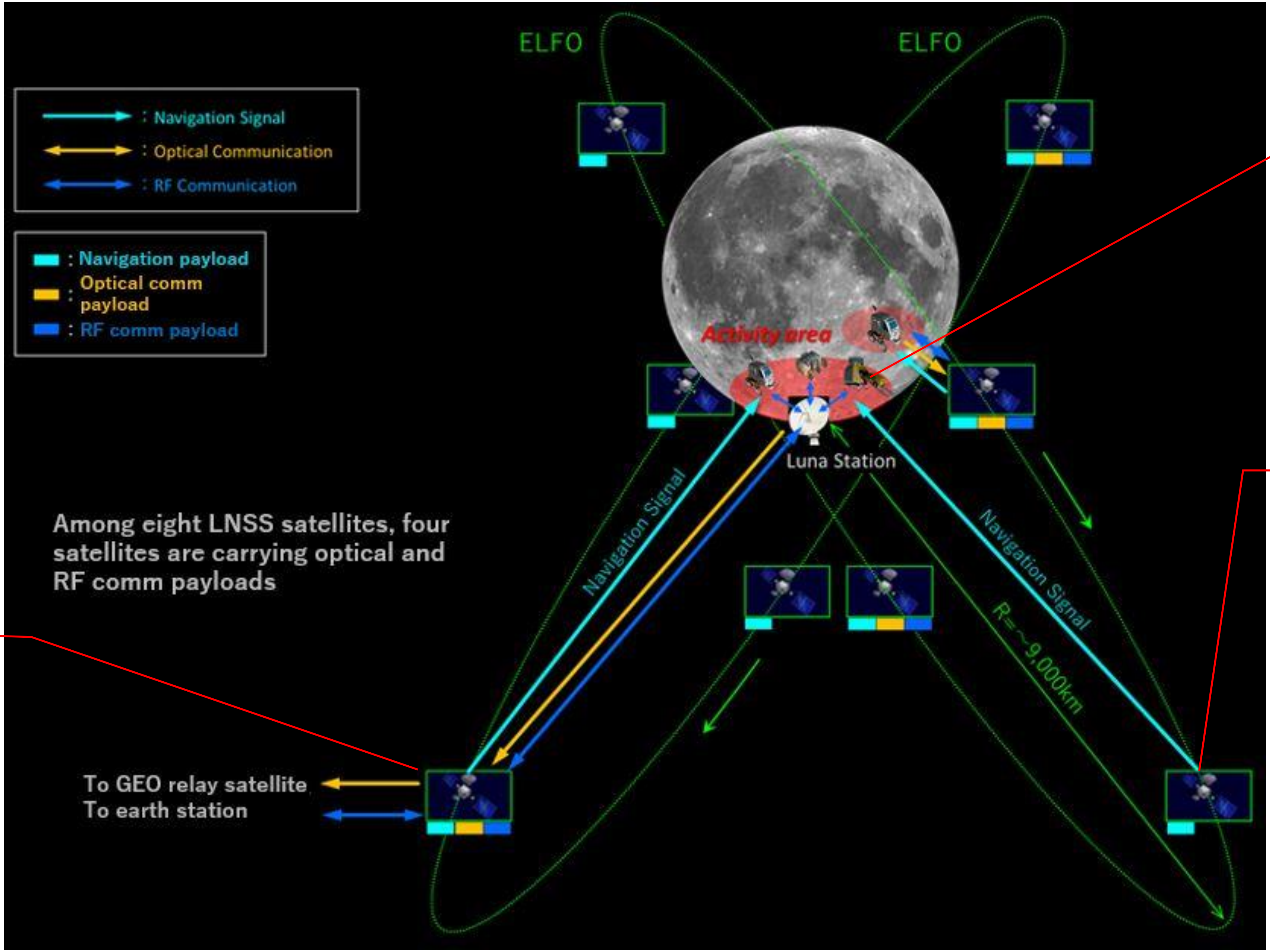
Lunar PNT collaboration proposal between LNSS (JAXA), Moonlight (ESA), and LCRNS (NASA)

Masaya Murata (JAXA)

Japan Status

Lunar Navigation Satellite System (LNSS)

