Lunar Pathfinder

Moonlight

WG- B Presentation

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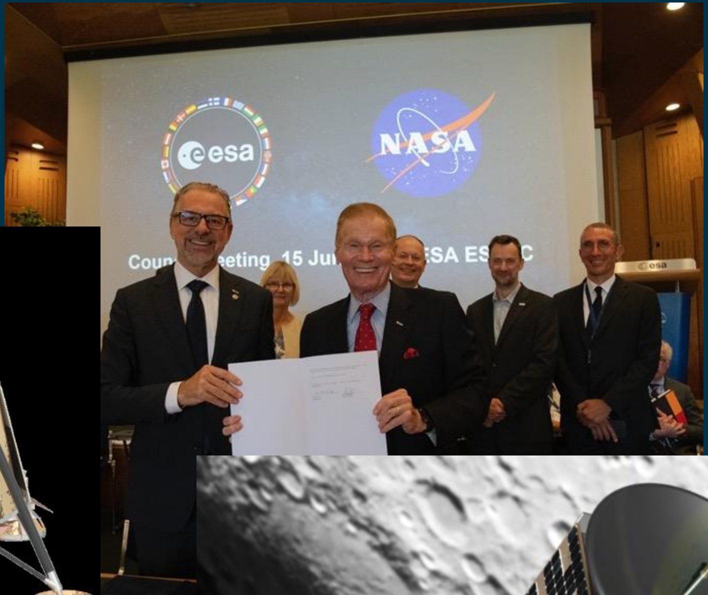
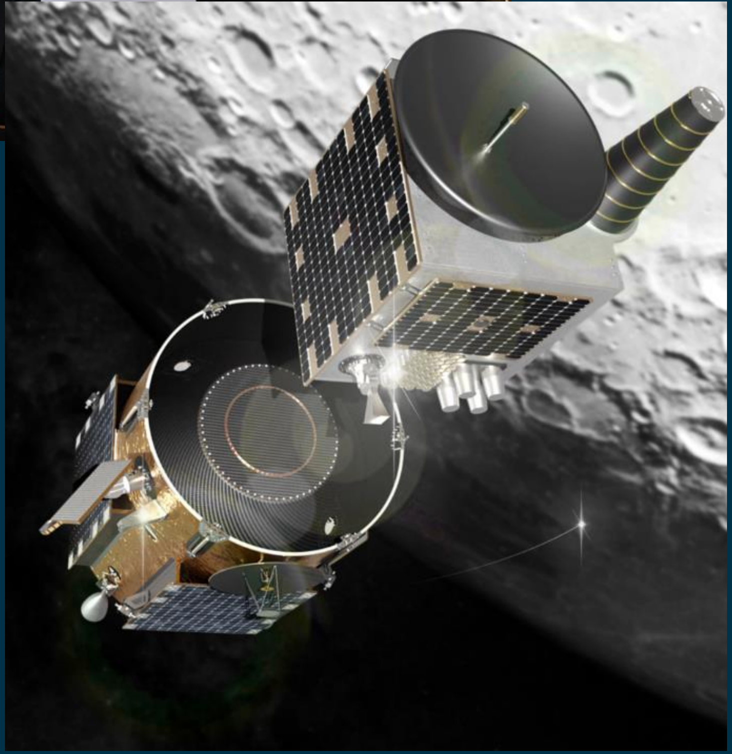
European Space Agency

ESA Roadmap plans for Lunar Navigation Services

Phase 1: Use of Existing Earth-GNSS (2025 – onwards)	Phase 2: Moonlight NAV Initial Services (2027 – 2035)	Phase 3: Moonlight NAV enhanced services (2035 – onwards)
Preliminary Lunar PNT services	**Moonlight Lunar PNT services**	**Enhanced Moonlight Lunar PNT services**
Use Earth-based GNSS (Galileo and GPS) signals and high-sensitive GNSS Receivers	Initial lunar orbit GNSS-like constellation supporting South Pole surface and cislunar orbit services	Enhanced Lunar NAV Satellites constellation (complemented by lunar surface elements) to provide Full lunar surface coverage and enhanced performances PNT performances
Lunar Pathfinder GNSS Payload IoD	**MOONLIGHT / LCNS IOC / FOC Services**	**MOONLIGHT / LCNS: Enhanced Services**





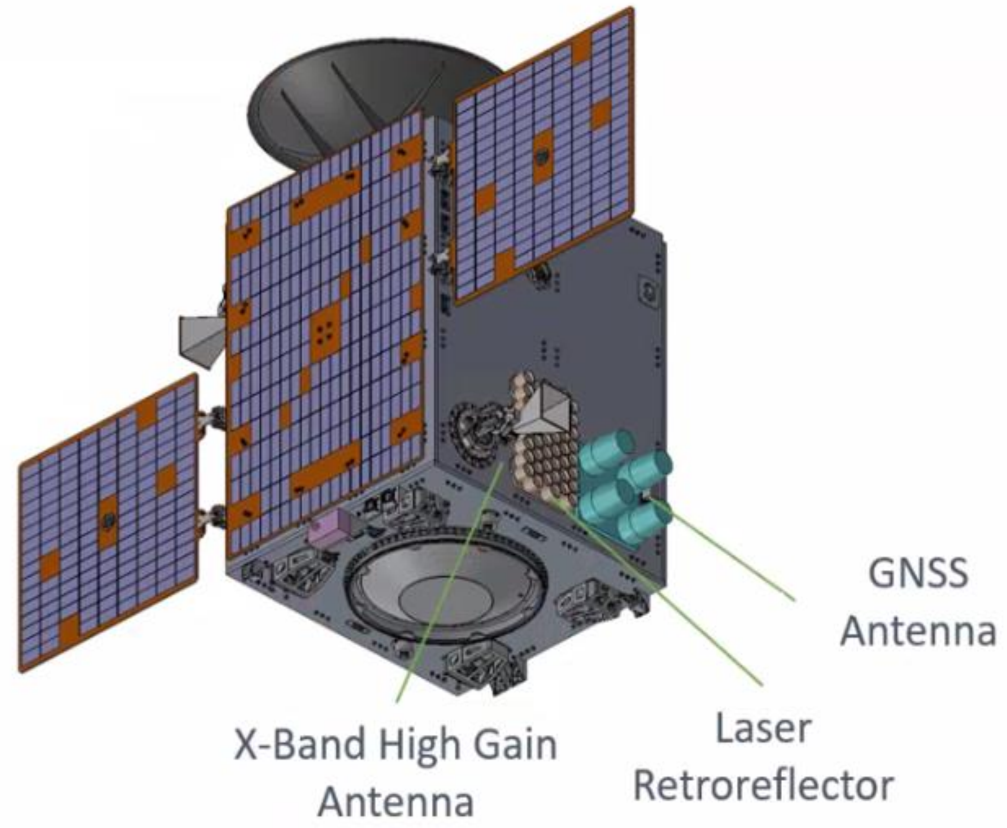
MOONLIGHT STEP 1: Lunar Pathfinder

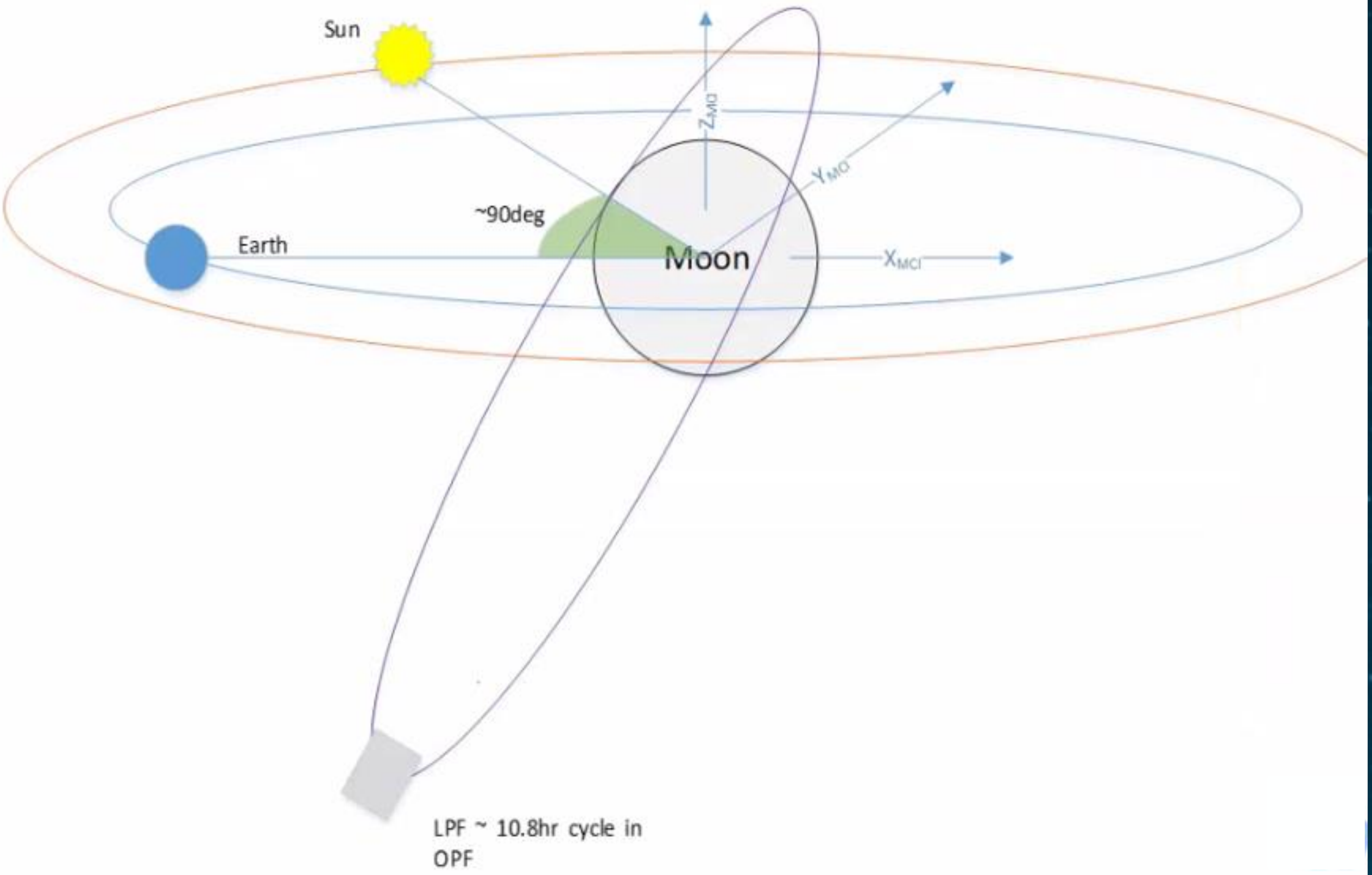
Lunar Pathfinder will be launched by Firefly Aerospace end of 2025 !

Lunar Pathfinder, a pioneer:

- ESA partnership with SSTL
- Provides commercial lunar relay communications
- GPS/Galileo reception on lunar orbit!
- ESA as Anchor customer
- NASA LuSEE mission (launched together with Lunar Pathfinder) will be first Lunar Pathfinder user.
- NASA provides the launch (via CLPS)

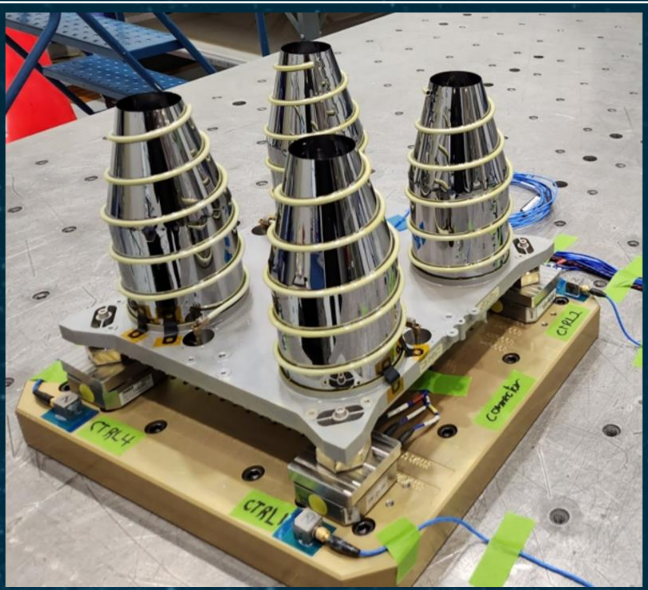
Lunar Pathfinder Satellite –
First ever GPS/GALILEO reception on lunar orbit





Lunar Pathfinder Navigation Payload In-orbit Demonstration
All flight units now manufactured and tested

