TOWARDS LUNANET LUNAR AUGMENTED NAVIGATION SERVICE (LANS) INTEROPERABILITY DEMONSTRATION AND MONITORING

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Topics

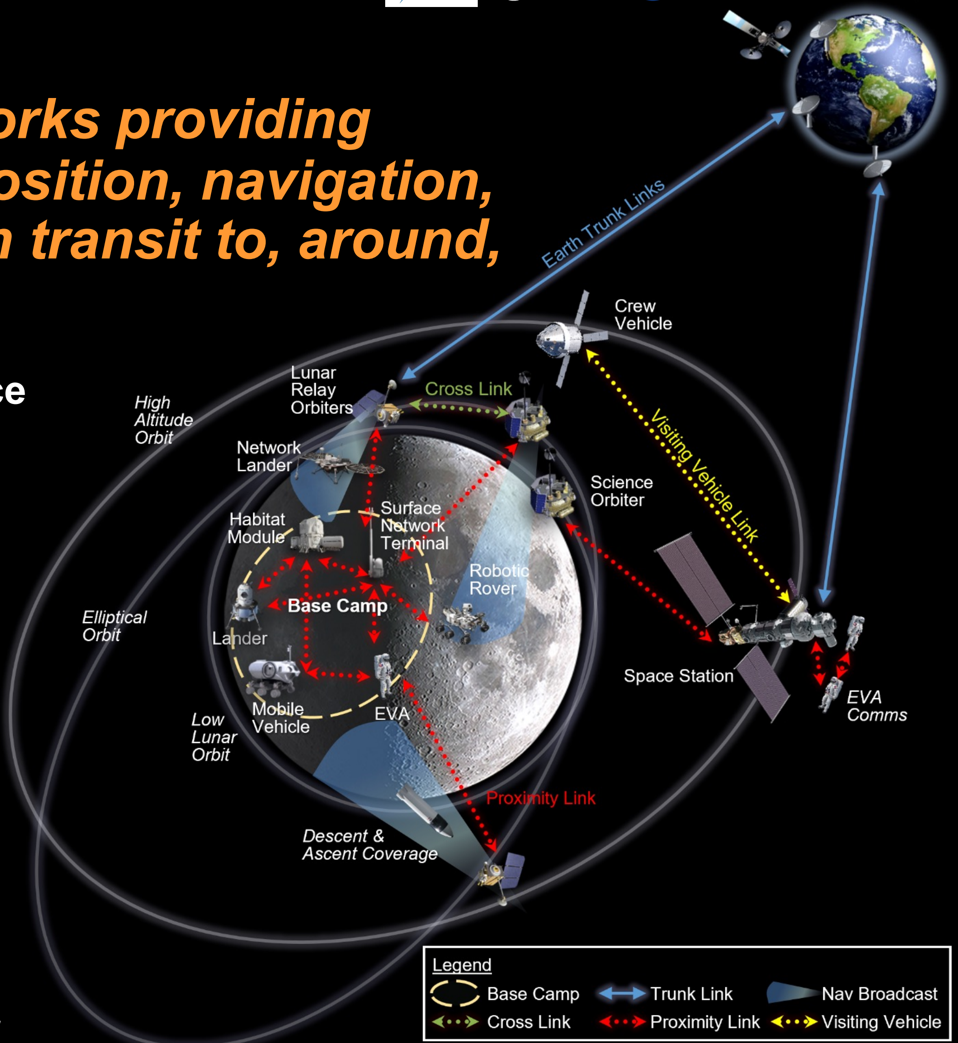
- LunaNet and Lunar Augmented Navigation Service
- Overview LunaNet Service Providers
- Demonstration Objectives
- Demonstration Architecture
- Payload and Concept of Operations
- Analysis
- Future Plans

What is LunaNet?

LunaNet is a set of cooperating networks providing interoperable communications and position, navigation, and timing (PNT) services for users in transit to, around, and on the Moon.

- **Based on a framework of mutually agreed-upon standards, protocols, frequency bands, and interface requirements that enable interoperability.**
- **Allows many lunar mission users to engage the services of diverse commercial and government service providers in an open and evolvable architecture.**
  - **Service-Oriented**
  - **Scalable**
  - **Open**
  - **Resilient**
  - **Secure**
  - **Extensible**

LunaNet consists of Earth Ground Stations (for Direct with Earth links), lunar orbital relays (lunar proximity and Earth trunk links), and surface assets.



LunaNet LANS

Regional Lunar "GNSS"

The concept of interoperable lunar PNT system of systems (Lunar Augmented Navigation Service (LANS))

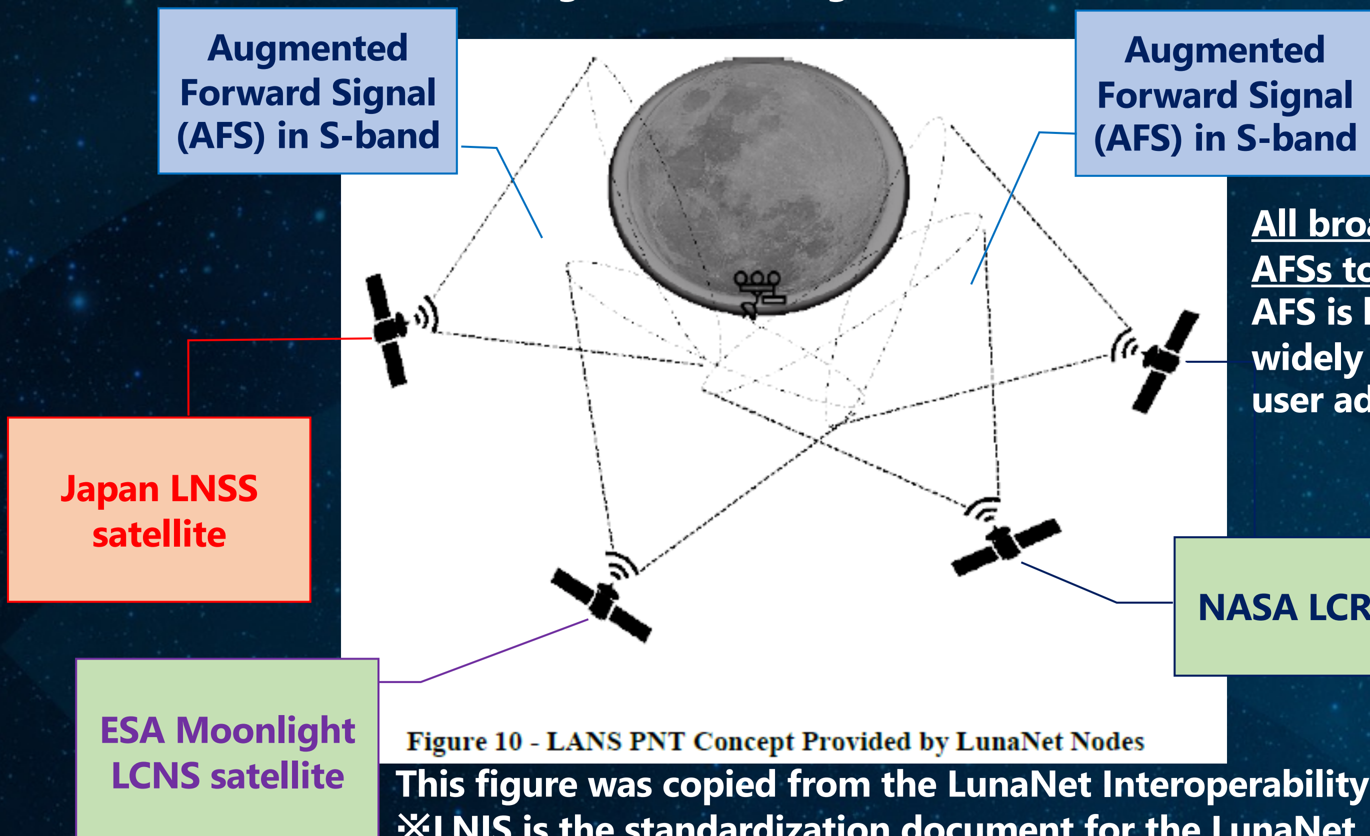


Figure 10 - LANS PNT Concept Provided by LunaNet Nodes

<u>All broadcast the standardized AFSs to form the LANS.</u>
AFS is based on parameters widely used in GNSS to ease user adoption.

