# Enabling Lunar Exploration:

# ESA's PNT Roadmap & User Benefits

**UN Cislunar Workshop**
10 – 13 February 2026
Vienna. Austria

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European Space Agency

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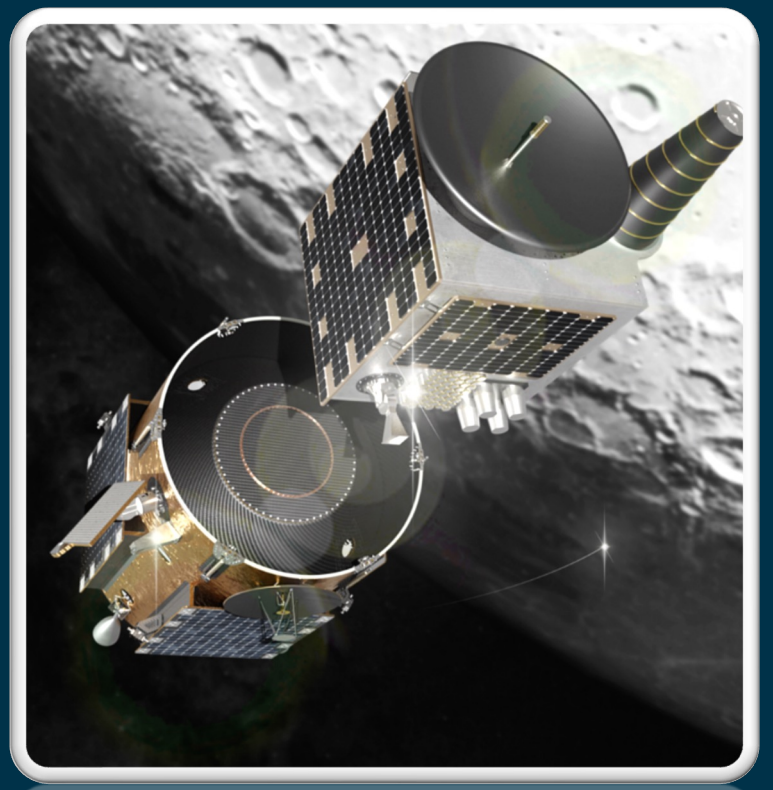
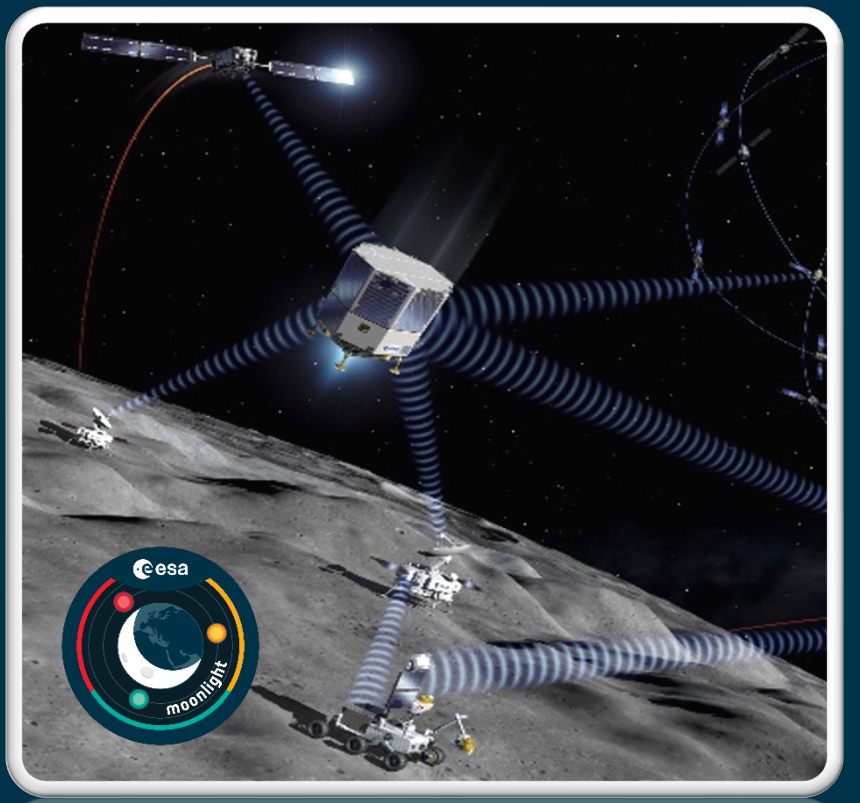
# ARTEMIS-2 upcoming launch with ESA's European Service Module in ORION

# ESA Roadmap For Lunar PNT Services



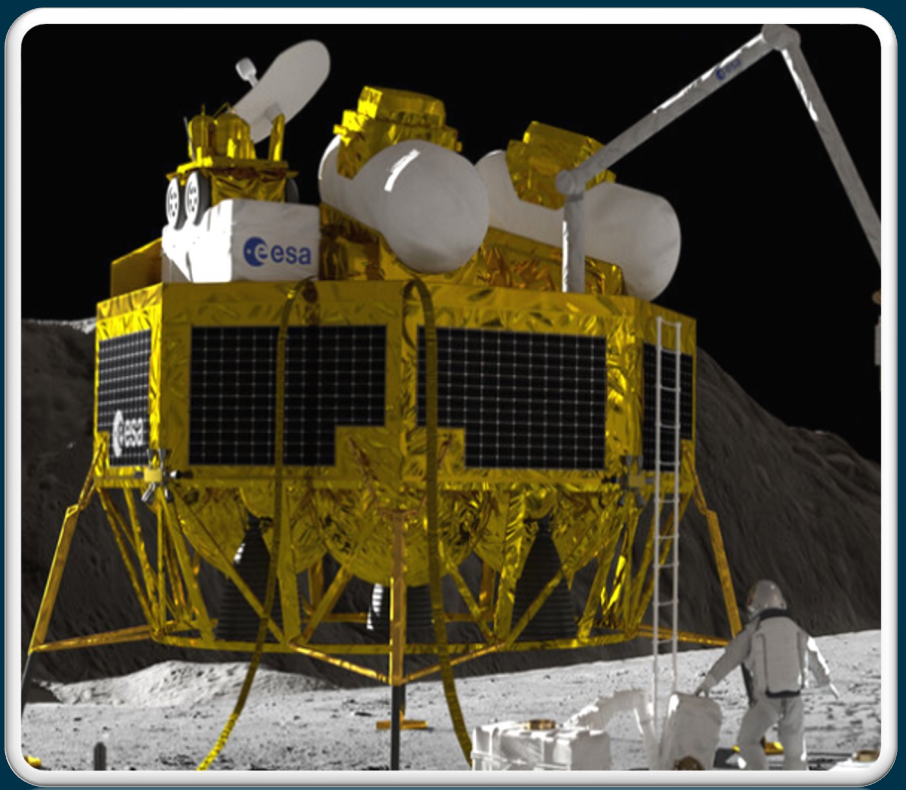
**STEP 1:**
**LUNAR PATHFINDER**

**(Launch 2027)**



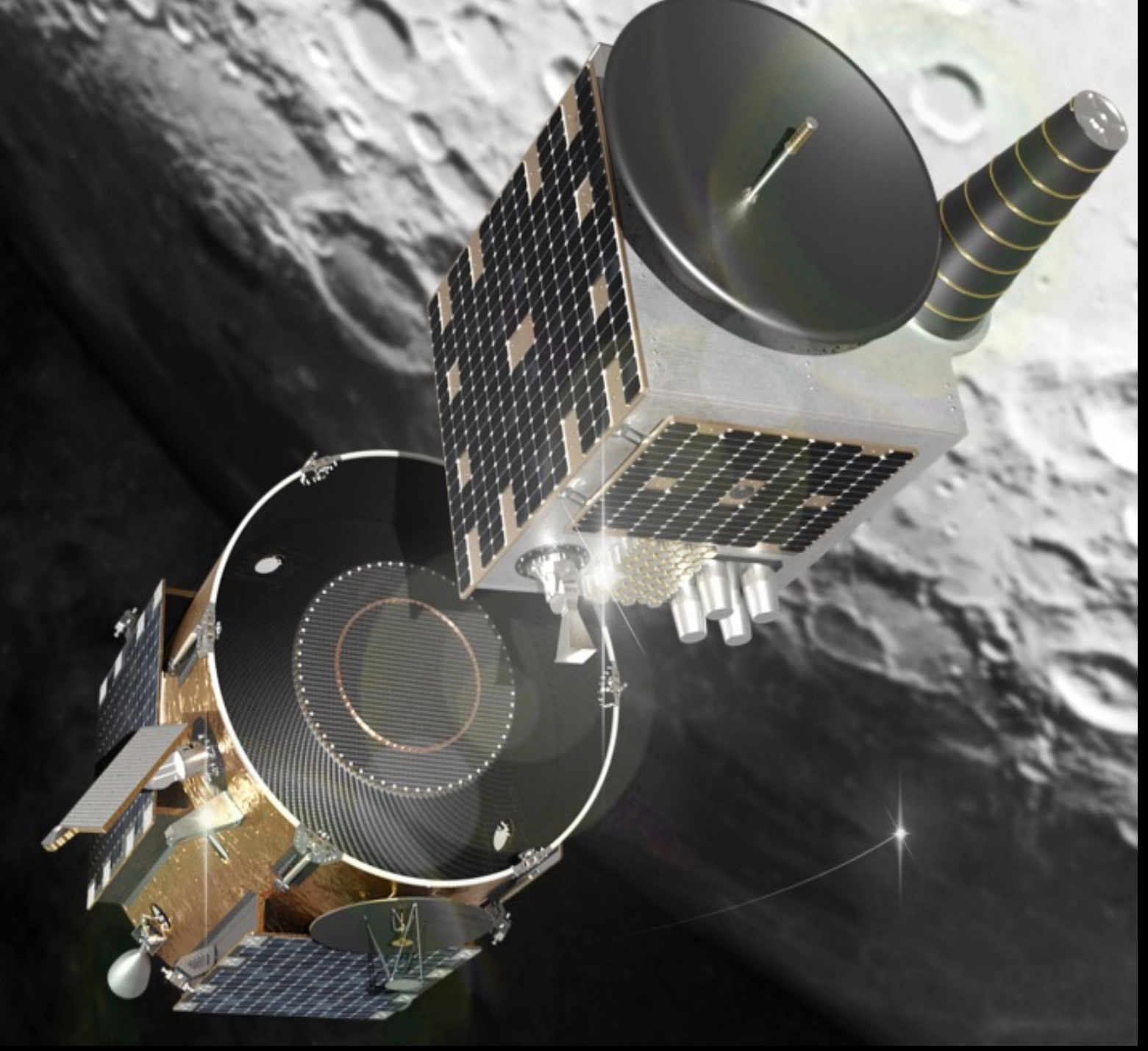

**STEP 2:**
**MOONLIGHT System**

**(Initial: 2029; Final: 2031)**




**STEP 3:**
**NOVAMOON: Lunar-based PNT Differential Station**

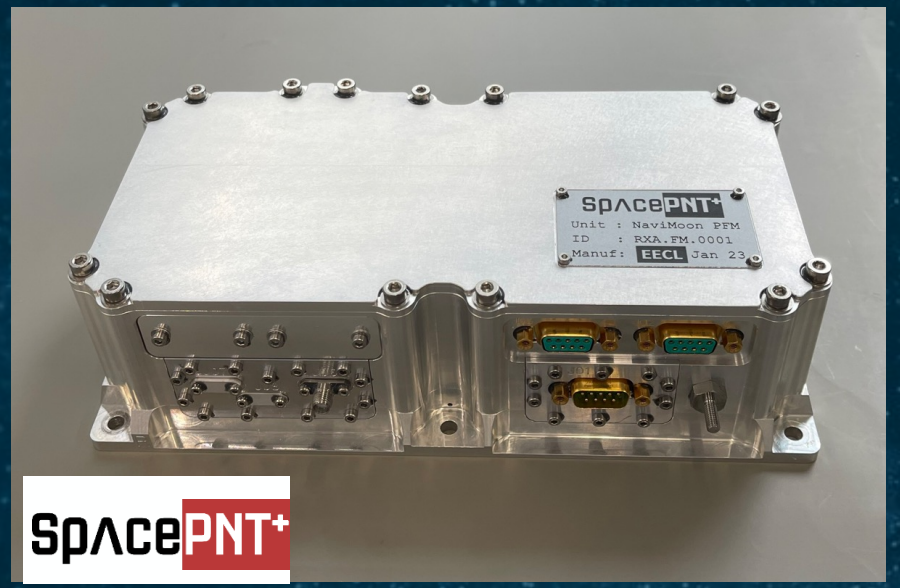
**(Launch target: 2029+)**



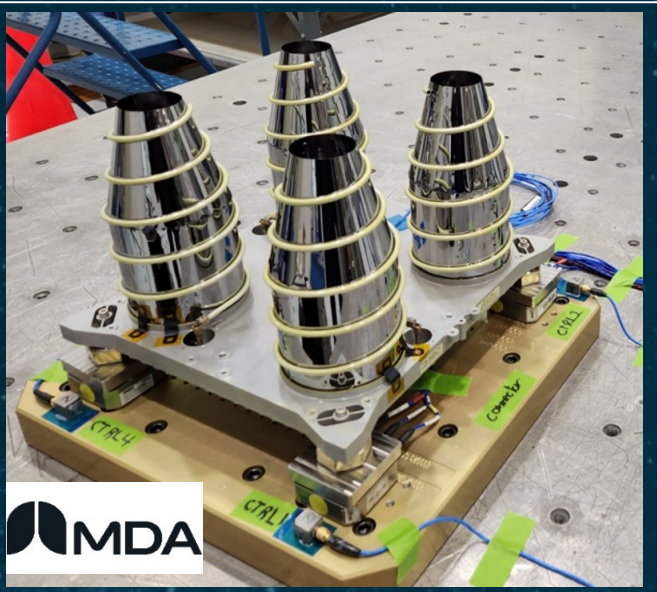
- **Commercial** Lunar Communication **Relay** Satellite (real time S-band services) (**Moonlight Step-1**)
- Public-Private Partnership (**PPP**) between **ESA** and Surrey Satellite Technology Limited (**SSTL- UK**)
- Will provide data realy operation for the **first** US lander on the **far side (LuSEE-Night)**
- **Launch:** Q1 2027
- FireFly's Blue Ghost CLPS-CS3
- **8.5 years lifetime**

