月版GNSS（Lunar Augmented Navigation Service）における欧米日の連携と実証ミッションについて

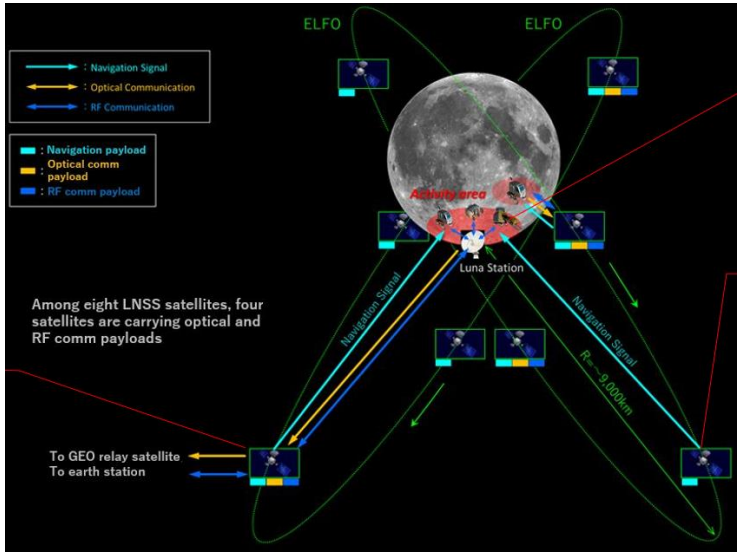
村田眞哉（JAXA）

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

ESA Moonlight LCNS (2027～)

NASA LCRNS (2025～)

JAXA LNSS (2028～)



LCNS:
Lunar Communications Navigation Services

LCRNS:
Lunar Communications Relay and Navigation Systems

LNSS:
Lunar Navigation Satellite System

Towards the establishment of the Moon GNSS (LANS)

The concept of the Moon GNSS called the Lunar Augmented Navigation Service (LANS)

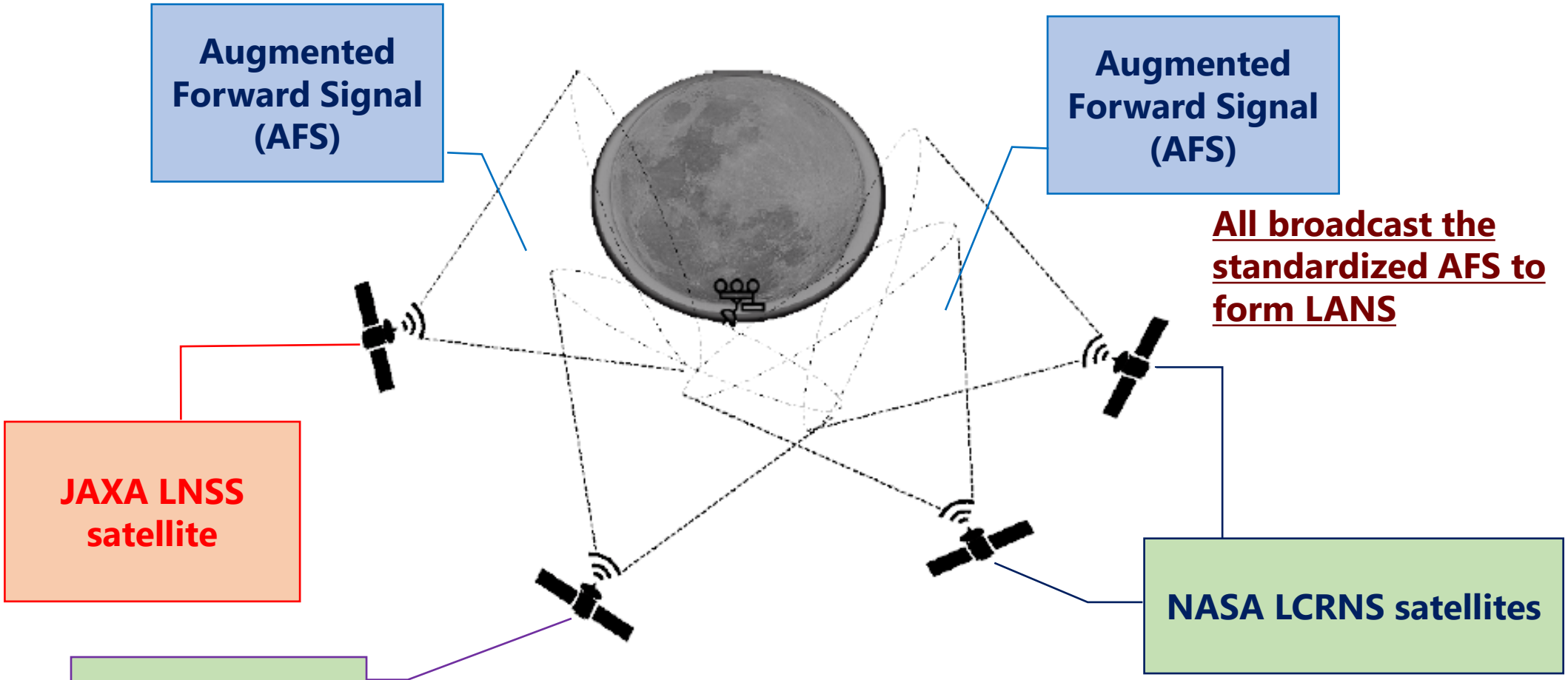


Figure 10 - LANS PNT Concept Provided by LunaNet Nodes

This figure was copied from the LunaNet Interoperability Specification (LNIS)

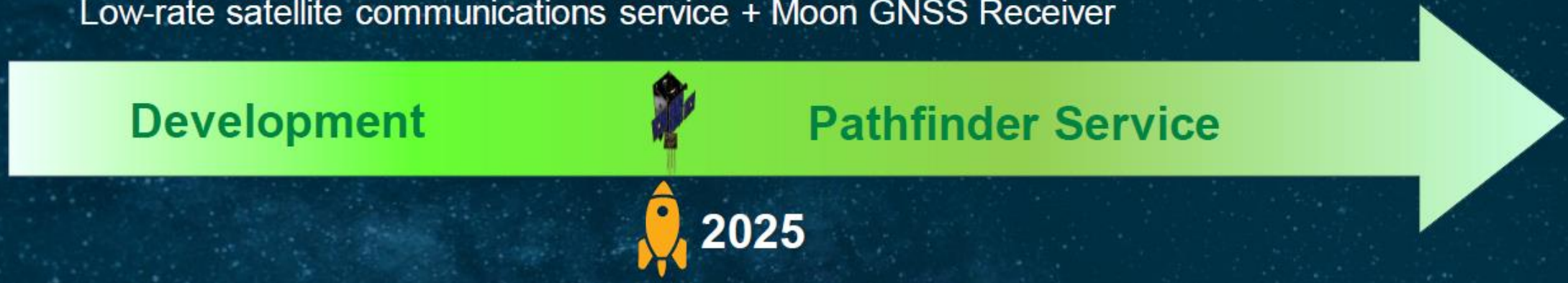
※LNIS is the standardization document for the LunaNet