This figure was copied from the LunaNet Interoperability Specification (LNIS)
※LNIS is the standardization document for the LunaNet

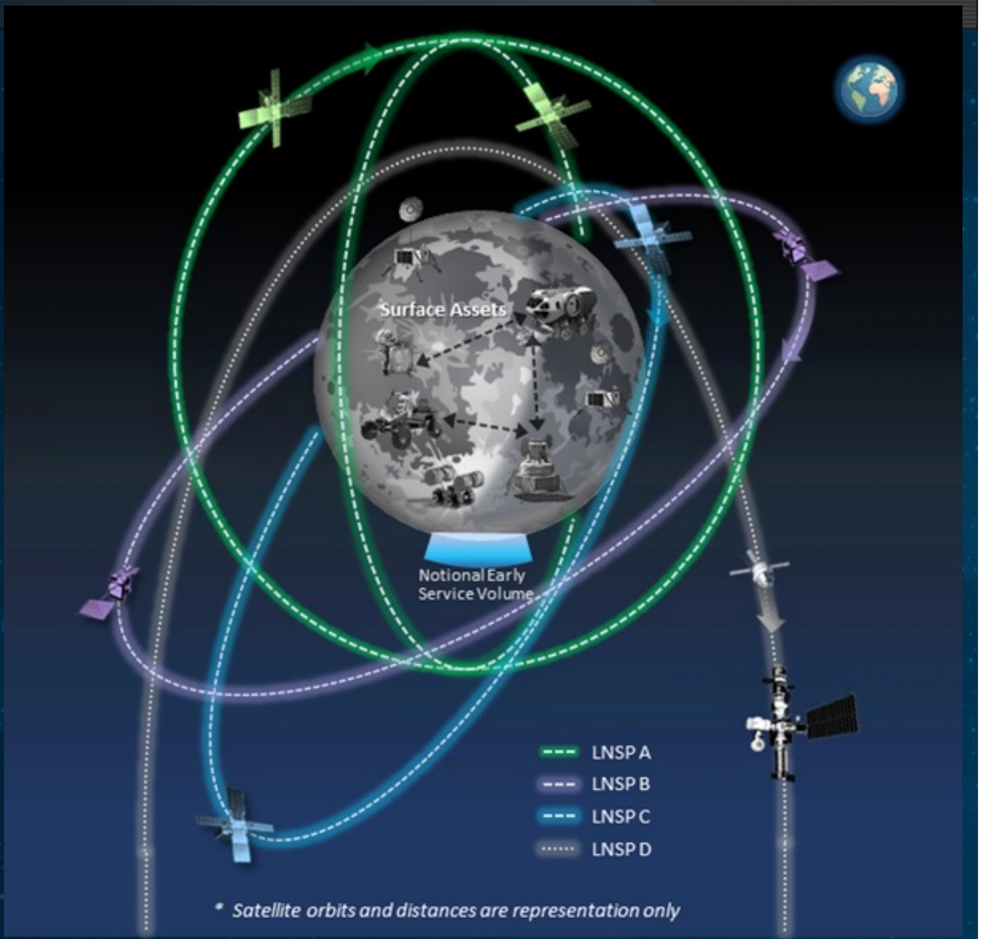
Interoperability is Critical to LANS

Current concept is to combine different LunaNet Service Provider (LNSP) space vehicles to create a constellation of AFS broadcasters for LANS. **(Lunar Augmented Navigation Service)**

- ➢ **Interoperability is critical to achieve this.**

LANS Interoperability[1]: each service provider that claims to be LunaNet compliant (becoming a LunaNet Service Provider, LNSP) for the LANS service, must:

- ➢ Comply with a common signal and message structure (Augmented Forward Signal, AFS).
- ➢ Comply with the Signal In Space Error requirements.
- ➢ Assure compliance with the Received Power at the Lunar Surface requirement.



[1] ICG SSV booklet: "(interoperability is defined as) the ability of global and regional navigation satellite systems, and augmentations and the services they provide, to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system"

LunaNet Interoperability Specification (LNIS) Version 5 now available on the internet

LunaNet Interoperability Specification Document

Version 5

Published by NASA-ESA-JAXA

29 January 2025

LNIS V005

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

Version 1

Noted as Applicable Document 1 [AD1 Vol-A] in LNIS V5

LSIS V1.0 29 January 2025 1

The LNIS and its *Applicable Document* includes:

- Concept of the LANS, message format of the Augmented Forward Signal (AFS), signal frequency, power, signal modulation, etc.
- Signal-In-Space-Error (SISE) requirement for LunaNet Service Providers (LNSPs)
- Lunar Reference System and Lunar Time System Standard (forthcoming)

JAXA/ESA/NASA comply with the LNIS to become interoperable LNSPs

JAXA, ESA, and NASA continue developing the LNIS documents and to ensure the success of the LANS

Lunar Comm & Nav (C&PNT) systems by US, Europe, Japan

ESA Moonlight LCNS (2028〜)

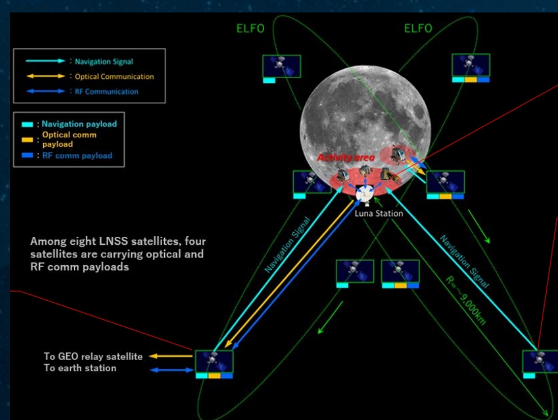
Contractor: Telespazio

NASA LCRNS (2026〜)

Contractor: Intuitive Machines

Japan LNSS (2029〜)