**Will host a high-sensitive GNSS receiver on board**

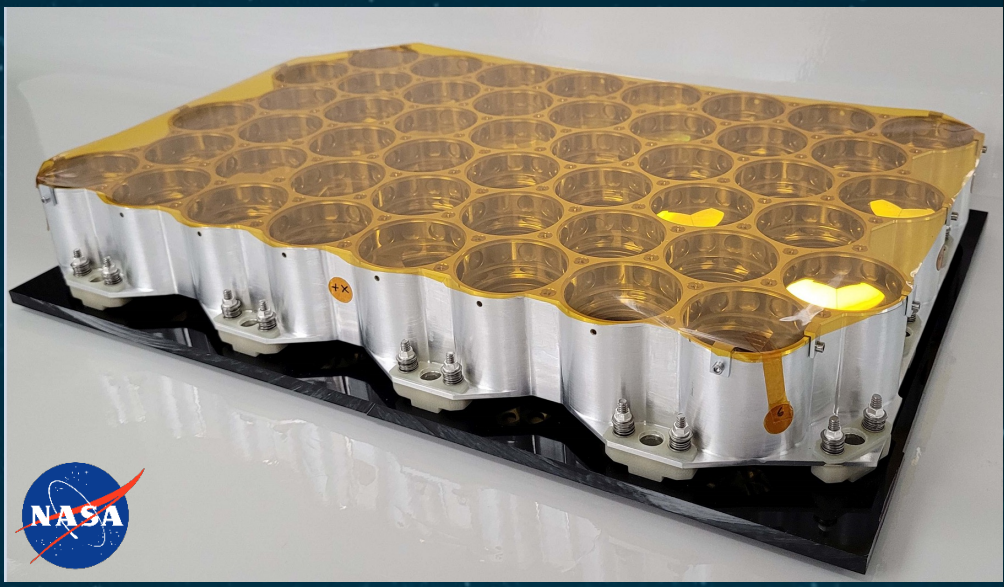
# Lunar Pathfinder GPS/ Galileo Reception




GNSS High-sensitive receiver Flight unit




GNSS High-gain Antenna Flight unit



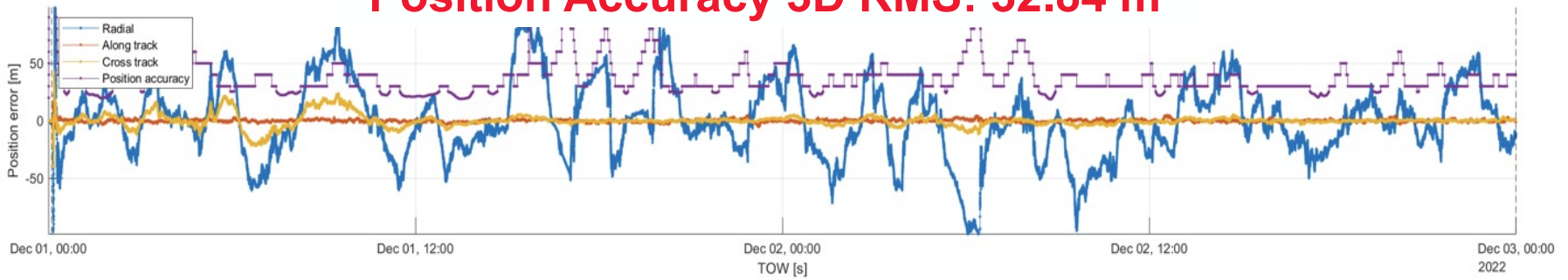

Laser Retroreflector Flight unit (NASA)

Full demonstration of GPS/Galileo PNT on a Lunar orbiting satellite

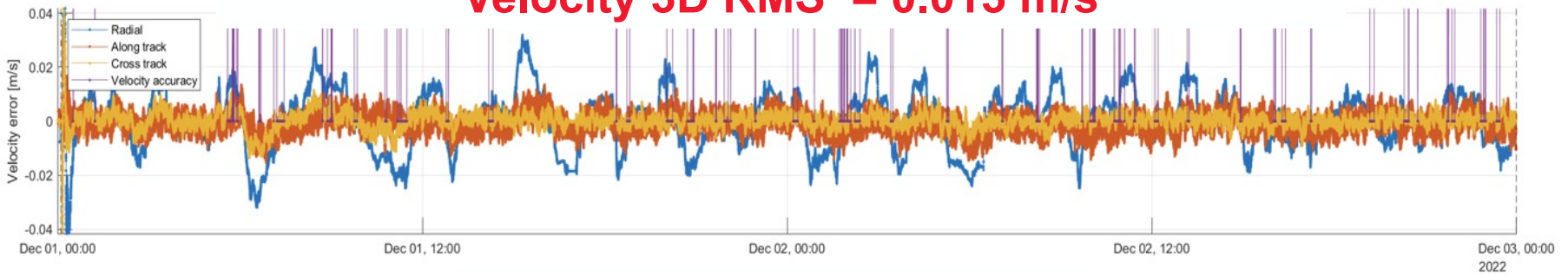
First time three ranging techniques (GNSS, Laser and X-band ranging) are used simultaneously on lunar orbit for orbit determination

# Lunar Pathfinder GNSS Rx end-to-end hardware in the loop updated results with delivered Flight GNSS Rx HW and on-board SW

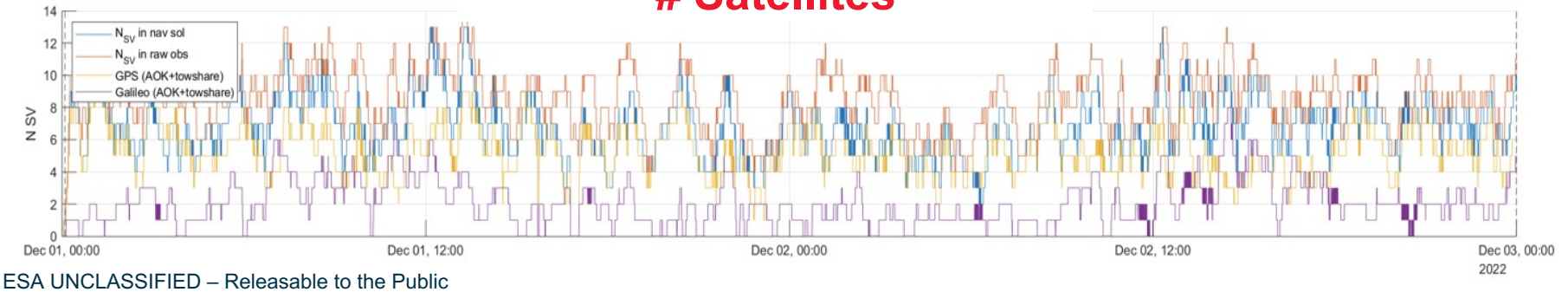
## Position Accuracy 3D RMS: 32.84 m




## Velocity 3D RMS = 0.013 m/s




## # Satellites




Well below 100m 3D rms initial Requirement on lunar orbit!

SpacePNT Lunar Pathfinder GNSS Receivers provides today the space receiver with the highest sensitivity

(with 15 dB tracking threshold and 18 dB acquisition threshold !)

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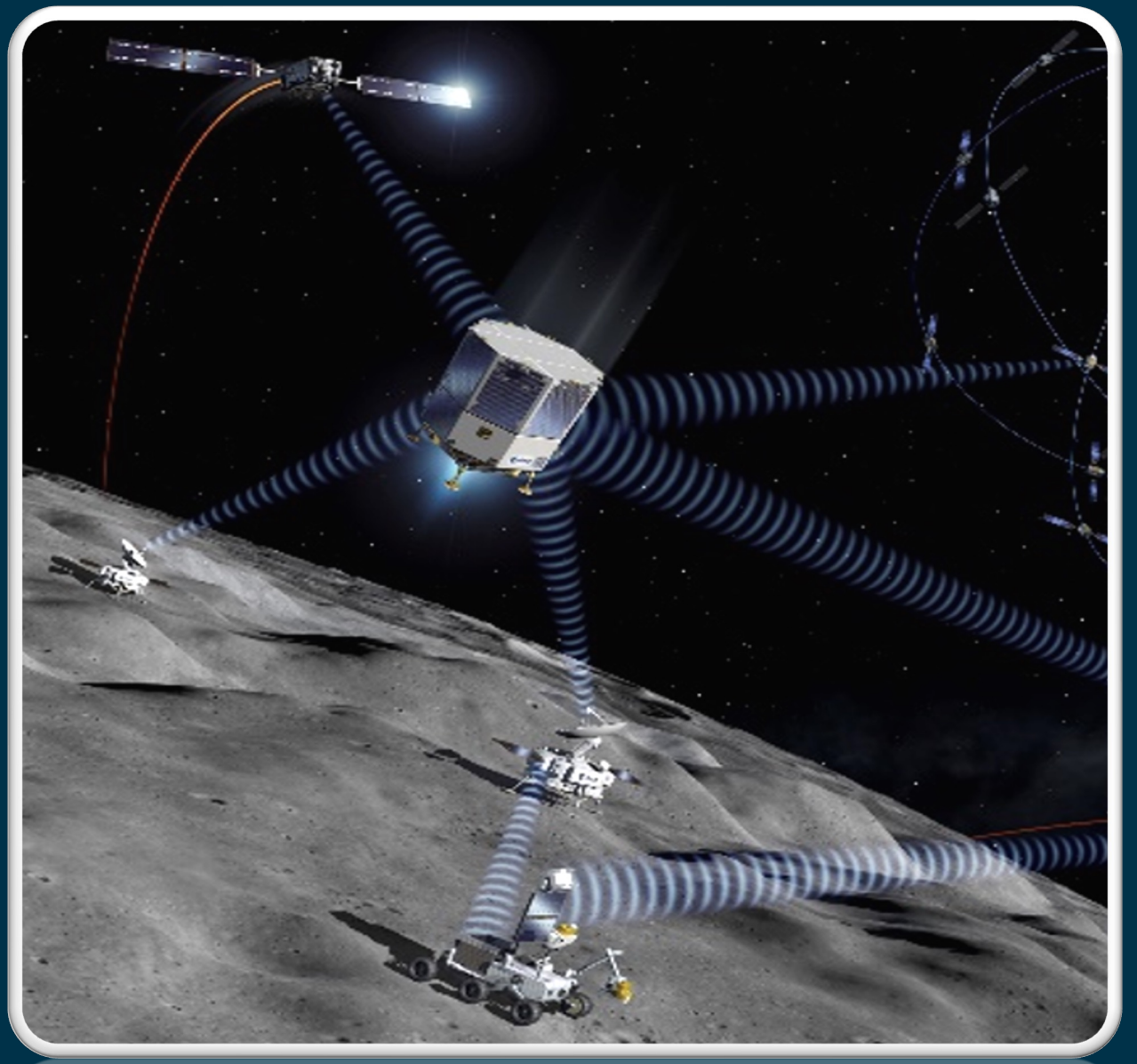
# Lunar Pathfinder GNSS Experiment: User Benefits

- Following launch, ***dedicated experimental windows*** (~ 5 to 7 days with continuous Earth visibility) are planned, using also laser ranging stations ***from Apache (USA), Grasse (France), Wetzell (Germany) and Matera (Italy).***
- This should allow confirming ***operational benefits of GNSS for lunar orbit determination and time transfer***
- ***The 8.5 years nominal life-time of Lunar Pathfinder*** will also allow:
  - Upgrades on GNSS Receiver Software for improvements based on experimentation return
  - Assess GNSS cislunar performance with future Galileo G2G and GPS IIIF satellites
  - Collection long-term GNSS dataset in lunar orbit for international scientific analysis
  - To perform joint experiments with GNSS Receiver in orbit and lunar surface (with NovaMoon)