ESA Roadmap

ESA's plan

STEP 1: LUNAR PATHFINDER

Low-rate satellite communications service + Moon GNSS Receiver

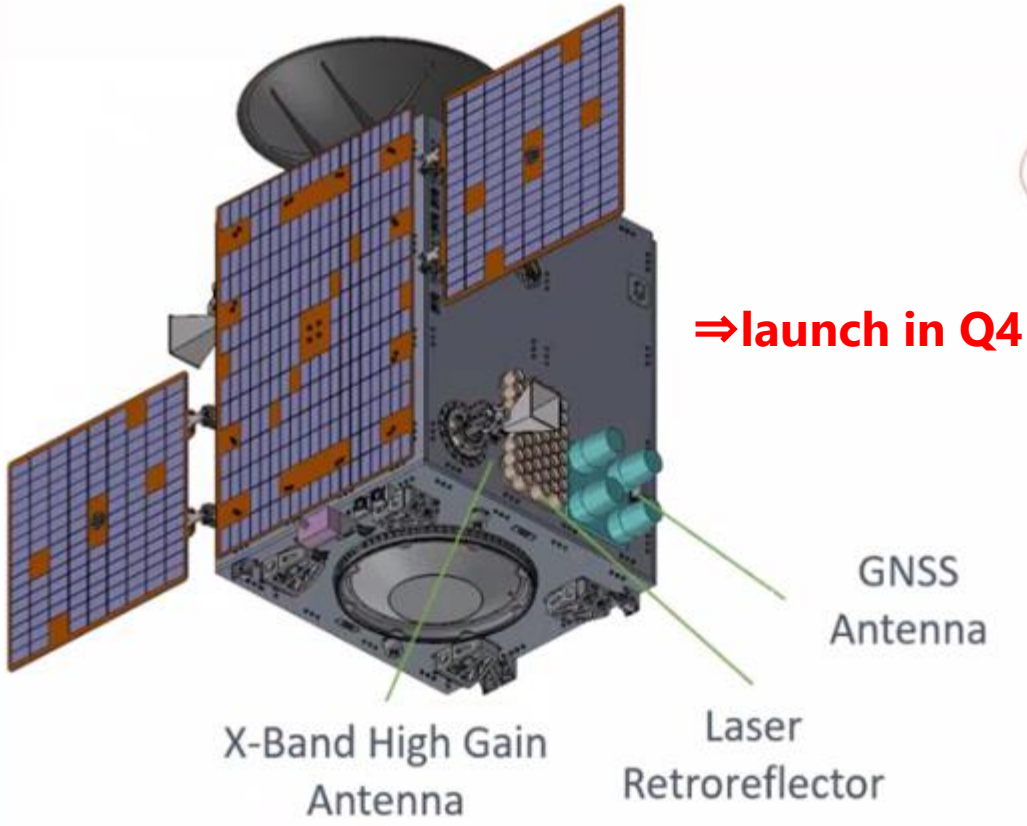


STEP 2: MOONLIGHT LCNS CONSTELLATION

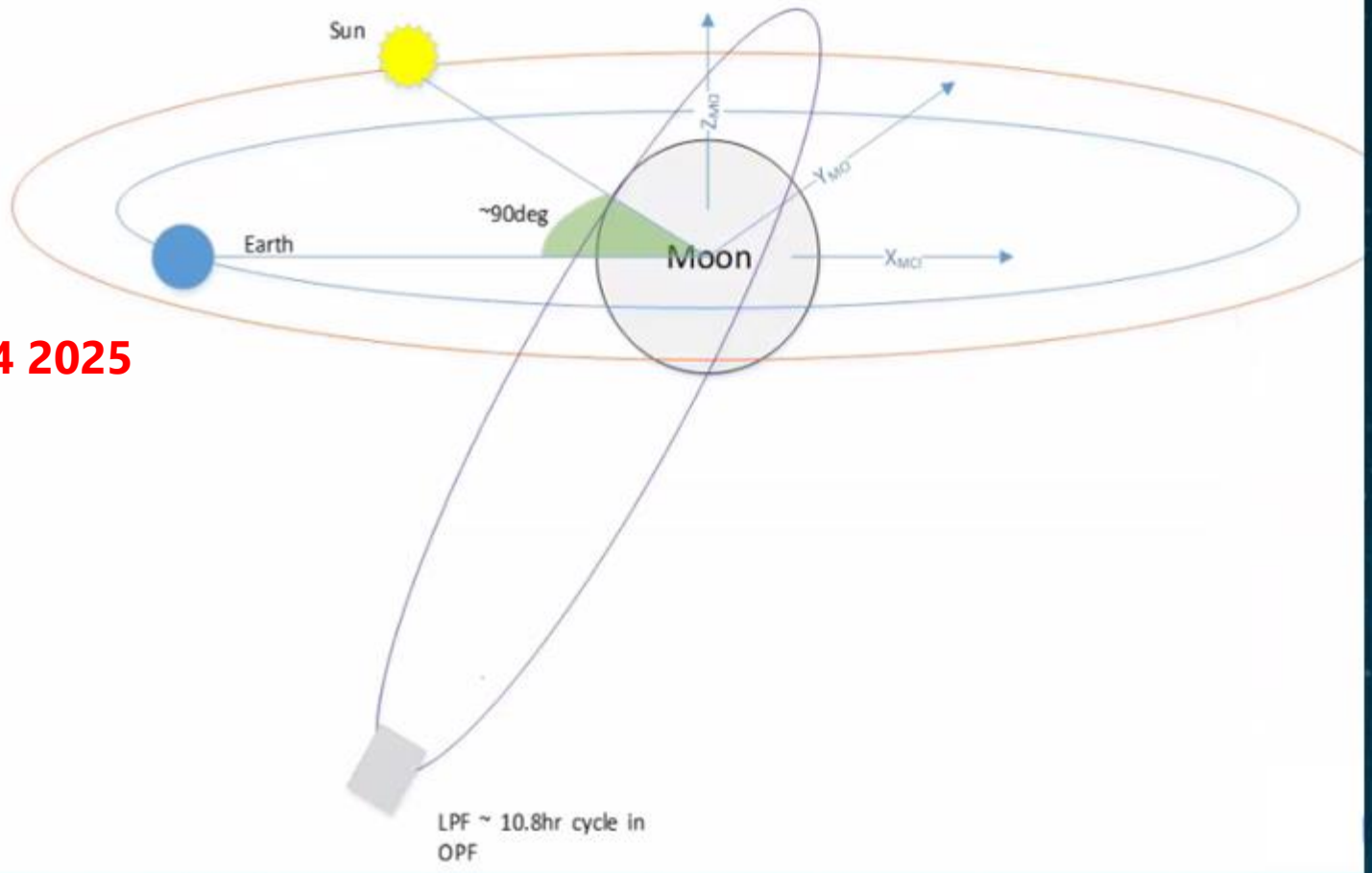
High-data rate satellite communications and navigation service

ESA's plan

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



⇒launch in Q4 2025



Mid term - Moonlight IOC

ESA's plan

- IOC phase will start by end of 2027 with at least one satellite transmitting the one-way (AFS) navigation signal
- Signal will be compliant with LunaNet requirements ensuring interoperability (same user terminal can work with multiple LNSP with minor SW modifications)
- Orbits will be defined by the service provider, however ELFO orbits are expected (e.g.: 24h orbit period)

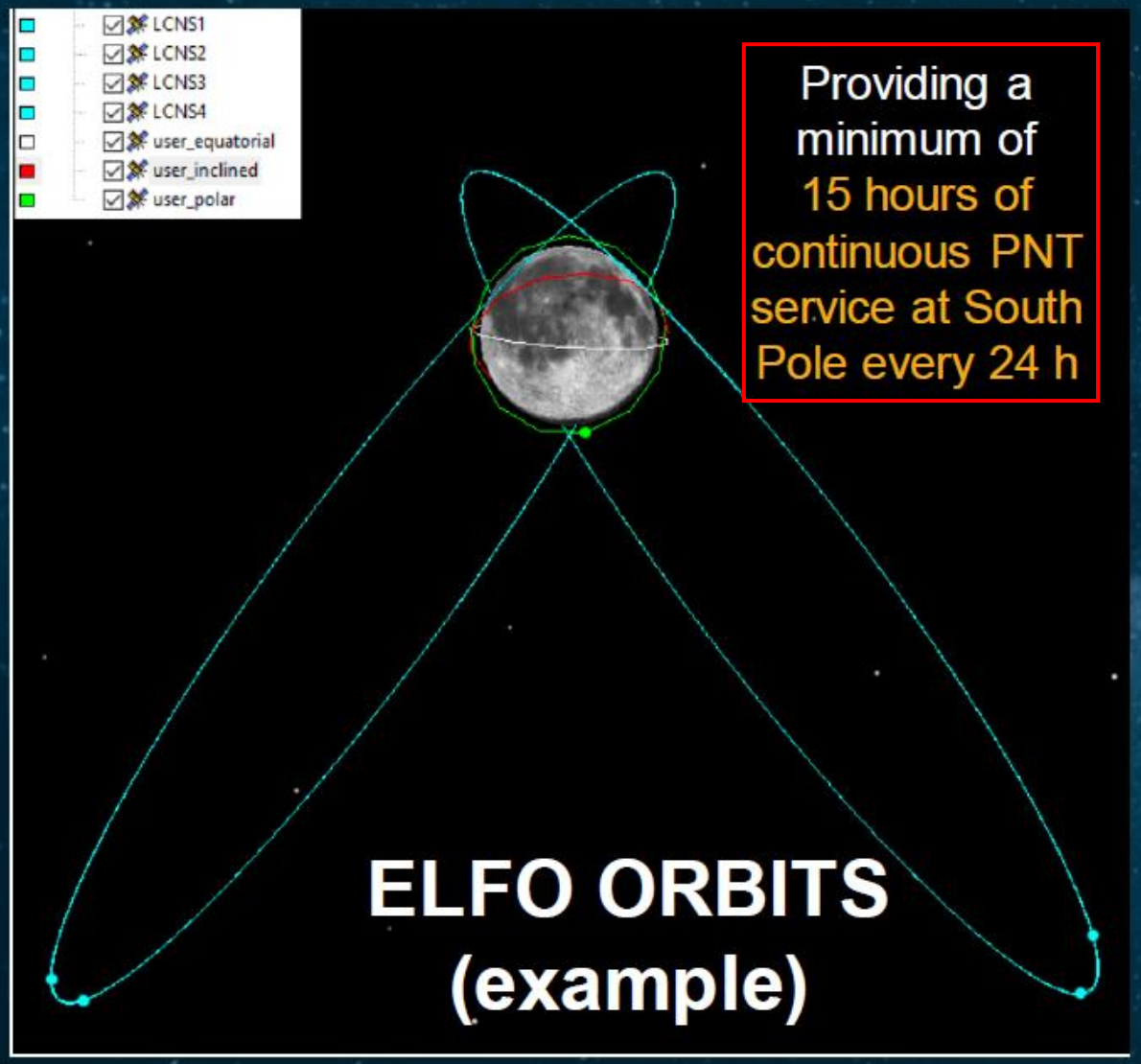
From LNIS:

*The **SISE** is defined as the instantaneous difference between the position, velocity and time of a LunaNet satellite as broadcast by the LunaNet node navigation message and the true satellite position, velocity and time, respectively expressed in the lunar reference frame [AD5] and the lunar system time reference [AD6].*

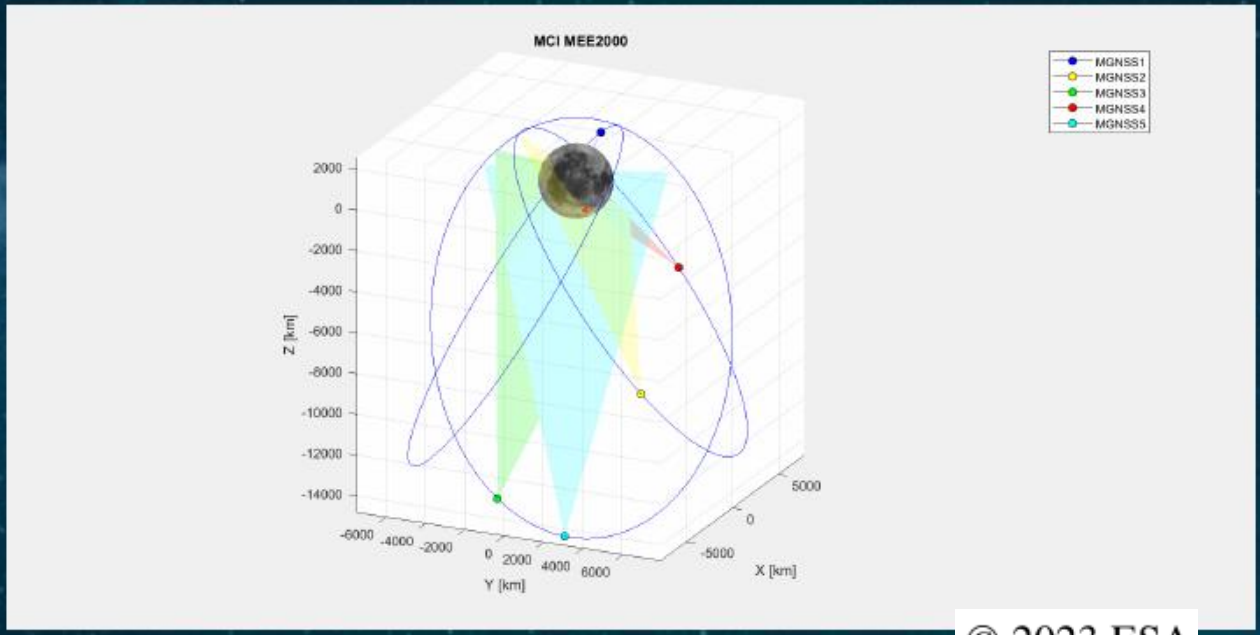
LCNS NAV service main targets (IOC)	
Requirement	Value
SISE	< 20m 95%
OWR availability	> 80%

A GNSS-like system on lunar orbit (example)

ESA's plan



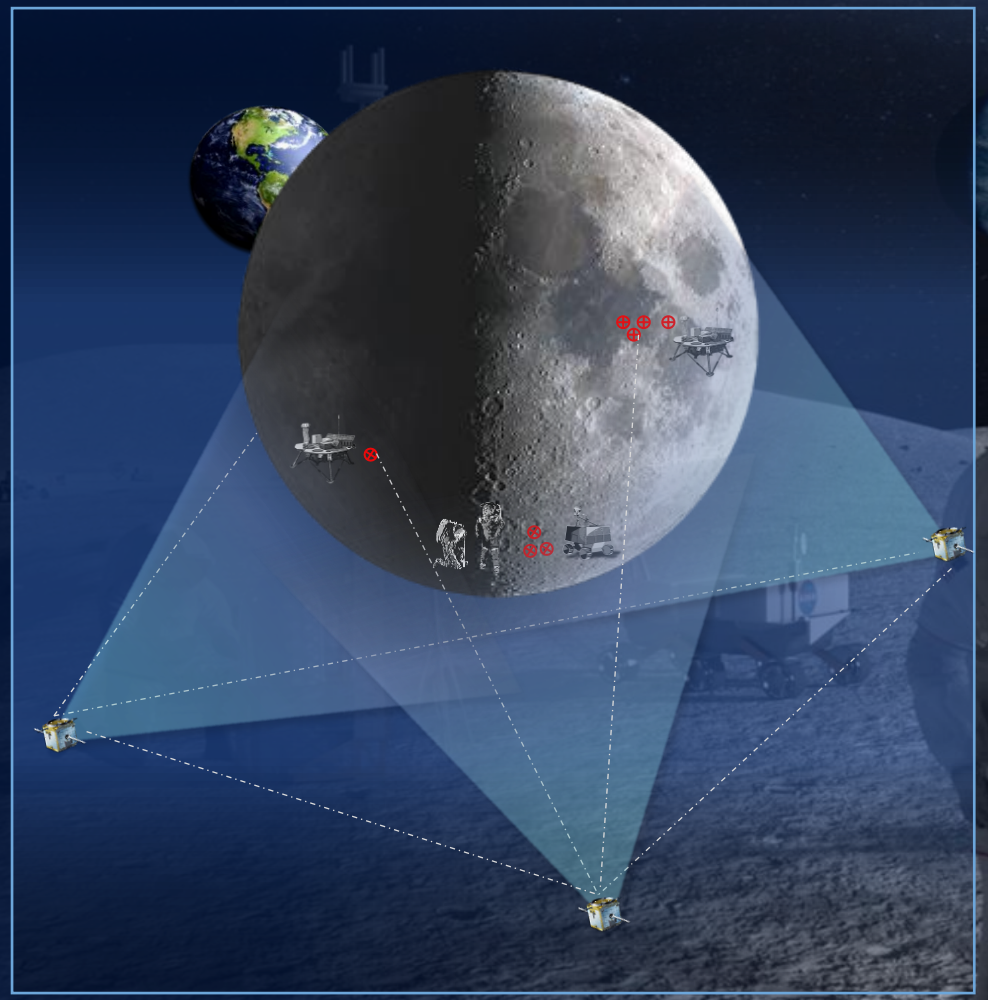
Satellite Id	1	2	3	4
Semi-Major Axis (km)	9750.73	9750.73	9750.73	9750.73
Eccentricity	0.6383	0.6383	0.6383	0.6383
Inclination (°)	54.33	54.33	61.96	61.96
Argument of pericenter (°)	55.18	55.18	121.7	121.7
RAAN (°)	277.53	277.53	59.27	59.27
True Anomaly (°)	123.42	0	180	0