GNSS High-sensitive receiver
Flight unit



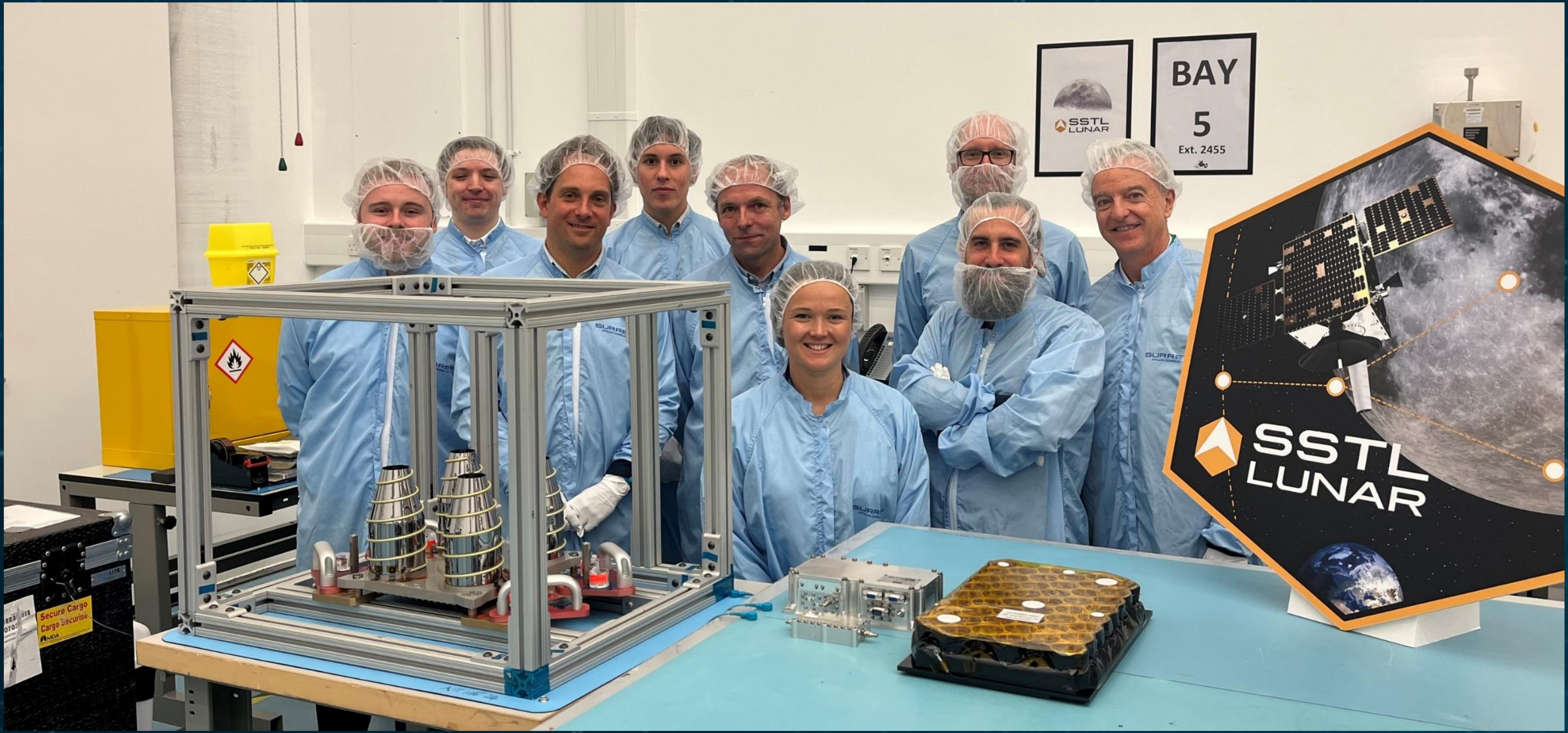
GNSS High-gain Antenna
Flight unit

Laser Retroreflector
Flight unit (NASA)

Demonstration of GPS/Galileo PNT on a Lunar orbiting satellite

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

Lunar Pathfinder Navigation Payload In-orbit Demonstration
All flight units delivered



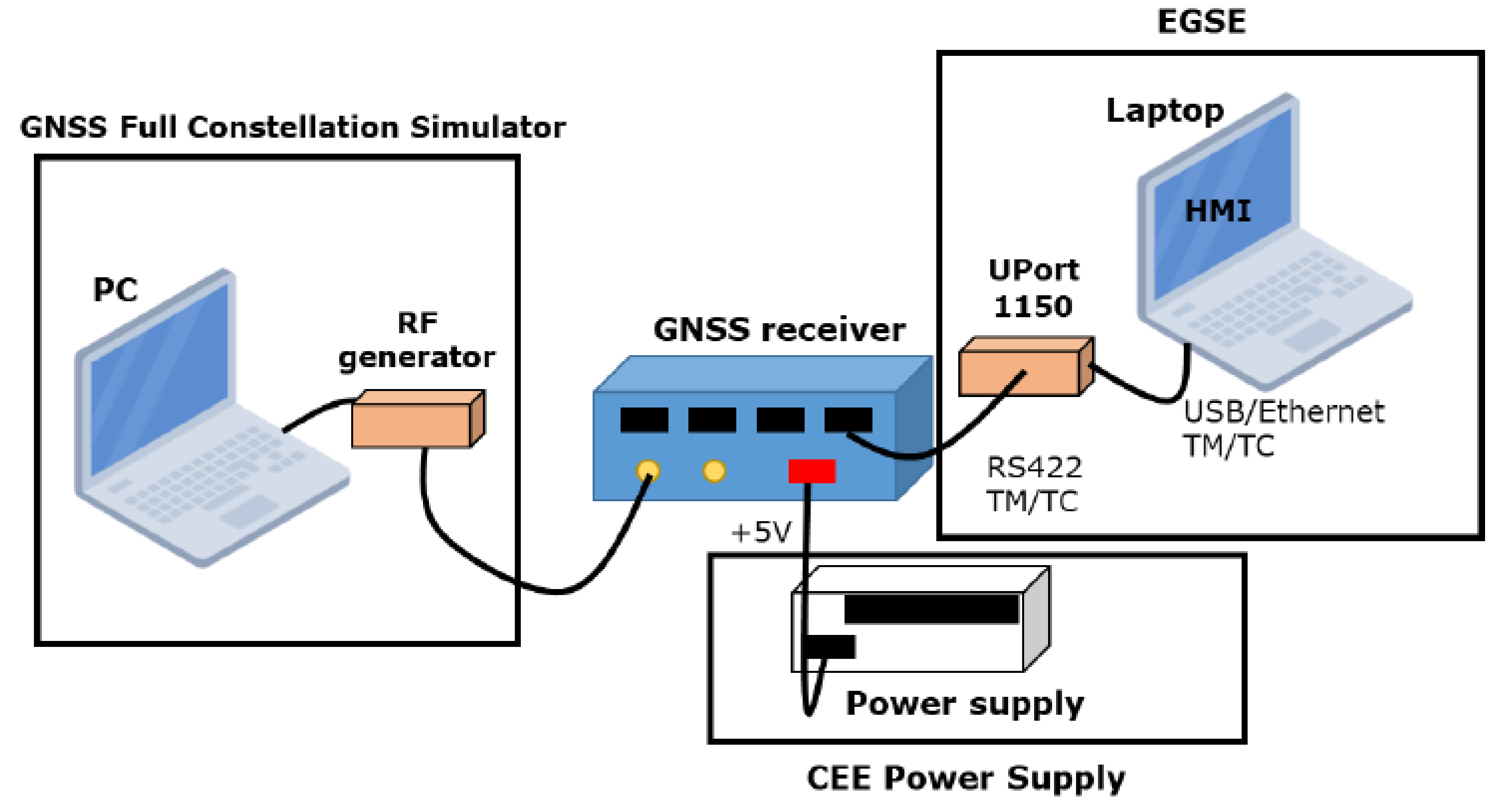
Functional and Performance test set-up

The receiver has been tested with Skydel and Spirent RFCS

The reference user trajectory has been generated with GMAT, using realistic dynamic models (tests performed in MTO and NRHO orbit)

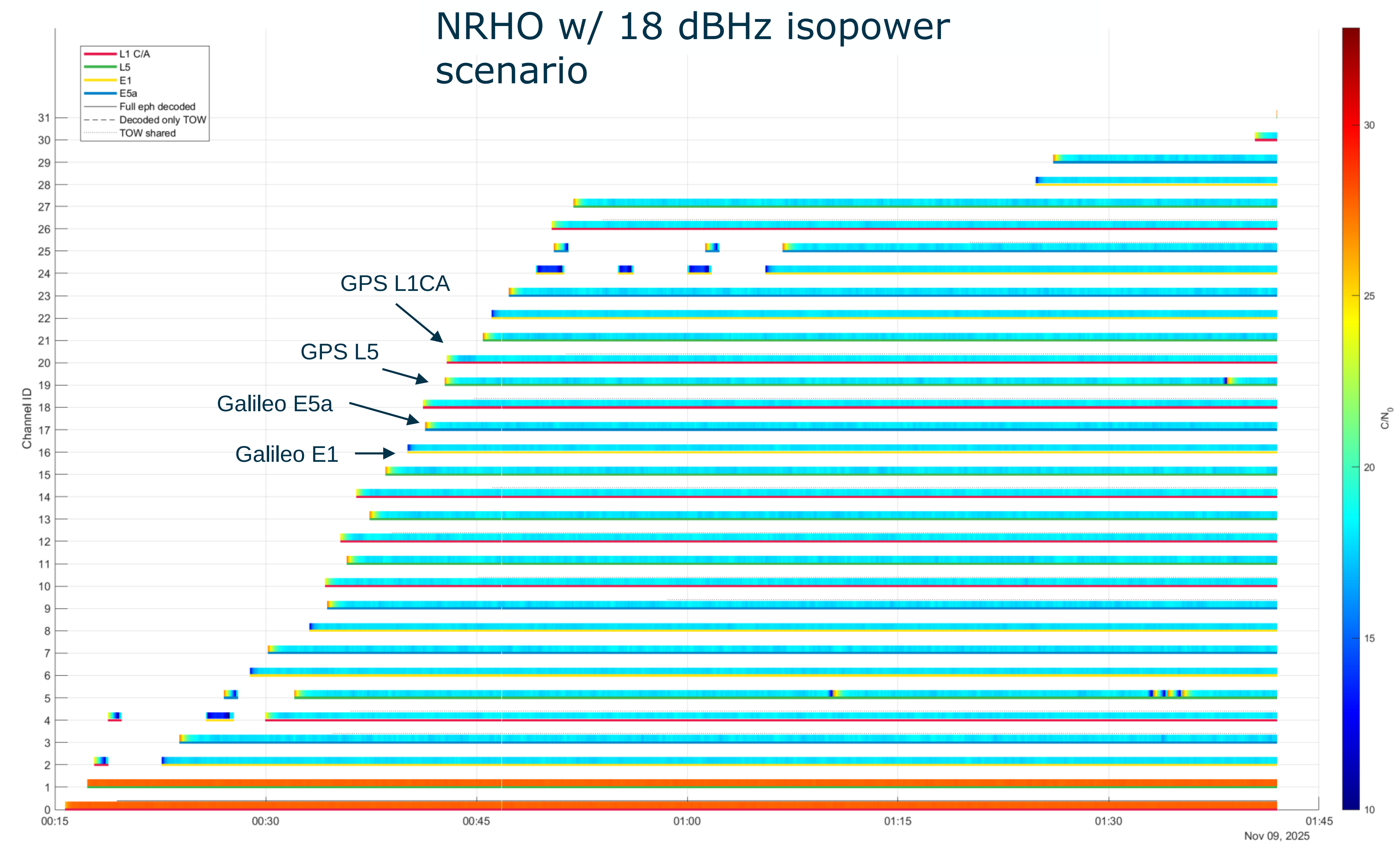
Simulation power has been fine tuned to be representative of GPS and Galileo EIRP and Tx antenna gain pattern

Receiver antenna gain pattern has been simulated



Acquisition sensitivity – real hardware in the loop test

NRHO w/ 18 dBHz isopower scenario



MTO – real hardware in the loop test

→ THE EUROPEAN SPACE AGENCY

High level CONOPS Lunar Pathfinder planned experiment (in cooperation with NASA and JAXA)

The experiment will be conducted in slots of 4-5 days of duration

The receiver configuration will be uploaded at the beginning of the slot and during the experiment the receiver will be fully autonomous (without any external aiding)

ESA Roadmap

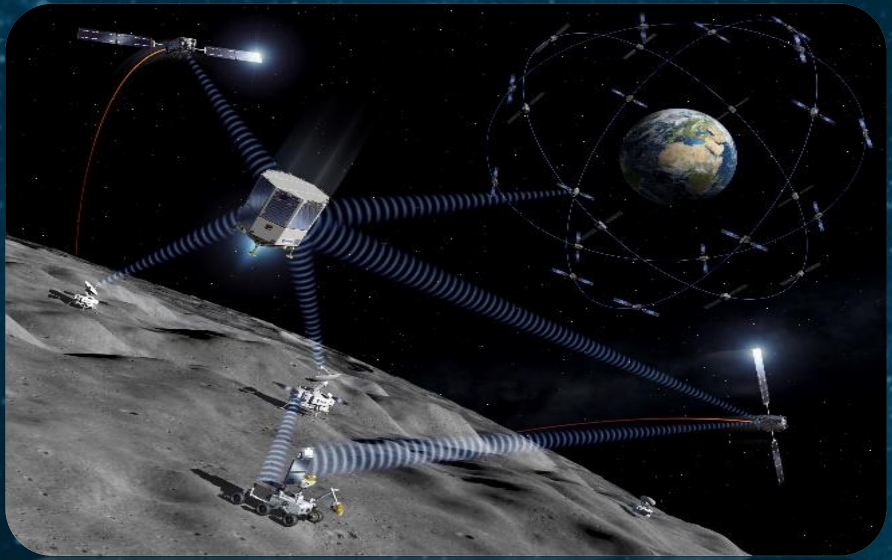

STEP 1: LUNAR PATHFINDER
Low-rate satellite communications service + Moon GNSS Receiver
Development
Pathfinder Service
2025
STEP 2: MOONLIGHT LCNS CONSTELLATION
High-data rate satellite communications and navigation service
Design
Development
IOC Services
FOC Services
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030

Moonlight Vision

To enable the delivery of Communications and Navigation Services that will support the current and next generations of institutional and commercial Lunar explorers

Moonlight Approach & Services

Service development Approach: ESA supporting infrastructure development and acting as Anchor customer