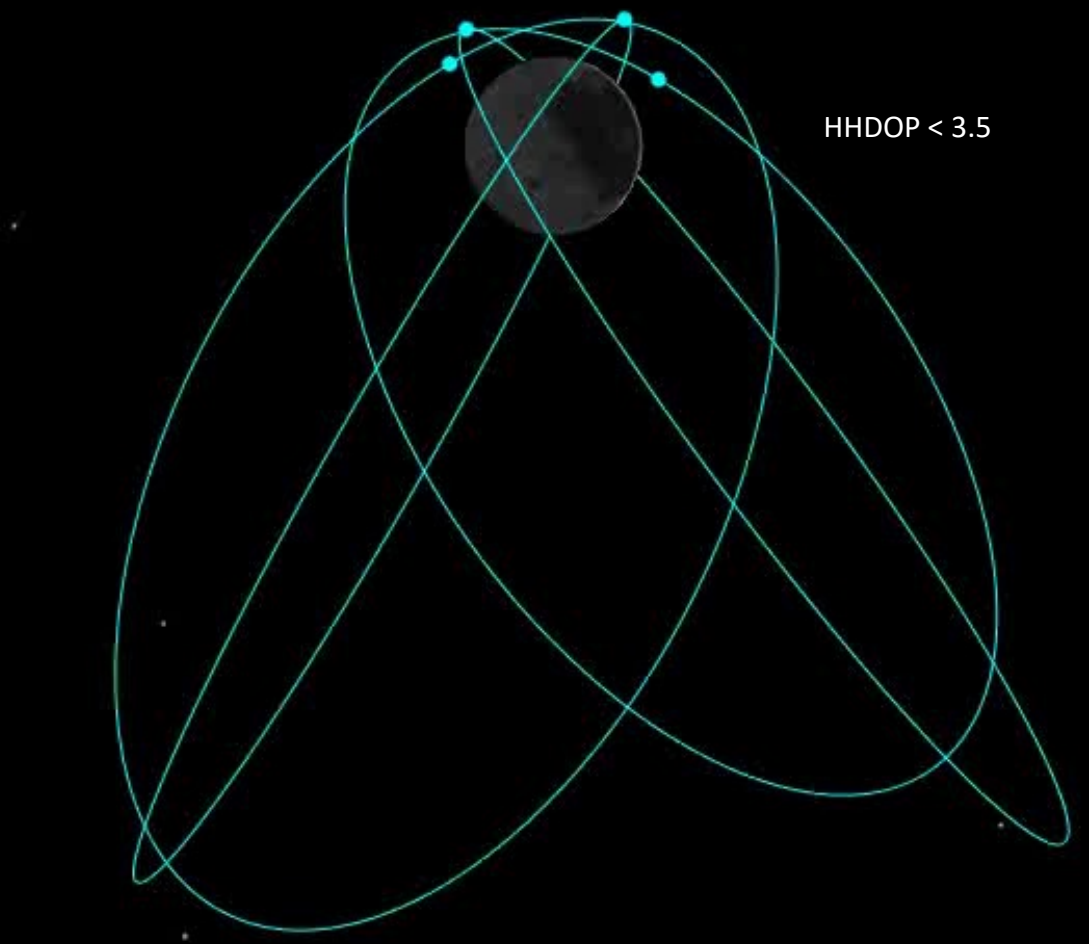


# STEP 2

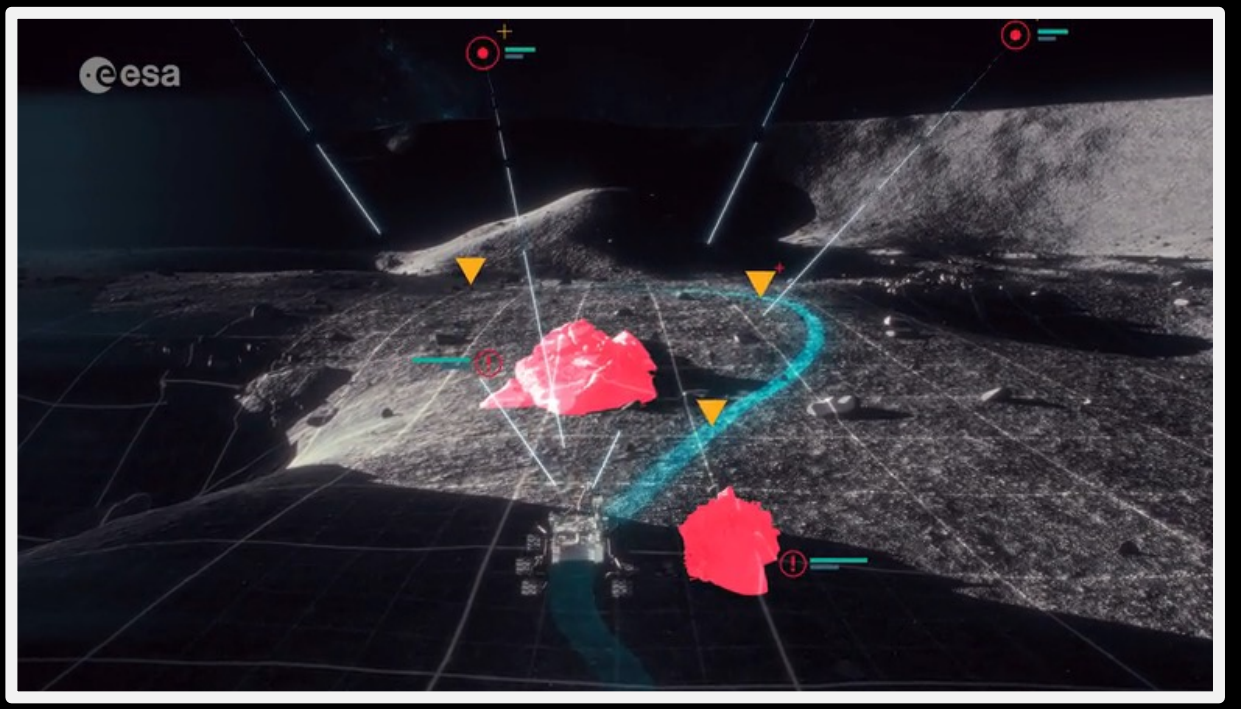
## MOONLIGHT System

## IOC: 2029 & FOC: 2031

# Moonlight 4 NAV Satellites constellation

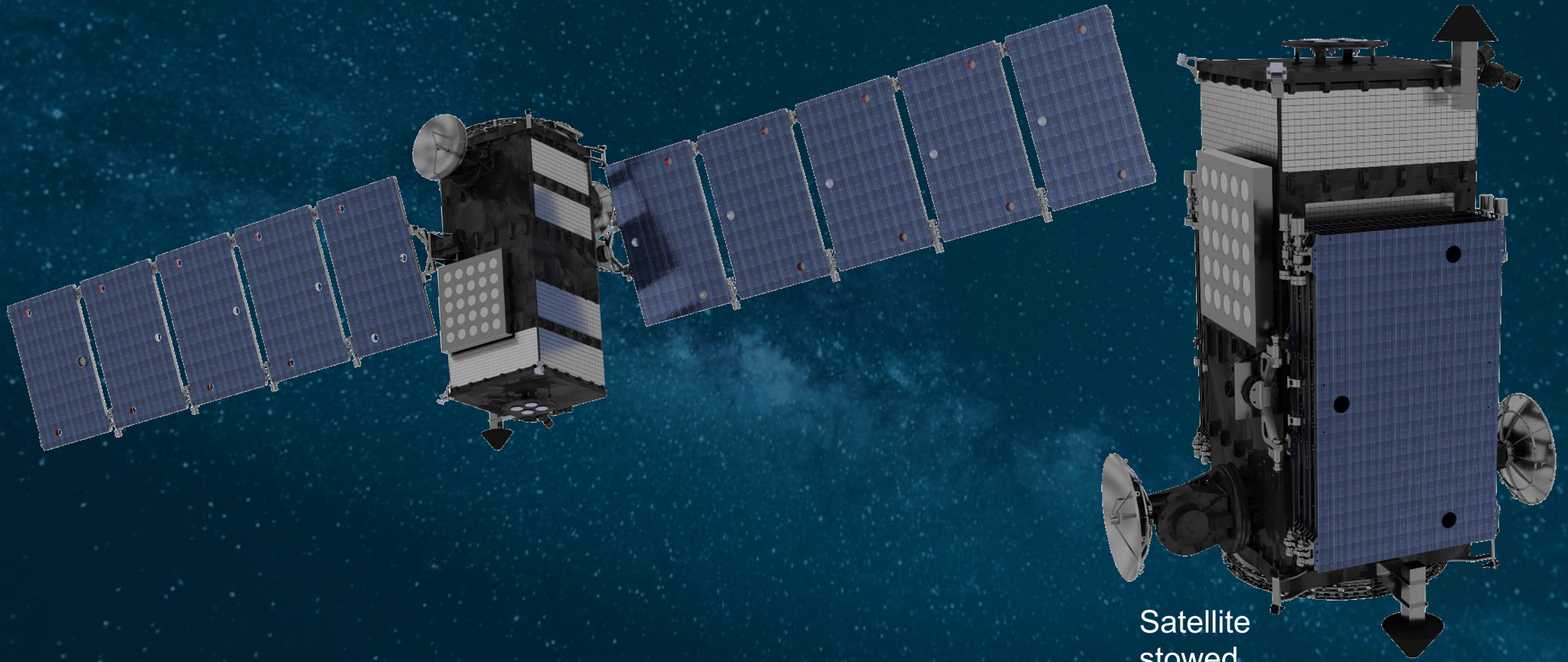



**24h ELFO ORBITS**



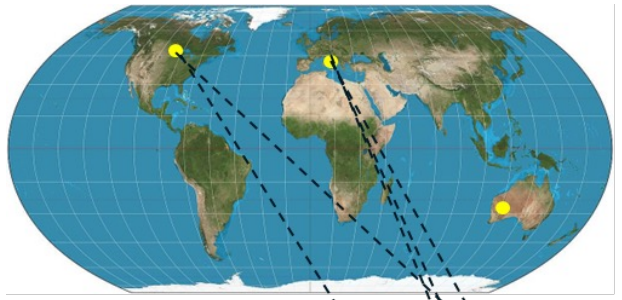

A minimum of
15 hours of continuous PNT service at South Pole every 24 h

# Moonlight NAVSAT

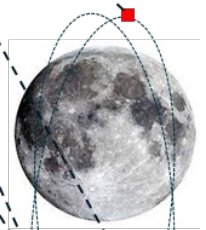


Satellite stowed

# Moonlight ODTS Concept: MSPA Technology

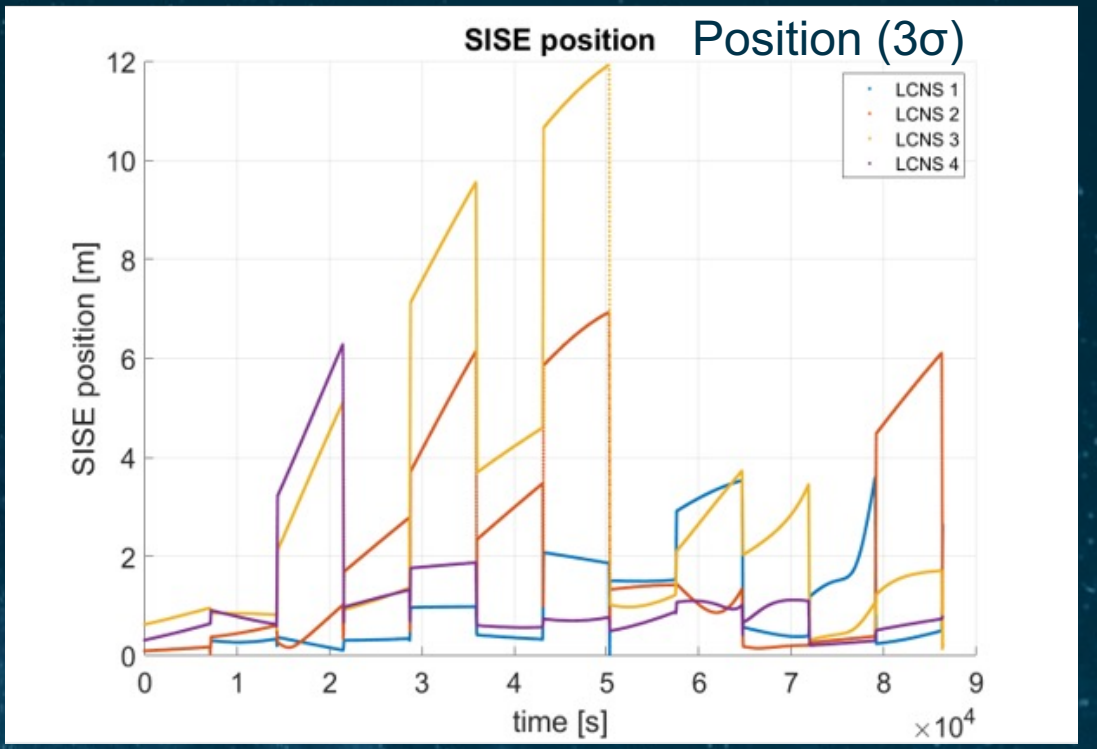


Multiple Spacecrafts per Apperture (MSPA)



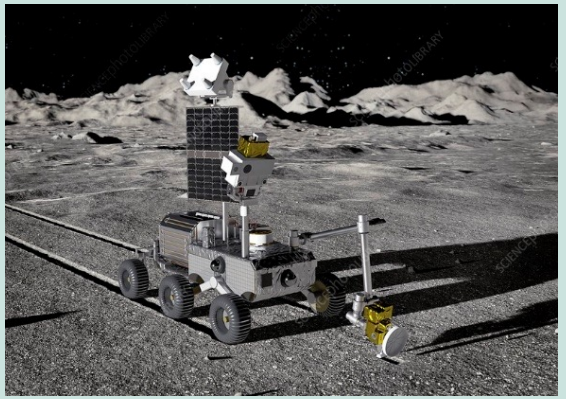
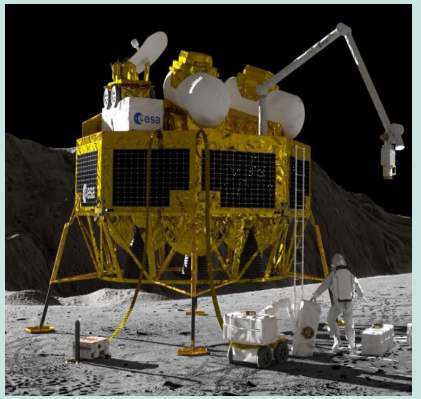
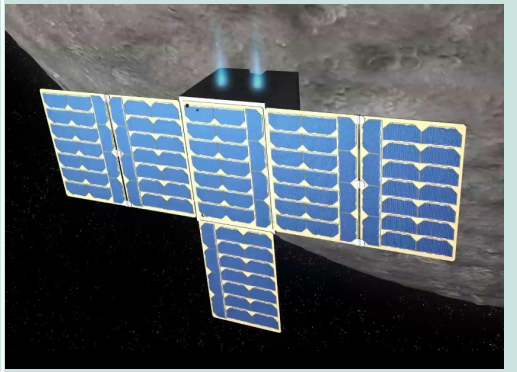
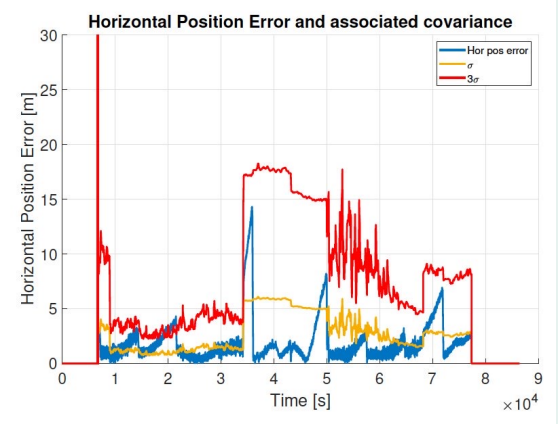
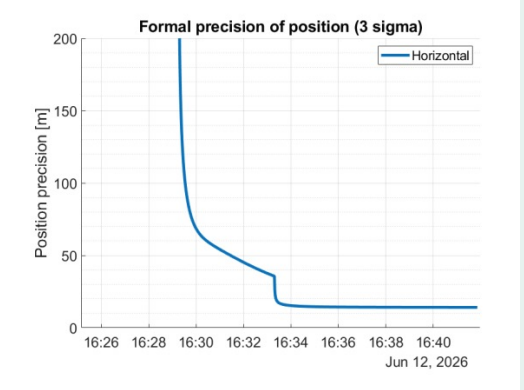
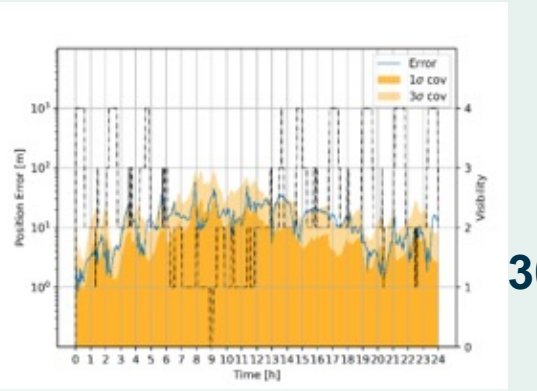
$$SISE_{pos} = \sqrt{(x-\tilde{x})^2 + (y-\tilde{y})^2 + (z-\tilde{z})^2 + (ct-c\tilde{t})^2}$$

<10 m (95%) over any 24 hours




- Two-Way Time Transfer between NAV SATs and EGS and use of stable Atomic clocks on board
- Ranging and Doppler measurements between NAV SATs EGS
- Navigation message generated from EGS and uplinked to NAV sats

# Moonlight FOC LCNS High-level PNT Performances

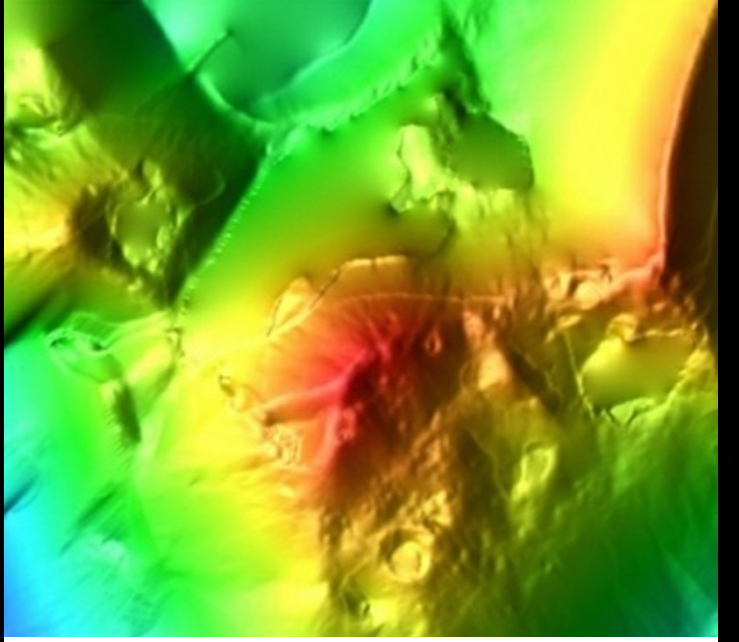
| Surface Rover | Lunar Lander | Lunar Orbiter |
|---|---|---|
|  |  |  |
| Real time<br>**< 10 m (95%)**<br><br>Post-processing<br>< 3 m (95%) | **< 50 m (95%)**<br><br>Landing accuracy | Real time<br><br>**< 100 m (95%)**<br><br>LLO accuracies |
|  |  |  |
| **< 5 meters** | **~20 meters** | **30-60 meters** |