Initial Capability for **LCRNS**

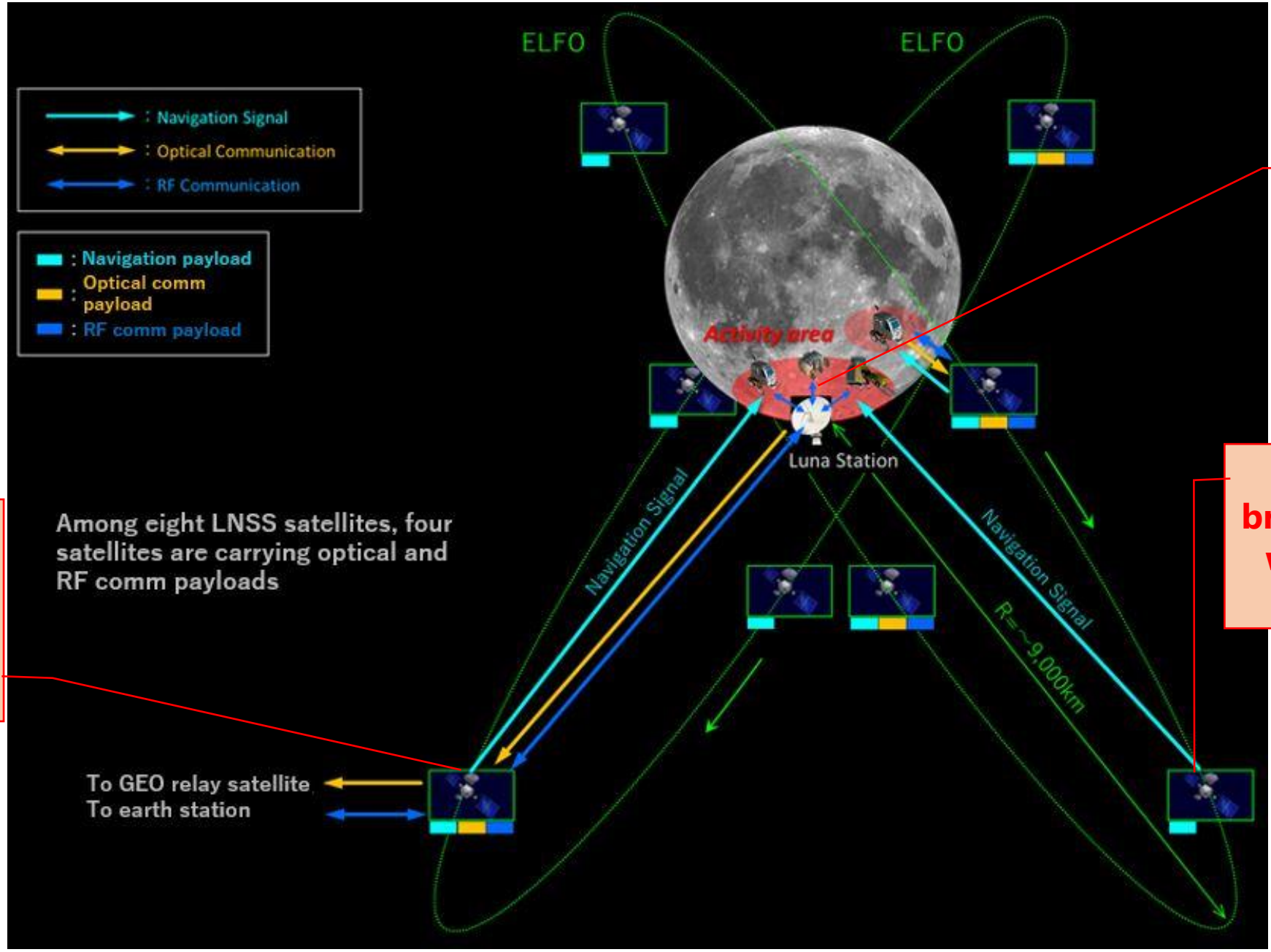
NASA's plan

- IOC phase will begin late 2025 with IOC-Alpha with a minimum of one Augmented Forward Signal (AFS) broadcast over the South Pole region.
- IOC-Bravo is expected by 2027 with a minimum of two AFS over the same South Pole region.
- Service continues over an expanded South Pole volume with IOC-Charlie broadcasting a minimum of four AFS, also meeting a requirement for GDOP for a limited portion of an Earth day.
- The LCRNS AFS will comply with the LunaNet Interoperability Specification.
- LCRNS orbit(s) will be defined by the service provider and are expected to meet the Signal-in-Space-Error.
- It is expected that LCRNS will be capable of providing two-way measurements from Peer-to-Peer signals.
- Service delivery is reliant on defined lunar geodetic system and lunar time.



JAXA's plan

LNSS is GPS-like satellite constellation for the Moon designed by JAXA



Target: South Pole region

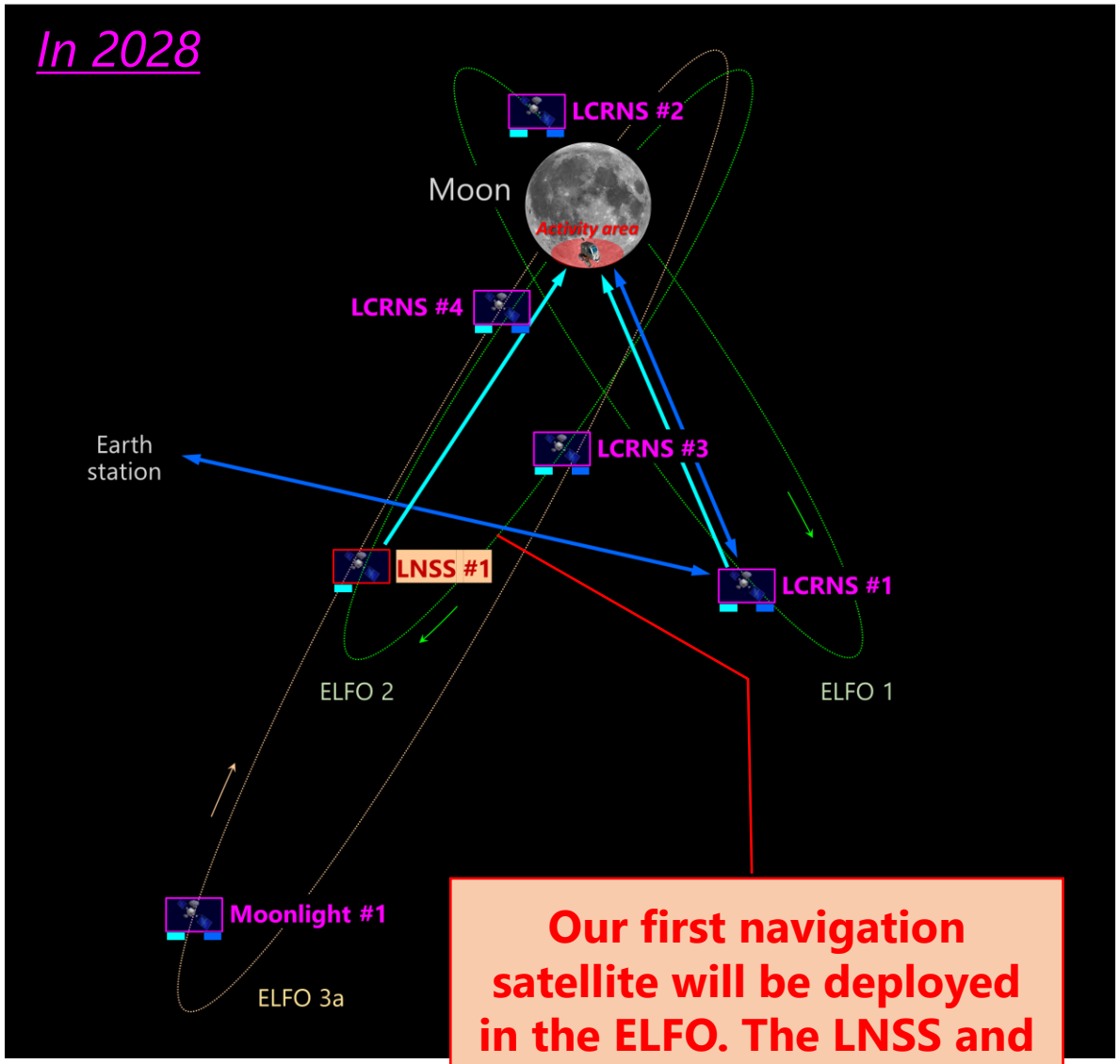
LNSS satellite broadcasting one-way navigation signal