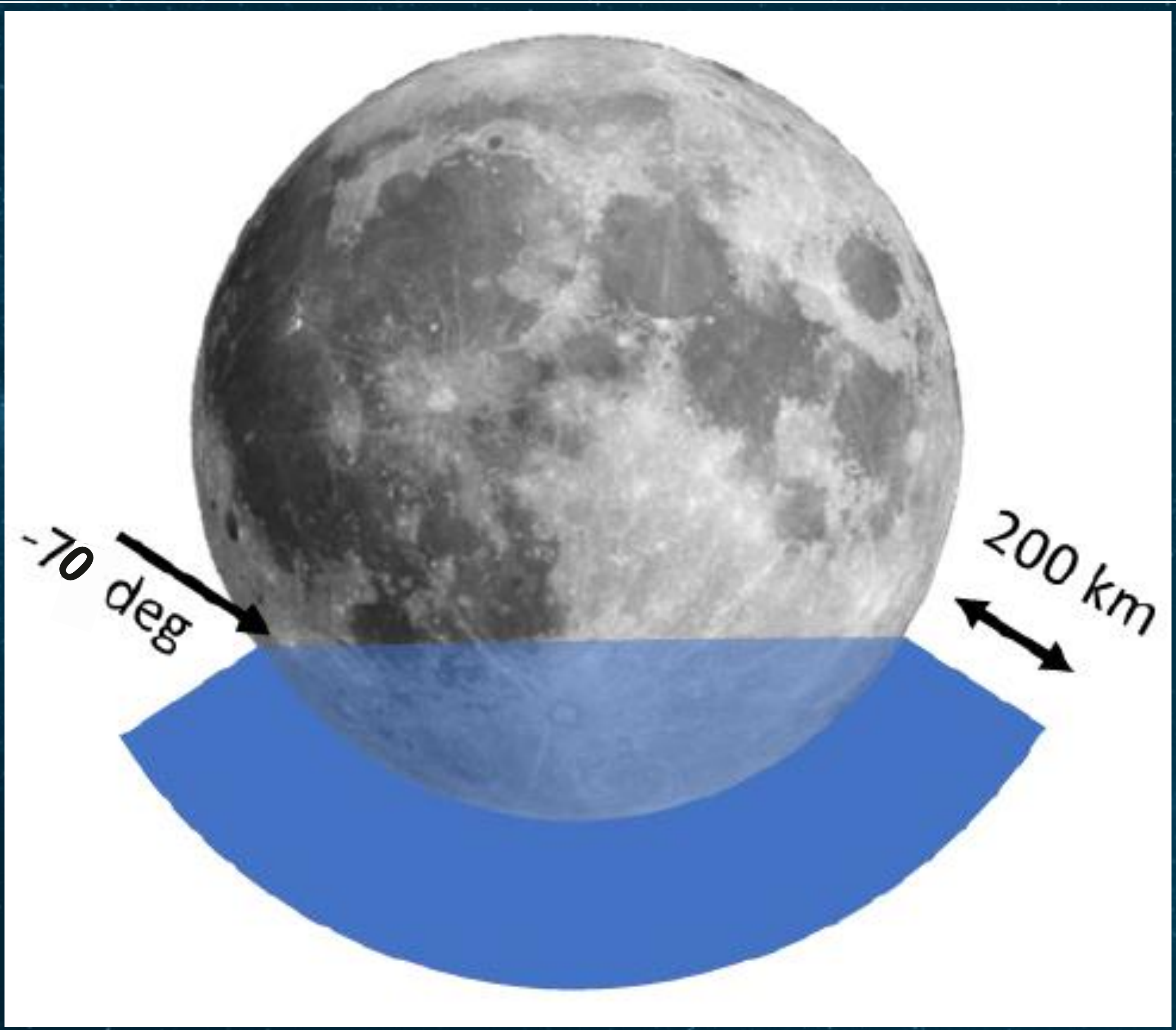


Data transport	Absolute Position
Tele-operations	Absolute Velocity
Audio/Video streaming	Universal time

Third-party payloads	Alert & Information
Over-the-top Services	Search and Rescue

- Public-Private Partnership: Private sector as service provider
- A dedicated constellation of satellites around the Moon

FOCUSING ON THE SOUTH POLE



Moonlight LCNS High-level Service Requirements

High DataRate (KBand)
Upto 200Mbps/user

Low Datarate (Sband)
Upto 1Mbps/user

Security functions

Slotted Real time services

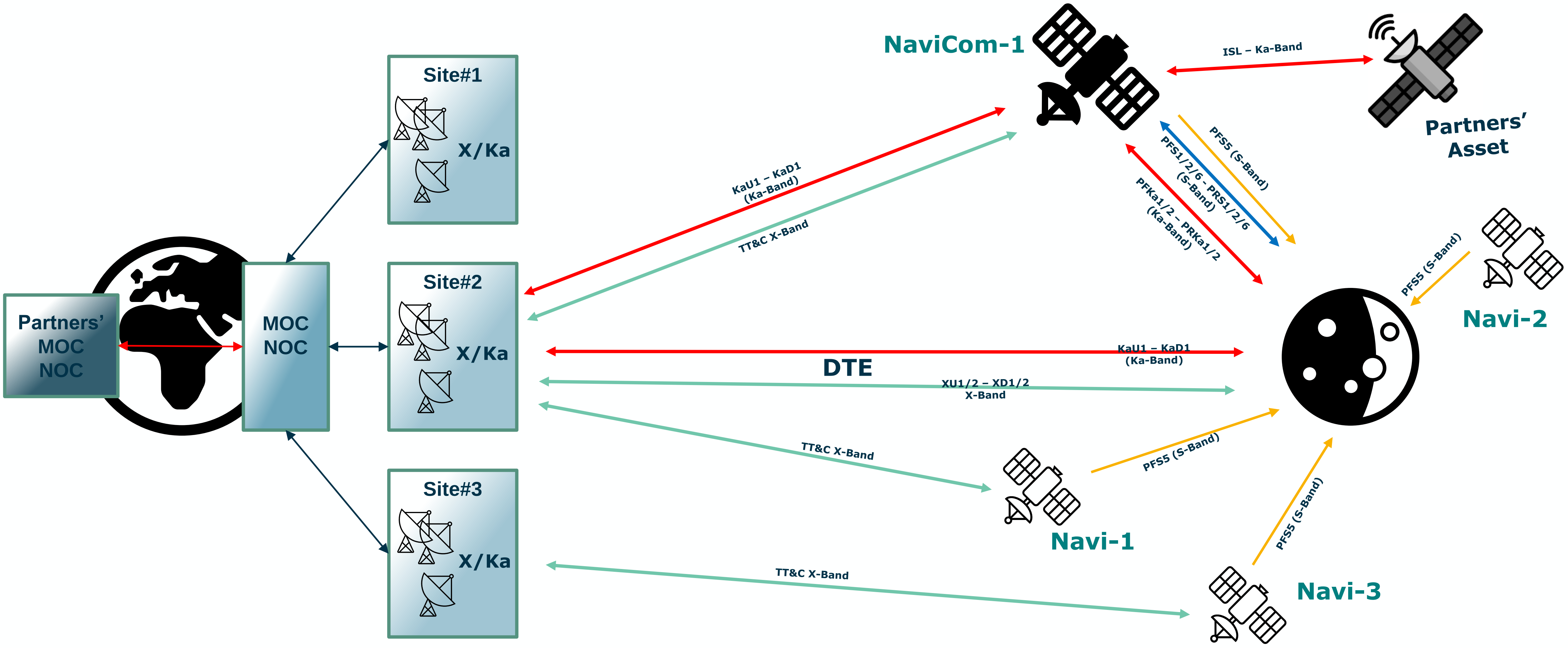
Based on GNSS technologies

Precise timing (95%)
(100 ns)

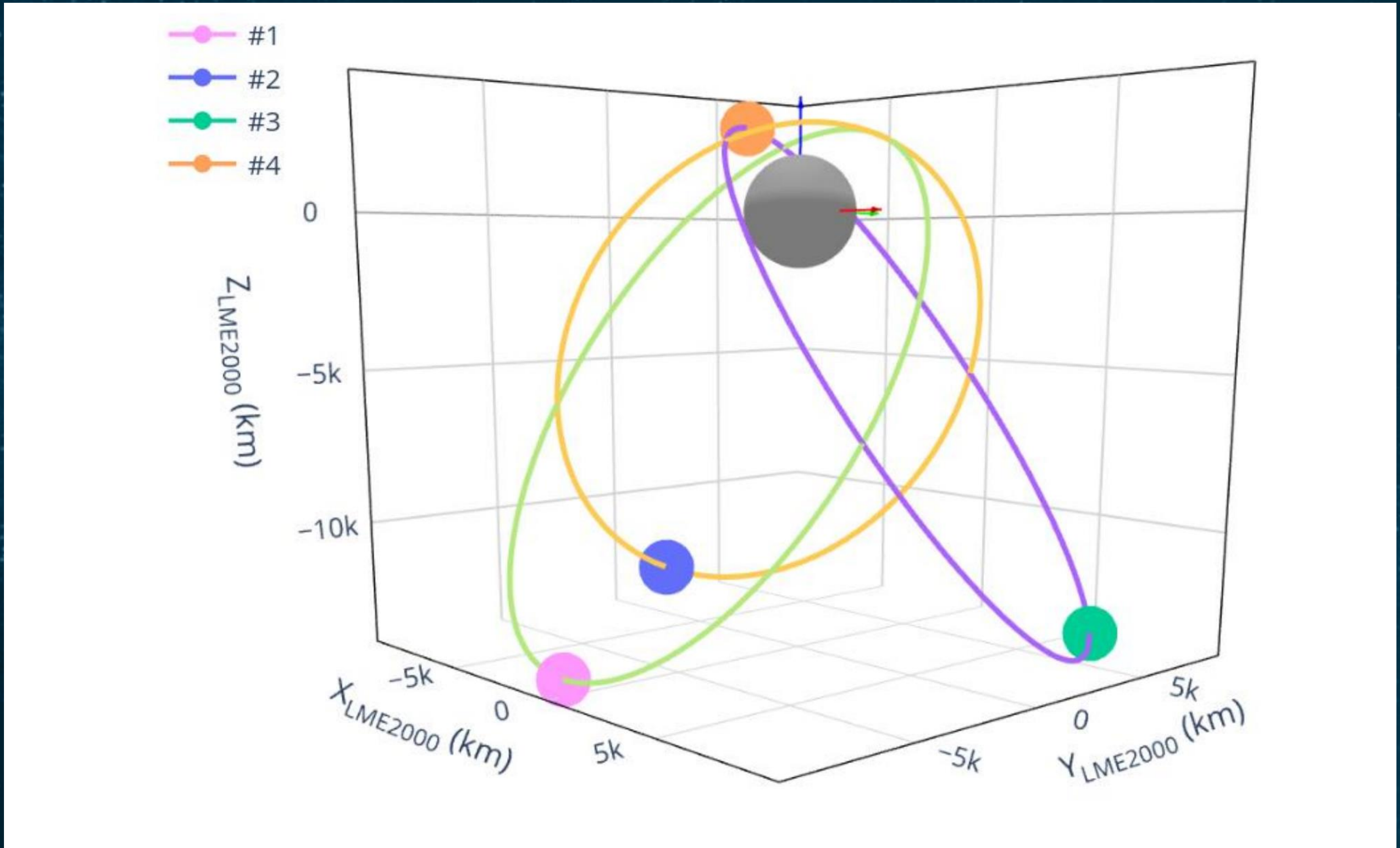
One Way Ranging
SISE ODTS (95%)
IOC: 20 m
FOC: 10 m

Position accuracy (95%)
Orbiters: 100m
Landing: 50m
Surface: 10m
(3m post- processing)

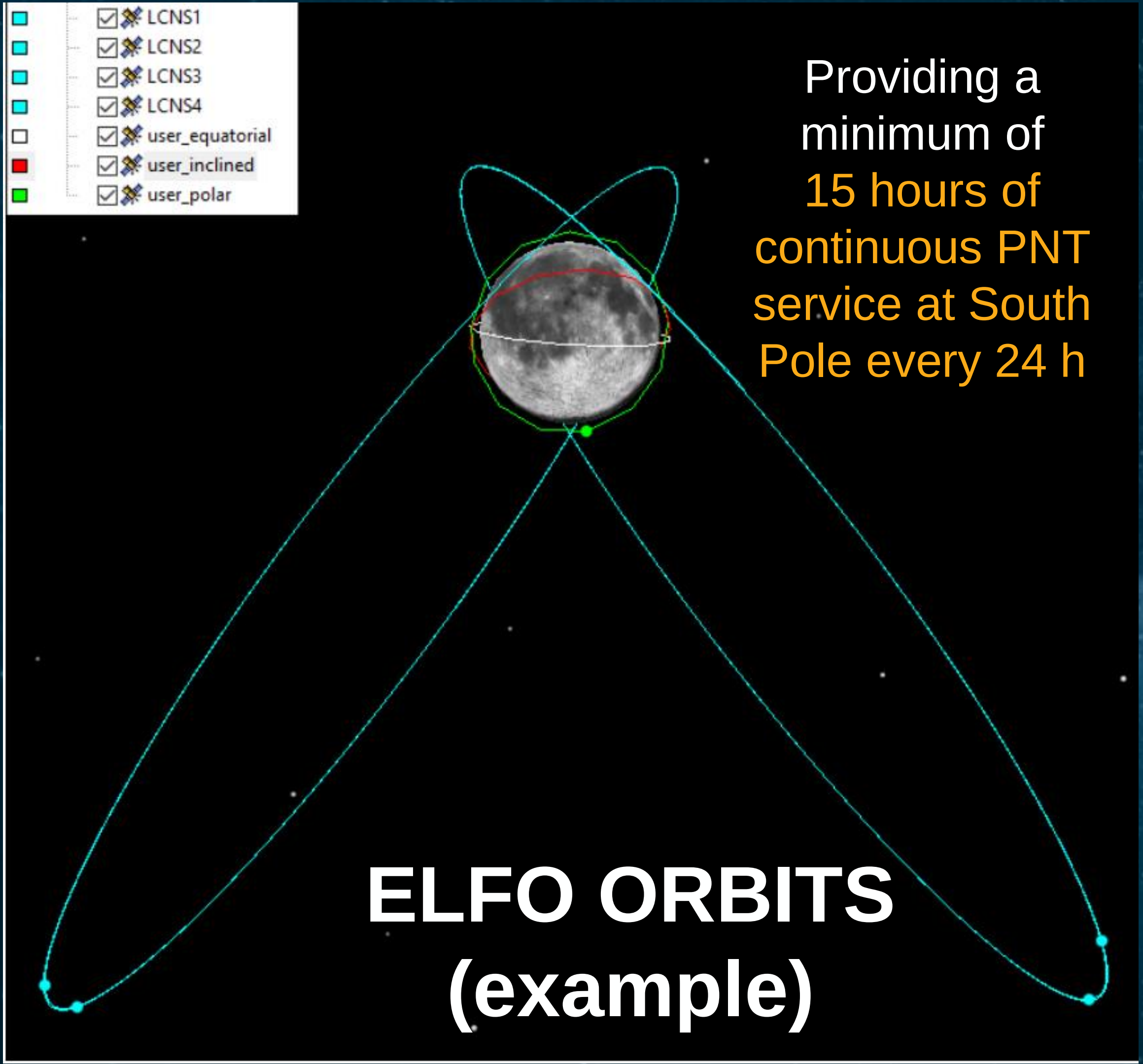
Moonlight: Mission Architectural Concept