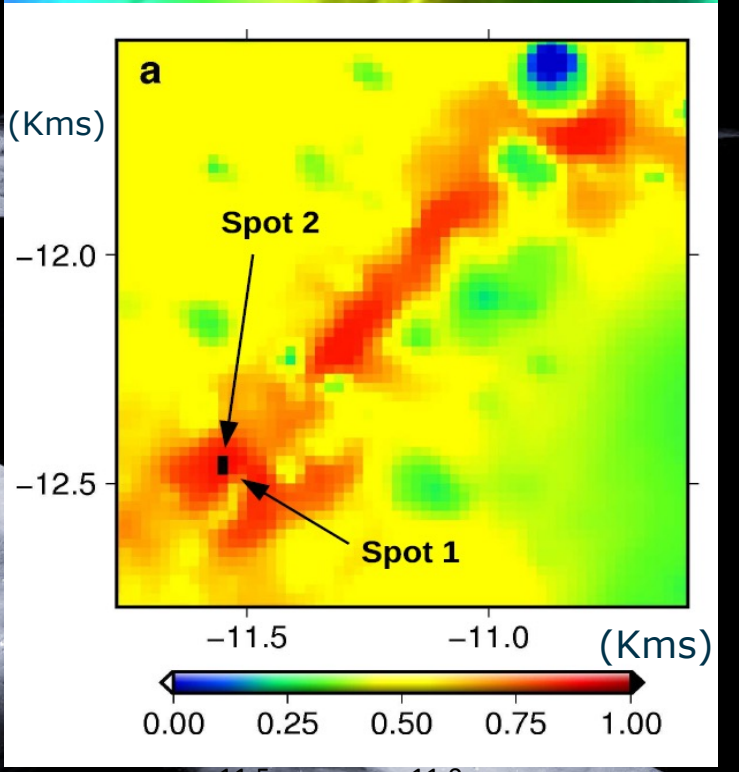
## ALSO CONFIRMED BY INDUSTRY (AT PDR Stage)

# Moonlight will make feasible landing in Peaks of Eternal Light (PEL) regions

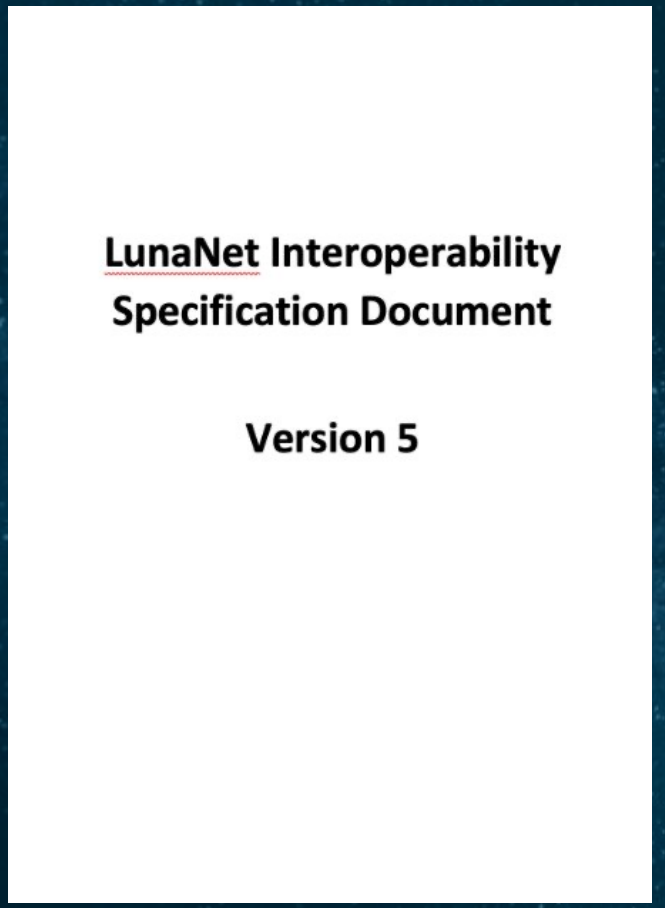
Over 20 years, the longest continuous periods in darkness are typically only 3-5 days.

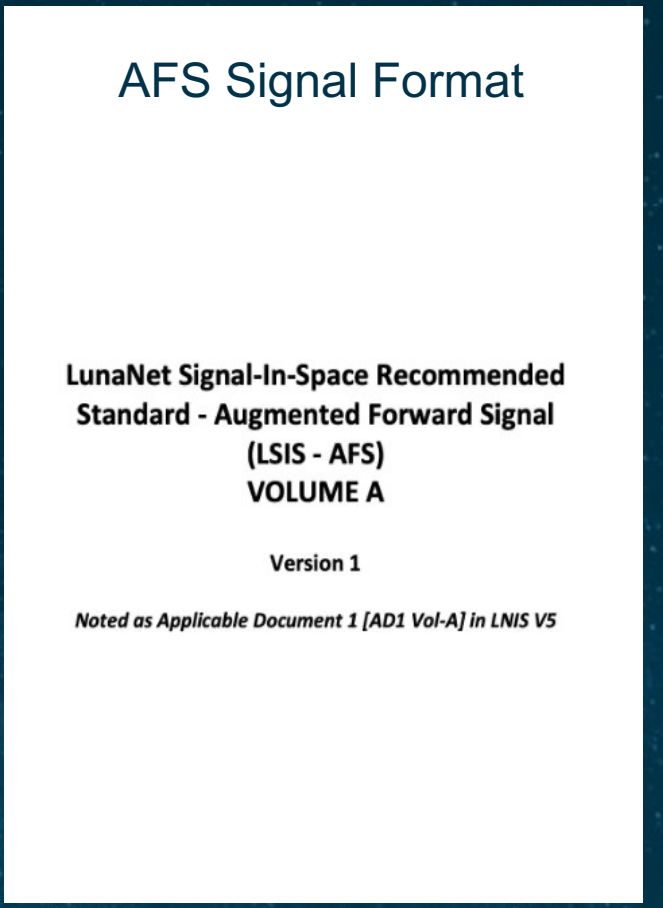
**Landing accuracies required < 50 metres**





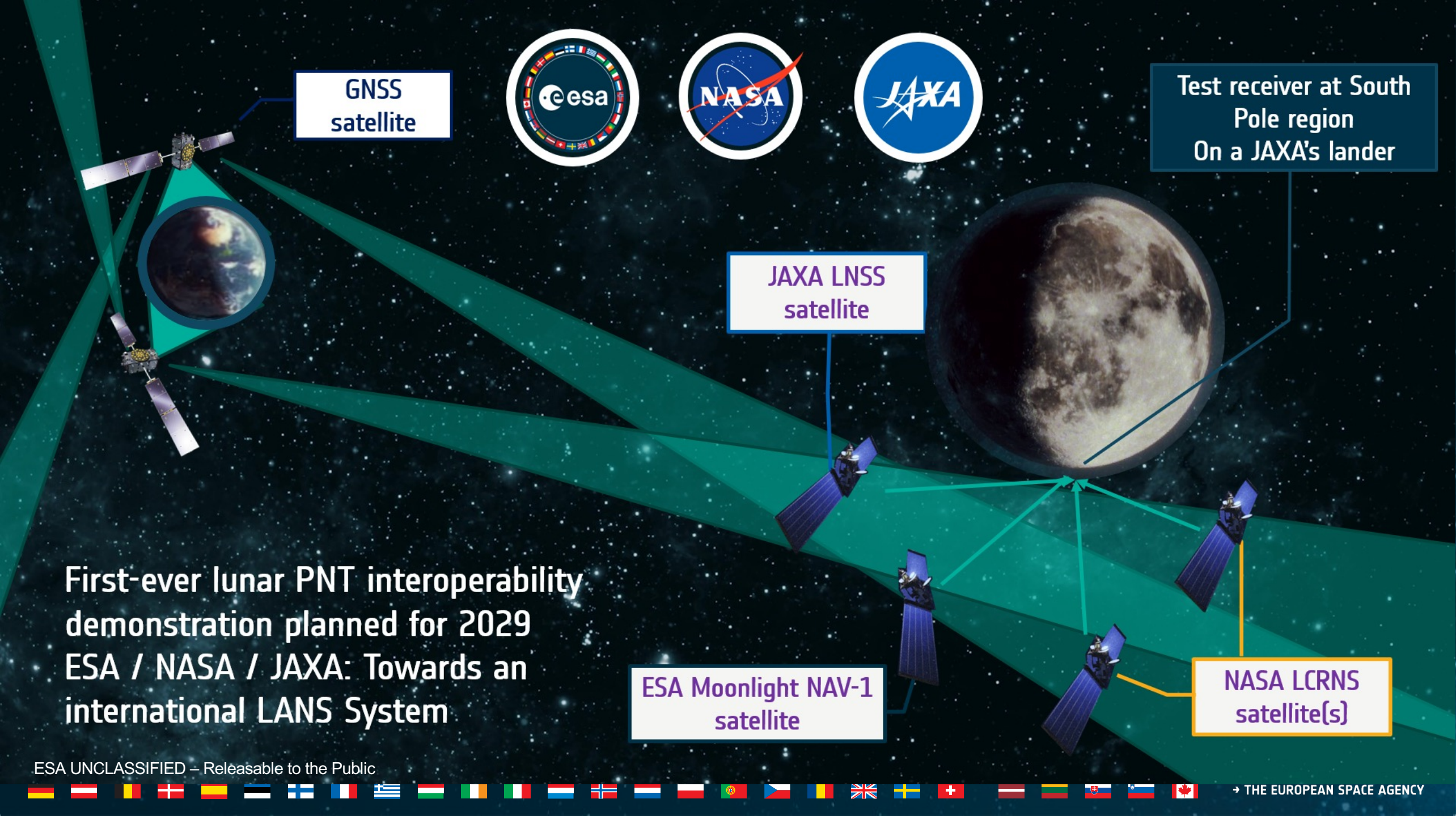
# MOONLIGHT will comply with LunaNet Interoperability Specifications






## Joint NASA, ESA and JAXA cooperation

LunaNet V5 released in January 2025 (working towards V6)




# First-ever lunar PNT interoperability demonstration planned for 2029 ESA / NASA / JAXA: Towards an international LANS System

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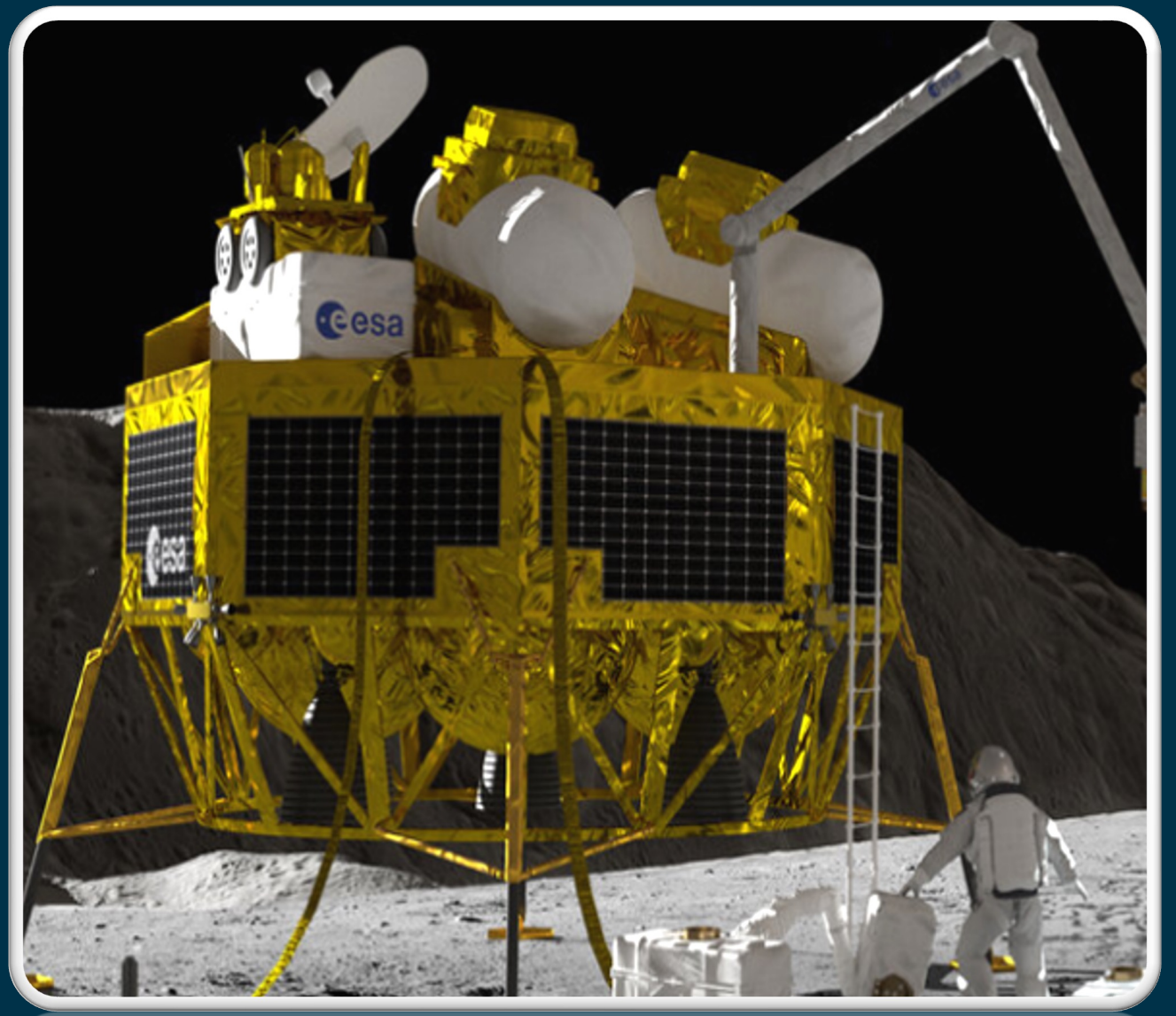