Contractor: ArkEdge Space



LCNS:
Lunar Communications and Navigation System

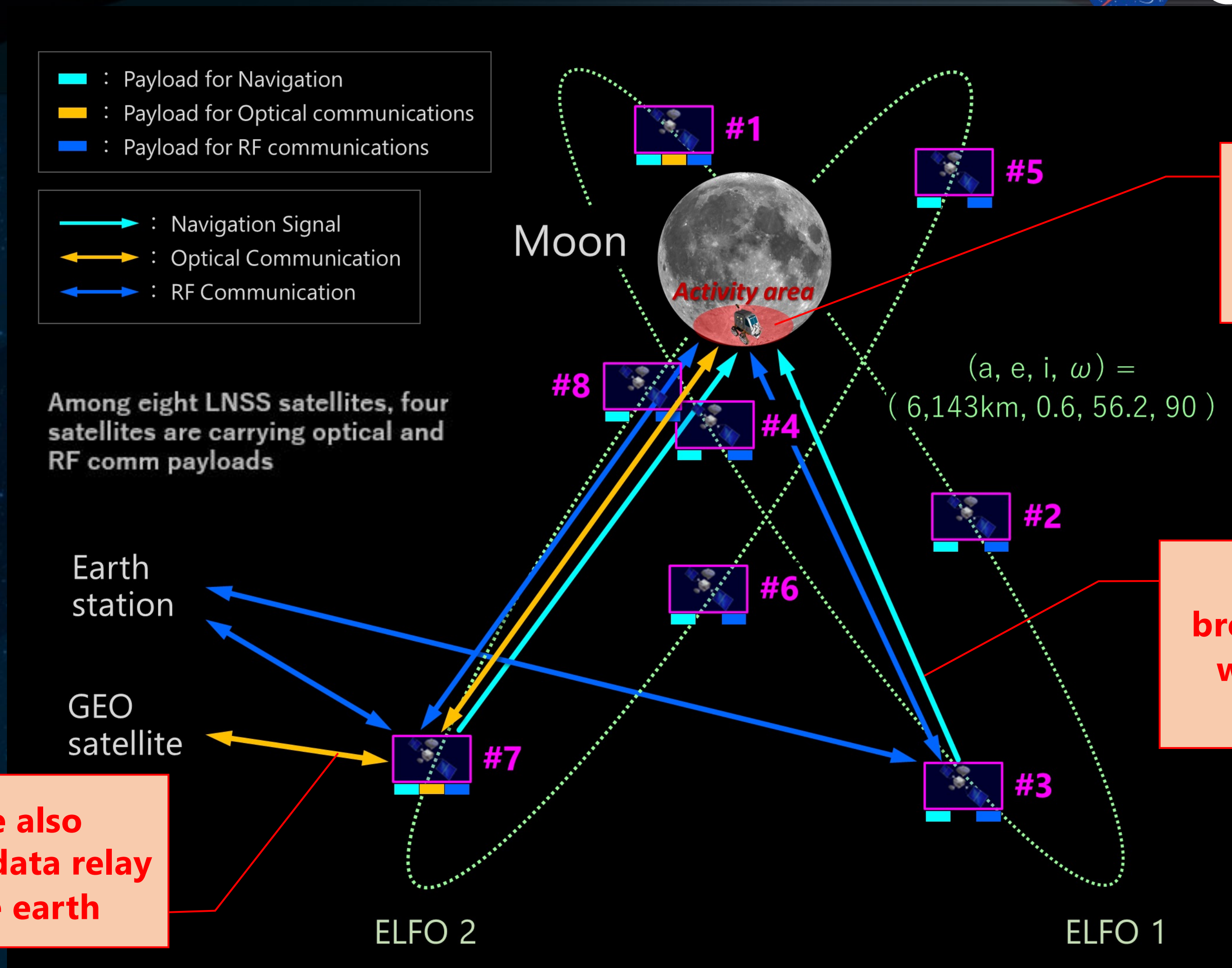
LCRNS:
Lunar Communications Relay and Navigation Systems

LNSS:
Lunar Navigation Satellite System

JAXA's plan

LNSS is GPS-like satellite navigation system for the Moon

LNSS:
Lunar Navigation Satellite System



Target: South Pole region

LNSS satellite broadcasting one-way navigation signal

LNSS satellite also functioning as a data relay satellite to the earth

ESA's Moonlight LCNS

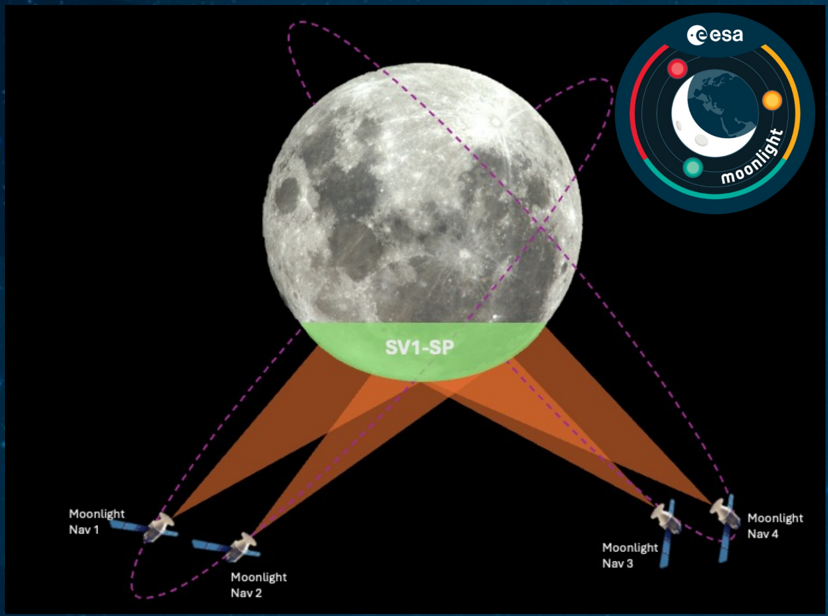
- Moonlight LCNS will provide interoperable **communication** and **navigation** services

- Navigation services are delivered in an incremental approach covering the lunar South Pole (until -75 degrees)
  - **IOC** (2029): 1 Navigation Satellite
  - **FOC** (2030): 3 additional (4 total) Navigation Satellites

- The navigation satellites will broadcast the LunaNet **Augmented Forward Signal** (AFS) compliant to AD1

- Eccentric orbits (ELFO's) are selected to ensure 15 hours of continuous coverage per Earth day (ensuring good geometry at user level)

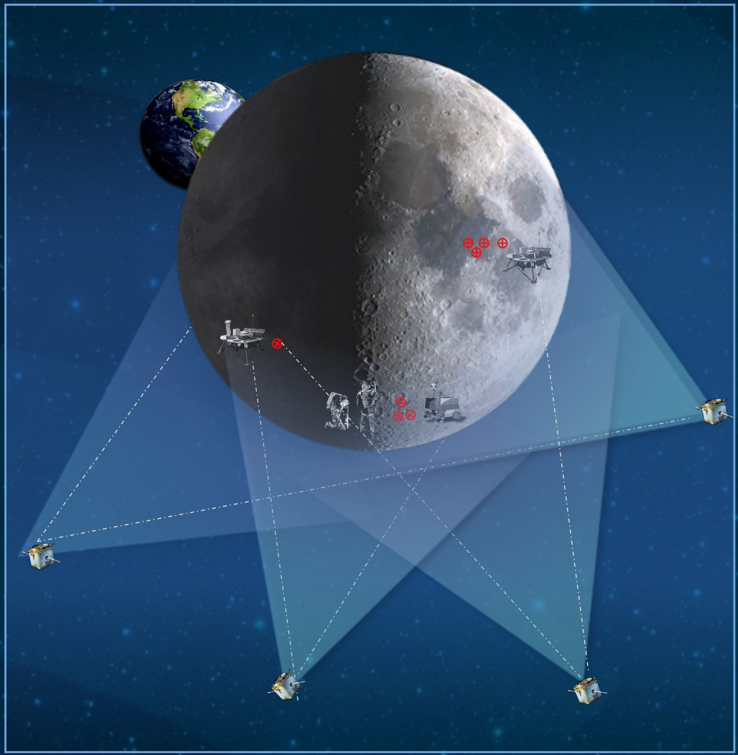
- Moonlight LCNS ensures a ranging error below 10 meters (2-sigma) at FOC.