Example: 4 satellites constellation: ELFO ORBITS



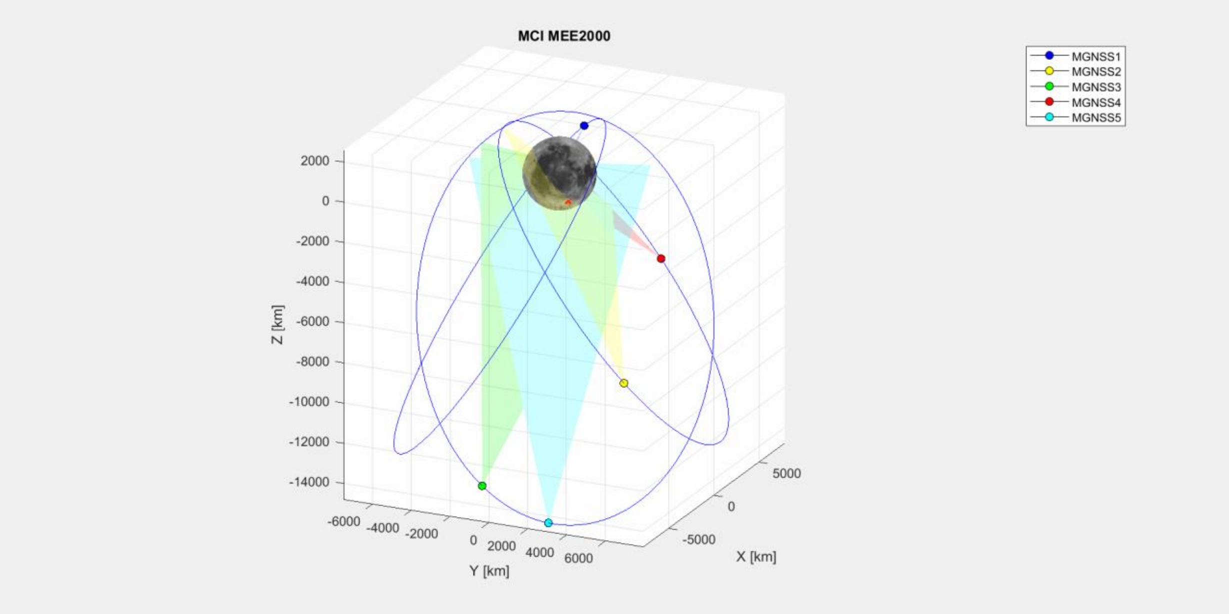
A GNSS-like system on lunar orbit (example)



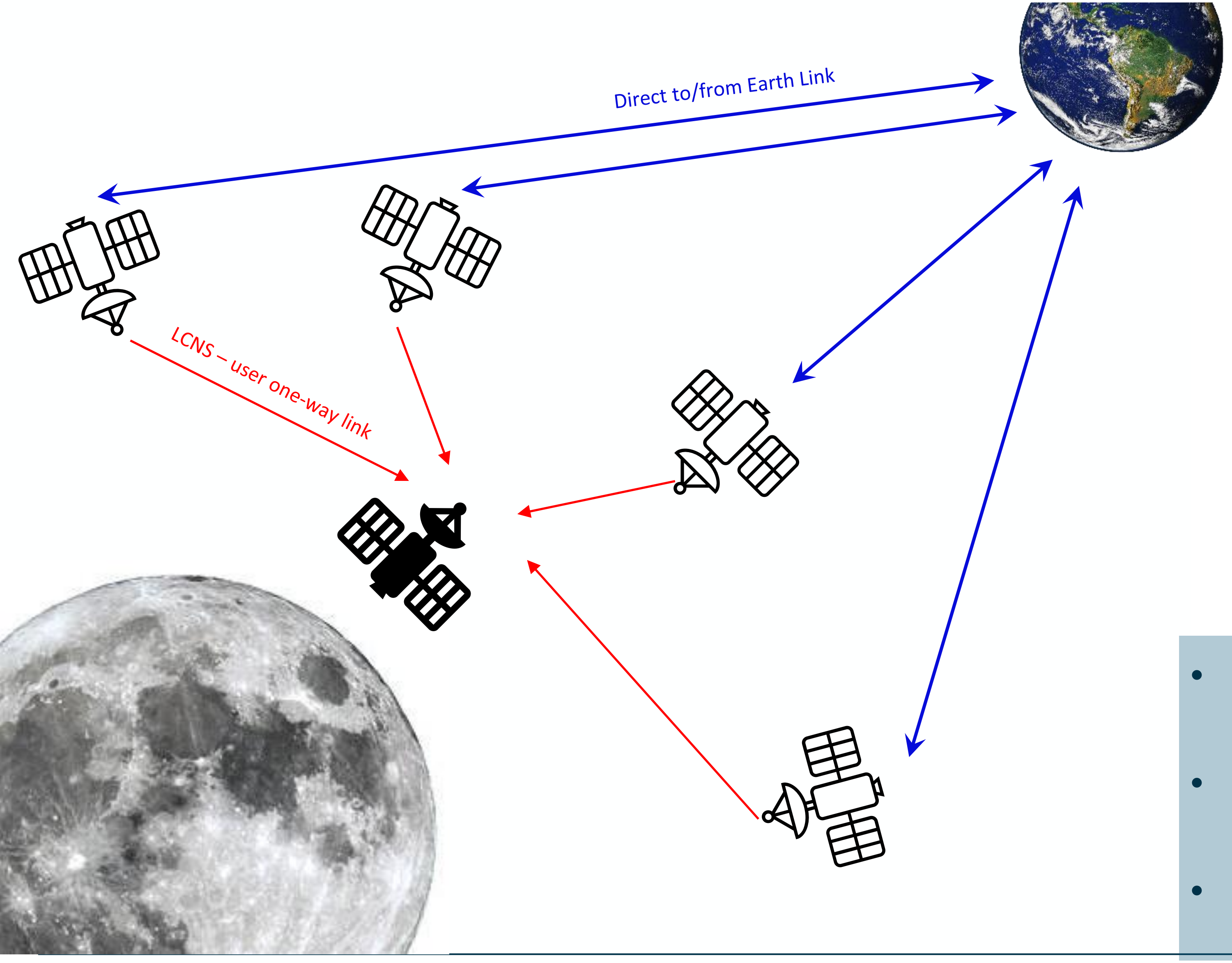
Providing a minimum of 15 hours of continuous PNT service at South Pole every 24 h

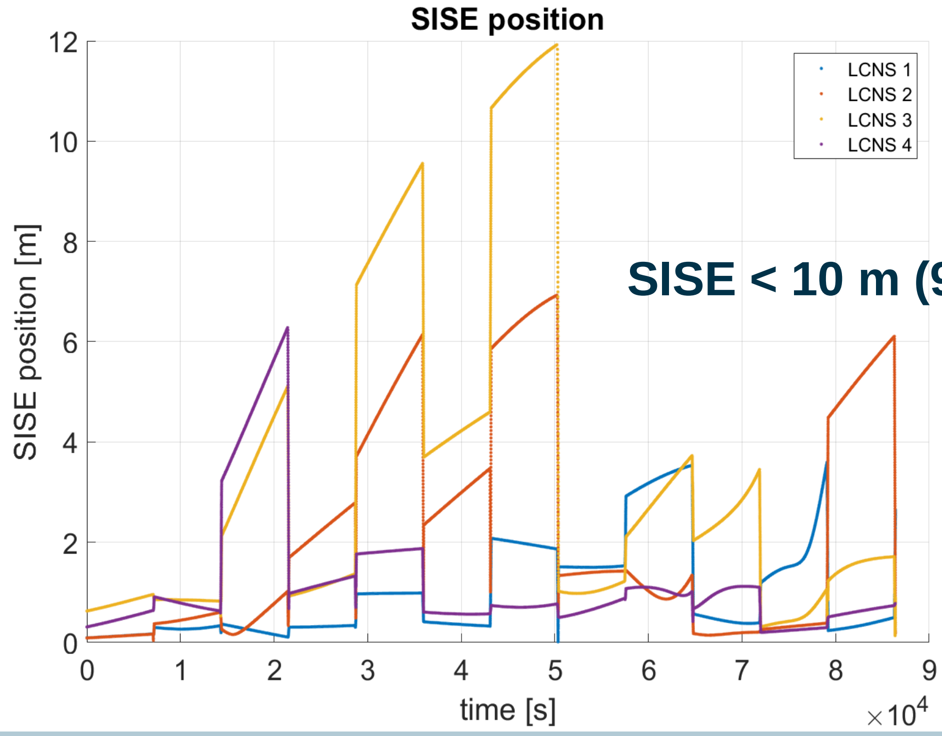
ELFO ORBITS (example)

Satellite Id	1	2	3	4
Semi-Major Axis (km)	9750.73	9750.73	9750.73	9750.73
Eccentricity	0.6383	0.6383	0.6383	0.6383
Inclination (°)	54.33	54.33	61.96	61.96
Argument of pericenter (°)	55.18	55.18	121.7	121.7
RAAN (°)	277.53	277.53	59.27	59.27
True Anomaly (°)	123.42	0	180	0



Navigation ODTS concept: Direct to Earth tracking

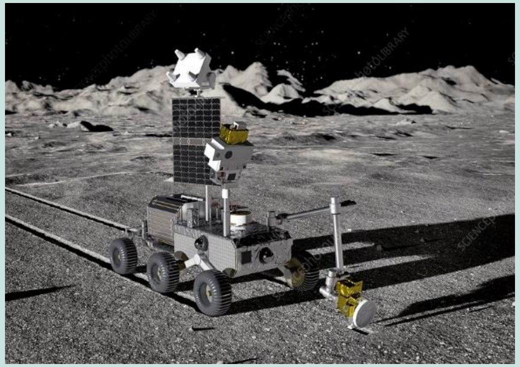
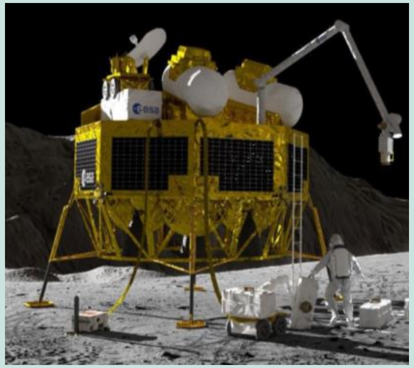
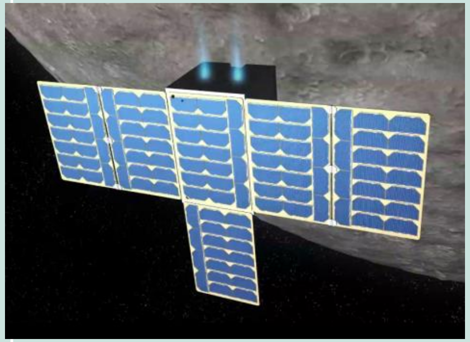
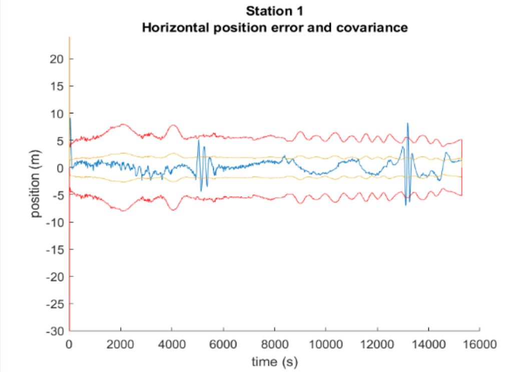
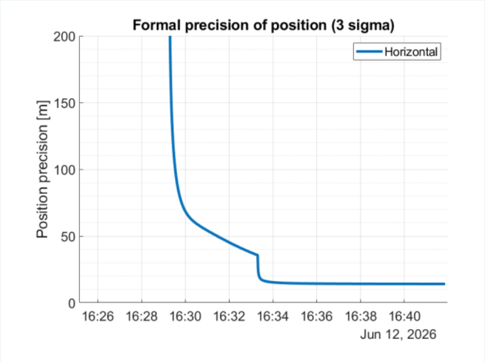
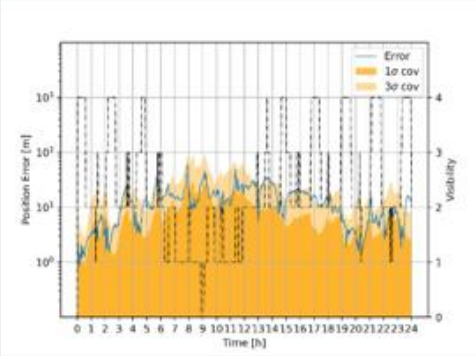




SISE < 10 m (95%)

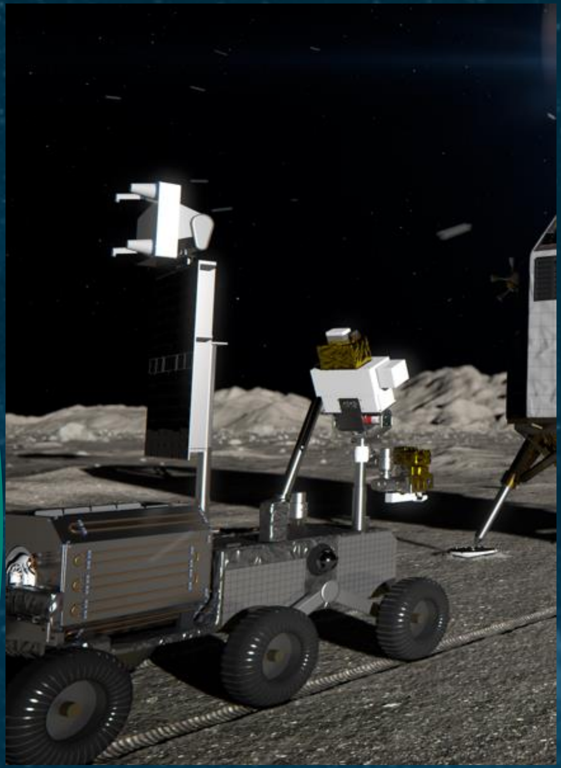
- Time Transfer between satellites and Earth ground stations (EGS)
- Ranging and Doppler measurements between satellites and EGS
- Navigation message generated on ground