## HOW MAY WE DO BETTER (e.g. reaching ~1m range lunar surface accuracies) ON A SHORT TERM after MOONLIGHT FOC?

# STEP 3

## NOVAMOON Local PNT Differential Selenodetic and time-reference Station

**Formally approved by ESA Members States in November 2025 (CMIN25)**

**Full NovaMoon will be integrated on ESA's Argonaut-2 (2032)**

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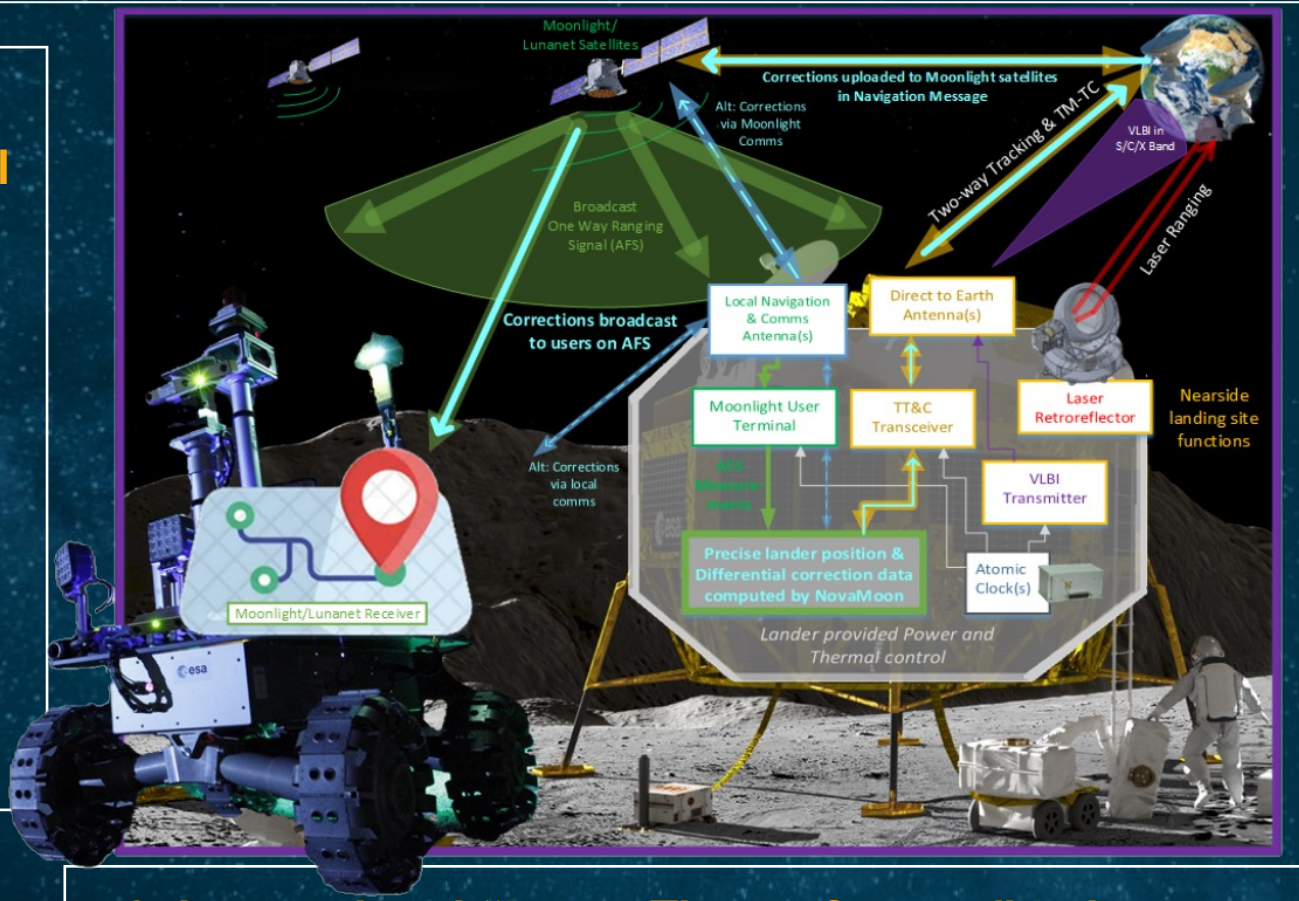
# NovaMoon towards ultimate accuracy

**1. Reference local differential station on the lunar surface**

**(augmenting and monitoring Moonlight and potentially other LunaNet compatible systems)**

Sub-meter level accuracies over the Lunar South Pole




**2. International "geodetic" Reference Station on the lunar surface (4 collocated ranging techniques)**

Towards an accurate Lunar Reference Frame realisation

**NovaMoon Full Payload integrated in ESA Argonaut lunar lander**

**5 years mission –Long-term exoerimentation opportuntiies**

**3. International "Lunar Time-reference" Laboratory**

Supporting experimentation setting the basis for future lunar-base time realisations

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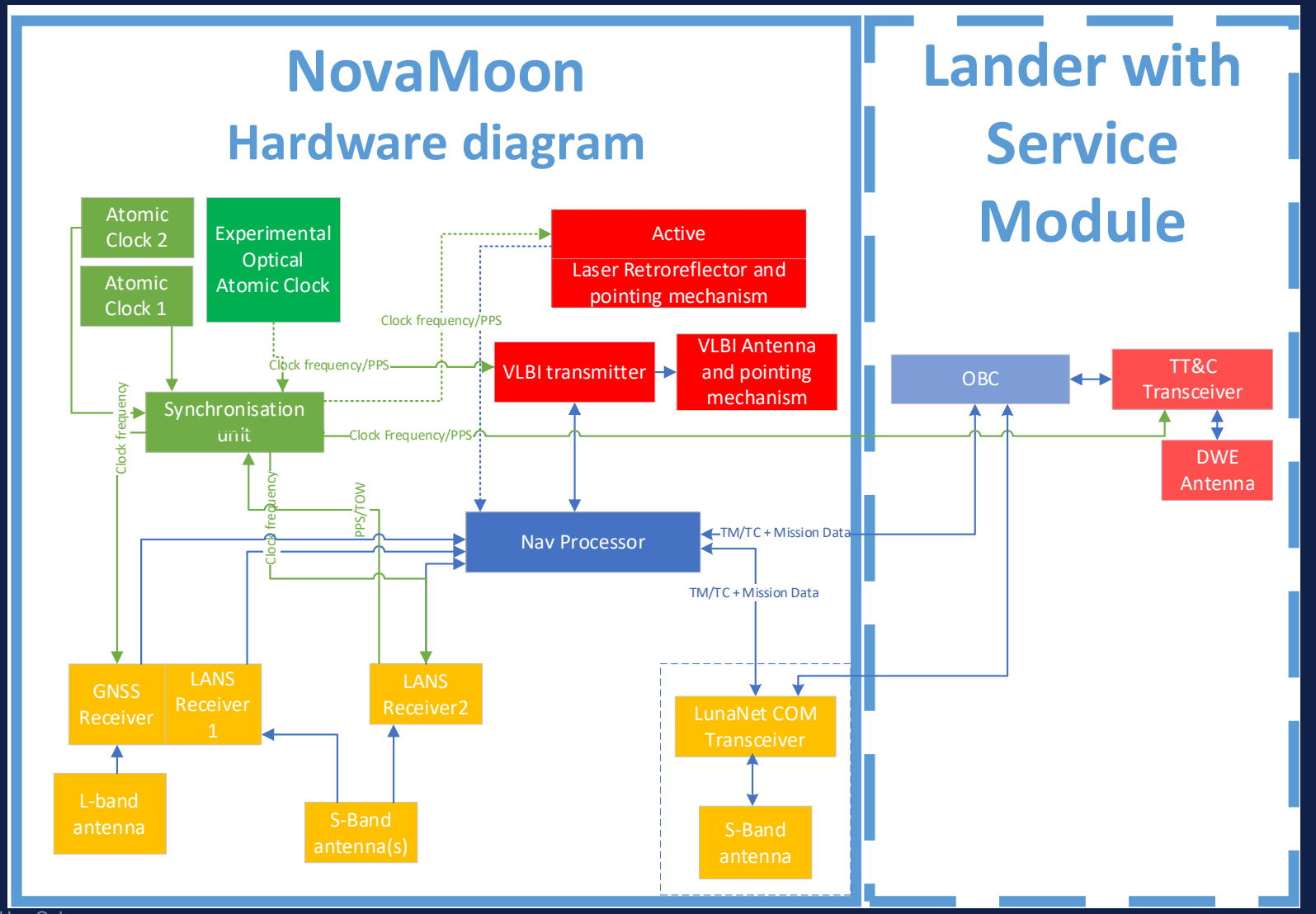
# NovaMoon Complete Architecture

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# NovaMoon Three incremental Builds & Three Launches !!

Step wise Approach for NovaMoon

## BUILD 1

- LunaNET + GNSS Receiver
- MiniRAFS Atomic Clock
- Advanced Laser Retroreflector

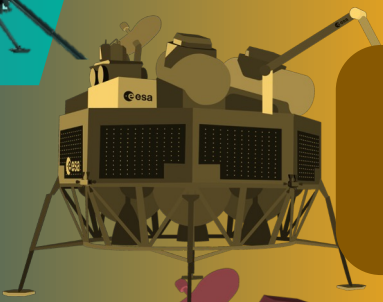
- **High accuracy in static conditions**
- **First lunar clock on the Moon**
- **Moonlight / GNSS combination**
- **LunaNET interoperability demo**

**Launch 2029**

## BUILD 2 adds

- Moon VLBI Transmitter
- LunaNet Rx on Lunar Rover

- First European lunar VLBI instrument
- Test IVS and VGOS experimentation
- Enhanced lunar reference frame experimentation
- High accuracy in dynamic conditions



**Planned on Argonaut-1 Launch target 2030**

## BUILD 3 adds

- Additional Moonlight/LunaNET Rx
- Navigation Processor
- Additional MiniRAFS Clock
- Experimental Optical Clock
- Active Laser Ranging

- All NovaMoon services demonstrated & long-term operations (5 years !)
- All NovaMoon Scientific benefits achieved
- Moonlight High-Accuracy Service provision
- Long-term international Lunar Time, geodetic and Interoperability Platform

**On Argonaut-2 Launch target ~ 2032**

***5 Years mission !***

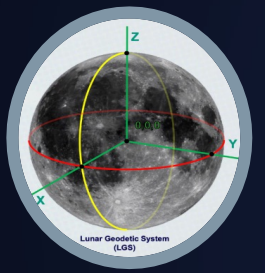
# Moonlight NAV and LunaNET Monitoring & High-Accuracy Service

## NovaMoon User Benefits

Lunar time realisation
International Lunar Time reference laboratory

An International LunaNET Interoperability Reference Platform

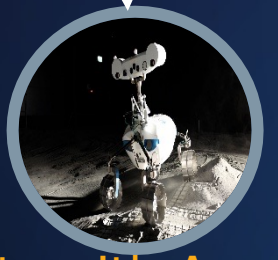
Lunar Reference Frame enhancement



GNSS and LunaNET satellites combined

Extracting UTC-time to Moon

Supporting IGS – Moon Station
Supporting the set-up of Lunar-Rinex
LUNEX standards



Mobility tests with Argonaut rover

A plethora of scientific Applications-

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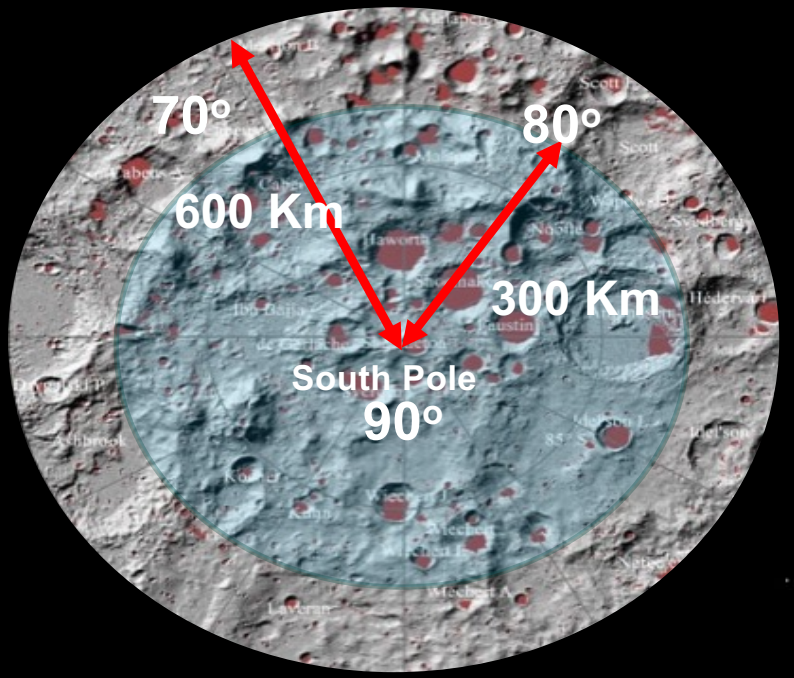
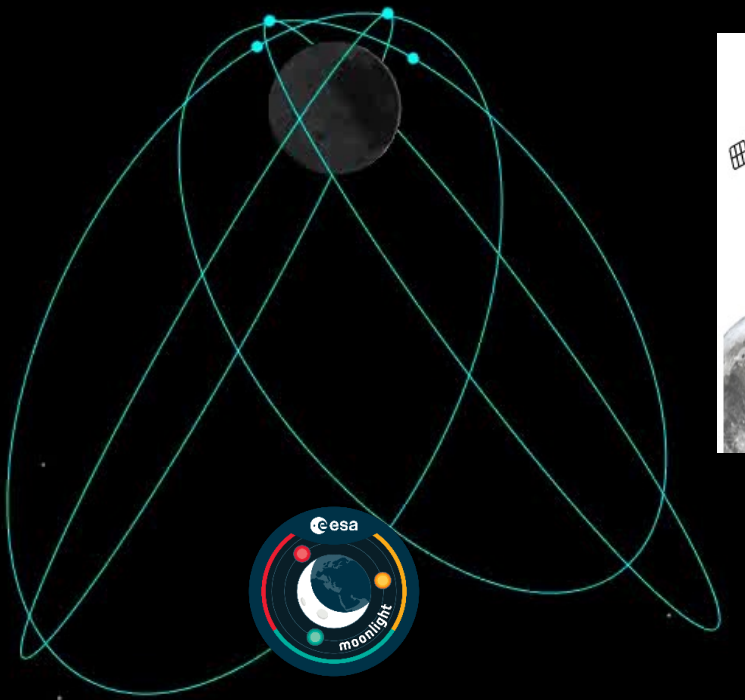
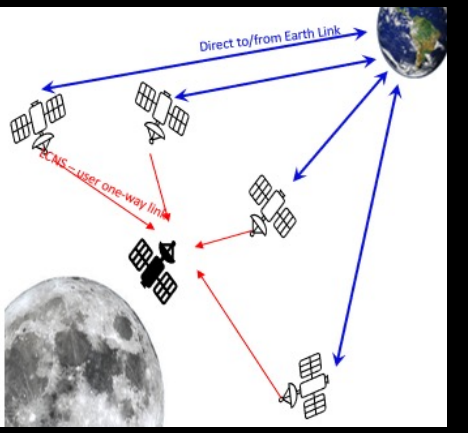
# Single NOVAMOON station with MOONLIGHT will provide Sub-meter accuracies over the whole South pole

ARTEMIS SERVICE AREA

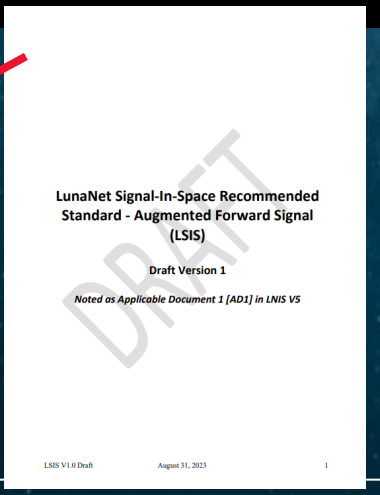



ODTS estimation

| LunaNet Interoperability Specifications [AD.1] | | | LSIS (this document) | | |
|---|---|---|---|---|---|
| MSG ID | MSG Title | Category | Subframe | Notes | LNIS 1.0 |
| … | | | | | |
| MSG-G31 | Augmentation Differential Corrections | O | SB3 and/or SB4 | Ad-hoc | yes |


LunaNet Signal-In-Space Recommended Standard - Augmented Forward Signal (LSIS)