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

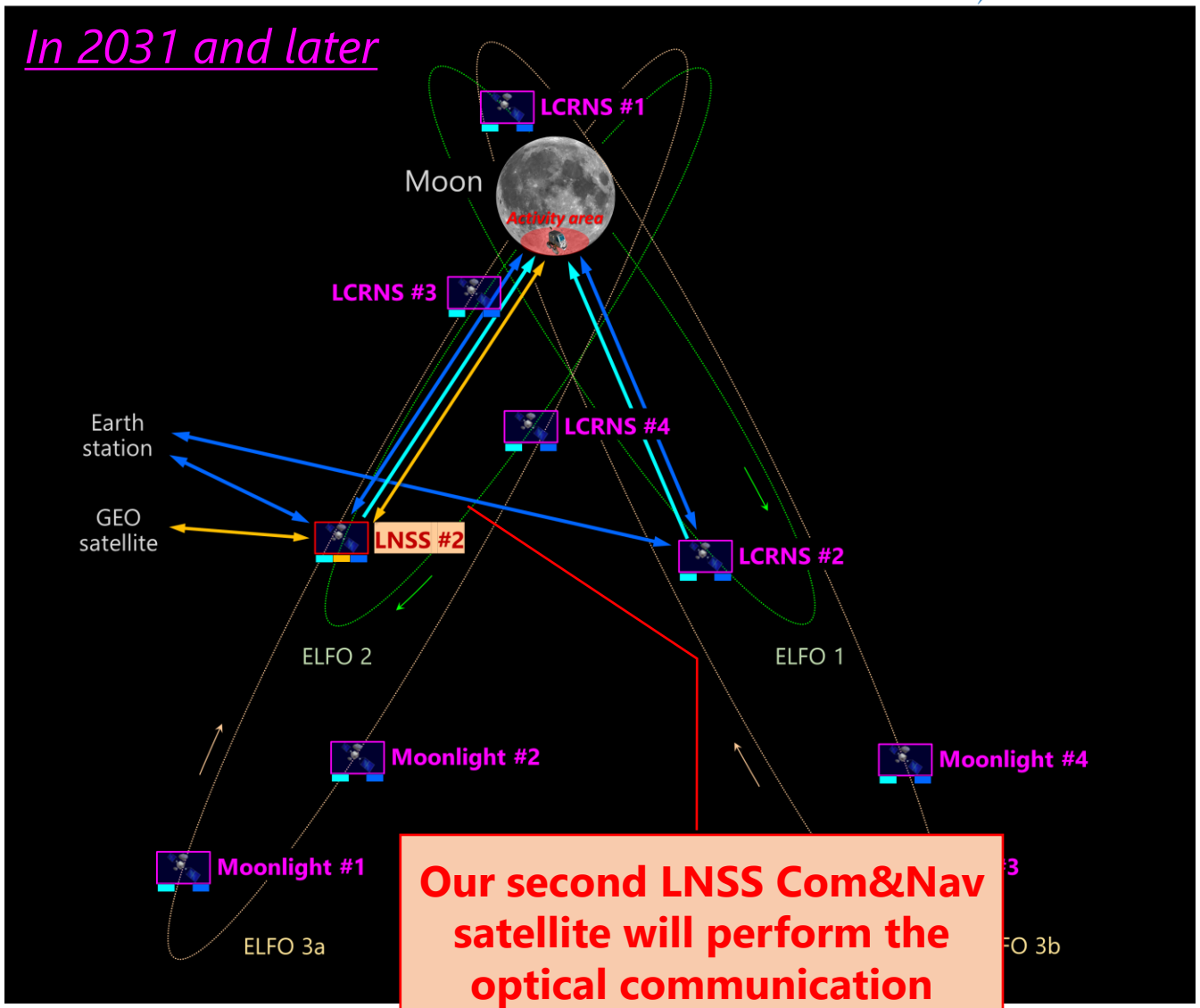
JAXA's plan

LNSS contribution towards the establishment of Moon GNSS (LANS)

※ ESA Moonlight and NASA LCRNS orbits are notional in figures below

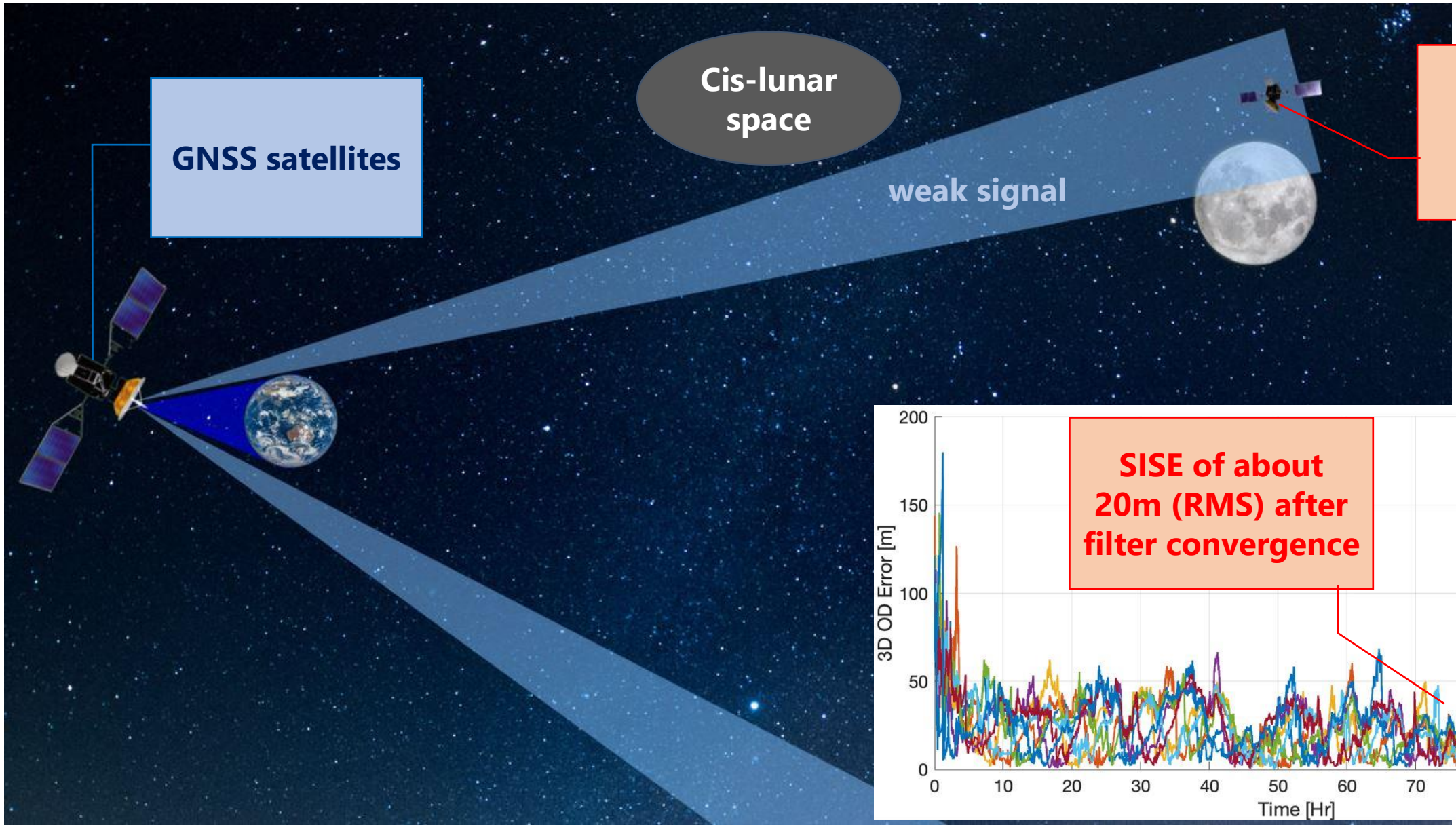


Our first navigation satellite will be deployed in the ELFO. The LNSS and LANS IOC accuracy will be both evaluated



Our second LNSS Com&Nav satellite will perform the optical communication experiment between Moon and Earth

GNSS navigation (real-time OD) for LNSS satellites, making the lunar PNT autonomous



LNSS single point positioning (SSP) accuracy for a fixed station at the South Pole

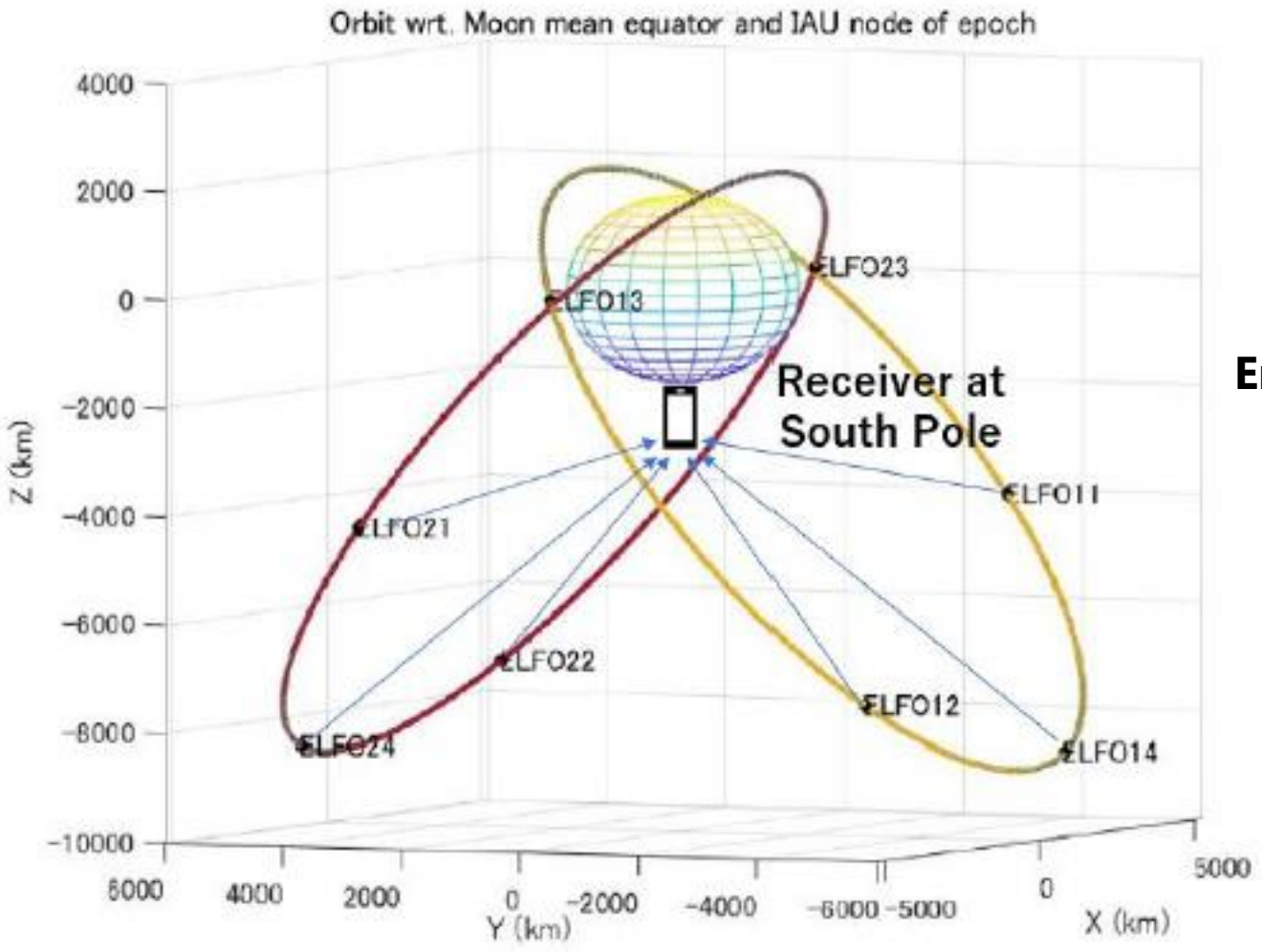
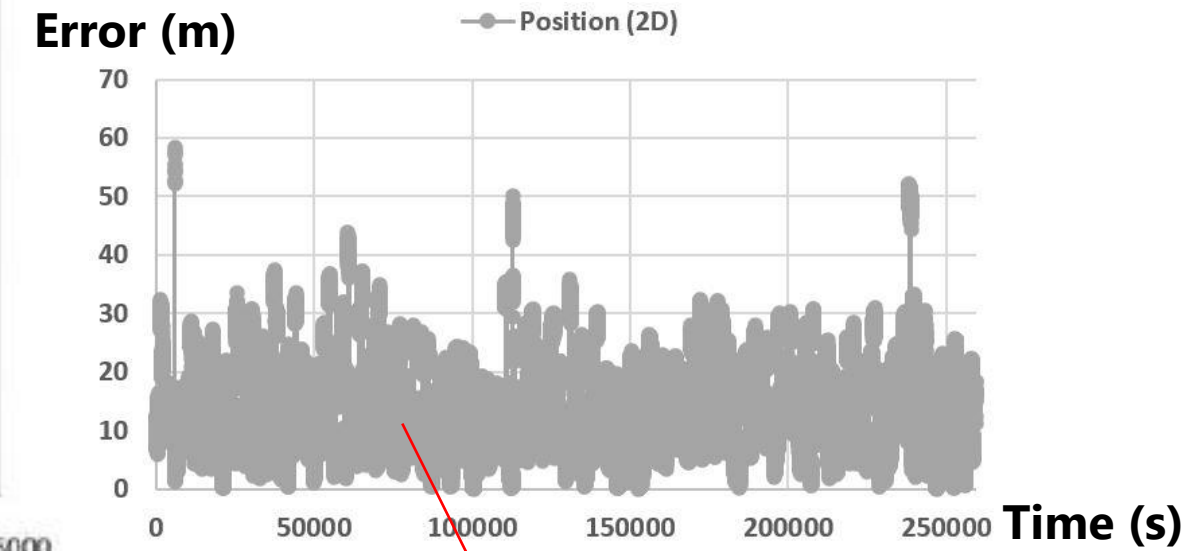


Figure 2: LNSS satellite constellation and receiver at South Pole.