Moonlight PNT services are at reach with proposed GNSS technologies ! Extensive ESA and industrial simulations & analysis performed

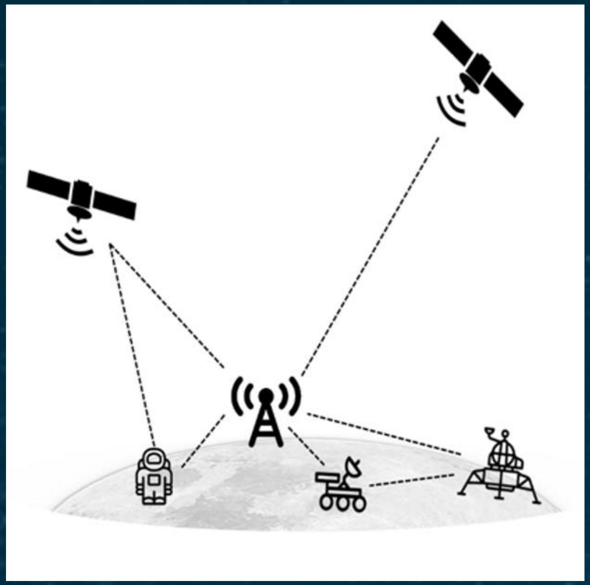
Surface Rover	Lunar Lander	Lunar Orbiter
 Real time < 10 m (95%) Post-processing < 3 m (95%	 < 50 m (95%) Landing accuracy	 Real time < 100 m (95%) LLO accuracies
 3-5 meters	 ~20 meters	 30-60 meters
Ref: Navigation Performance of a Lunar Surface Rover Using LCNS Positioning Assuming Realistic ODTS Performances, EUROPEAN NAVIGATION CONFERENCE 2023	Ref: Positioning and Velocity Performance Levels for a Lunar Lander using a Dedicated Lunar Communication and Navigation System, Navigation Journal 2022	Ref: Navigation performance of Low Lunar Orbit satellites using a Lunar Radio Navigation Satellite System, ION-GNSS 2023

Enhancing Moonlight Capabilities: On-going R&D

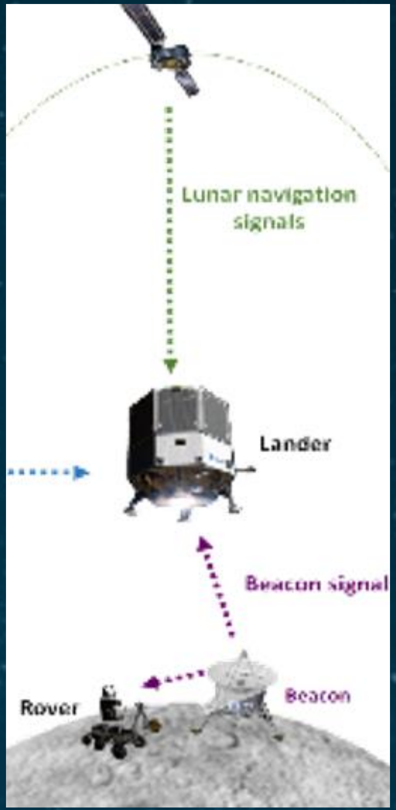
Optimal combination of Moonlight Navigation signals with landing sensors (enhanced GNC system)



Combining Moonlight Navigation signals with rover sensors

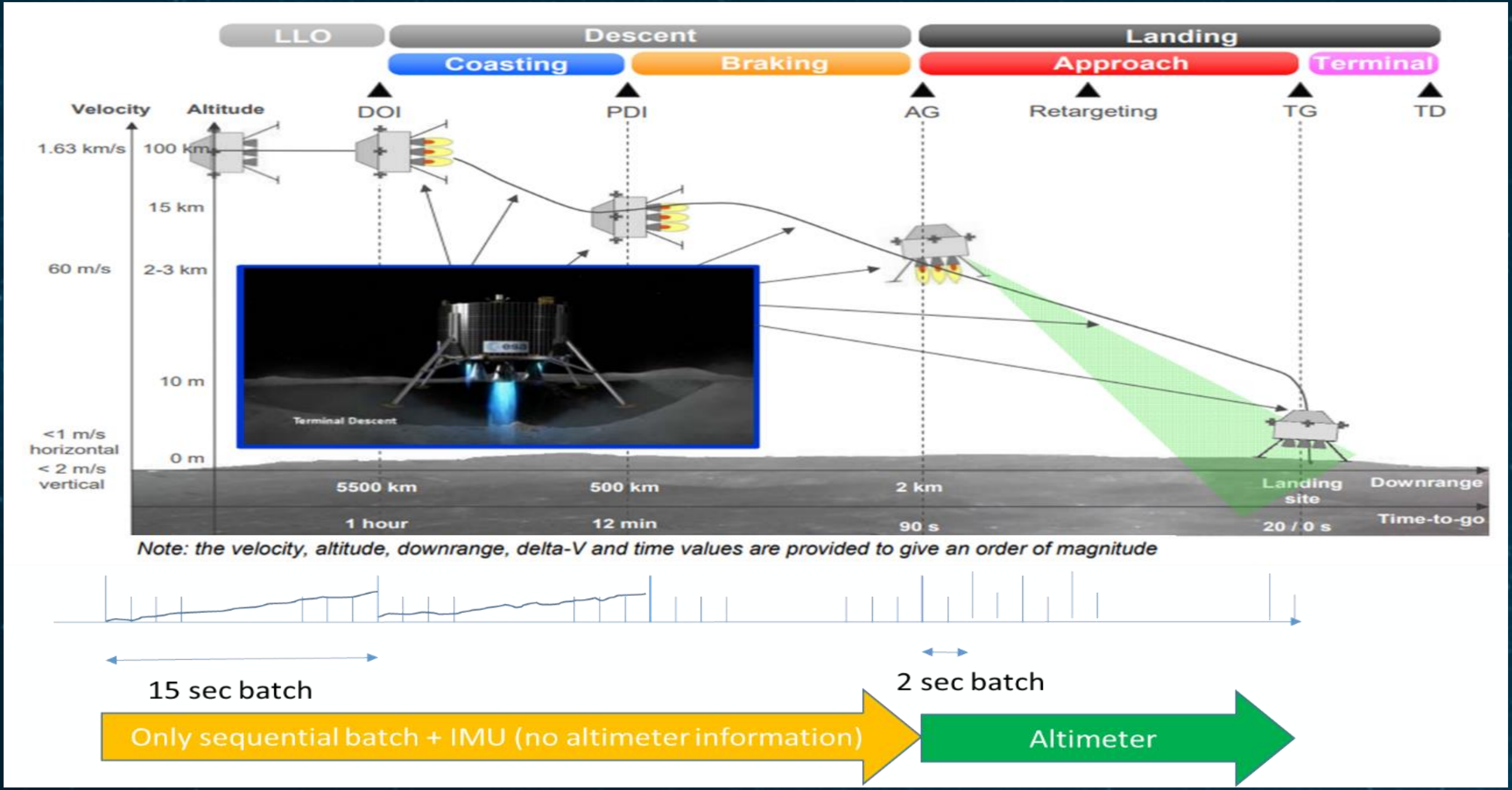


Lunar Local Differential Navigation systems based on Moonlight System

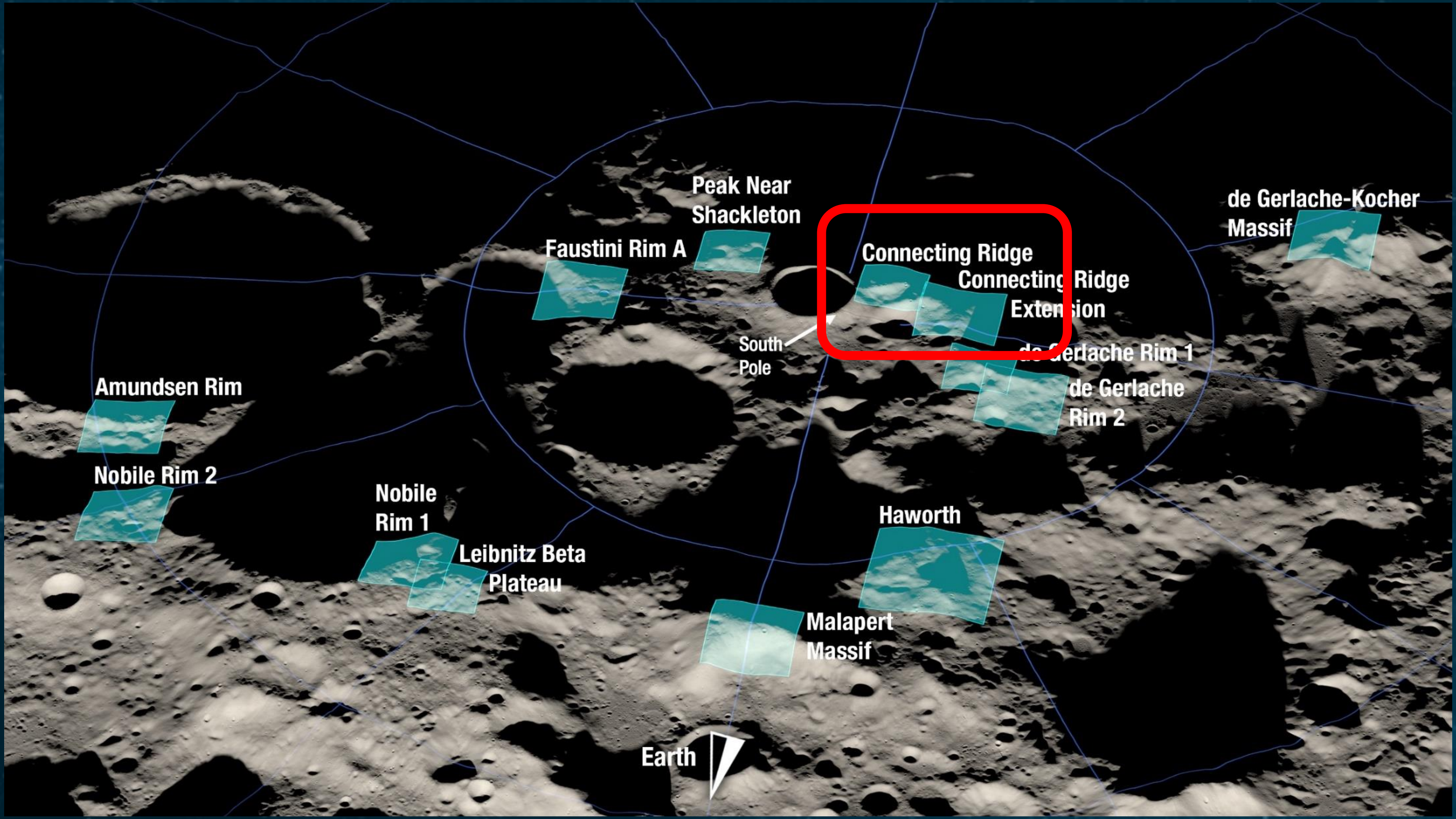


Addition of Lunar-based ranging beacons

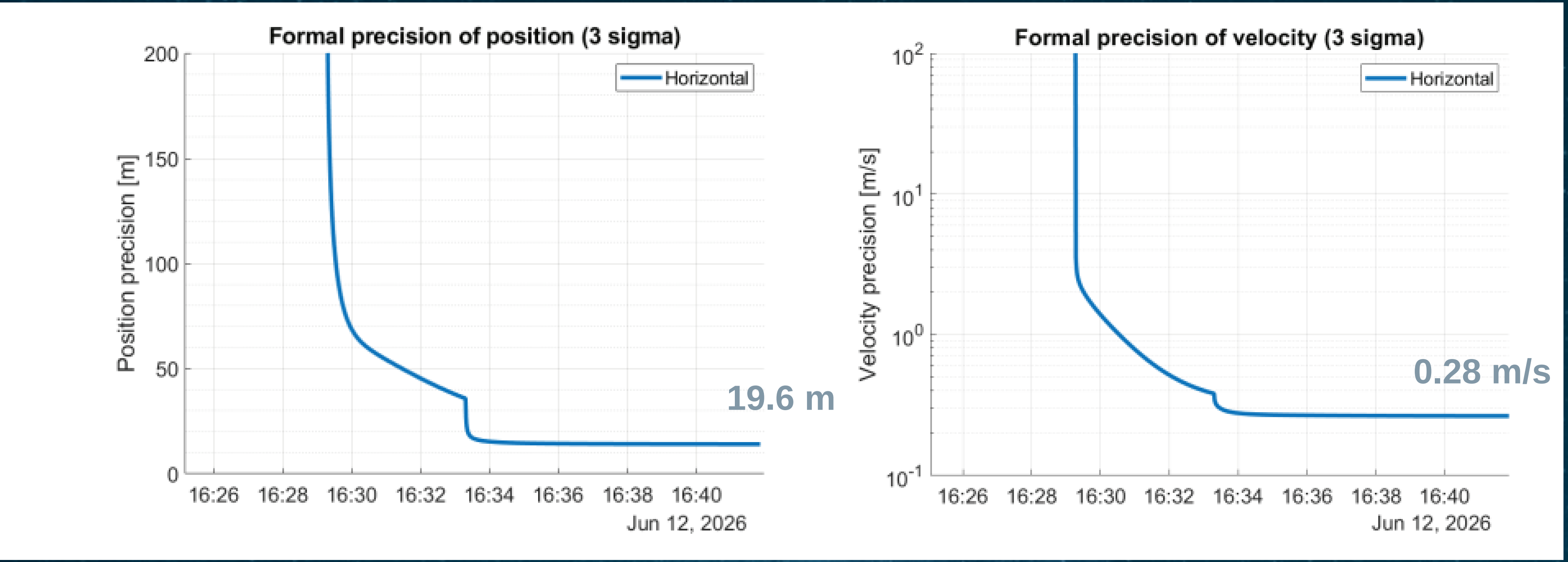
Example of potential Moonlight Performances for Moon landing