Draft Version 1

*Noted as Applicable Document 1 [AD1] in LNIS V5*

DRAFT

LSIS V1.0 Draft August 31, 2023 1

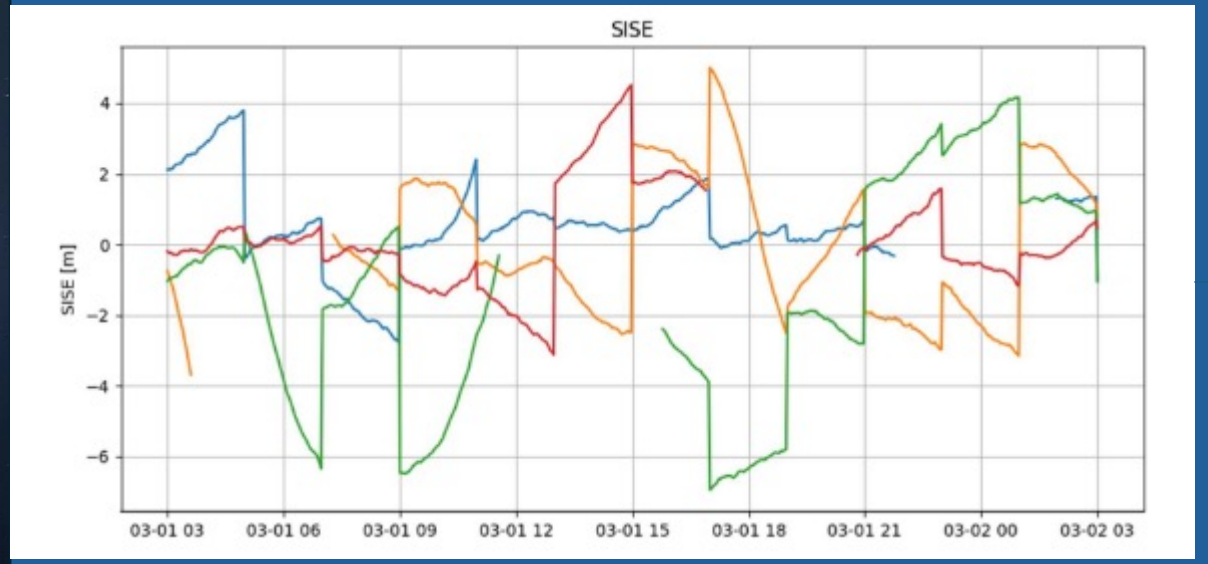
**Our analysis demonstrate that a Single station will serve the whole South Pole**

- NO ionosphere
- NO troposphere
- Minimum Orbital projection error
- Lunar South pole message reception

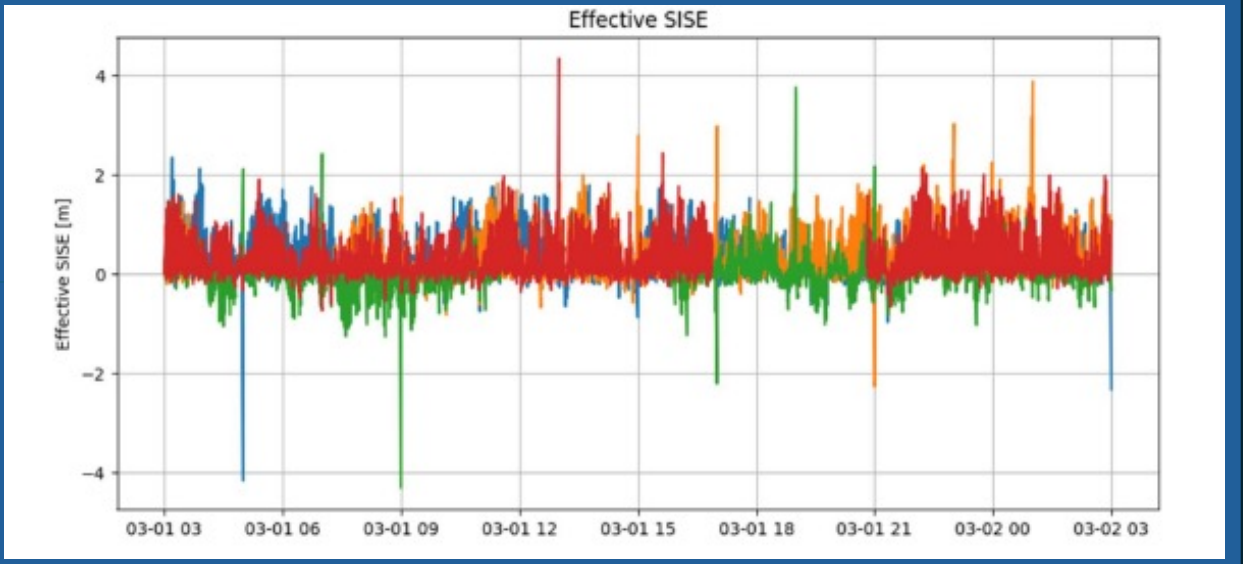
# Moonlight equivalent-SISE after NovaMoon corrections < 1 metre ( 1 sigma)

NovaMoon allows to compute an equivalent SISE metric defined as the residual impact of the satellite SISE on the measurements once the differential corrections are applied (5 min update)

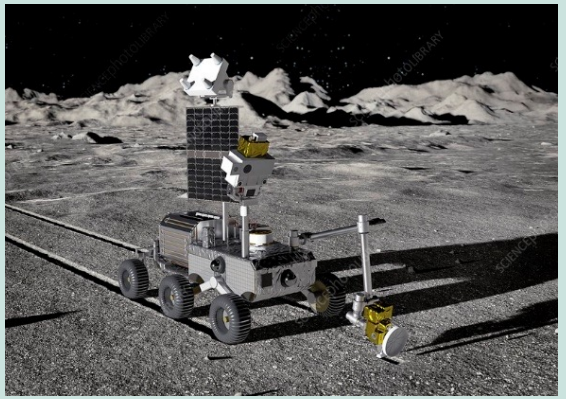
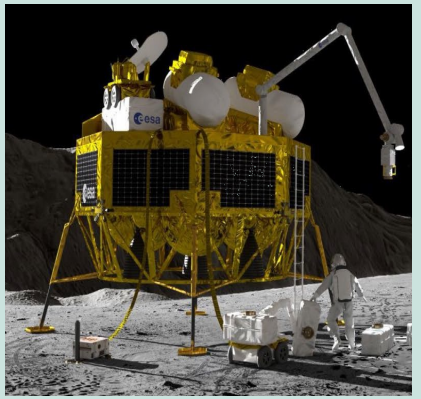
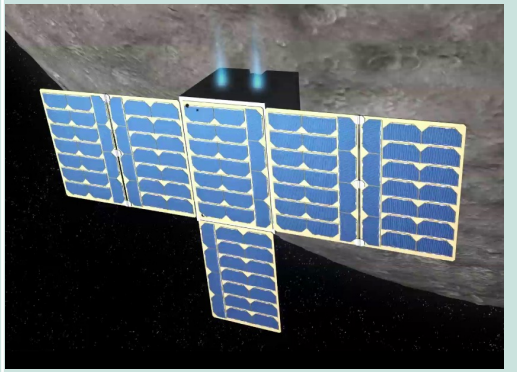
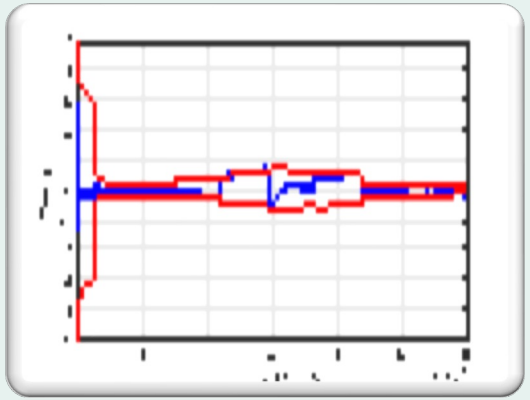
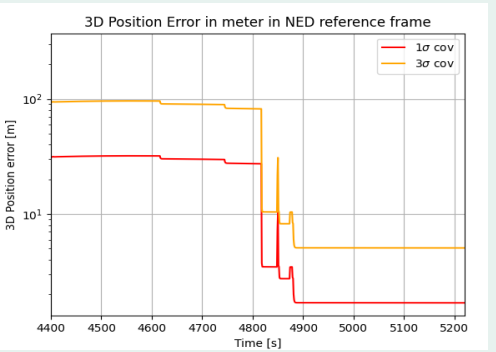
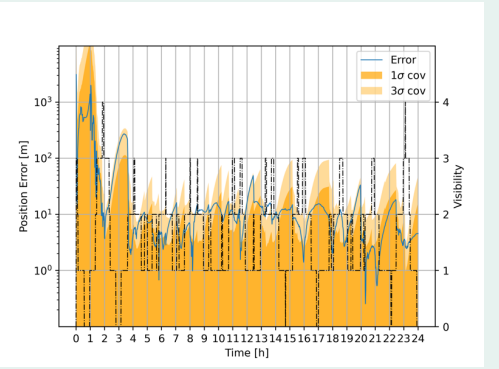
Moonlight 4 satellites SISE (1 sigma)




Moonlight equivalent SISE with NovaMoon (1 sigma)

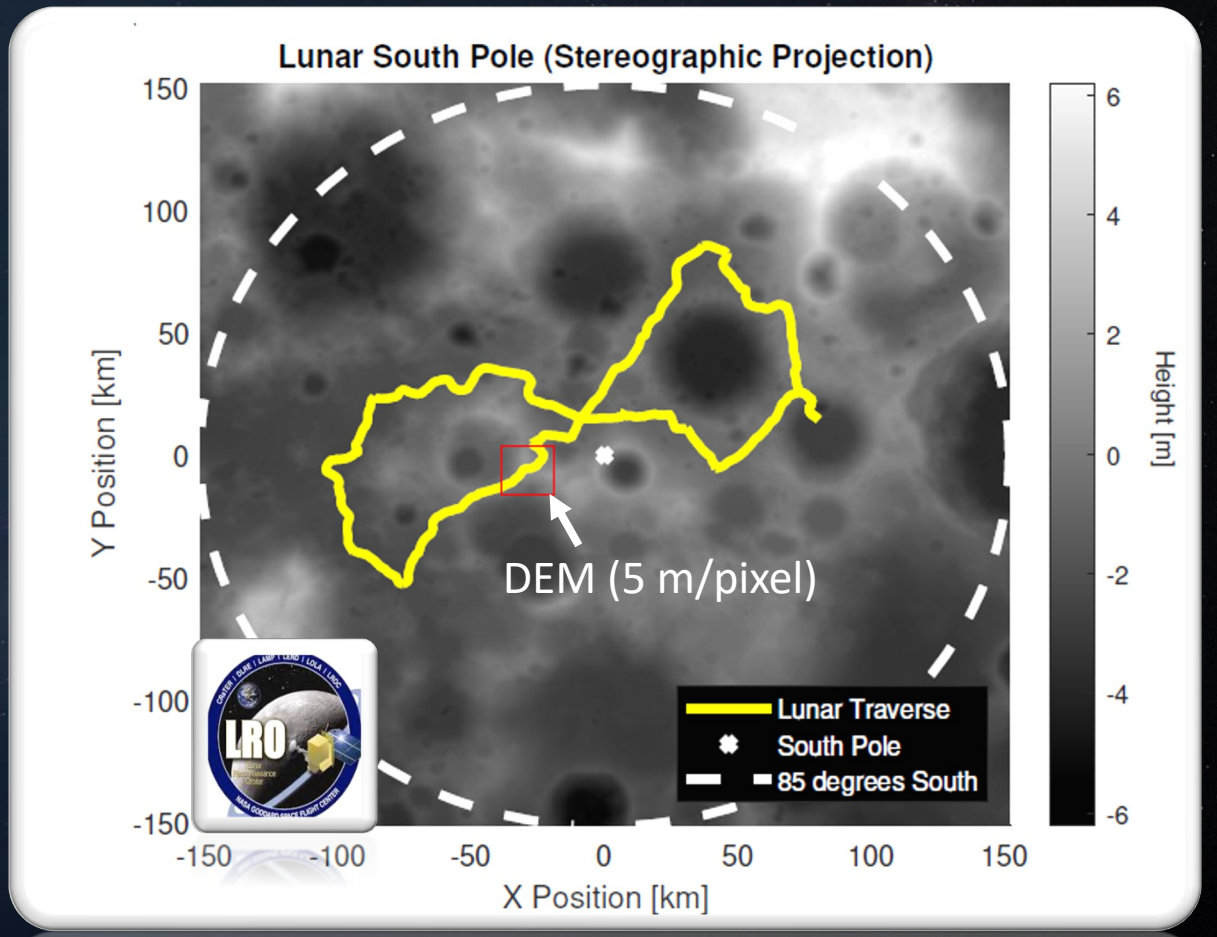


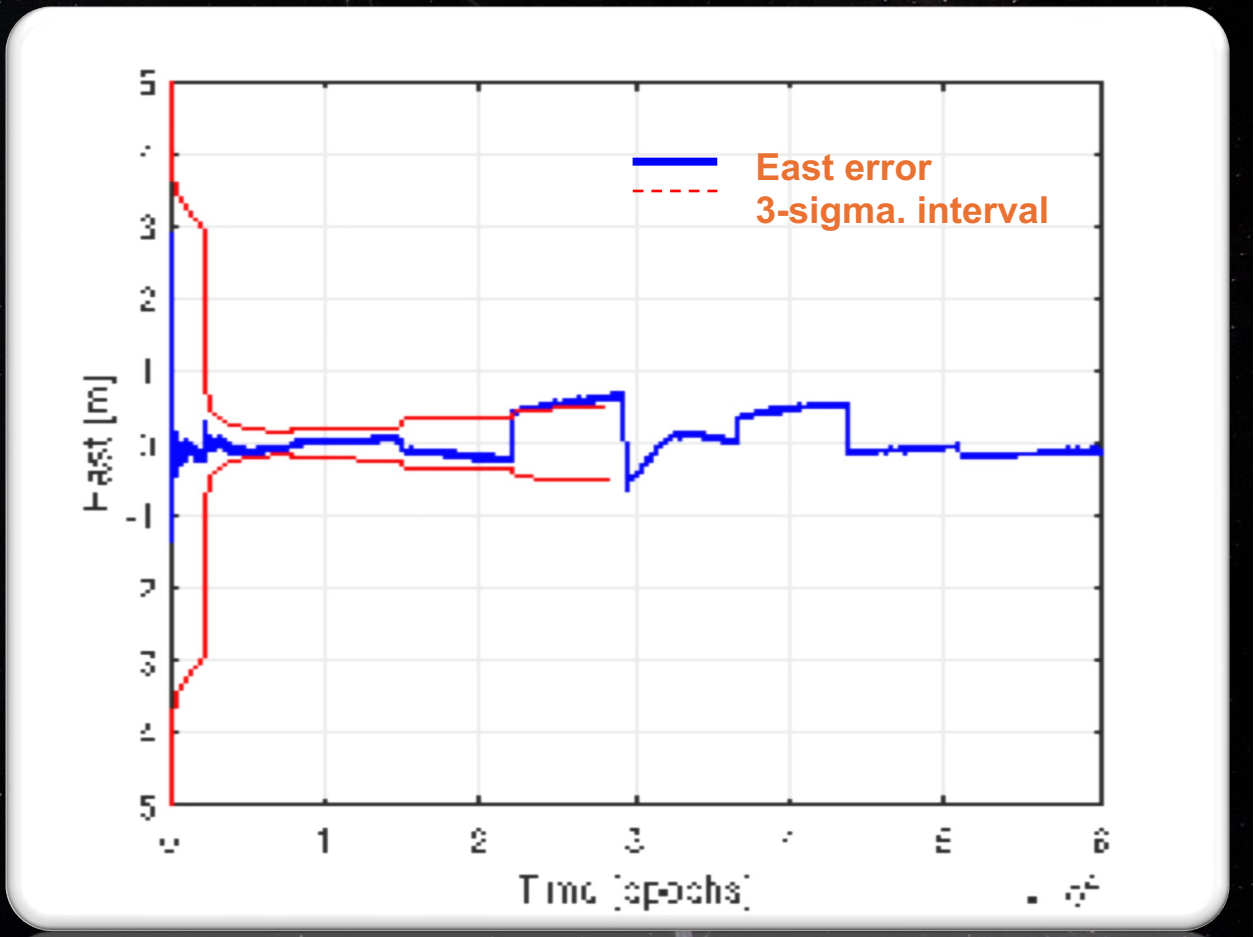
# Moonlight + NovaMoon joint performances

| Surface Rover | Lunar Lander | Lunar Orbiter |
|---|---|---|
|  Real time **< 10 m (95%)** |  **< 50 m (95%)** Landing accuracy |  Real time **< 100 m (95%)** LLO accuracies |
|  **< 1 m** |   **< 5 m** |   **< 10 m** |