LANS = Lunar Augmented Navigation Service
LCNS = Lunar Communication and Navigation System

NASA's Lunar Communications Relay and Navigation System (LCRNS)

- Initial Operating Capability is expected to consist of three distinct phases over a period of approx. 5 years:
  - Phase Alpha, with a minimum of one Augmented Forward Signal (AFS) expected to broadcast over the South Pole region.
  - Phase Bravo, with a minimum of two AFS expected over the same South Pole region.
  - Phase Charlie, with an expected minimum of four AFS in view in an expanded service volume (for a limited portion of each Earth day). Additionally meeting a requirement for Geometric Dilution of Precision (GDOP).
- The LCRNS AFS is expected to comply with the LunaNet Interoperability Specification.
- LCRNS orbit(s) are defined by the service provider and relays are expected to meet the Signal-in-Space-Error in the LCRNS SRD.
- Service delivery is reliant on defined lunar geodetic system and lunar time.



LANS = Lunar Augmented Navigation Service
LCRNS = Lunar Communications Relay and Navigation System

Demonstration Objectives

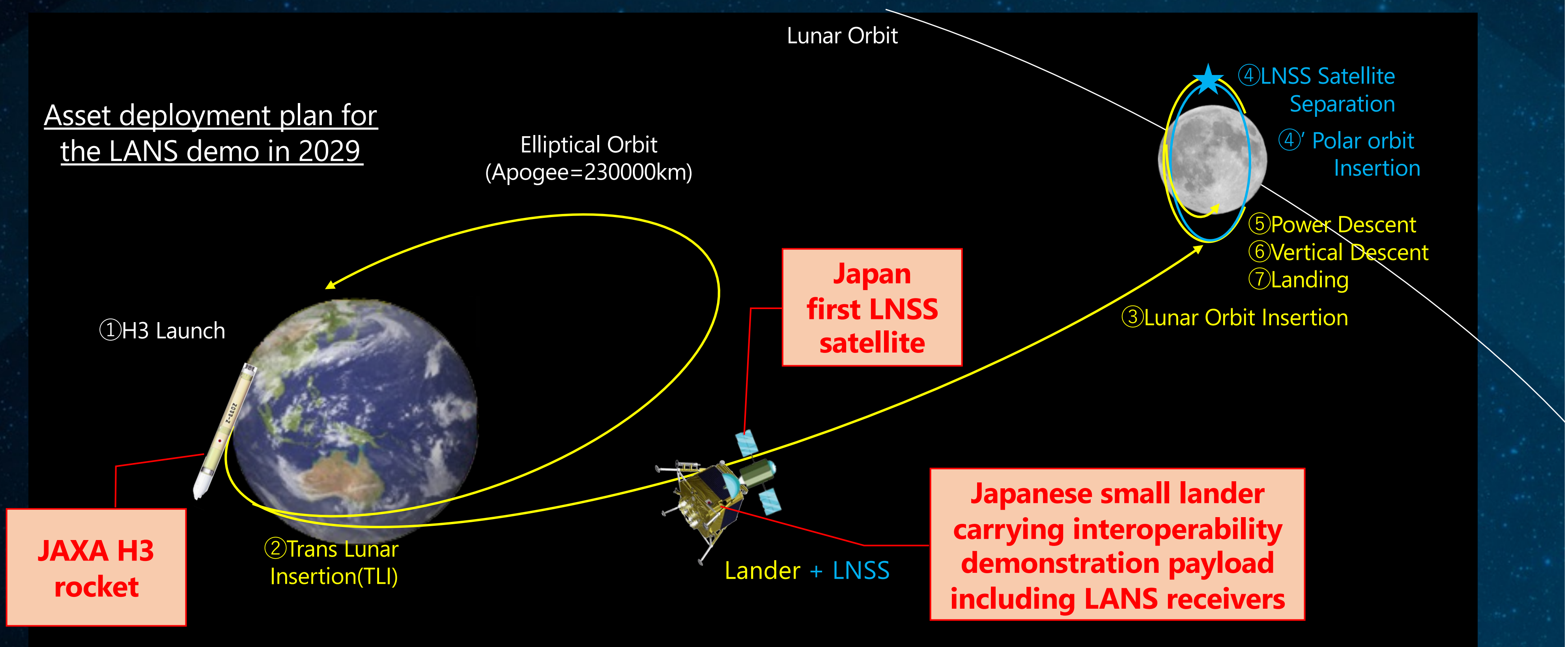
OBJ-1 - To **receive AFS** from each LNSP node and assess the **signal quality**

OBJ-2 - To compute and **validate** the **Signal In Space Error** (SISE) for each LNSP node

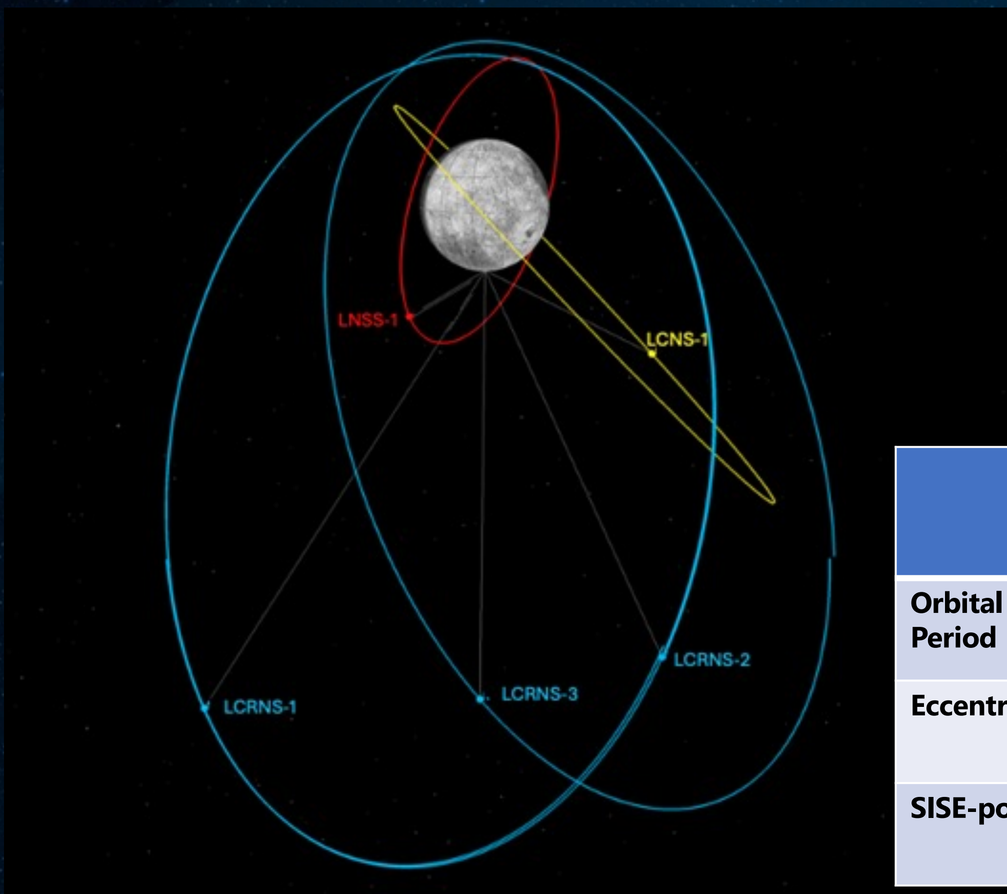
OBJ-3 – To validate the **achieved** user Position, Velocity, and Time (**PVT**) knowledge from **combined LANS**