Lunar Landing locations proposed for Artemis 3



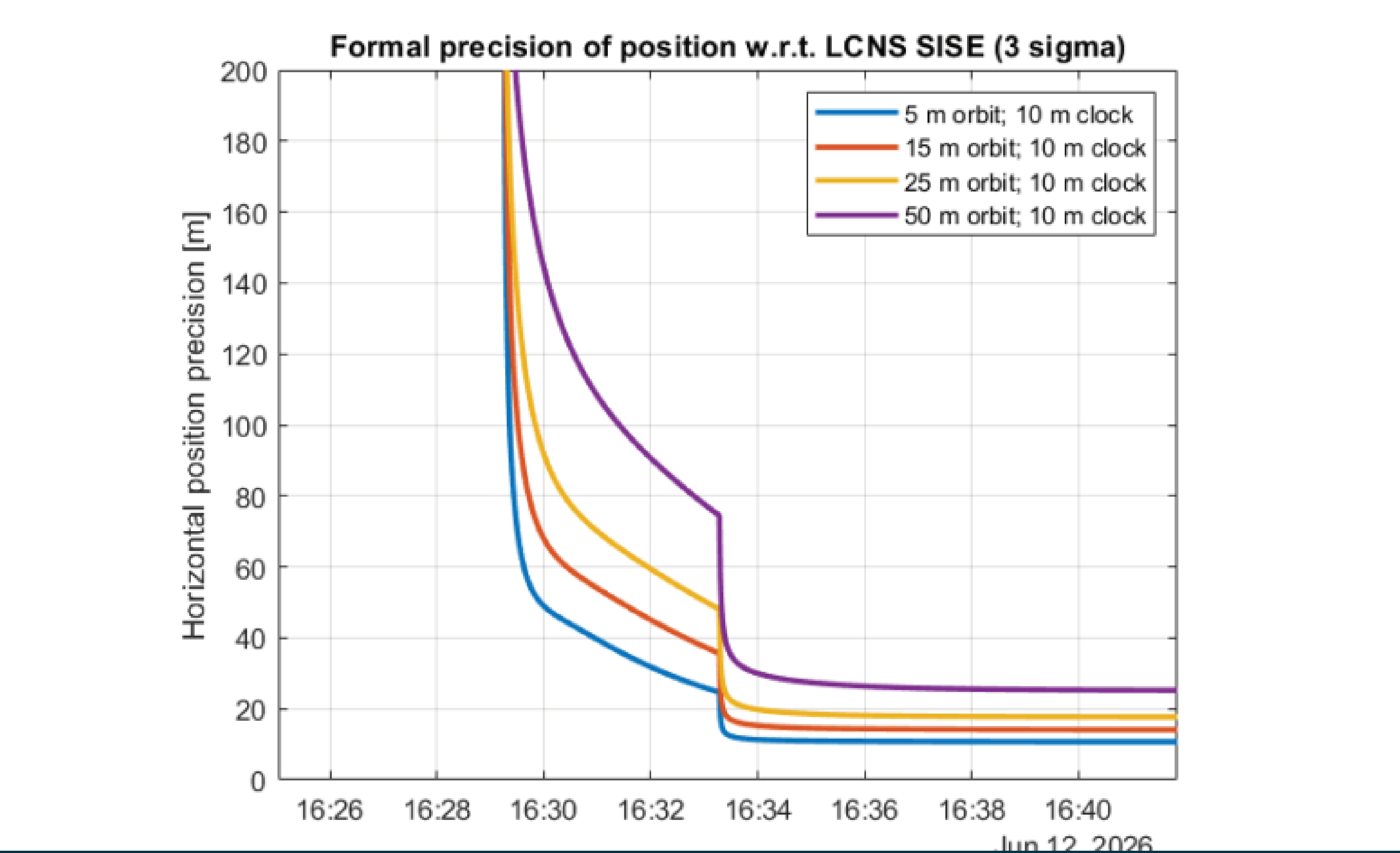
Landing performances assuming ODTS orbit errors (x,y,z) (15, 15 , 15) m and clock errors of 10 m (all values 1 sigma)



Combining LCNS signals with a simple IMU and an altimeter the achieved final landing horizontal precision is below 20 m 3-sigma !!

Note: Details published at "*Positioning and Velocity Performance Levels for a Lunar Lander using a Dedicated Lunar Communication and Navigation System* " ION Navigation Journal 2022

Landing accuracy: sensitivity to LCNS ODTS SISE Values

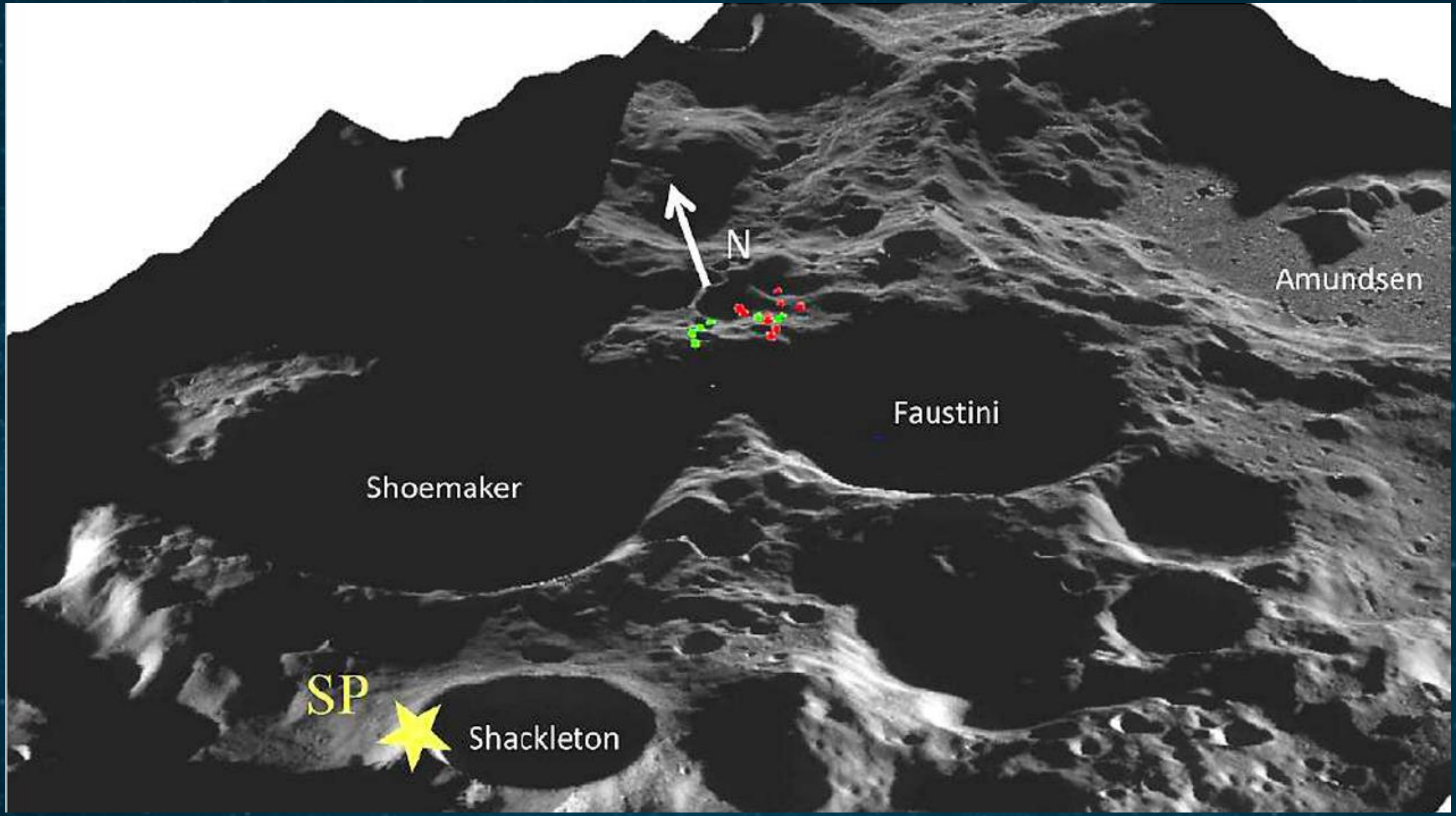


Landing on Permanent Shaded Regions (PSRs)

Areas on some craters near the Moon's poles where sunlight never shines (permanently shadowed)

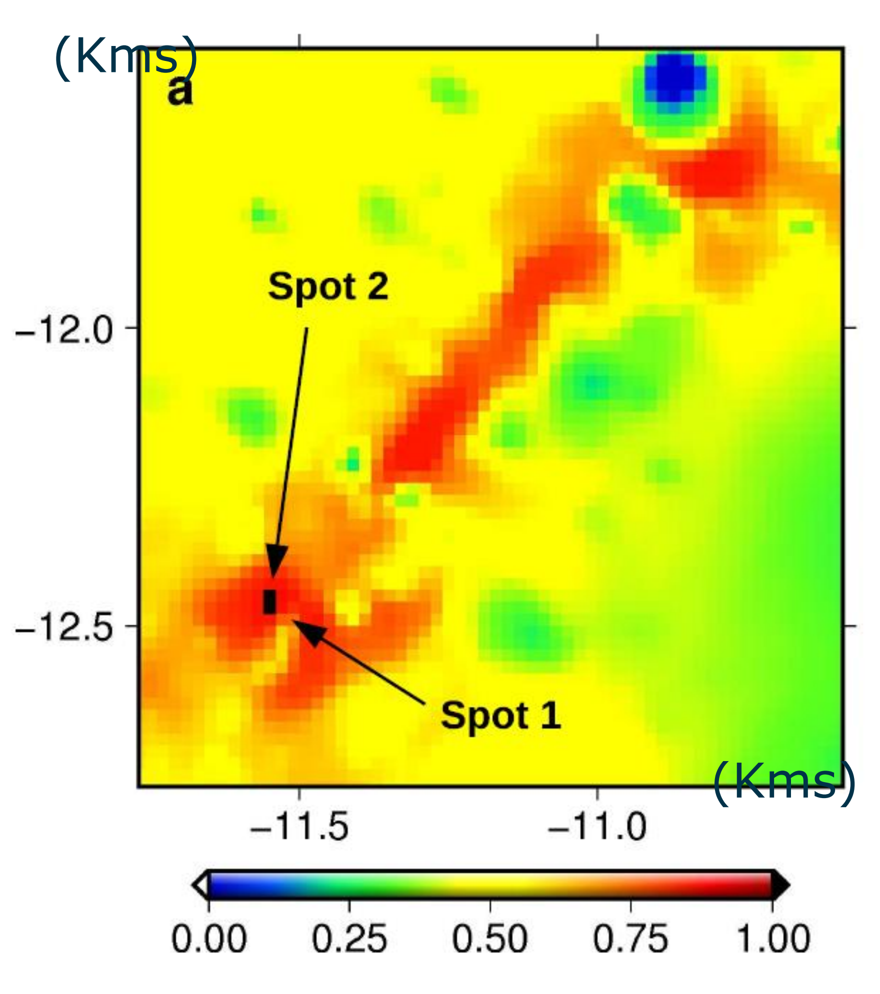
These are of high interested because they preserve water ice and other minerals.

Key to support sustainable exploration, of high scientific interest and may also lead to commercial opportunities.



Landing on these sites is challenging due to the difficulty to use optical/visual navigation sensors !

Landing at Peaks of eternal light (PELs) require very high landing accuracies



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

Source: EPSC Congress

Areas wit extended periods of sunlight exposition, on some crater rims near the poles

Example Connecting Ridge-1 (89.4 South, 222.6 East). connecting the Gerlache and Shackleton craters.

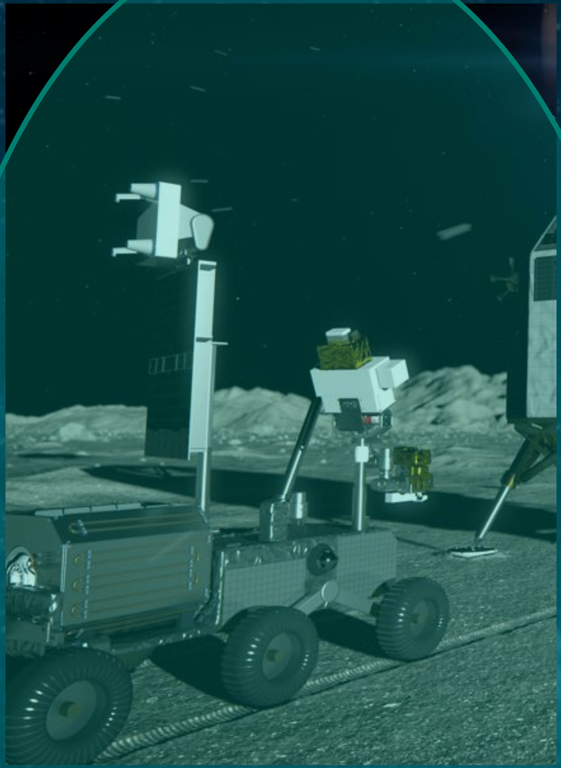
PELs are of very high interest since they potentially allow the exclusive use of solar panels over long mission durations.

PELs are key for sustainable lunar exploration and for future lunar Base settlements.