## Results based on ESA and Industry Analysis (NovaMoon Phase A)

# Lunar Rover – Performance when combining Moonlight + NovaMoon
# Sub-metre Accuracy achievable in real time !



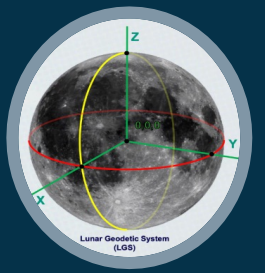

# Accuracy < 1 metre level at Lunar South pole !

# Moonlight NAV and LunaNET Monitoring & High-Accuracy Service

## NovaMoon User Benefits

**Lunar time realisation**
International Lunar Time reference laboratory

**Lunar Reference Frame enhancement**

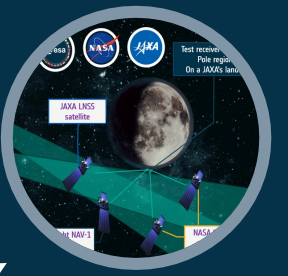



**Supporting IGS – Moon Station**
Supporting the set-up of Lunar-Rinex LUNEX standards

**Mobility tests with Argonaut rover**

**A plethora of scientific Applications-**

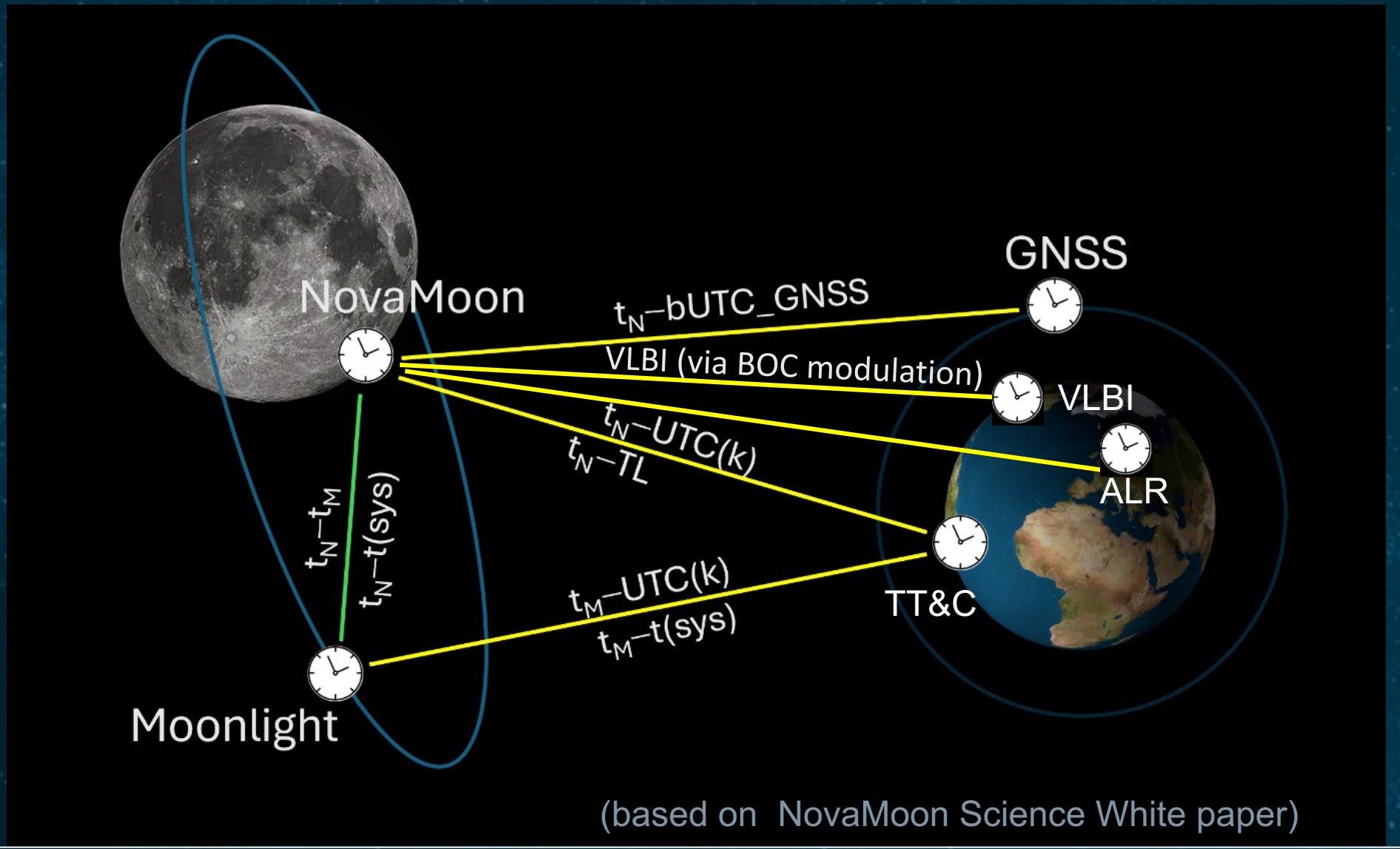
**An International LunaNET Interoperability Reference Platform**




**GNSS and LunaNET satellites combined**

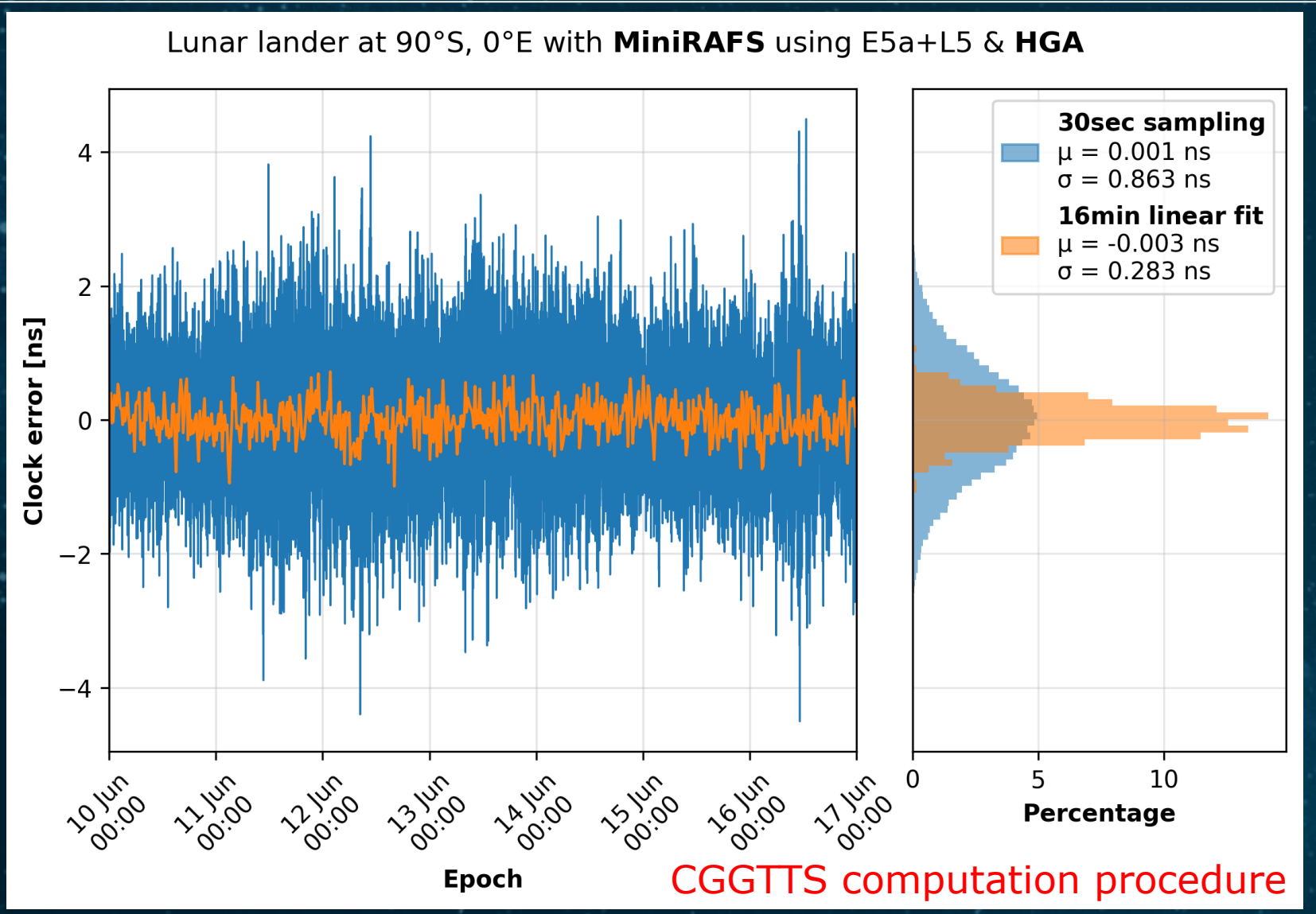
**Extracting UTC-time** to Moon

# NovaMoon: A unique Lunar Time Laboratory




(based on NovaMoon Science White paper)

# NovaMoon: Example of GNSS UTC Time transfer




CGGTTS computation procedure

GNSS time transfer shows to be a good solution to access UTC on NovaMoon in real-time.

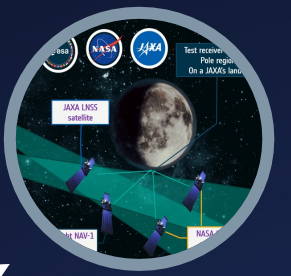
Additional available Time-Transfer method allow for higher accuracy

This accurate time-transfer could support the characterization of relativistic offsets between Moon- and Earth-based clocks

# Moonlight NAV and LunaNET Monitoring & High-Accuracy Service

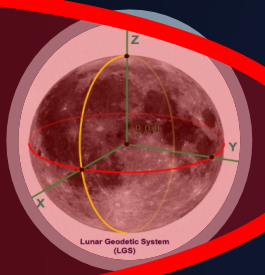
## NovaMoon User Benefits

### Lunar time realisation
International Lunar Time reference laboratory



### An International LunaNET Interoperability Reference Platform

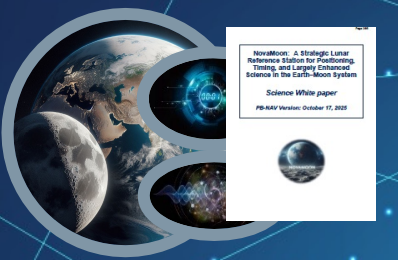
### Lunar Reference Frame enhancement



### GNSS and LunaNET satellites combined

### Extracting UTC-time to Moon

### Supporting IGS – Moon Station
Supporting the set-up of Lunar-Rinex LUNEX standards




### A plethora of scientific Applications-

### Mobility tests with Argonaut rover

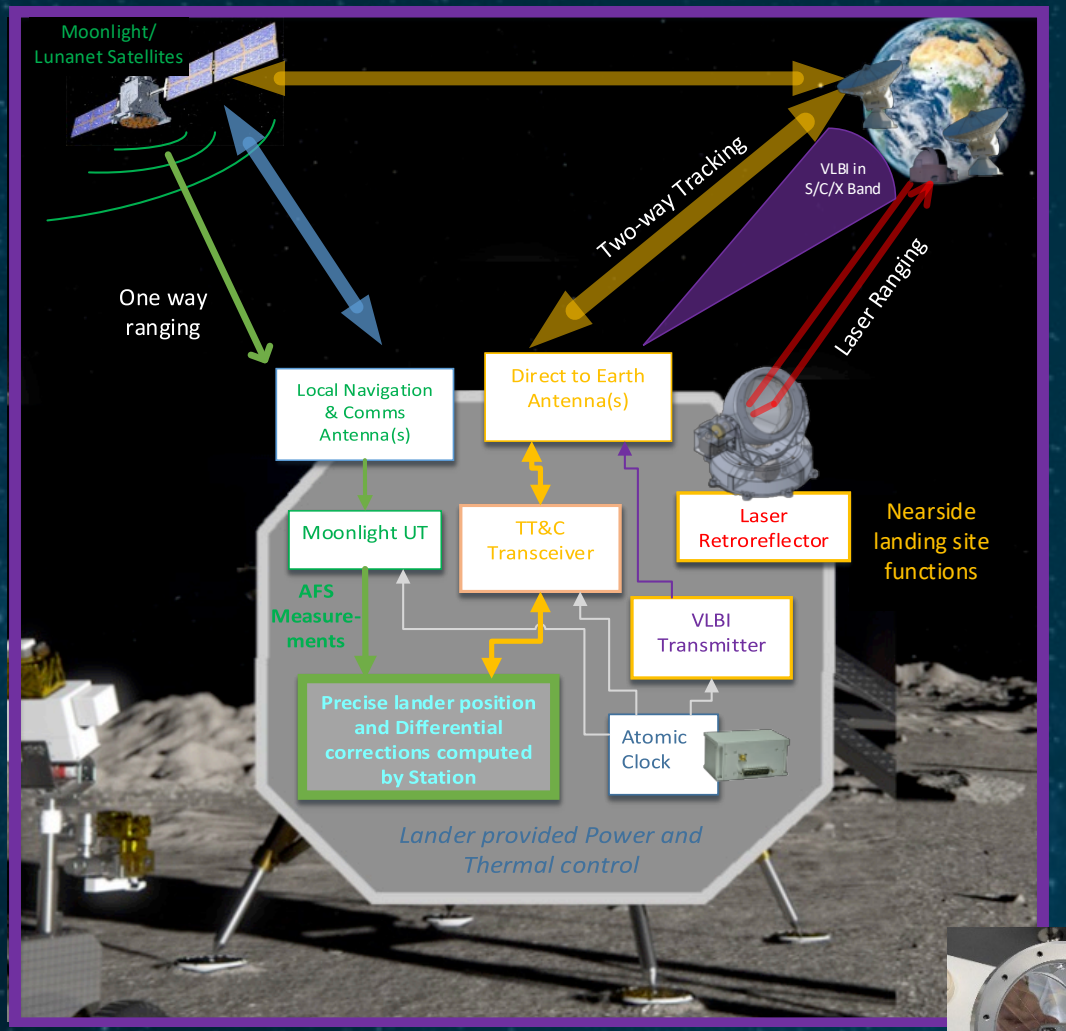
# Lunar Base Station Localisation

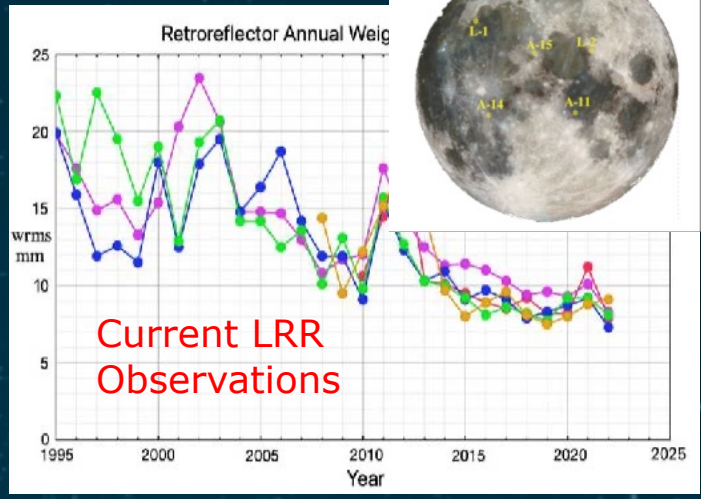
## cm-level (< 10 cm) position determination on the lunar surface !