- **Average SSP errors:**

3D position 37.7m,
2D position 13.8m,
Vertical 32.8m,
Clock bias 6.6E-08s

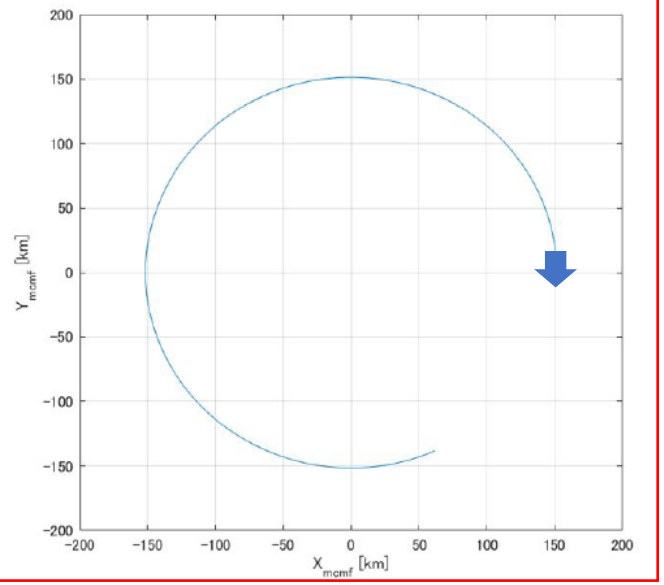
Our LNSS was designed to achieve the high 2D (horizontal) PNT accuracy

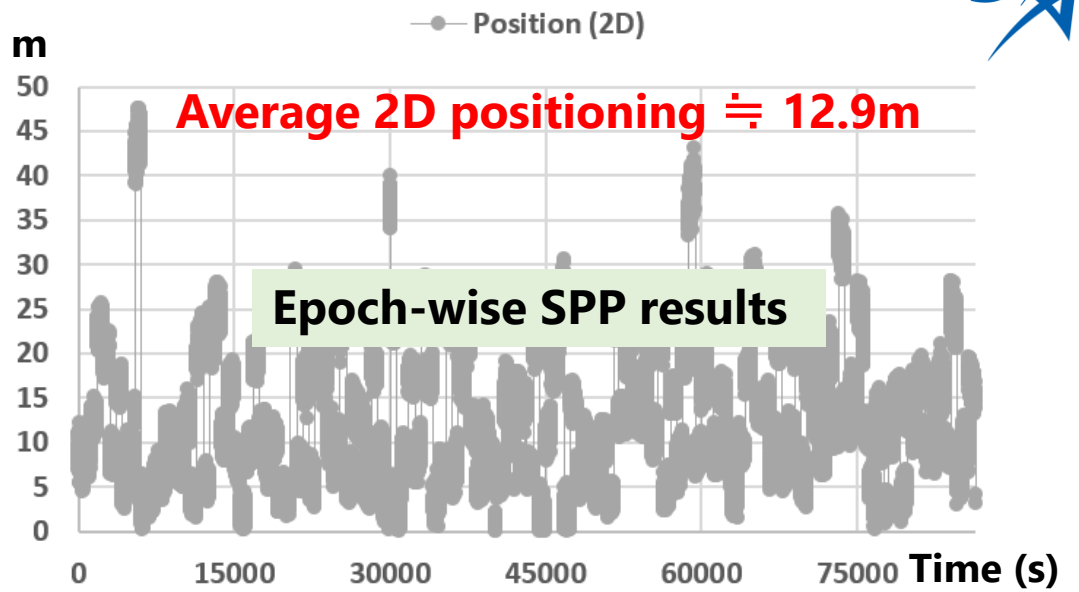


Less than 40m for most of the epochs

LNSS navigation accuracy for a moving object at the South Pole region

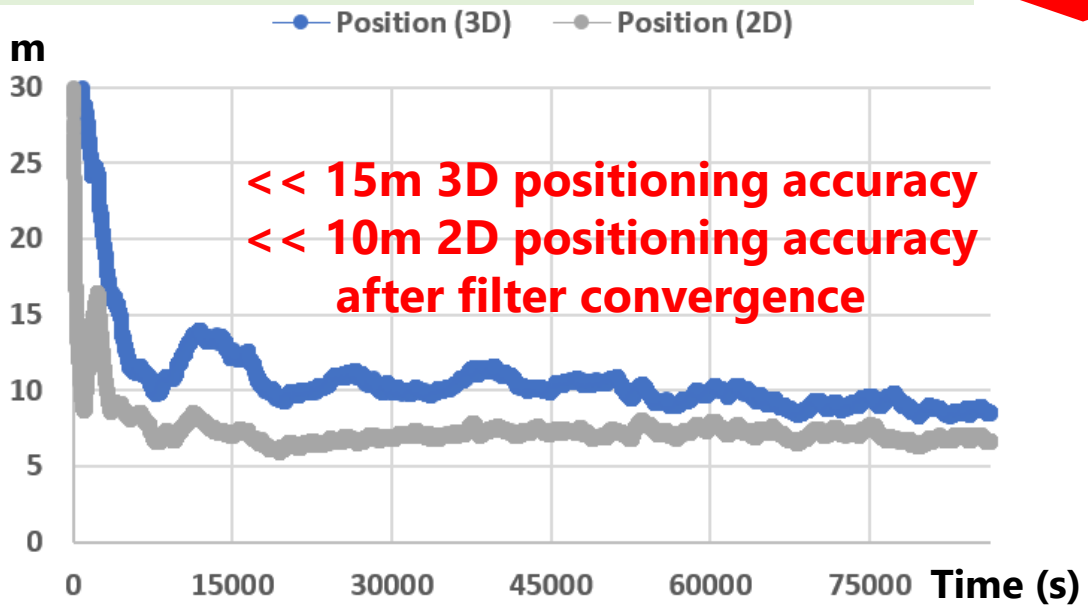
Assumed movement: circular movement with velocity of 3 m/s at south altitude of 85 degrees

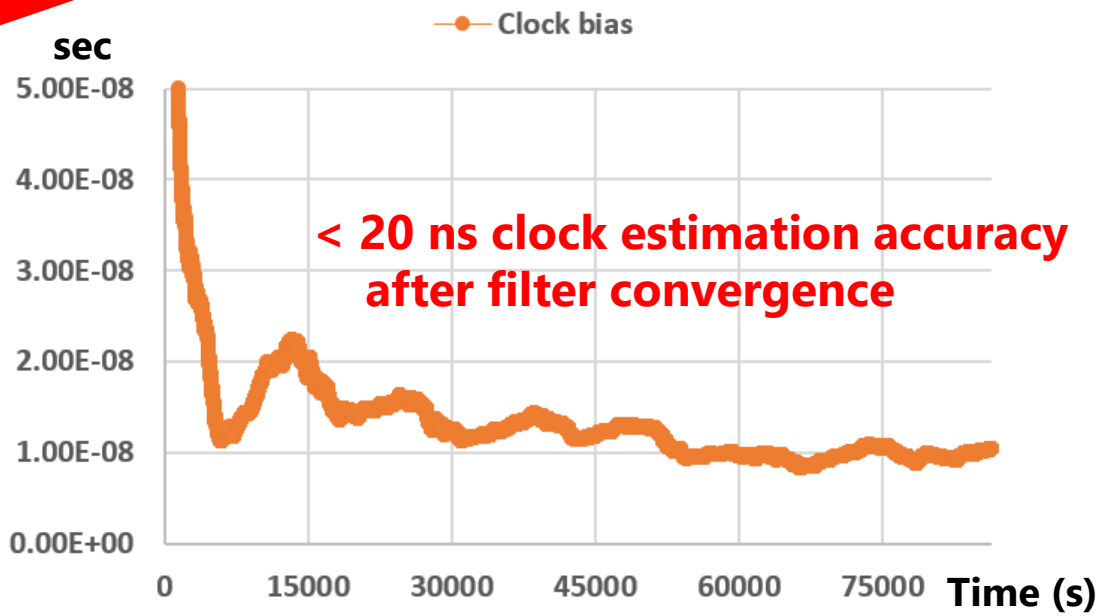




Navigation results (SISE vel of about 2cm/s)

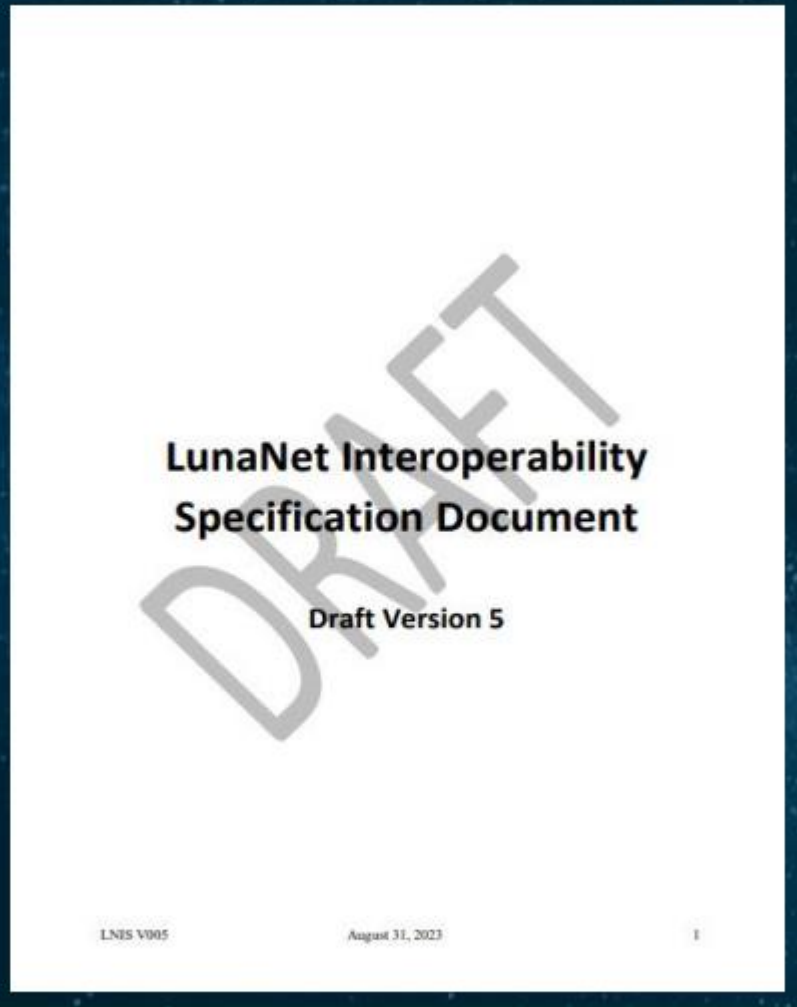
Applying sequential measurement filtering (EKF)