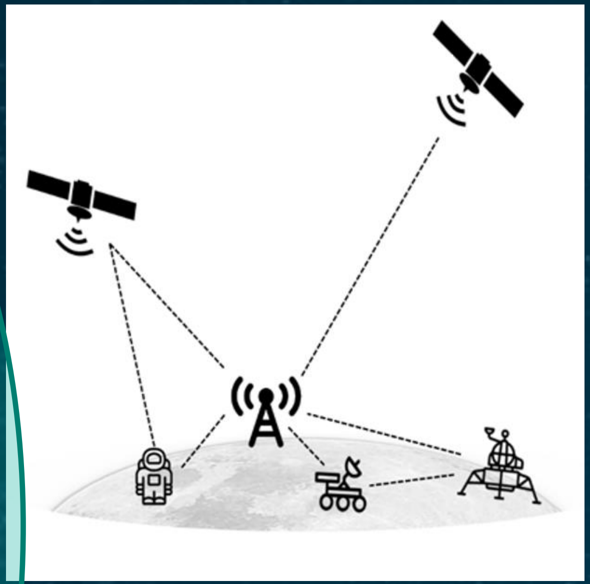
Landing accuracies required bellow 100 metres !!

Enhancing Moonlight Capabilities: On-going R&D

Optimal combination of Moonlight Navigation signals with landing sensors (enhanced GNC system)



Combining Moonlight Navigation signals with rover sensors



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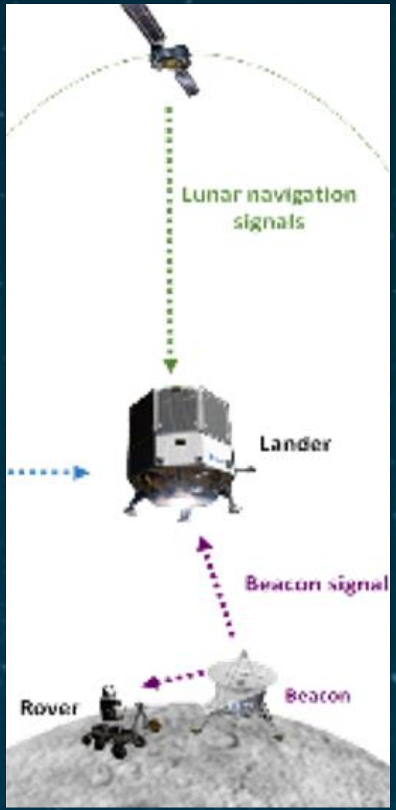
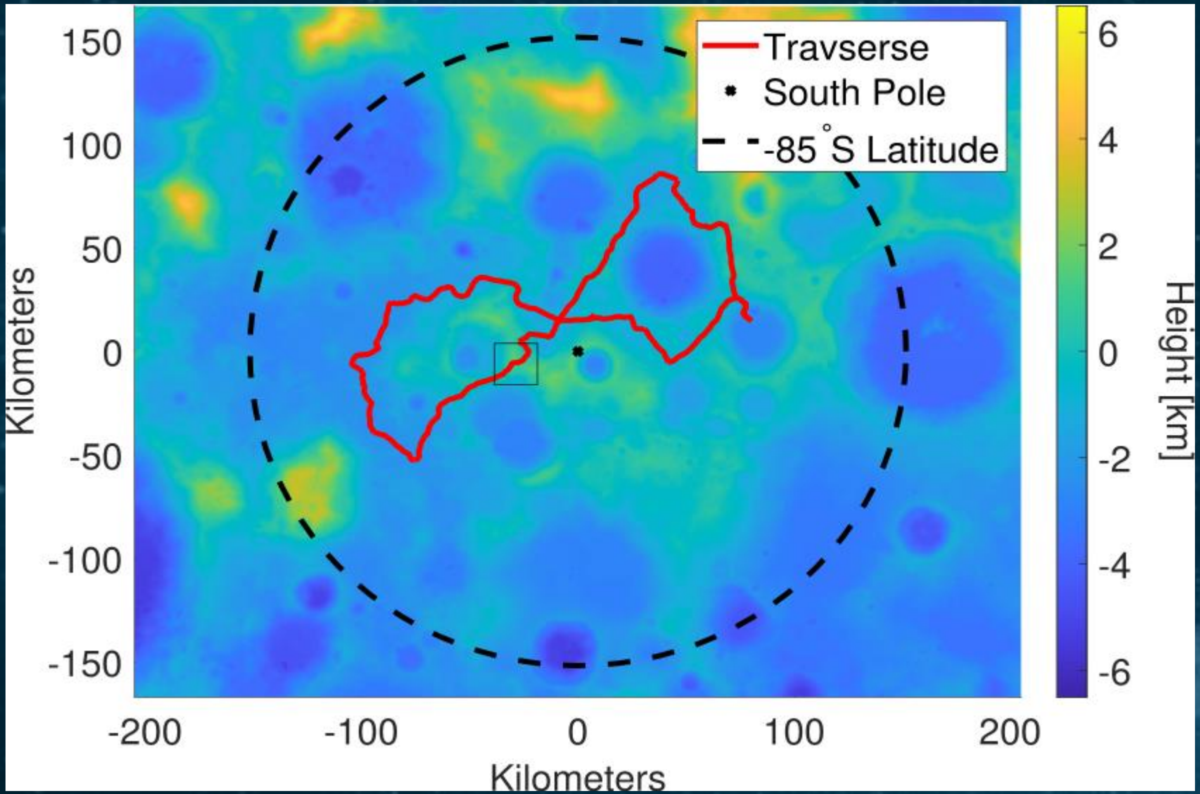
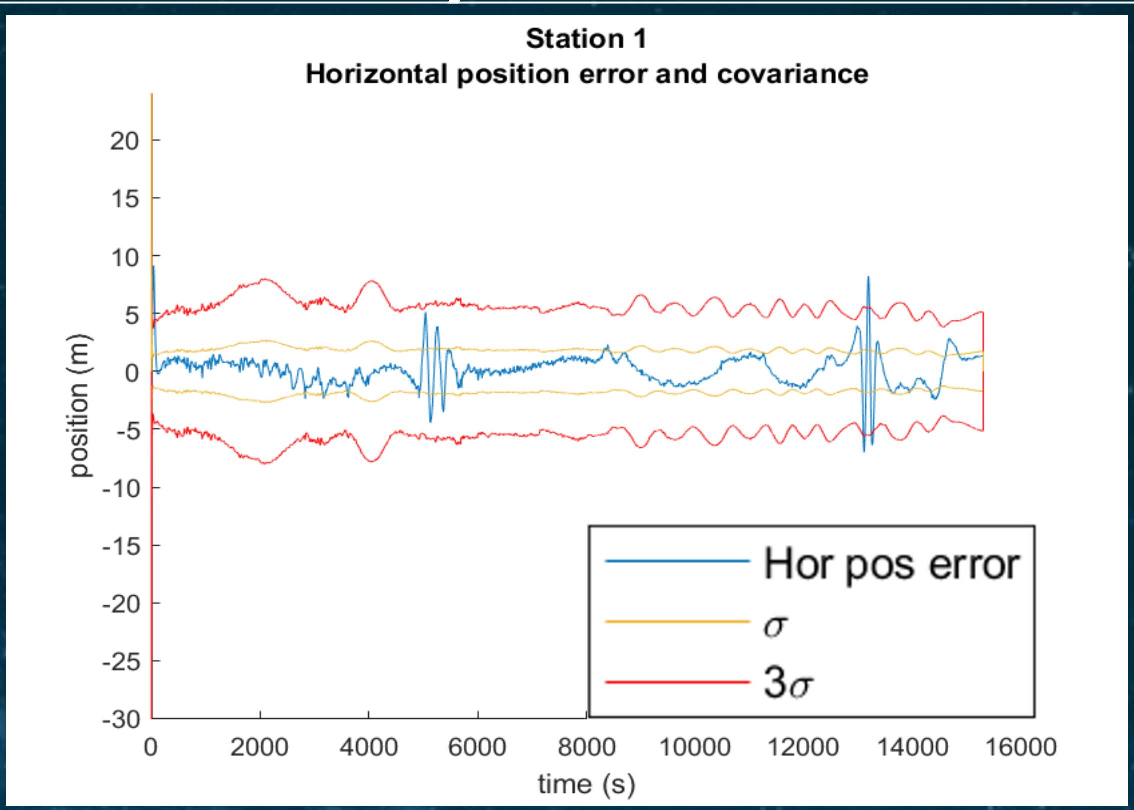


Addition of Lunar-based ranging beacons

Combining Moonlight ranging signals with DEM information (5 m/px assumed here)





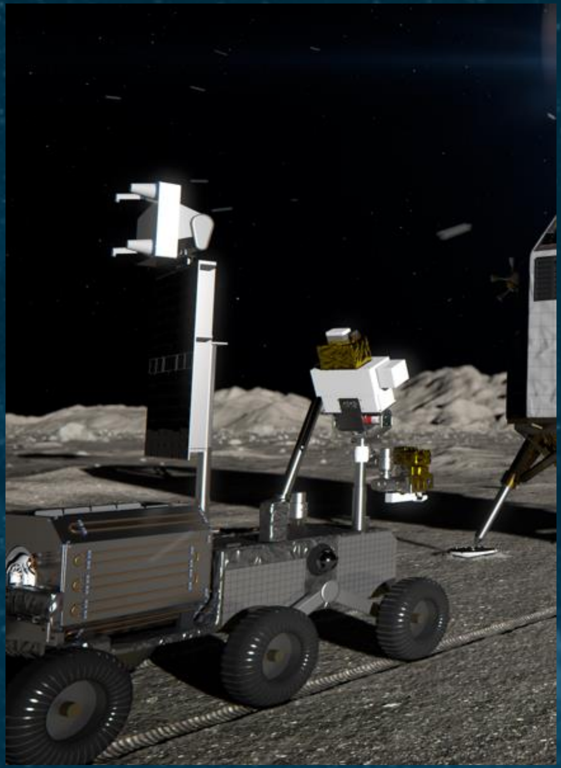
ODTS of Moonlight ELFO satellites simulated based on Direct-to-Earth Ranging measurements (from 3 Earth sites) for a lunar rover moving around 5 km/h.

Performances obtained when combining Moonlight resulting ranging signals with local DEM information: **Position errors (3 sigma values) below 10 meters shown to be at reach in real time** !

Note: Details at "*Navigation Performance of a Lunar Surface Rover Using LCNS Positioning Assuming Realistic ODTS Performances*", ENC Conference May 2023.

Enhancing Moonlight Capabilities: On-going R&D

Optimal combination of Moonlight Navigation signals with landing sensors (enhanced GNC system)



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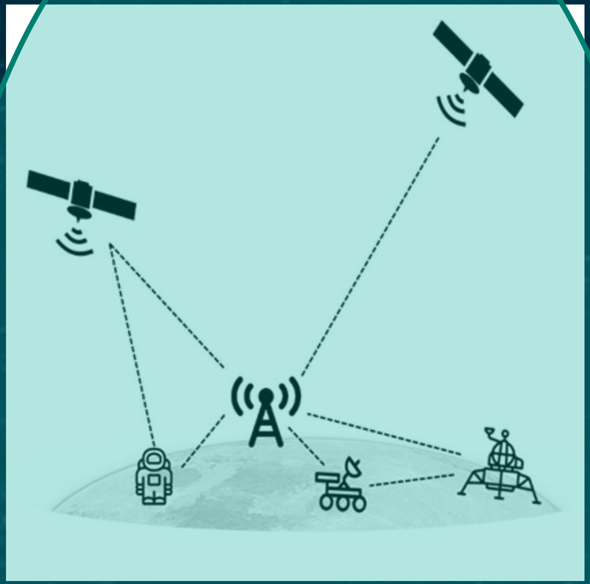

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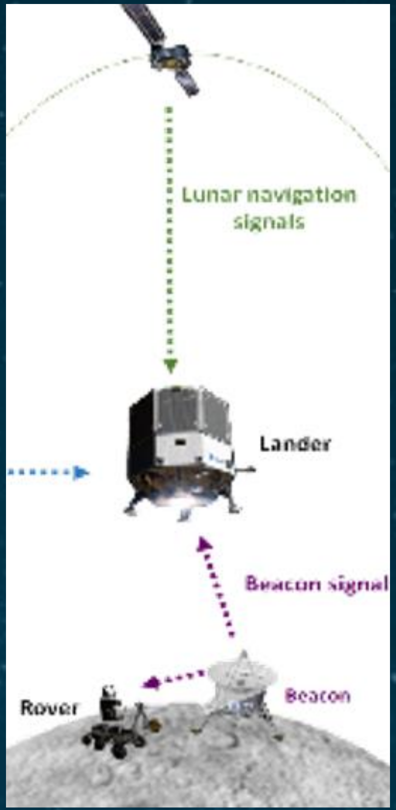
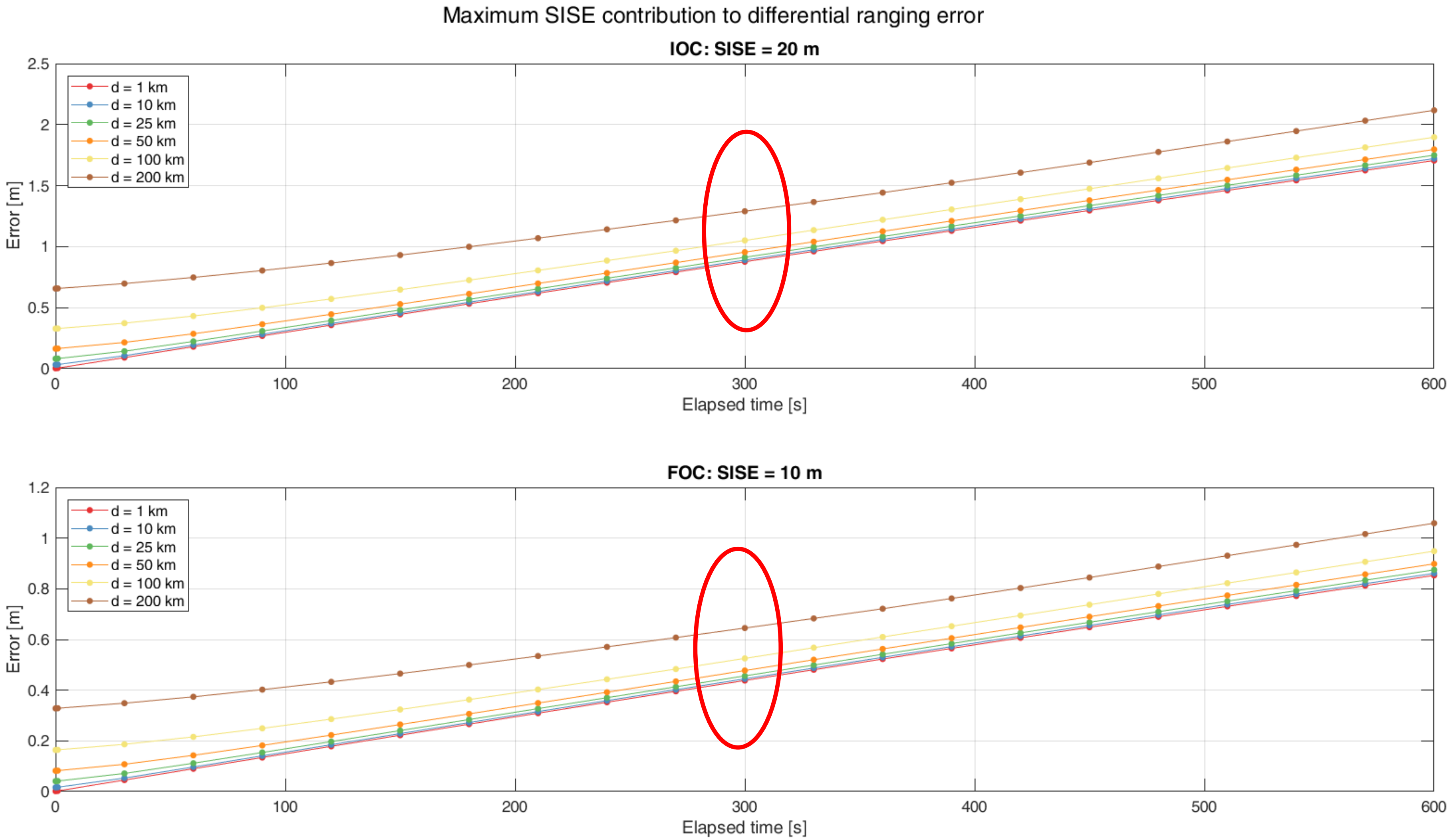