OBJ-4 – To validate the **LunaNet Time** and **Reference** Frame

Bringing LANS interoperability demonstration payloads to the Moon



Expected LANS constellation in 2029 (two or three LCRNS, one LCNS, one LNSS)

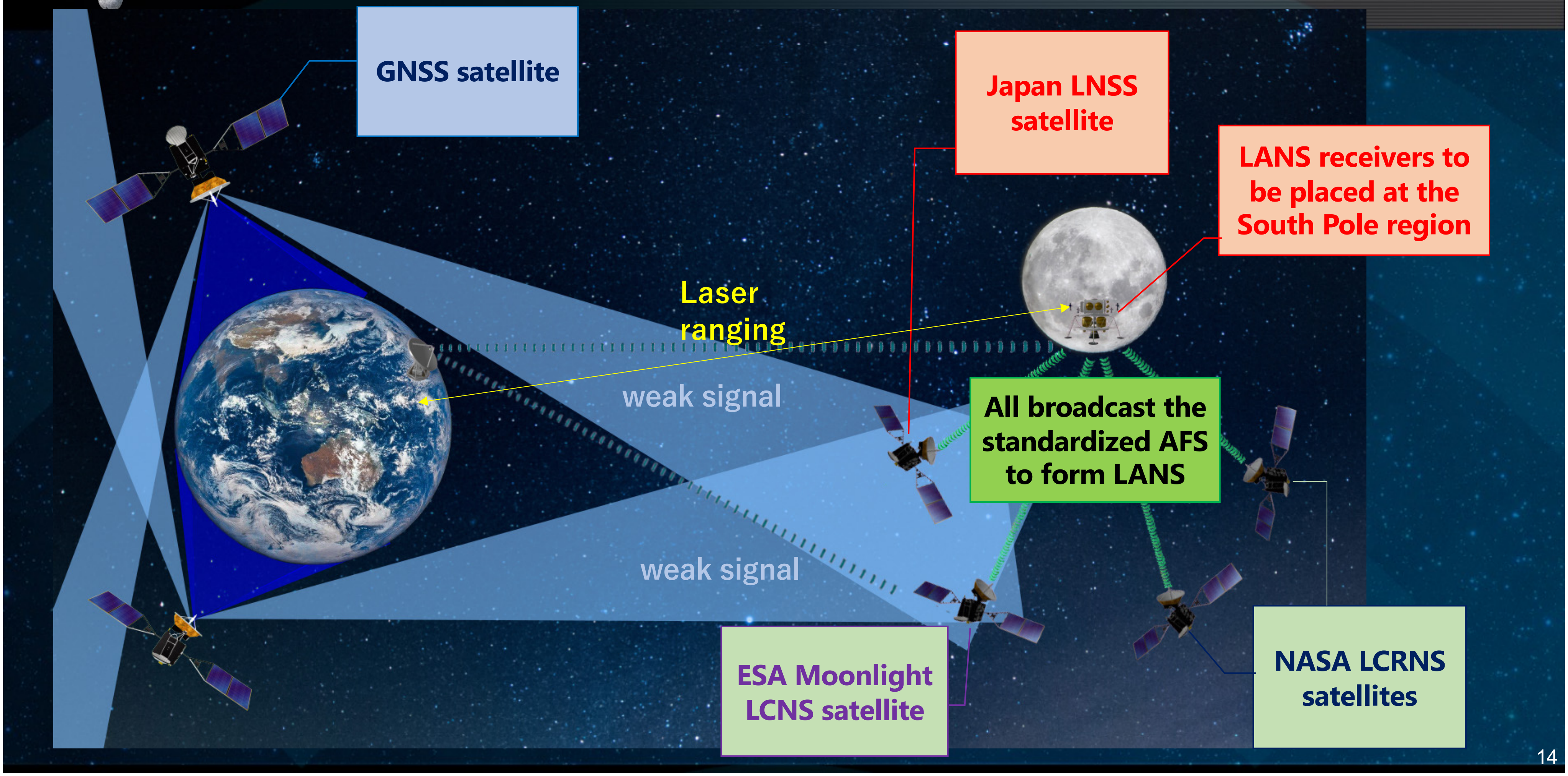


Lunar position, navigation, and timing services jointly provided by international LNSPs (ESA's LCNS, NASA's LCRNS, and Japan's LNSS)

Analyzed orbital and SISE features:

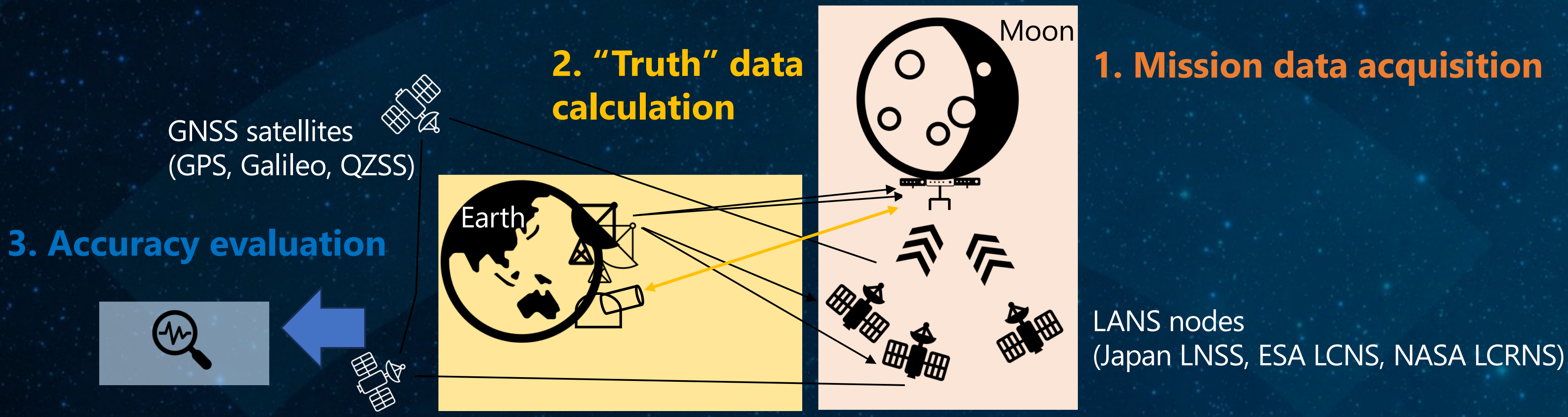
	ESA LCNS	Japan LNSS	NASA LCRNS #1	NASA LCRNS #2	NASA LCRNS #3
Orbital Period	24 hrs (ELFO)	6 hrs (Circular)	32.8 hrs (ELFO)	32.8 hrs (ELFO)	32.8 hrs (ELFO)
Eccentricity	0.7	0	0.678	0.678	0.678
SISE-pos	20 m (2-sigma)	20 m (2-sigma)	13.43 m (3-sigma)	13.43 m (3-sigma)	13.43 m (3-sigma)

The LANS receivers to be placed at the South Pole region will receive all broadcasted AFSs