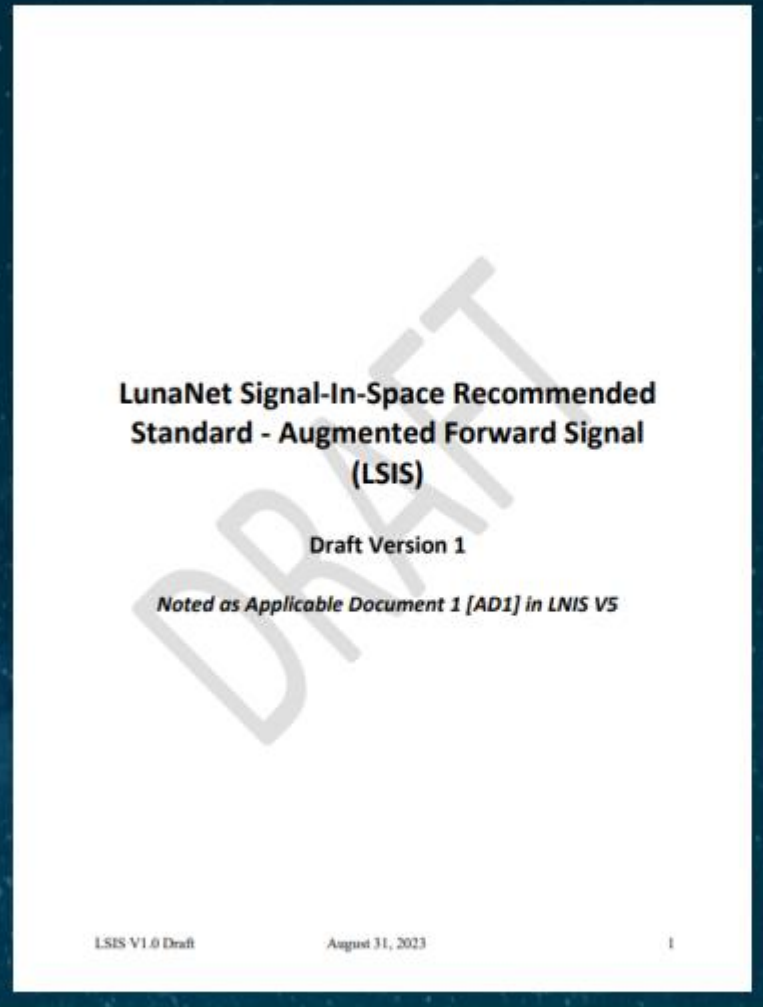




Collaboration with ESA and NASA and LunaNet Interoperability Specification (LNIS)

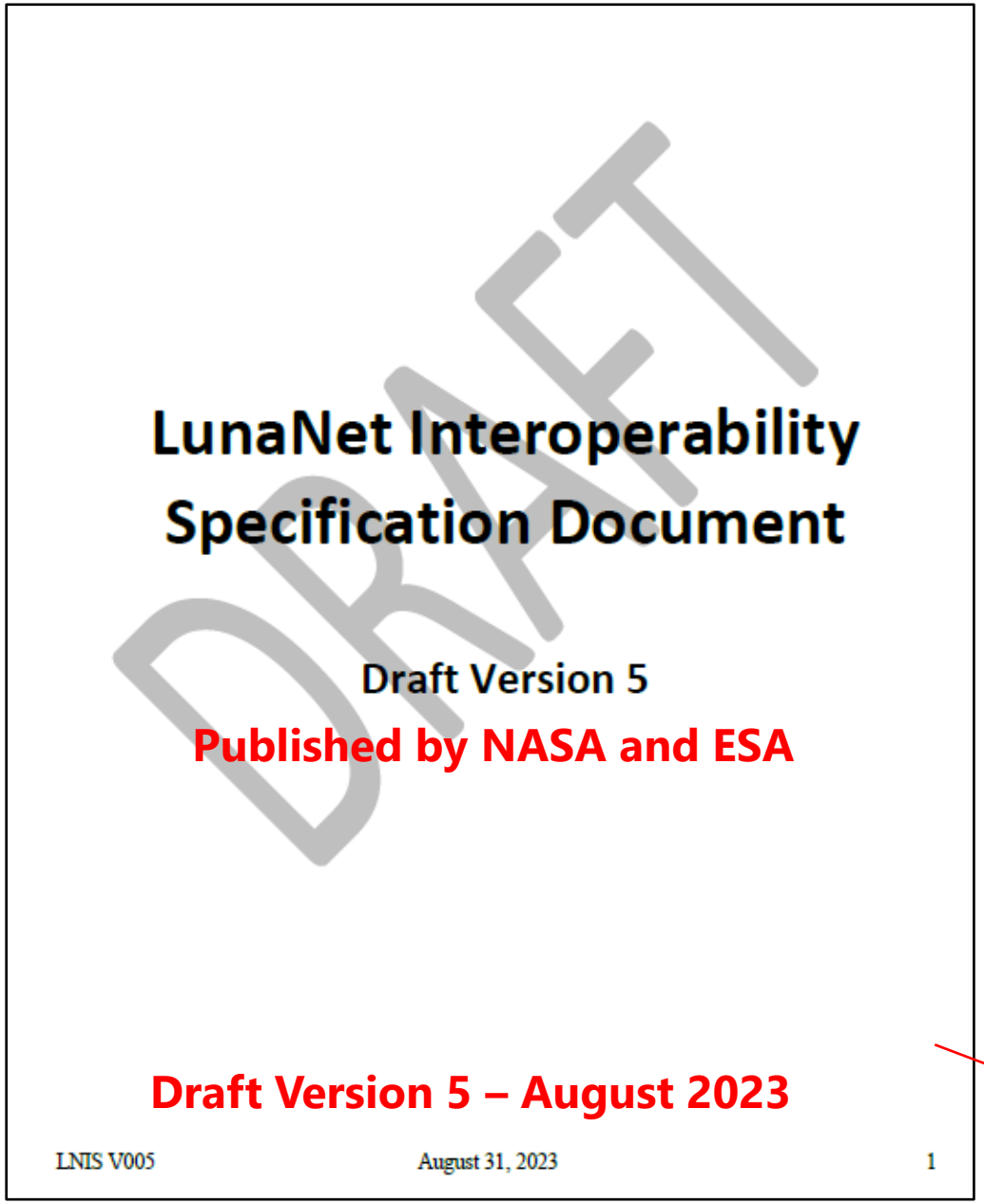
MOONLIGHT will be developed to comply with LunaNet Interoperability Specifications





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 Interoperability Specification (LNIS) in which the LANS is defined



The LNIS includes:

- **Concept of the LANS, message format of the AFS, signal frequency, power, etc.**
- **LANS Initial Operations Capability (IOC) and Enhanced Operations Capability (EOC)**
- **Signal-In-Space-Error (SISE) definition for the LunaNet Service Providers (LNSPs)**
- **Lunar Reference System and Lunar Time System Standard**

The JAXA LNSS complies with the LNIS and will be designed to become interoperable and comparable with the other LNSPs such as ESA and NASA

LANS South Pole service coverage and performance volume

Signal-In-Space-Error (SISE) requirement

Table C-1: LNSP SISE

Error	Value
SISE pos	≤TBD m (95%) - Calculated as the 95th percentile of the time series of instantaneous SISE values over a TBD hours period.
SISE vel	≤TBD m/s (95%) - Calculated as the 95th percentile of the time series of instantaneous SISE values over a TBD hours period.

LANS South Pole service coverage

Figure 10: Notional LANS South Pole Service Coverage and Performance Volume

1. Signal-In-Space Error for positioning (SISE pos)

$$SISE_{pos} = \sqrt{(x-\tilde{x})^2 + (y-\tilde{y})^2 + (z-\tilde{z})^2 + (ct-c\tilde{t})^2}\,, \quad 1$$

Where x, y, z, t are the true position and time, while the corresponding tilde parameters represent the values broadcasted in the navigation message.

2. Signal-In-Space Error for velocity (SISE vel):

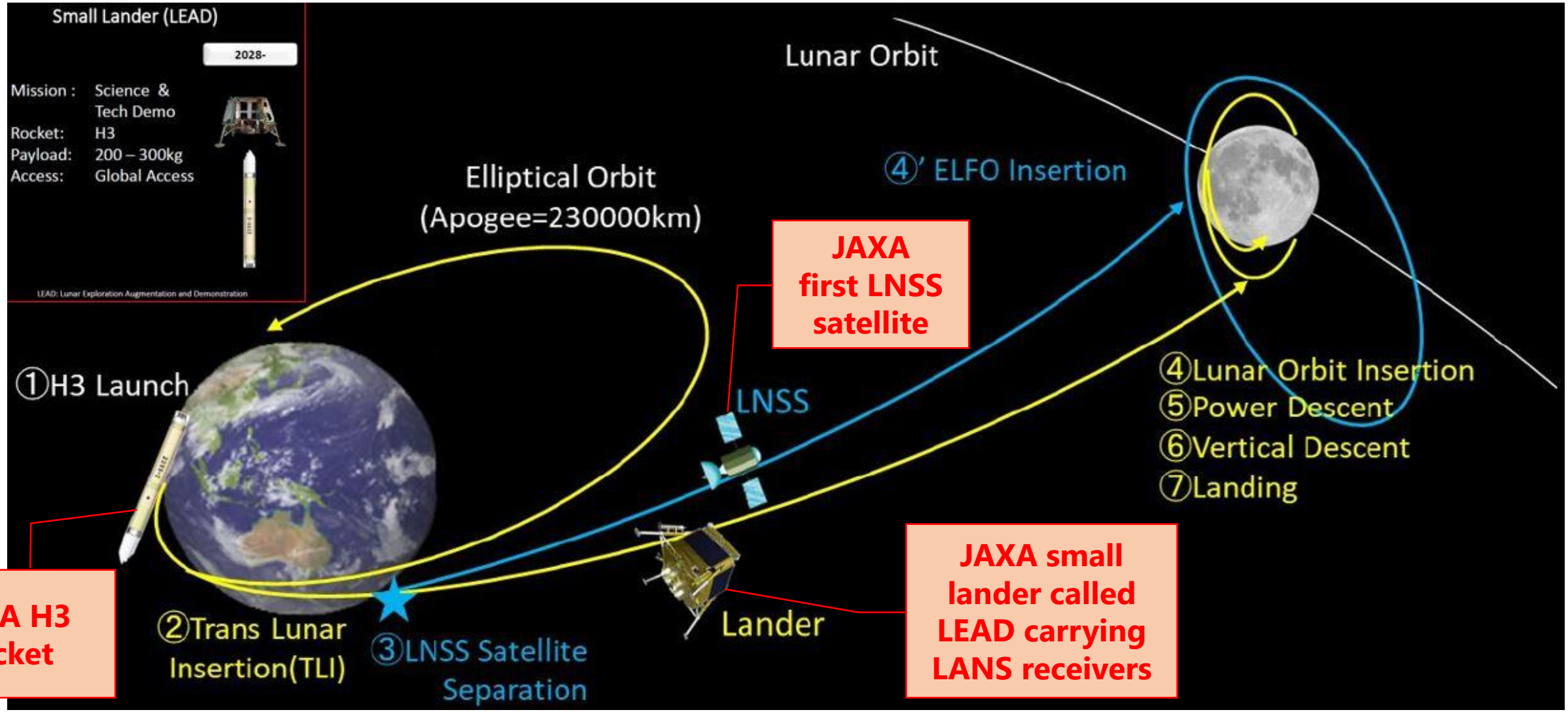
$$SISE_{vel} = \sqrt{(\dot{x}-\tilde{\dot{x}})^2 + (\dot{y}-\tilde{\dot{y}})^2 + (\dot{z}-\tilde{\dot{z}})^2 + (c\dot{t}-c\tilde{\dot{t}})^2}\,, \quad 2$$

Where $\dot{x}, \dot{y}, \dot{z}$ represents the velocity and $c\dot{t}$ the clock drift.