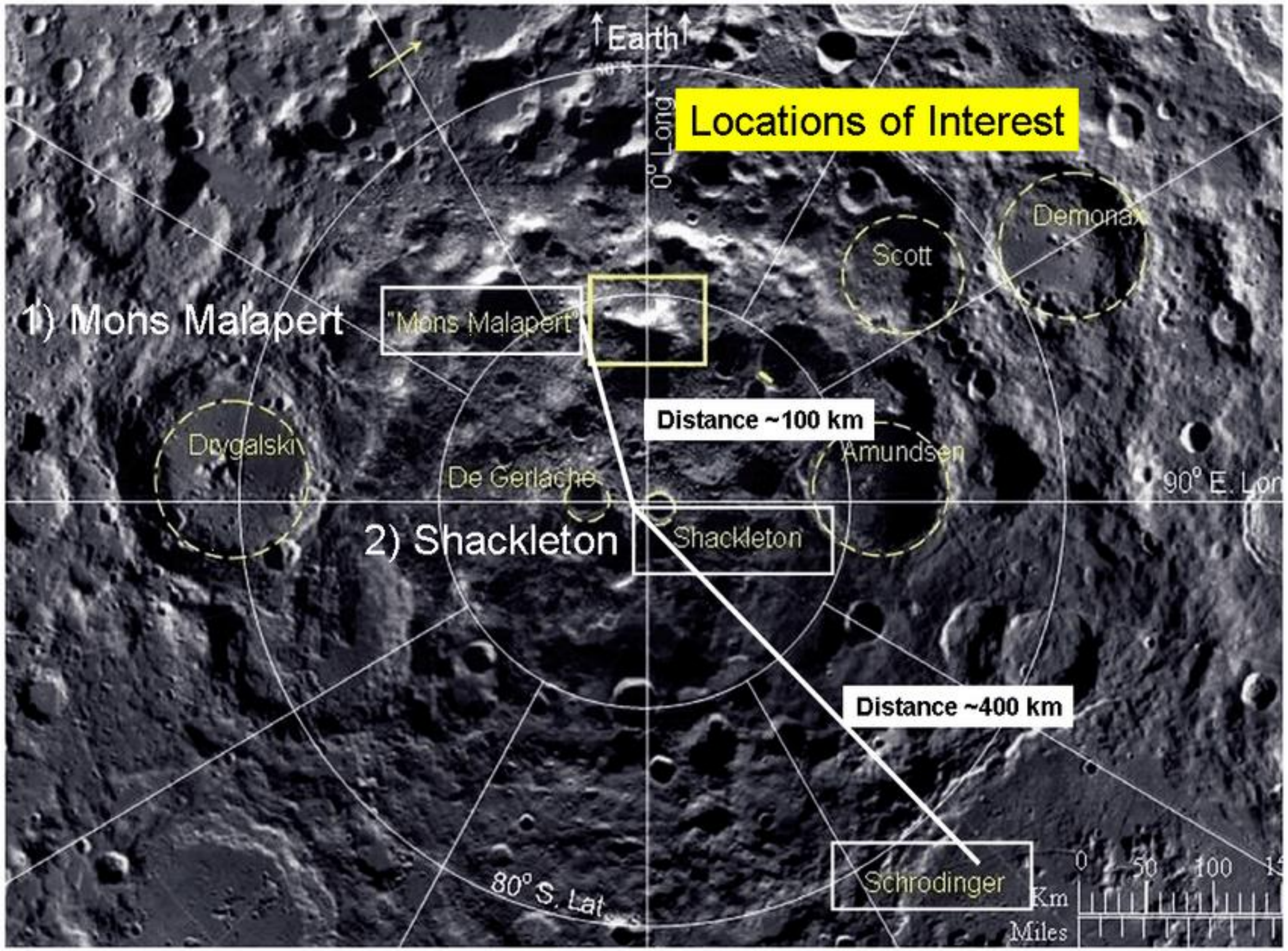
Addition of Lunar-based ranging beacons

Impact of a Moon-based local differential station on SISE Ranging error vs distance and message update rate



Source: QASCOM (ESA NAVISP-062 activity)

Complementing Moonlight with a Local Differential Station?



A well-placed single Moonlight Differential Station could potentially support a large part of the South Pole service volume.

The "augmentation" message (PR corrections) could also be broadcast via the Moonlight System.

MOONLIGHT will be developed to comply with LunaNet Interoperability Specifications

LunaNet Interoperability Specification Document

DRAFT

Draft Version 5

LNIS V005 August 31, 2023 1

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

DRAFT

Draft Version 1

Noted as Applicable Document 1 [AD1] in LNIS V5

LSIS V1.0 Draft August 31, 2023 1

Joint NASA and ESA cooperation initiative with the support also of JAXA. All our three systems will provide interoperable lunar GNSS-like Signals and messages, allowing common receivers and enhanced performances


LunaNet Signal-In-Space Recommended Standard - Augmented Forward Signal (LSIS)
Draft Version 1
Noted as Applicable Document 1 [AD1] in LNIS V5
ION GNSS+
SPEAKER

AD1 Introduction (4/4)

AFS signal specifications

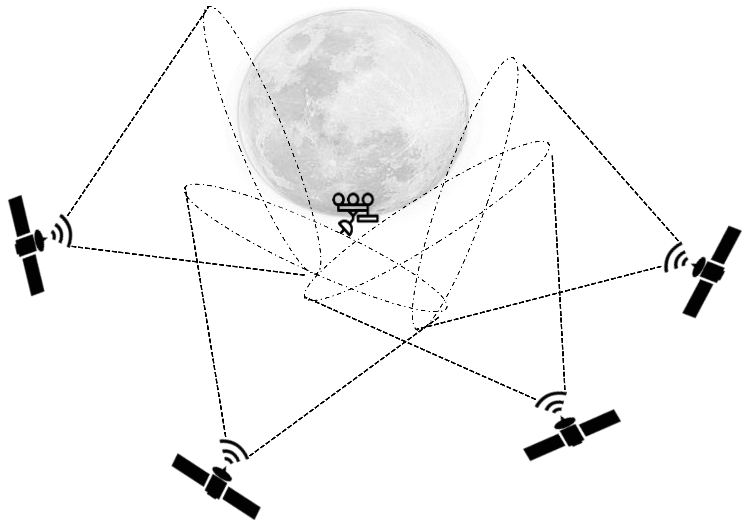
AFS Navigation message format specifications

AFS Message and data content specifications

AD1 Introduction

LANS characteristics:

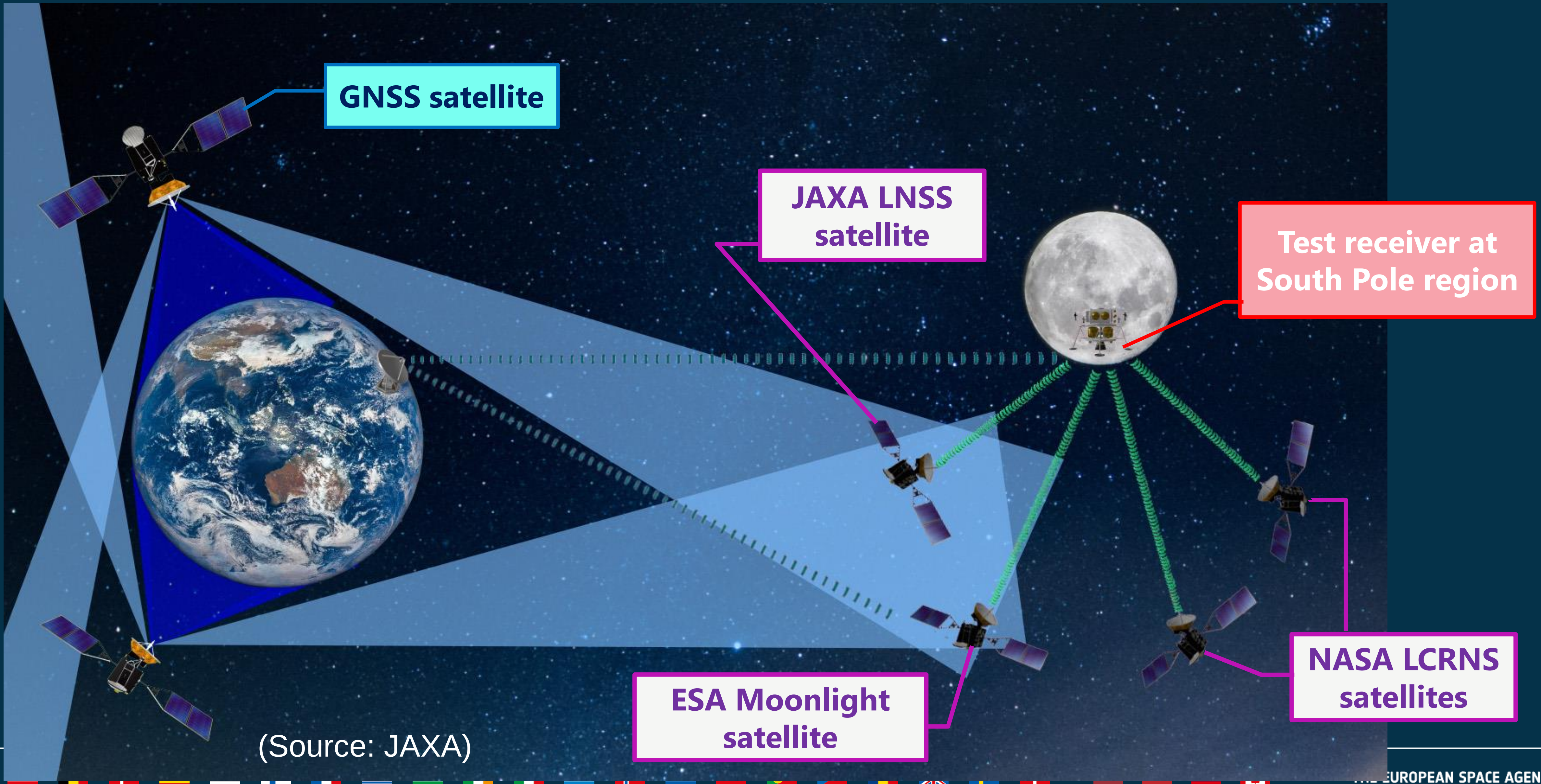
- The concept is similar to GNSS (maximum reuse of GNSS techniques and technologies).
- This service is provided from multiple providers nodes to multiple users at the same time.



LANS Interoperability: each service provider that claims to be LunaNet compliant (becoming a LunaNet Service Provider, LNSP) for the LANS service, must:

- **Be compliant to a common signal and message structure (Augmented Forward Signal, AFS).** — AD1 LSIS
- **Adopt a common lunar reference system (including reference frame) and lunar time system.** — Under definition
- **Be compliant to Signal In Space Error requirements.**

First-ever lunar PNT interoperability demonstration could take place in 2028 (under joint assessment by JAXA, ESA and NASA)



DISCUSSION ON WG B-ON POTENTIAL RECOMMENDATION IN SUPPORT OF LUNAR PNT INTEROPERABILITY

1. Several space agencies are currently planning to develop **dedicated lunar communication and navigation services within this decade**.

2. NASA, ESA and JAXA the three agencies are actively working together in the development of the **LunaNet** Interoperability Specification (LNIS), which is also being discussed at the IOAG and open publicly for comments. This includes now the AD1 SiS PNT description.

3. **Lessons learned ICG**: " Earth GNSS systems developed their own signal in space standards independently, which often required a major effort to ensure their mutual interoperability and widespread use by user equipment."

4. **Unique opportunity to work towards Lunar-based PNT systems interoperability recommending service providers provide the same Lunar PNT standards → Discussion of possible "*Joint Statement*" or "*Recommendation*" in support of Lunar PNT Interoperability and common stnadards.**

Thank you!