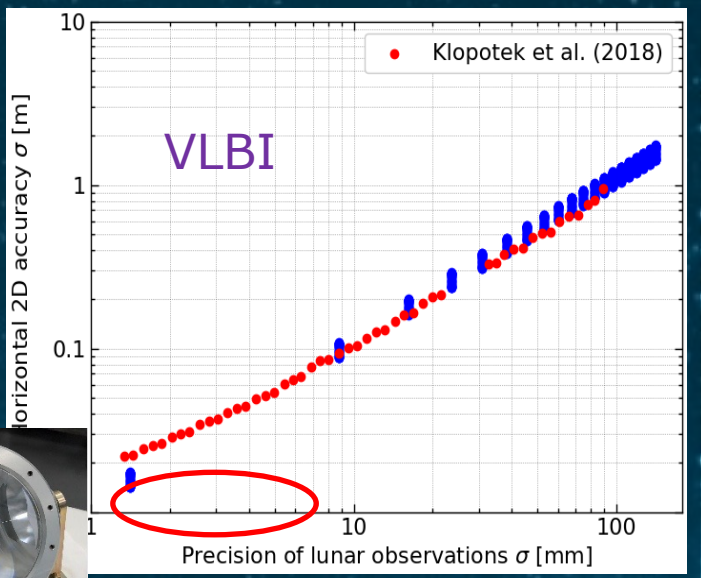
For the fist time 4 co-located geodetic techniques on-board:

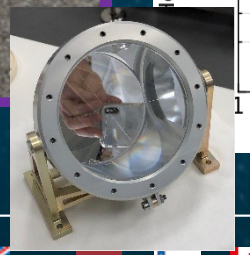
- Augmented PNT LunaNET
- VLBI transmission
- Laser Ranging Retroflector
- Two-way Direct To Earth

**3D localisation accuracies down to cm-level are at reach !**



# Lunar Base Station Localisation NovaMoon Station

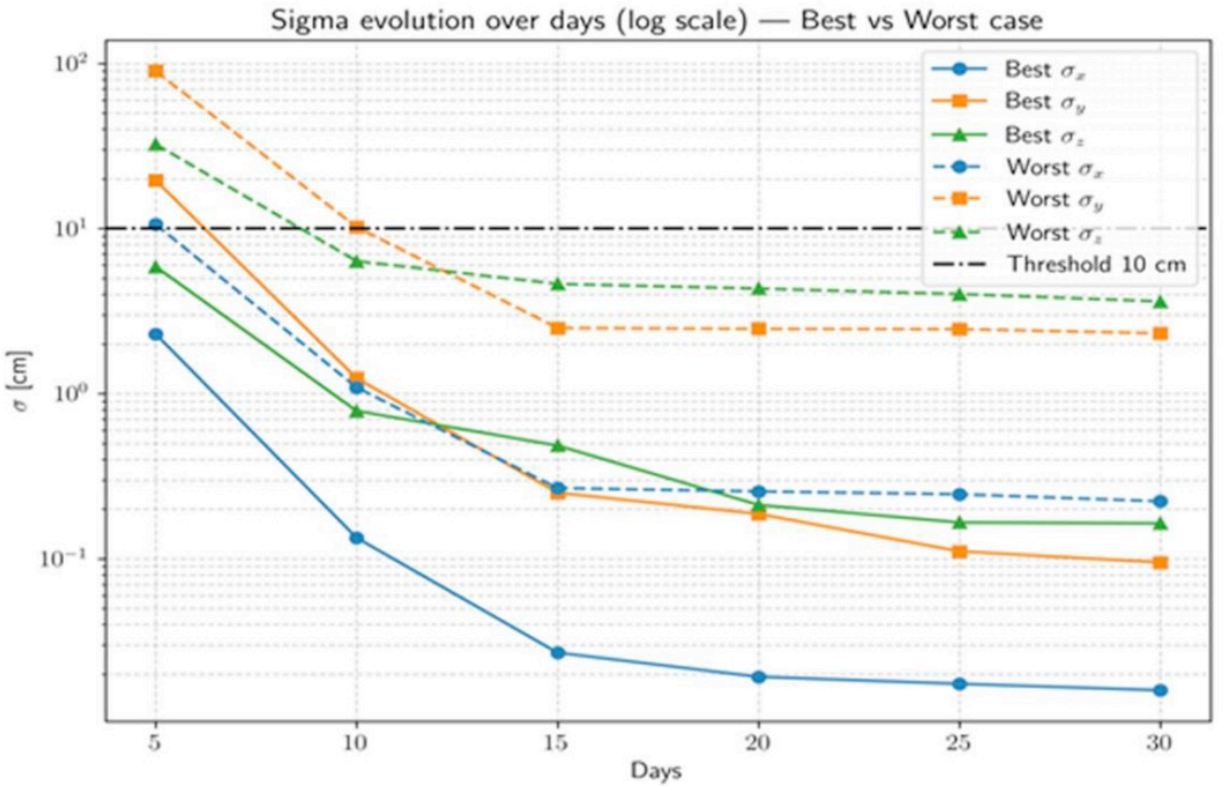
## cm-level (< 10 cm) position determination on the lunar surface !

For the fist time 4 co-located geodetic techniques on-board:

- Augmented PNT LunaNET
- VLBI transmission
- Laser Ranging Retroreflector
- Two-way Direct To Earth

**3D localisation accuracies down to cm-level are at reach !**

**Reference Position 1: 85S 3E (Example)**




| Worst case scenario (30 days) [cm] | |
|---|---|
| $\sigma_x$ | 0.22 |
| $\sigma_y$ | 2.32 |
| $\sigma_z$ | 3.62 |

| Best case scenario (30 days) [mm] | |
|---|---|
| $\sigma_x$ | 0.16 |
| $\sigma_y$ | 0.95 |
| $\sigma_z$ | 1.64 |

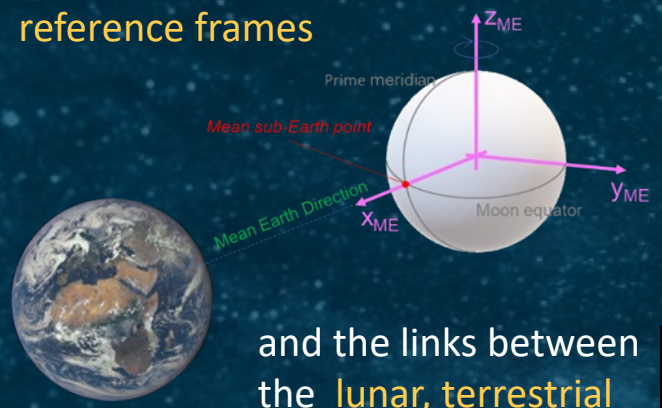
(Source CRAS, ESA NovaMoon Phase A Study)

~10 days of observation allow to reach a localisation accuracy < 10 cm

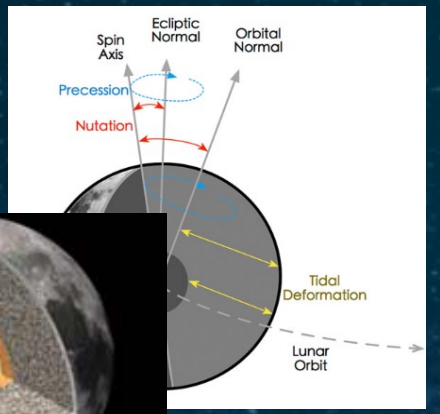
Could become a reference standard for Selenodetic Lunar-base stations

# NovaMoon VLBI a major asset to enhance Lunar Reference Frame and Lunar Geophysics knowledge

Enhancing the accuracy of Lunar reference frames



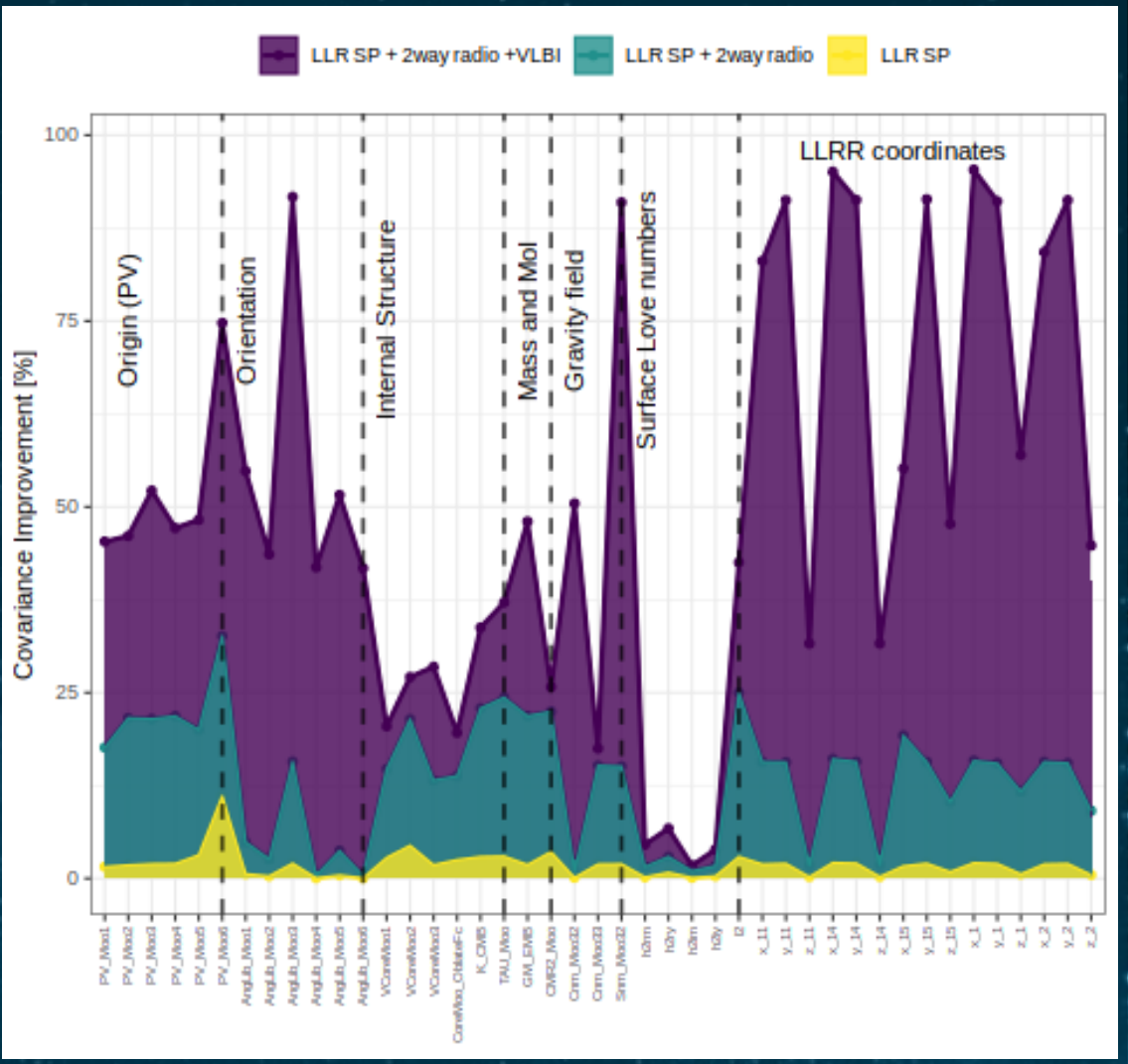

Supporting measurements of the Moon tidal deformations and Moon librations




and the links between the lunar, terrestrial and celestial frames

Improving the knowledge of the Moon Position/Velocity, Orientation, Internal structure, lunar gravity field, MoI, Surface love Numbers, Moon core dynamics,

Relative improvements (%) in the Lunar Reference Frame (LRF) through covariance matrix analysis of 40 years of LLR data.



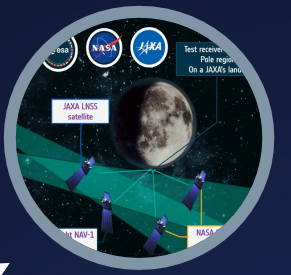

(Credits: A. Fienga, NovaMoon Science White Paper)

# Moonlight NAV and LunaNET Monitoring & High-Accuracy Service

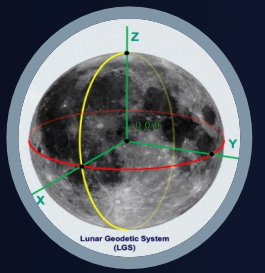
## NovaMoon User Benefits

Lunar time realisation
International Lunar Time reference laboratory

An International LunaNET Interoperability Reference Platform




Lunar Reference Frame enhancement

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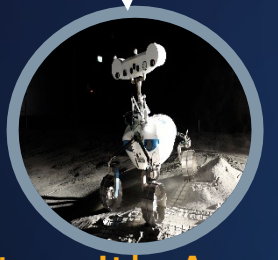

Mobility tests with Argonaut rover

A plethora of scientific Applications-

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# NovaMoon at the service of Science:

## NovaMoon Science White paper produced

The NovaMoon Science White Paper presents a very comprehensive set of ***primary and secondary scientific potential user benefits (objectives)*** identified for the NovaMoon mission.

This document is ***supported by 104 reputed Scientists*** (84 having directly contributed to the paper), ***representing 40 different European Research institutions***, covering a large variety of complementary fields.

This document has been submitted for publication to ***Space Science Reviews*** (*Springer* **-** Dec 2025)

**Preprint available from today at *arXiv repository***
https://doi.org/10.48550/arXiv.2602.08432

# ESA strong will to support Lunar PNT users benefits & to promote International collaboration

8 times on cislunar space supporting PNT between 2027-2032 !!

LPF (**2027**)

Moonlight NAV-1 **2029**
Moonlight NAV 2, 3 & 4 **2031**

**NovaMoon Build#1 2029**
**NovaMoon Build#2 2030**
**NovaMoon Build#3 2032**

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