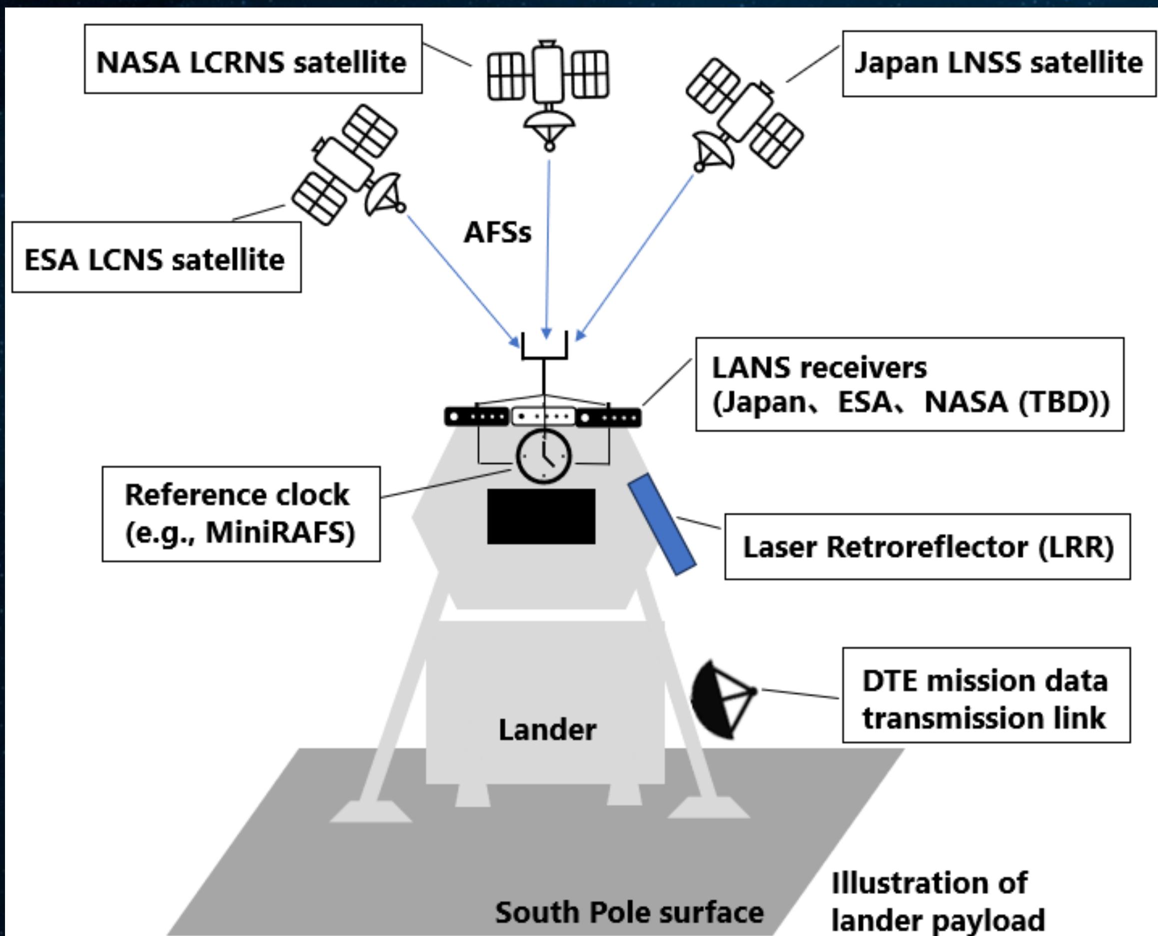


LANS interoperability and PNT demonstration – Three major steps

1. Acquisition of mission data (observations from the AFSs and terrestrial GNSS, LANS receiver PVT solutions) in Moon's environment
2. Calculation of "truth" data (precise LANS satellite orbits and clocks, precise LANS receiver positions and clocks) by Earth stations and laser stations
3. Evaluation of SISEs for LNSP nodes and LANS PVT accuracy by comparing the acquired mission data with the calculated "truth" data



The planned LANS interoperability demonstration payload (TBD)



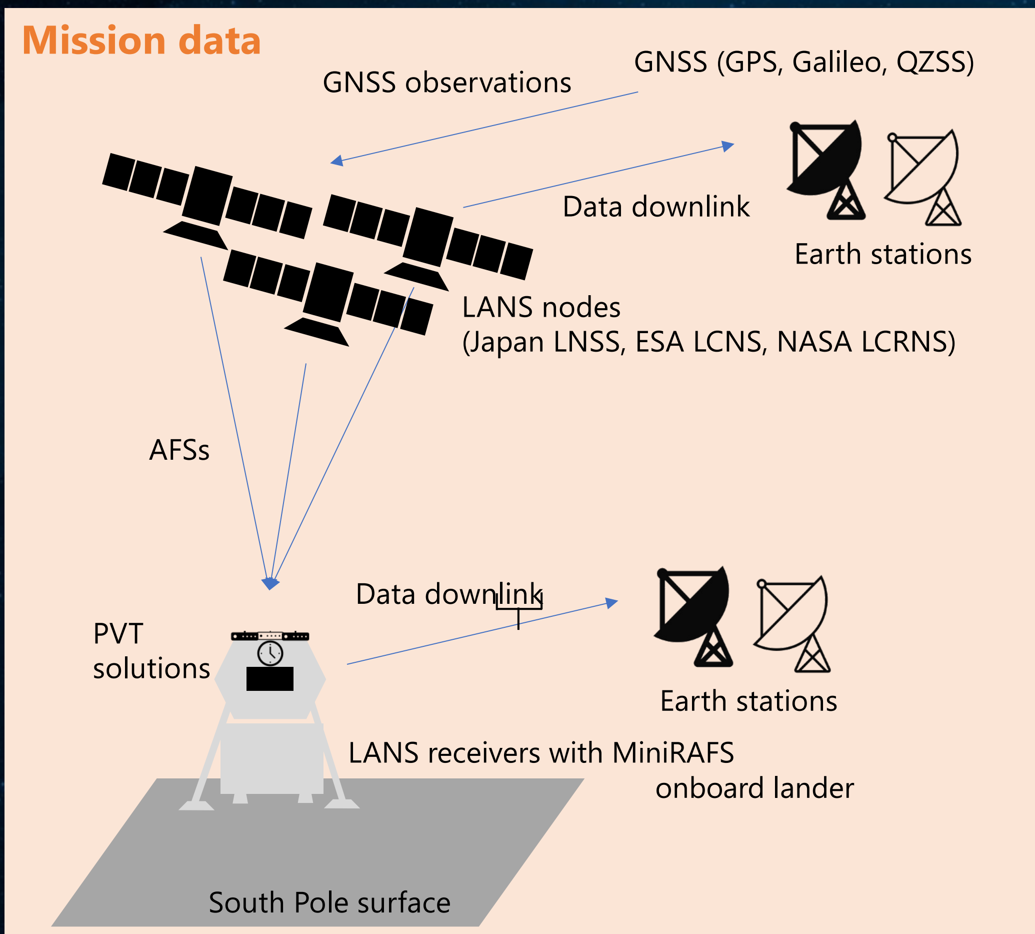
The LANS receivers connected to the reference clock receive all broadcasted AFSs

The LANS accuracy demonstration needs the "truth" data whose accuracy is one-meter-level for both the receiver's location and clock determination results

To achieve this level of accuracy, Laser retroreflector (LRR) and the MiniRAFS are both necessary

And during the demo period, the continuous AFSs and precise orbit & clock information of the LANS nodes are also necessary

