Réalisation : Le journal du CNRS

[Ils décrochent la lune](#) :
Un reportage présenté par Laurent Delahouse. Avec Clément Courde, Jean-Marie Torre, Agnès Fienga.

Sa. 20 juillet 2019 (début 21'20)
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