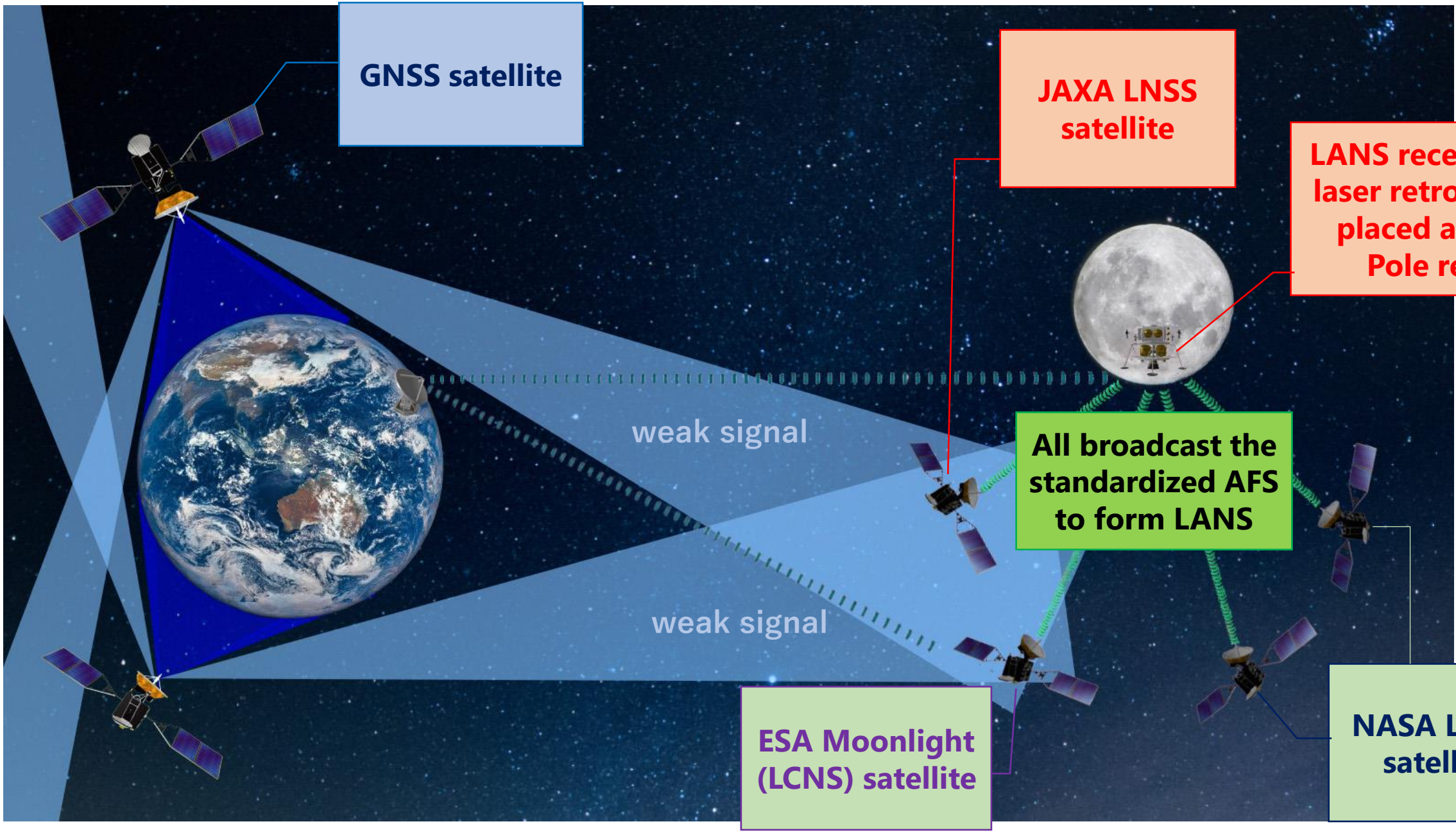
Both SISEs are based on lunar reference frame and time, which will be defined in the LNIS applicable documents called Lunar Reference System and Lunar Time System Standard

Plan of LANS interoperability demonstration mission targeting in 2028

Launching and deploying our first LNSS satellite and LANS receivers to the moon



Proposing the first-ever ESA-NASA-JAXA LANS interoperability and PNT demonstration



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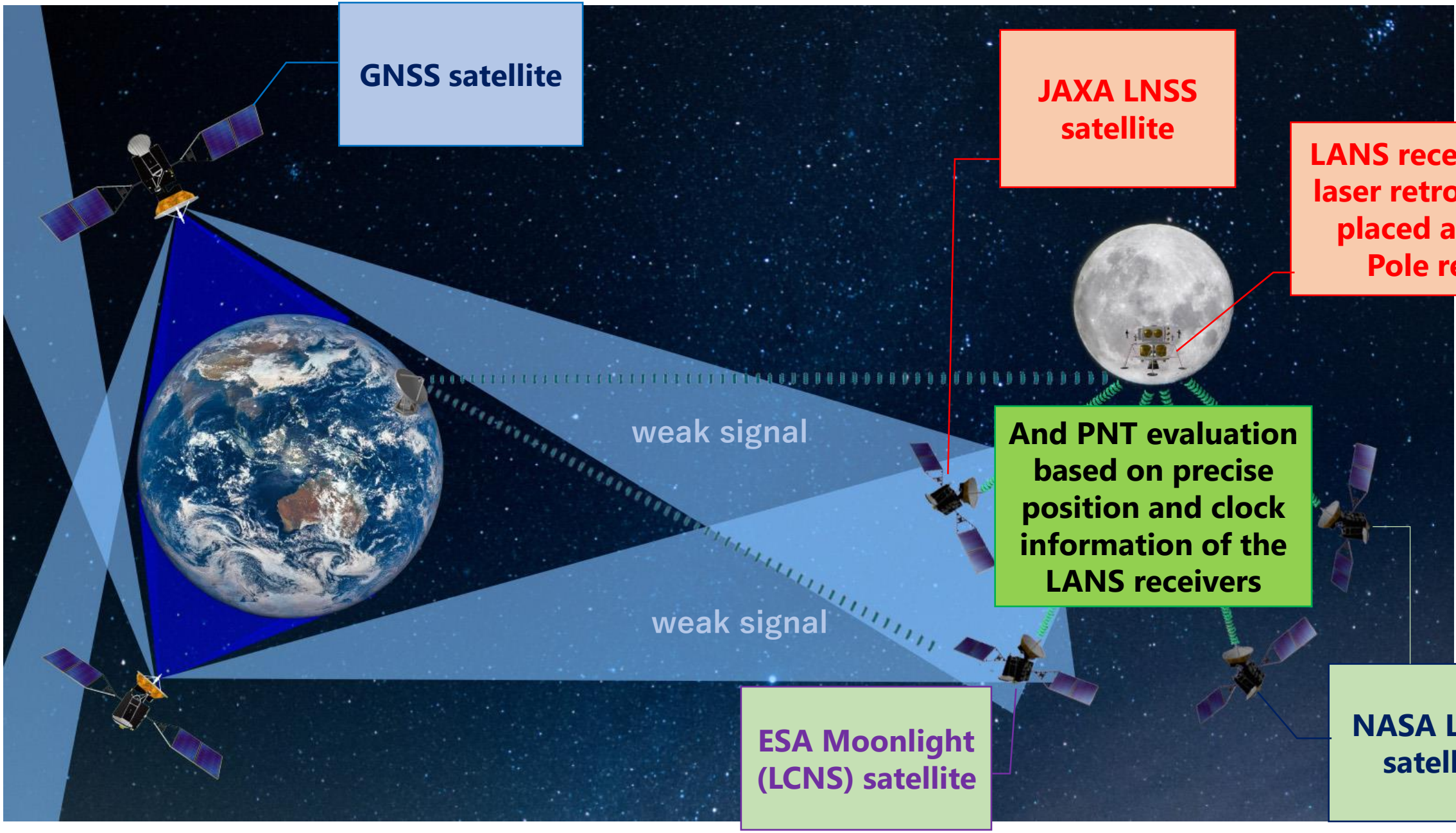
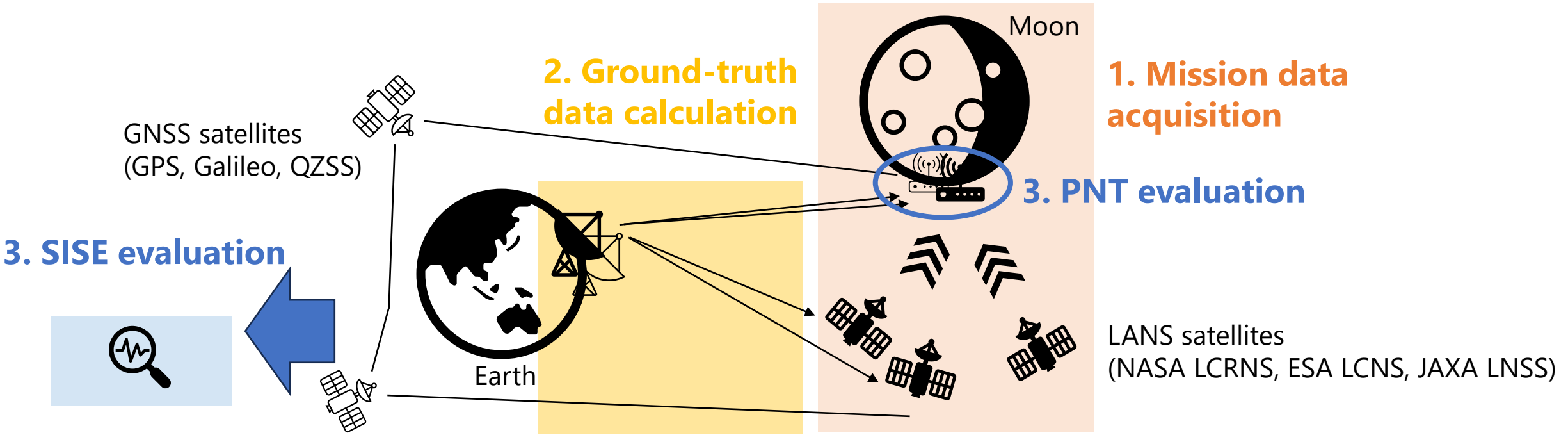