Real-time mission data acquisition



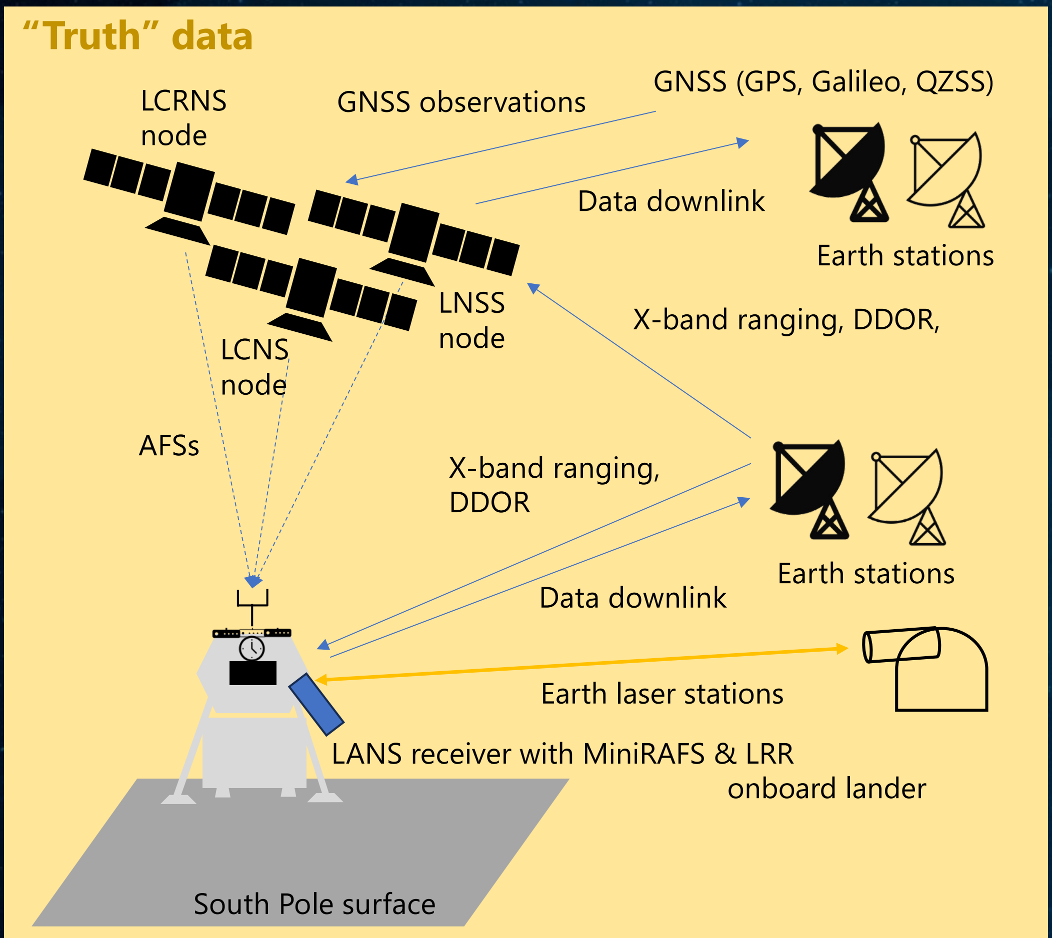
Acquisition of the LANS AFSs, LANS receiver PVT solutions, and GNSS observations

The LNSP nodes will broadcast their AFSs towards the LANS receivers on the lunar South Pole surface

Then, the LANS receivers will calculate their PVT solutions based on the AFS data and these AFS and PVT solution data will be all downlinked to the Earth stations

The GNSS observation data received by the LNSP nodes will be also downlinked to the Earth stations as the mission data

Offline "truth" data calculation



Calculation of the precise satellite orbits and clocks, precise receiver positions and clocks

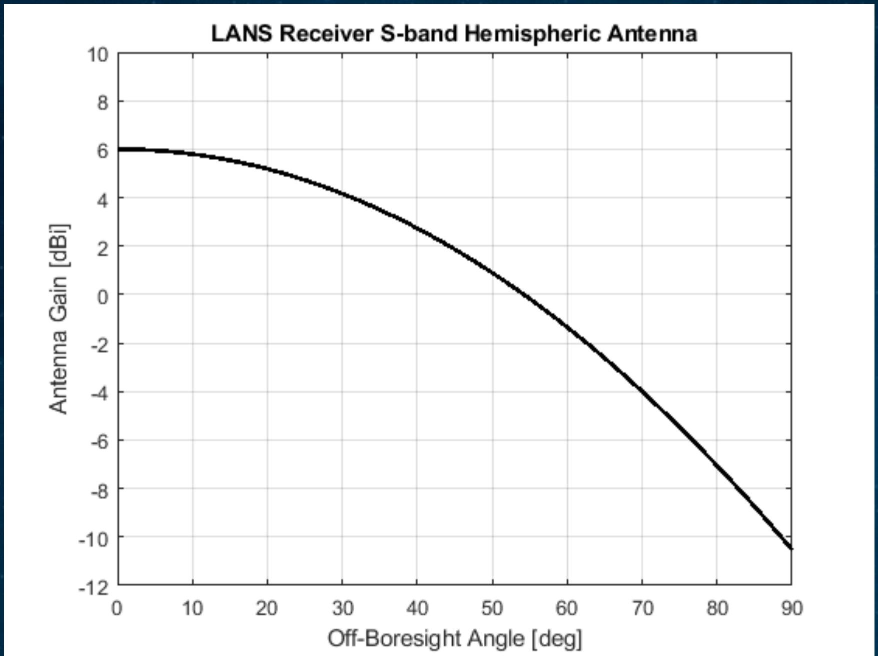
The Earth stations will perform the X-band ranging and DDOR for the LNSP nodes to determine their precise orbits

The Earth stations and laser stations will perform the X-band ranging, DDOR, and laser ranging for the LANS receivers on the lunar South Pole surface to determine their precise positions

The onboard clocks for the LNSP nodes and the LANS receivers will be determined by the received GNSS observations and AFS observations, respectively

Preliminary Analysis - Assumptions

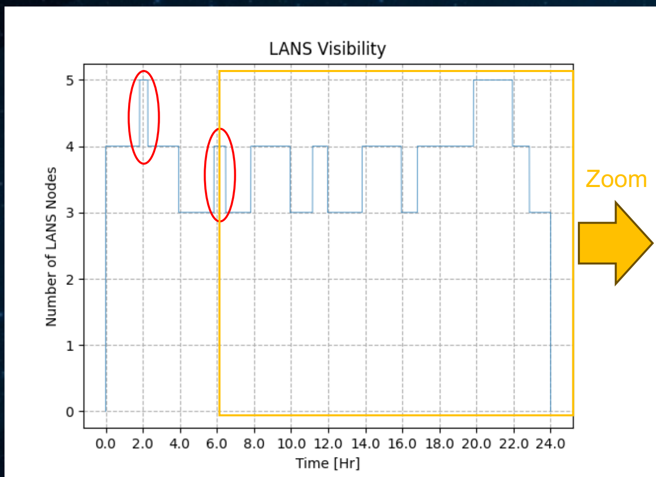
- **Static** lander (-87° N, 20° E)
- Equipped with **OCXO** (Oven Controlled Cristal Oscillator) and **MiniRAFS** (atomic clock)
- State-of-the-art AFS receiver (based on GNSS technology) with omnidirectional antenna and external **LNA**
- Height provided by digital elevation model (**DEM**)
- Accurate error modelling, accounting for receiver **thermal noise** and satellite clock and orbit errors (through **SISE**)
- Orbits are **phased** to realize **optimal visibility** (not geometry)



LANS Receiver Antenna (hemispherical)

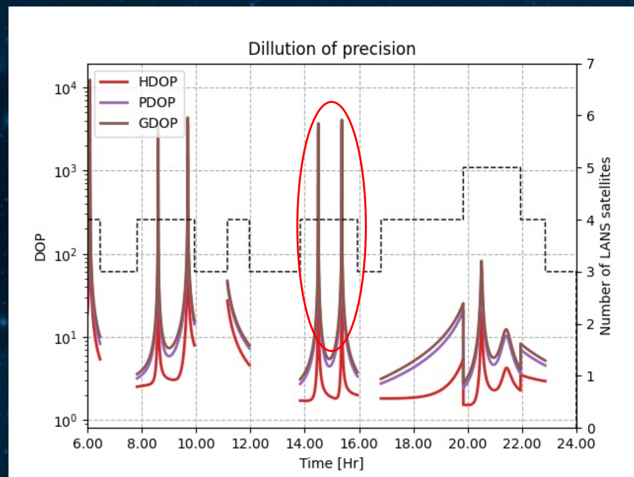
Preliminary Analysis – LANS Visibility

LANS Visibility



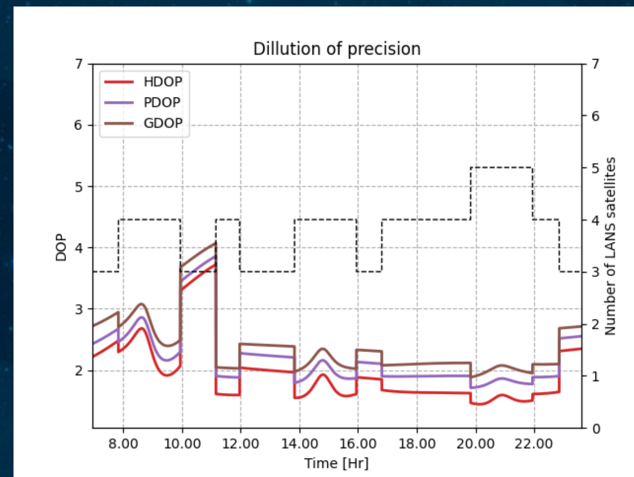
Short periods of time with 5 in view.

Without Height Constraint



Due to **non-optimal phasing** of the LANS satellites, the satellites line up in a specific way resuling in ***poor* geometry** (and high DOP)

With Height Constraint

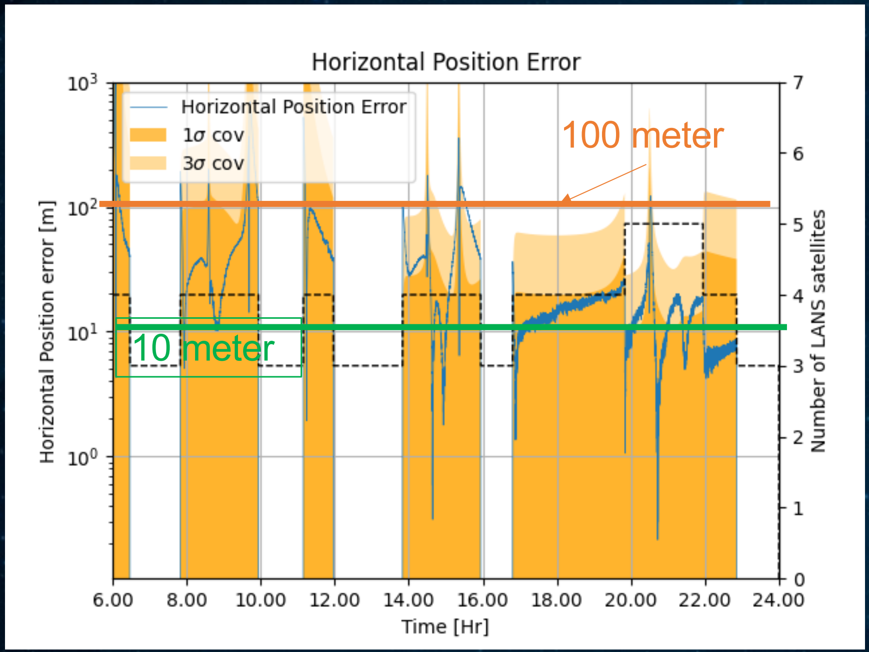


Using a **height constraint**, the impact of the poor satellite alignment is alleviated resulting **in *improved* geometry** (and low DOP).

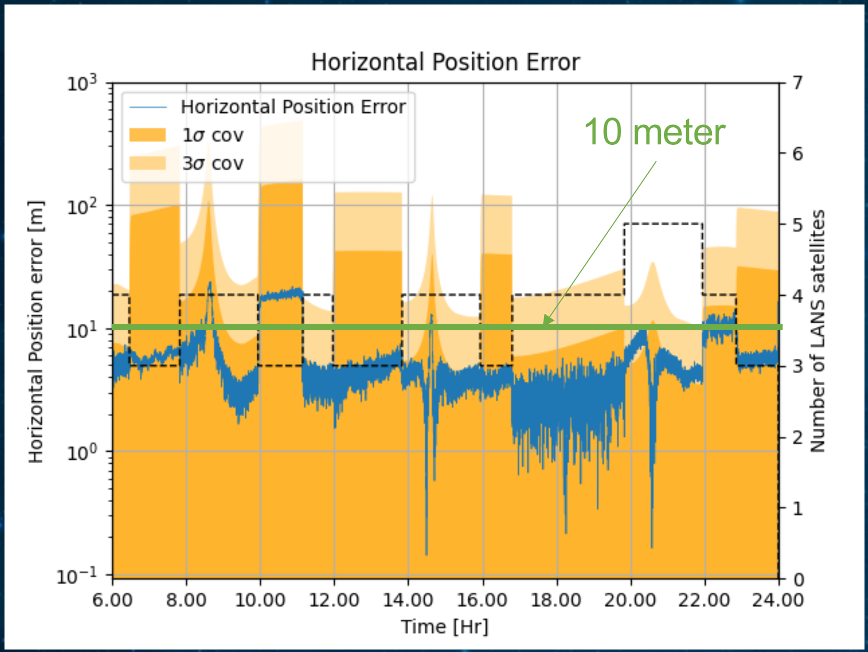
Note axes are not equal!

Preliminary Analysis – User Horizontal Error

No Height Constraint



With Height Constraint



- Impact of **high DOP** on position error is clearly visible
- **With DEM**, the horizontal position error is **less than 10 meter** most of the time (> 68%)

Preliminary Analysis – User Performance Summary

- Availability of **height constraint** results in **improvement of PVT** accuracy.
- An **accurate clock** (i.e., atomic clock) at user level can result **in better PVT** accuracy.
- **Optimization** of **relative phasing** may further **enhance PVT** accuracy (by **reducing spikes in DOP** resulting in poor geometry)

Future Endeavors

- **NASA LCRNS** will reach **Initial Operating Capability-Charlie** increment, for a total of **5 LNSP nodes**
- **ESA Moonlight LCNS** will reach **Full Operating Capability** with **3 additional LNSP LANS nodes**
- **JAXA** plans to enter into the development phase of **LNSS Full Operating Capability**