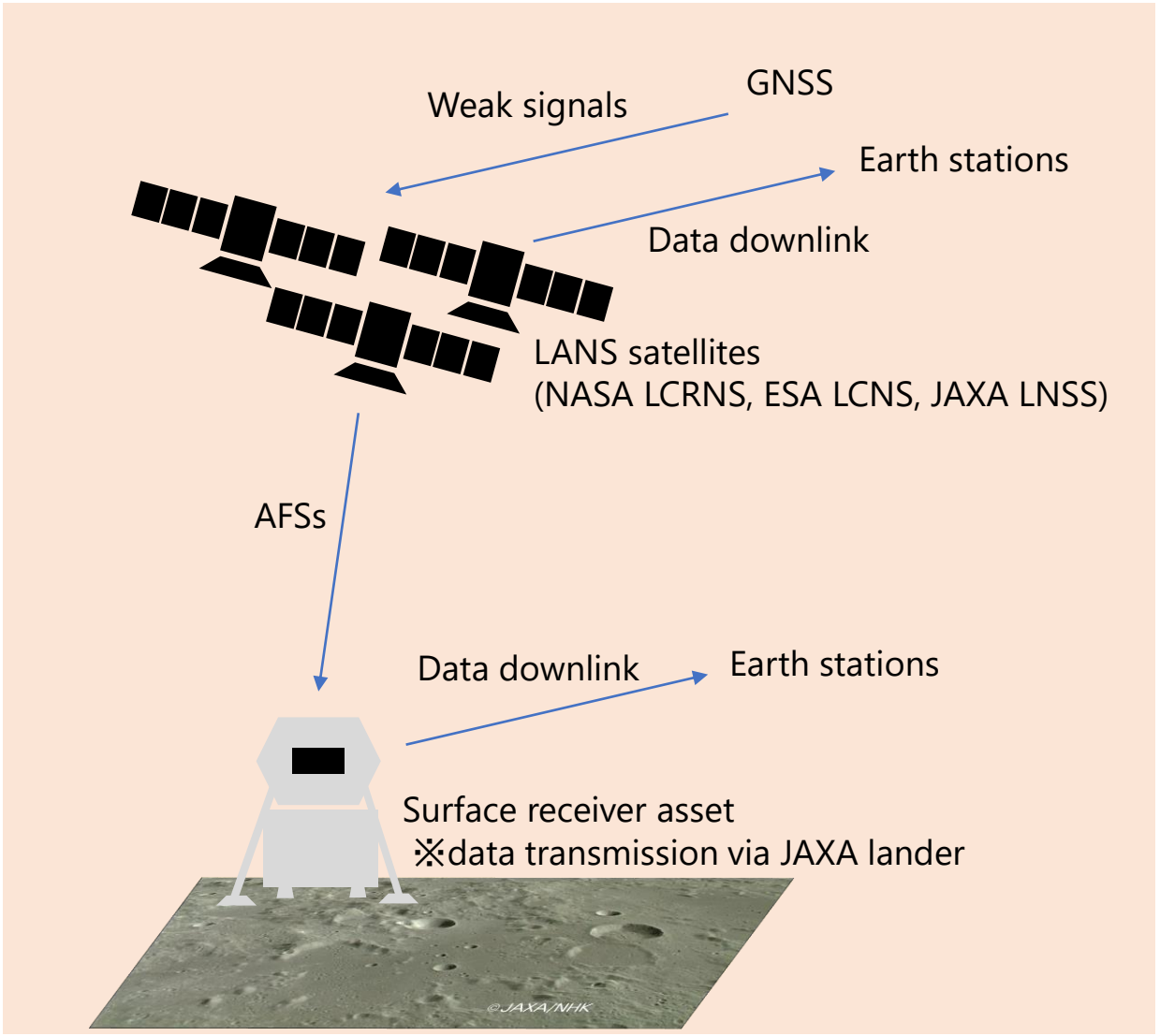
LANS interoperability and PNT demonstration – concept of operation

☐ Three major steps for the demonstration

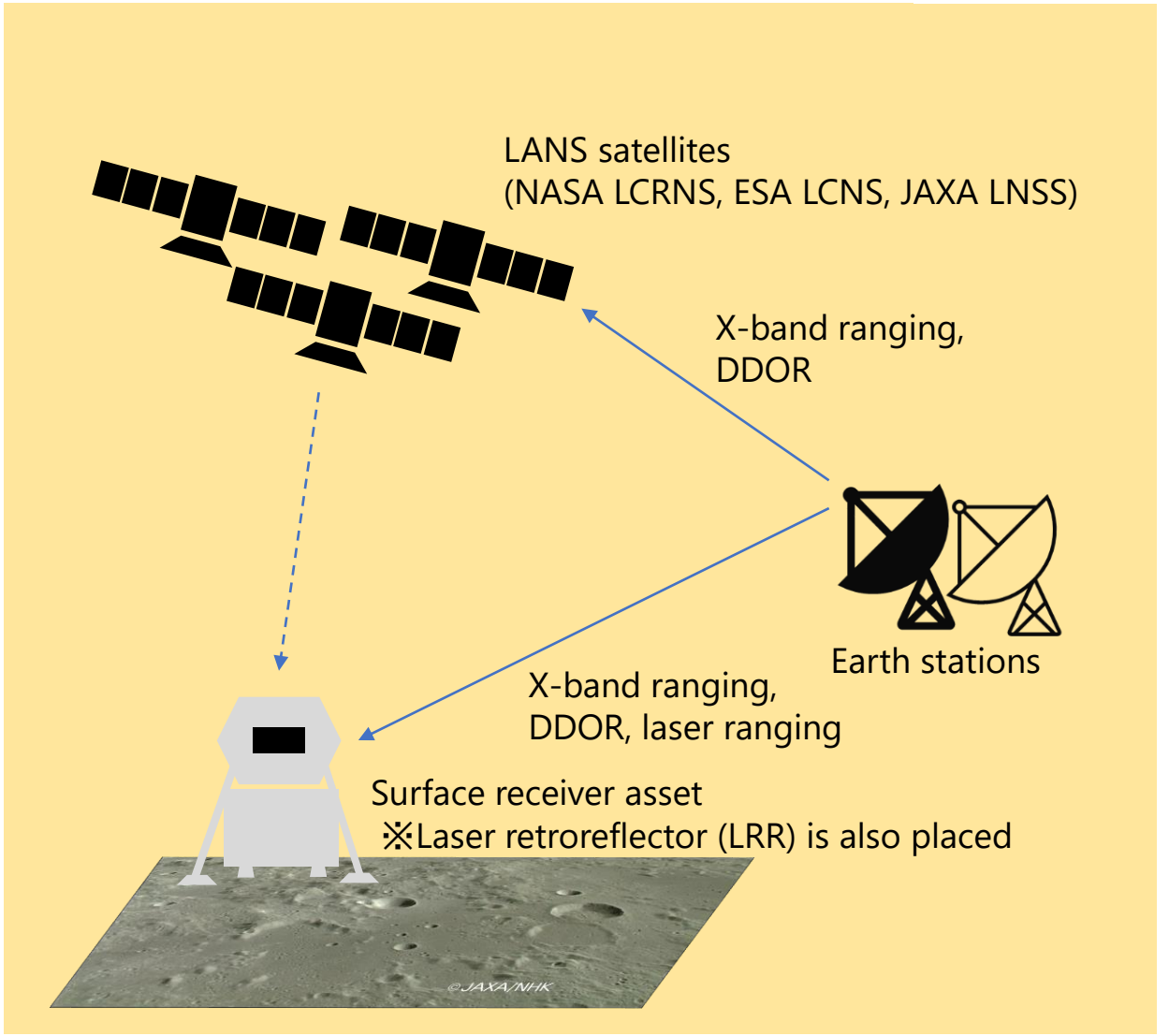
1. Mission data acquisition in Moon environment
2. Ground-truth data calculation by Earth stations
3. SISE and PNT evaluation by comparing the mission data with the ground-truth data



Mission data acquisition and ground-truth data calculation



GNSS weak signal and LANS AFS acquisition in actual Moon environment



Precise satellite orbit, receiver position, and clock determination using earth stations

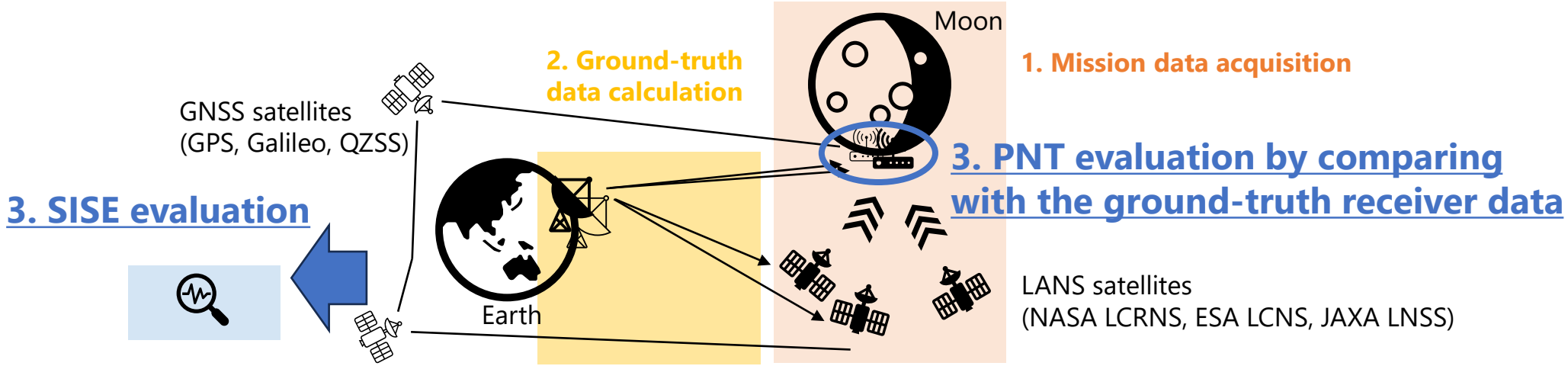
SISE and PNT evaluation

☐ The SISE evaluation procedure

① Calculate true pseudo ranges based on the ground-truth data and compare them with the actual pseudo ranges to evaluate unknown error caused by hardware and moon environmental delays

② Evaluate errors in the satellite ephemerides (orbit and clock prediction errors) by comparing the ephemerides with the ground-truth data

③ The SISE is assessed by adding the ephemeris error and the identified unknown error, based on which the moon surface positioning accuracy is evaluated by multiplying with the LANS DOPs



International lunar PNT activities

International Organizations Currently Involved in Lunar PNT

LunaNet Interoperability Specification development

LNIS WG

Space agency lunar PNT governance coordination

IOAG
Interagency Operations Advisory Group

Lunar PNT/GNSS interoperability, compatibility, availability

ICG

Space frequency coordination

SFCG

Reference system and time system recommendations

IAU

Exploration mission roadmaps and performance needs

ISECG
International Space Exploration Coordination Group

This year's ICG (International Committee on GNSS) just concluded

・Lunar PNT presentations were made by NASA, ESA, JAXA, China, and India. As of now, these five countries seem the active lunar PNT system developers

・Joint statement on encouraging interoperability and compatibility among the respective lunar PNT systems adopted

・Recommendation on holding joint ICG-IOAG multilateral workshop on cislunar PNT adopted. JAXA will show a key role in the workshop organization and planning

まとめ

・欧米が月測位を牽引する中、JAXAもLNSSの検討を進めており、欧米日の共同で月版GNSSに相当するLANSを構築する予定である。LANSの定義やAFSの仕様はLNISに記載されており、現在Version 5の制定に向けた作業が国際的に進んでいる

・JAXAはLANSの相互運用性・月測位の実証ミッションを2028年に実施することで検討を進めており、ESA・NASAとの共同実証を目指して調整を進めている。ESA・NASAとの共同で本実証を成功させることにより、2030年代以降にさらに活発になる国際的な月測位の枠組みに貢献していく

・本実証ミッションでは月の南極域に設置するLANS受信機の精密位置決定のためにLaser retroreflectorも設置する計画である。このレーザーレンジングのデータは月の座標系であるLunar Reference System（LRS）の高精度化といった国際貢献にも資するものである