LNSS is GPS-like satellite system for the moon designed by JAXA



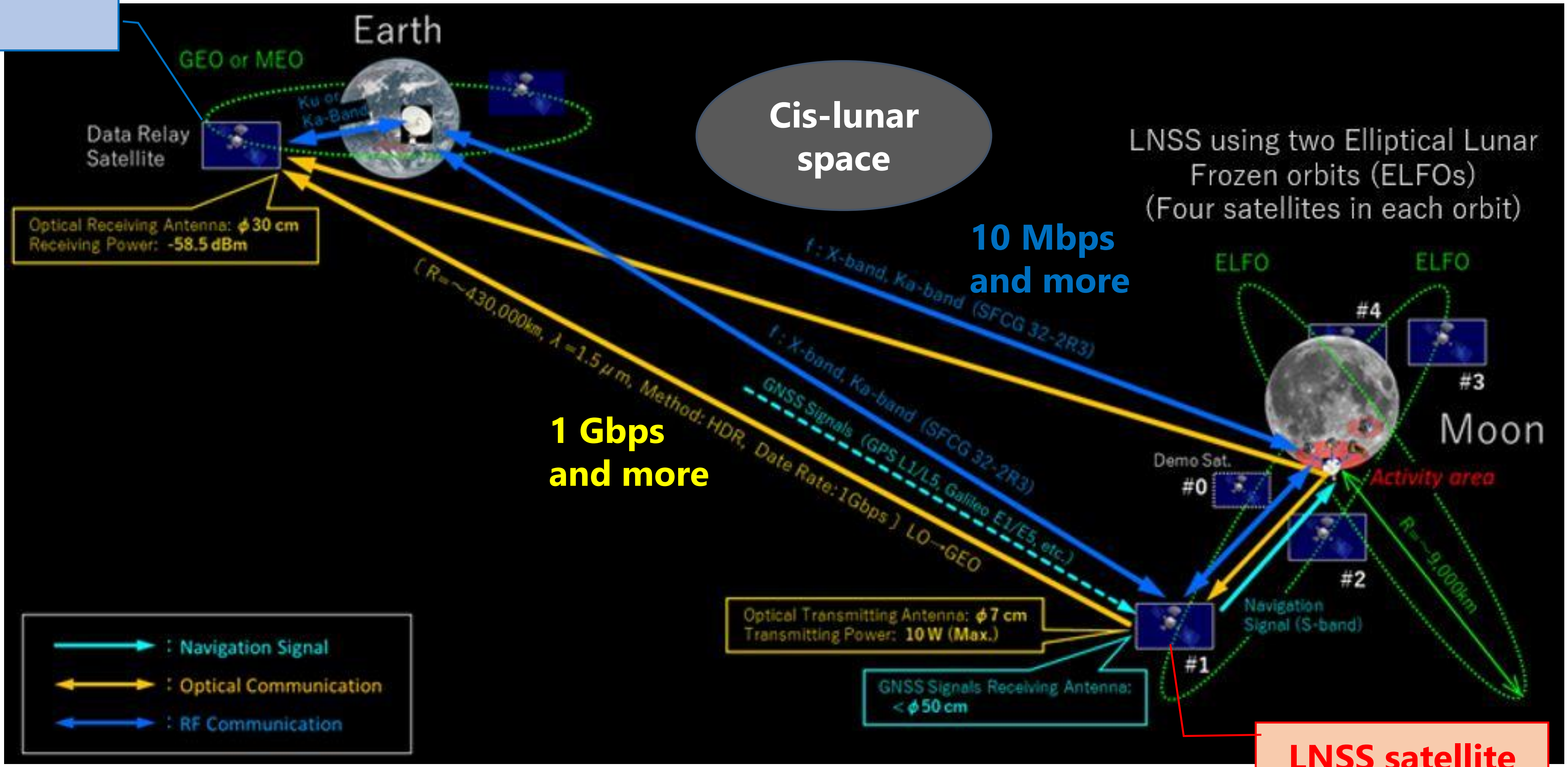
Target: South Pole region

LNSS satellite broadcasting navigation signal

LNSS satellite functioning as data relay satellite

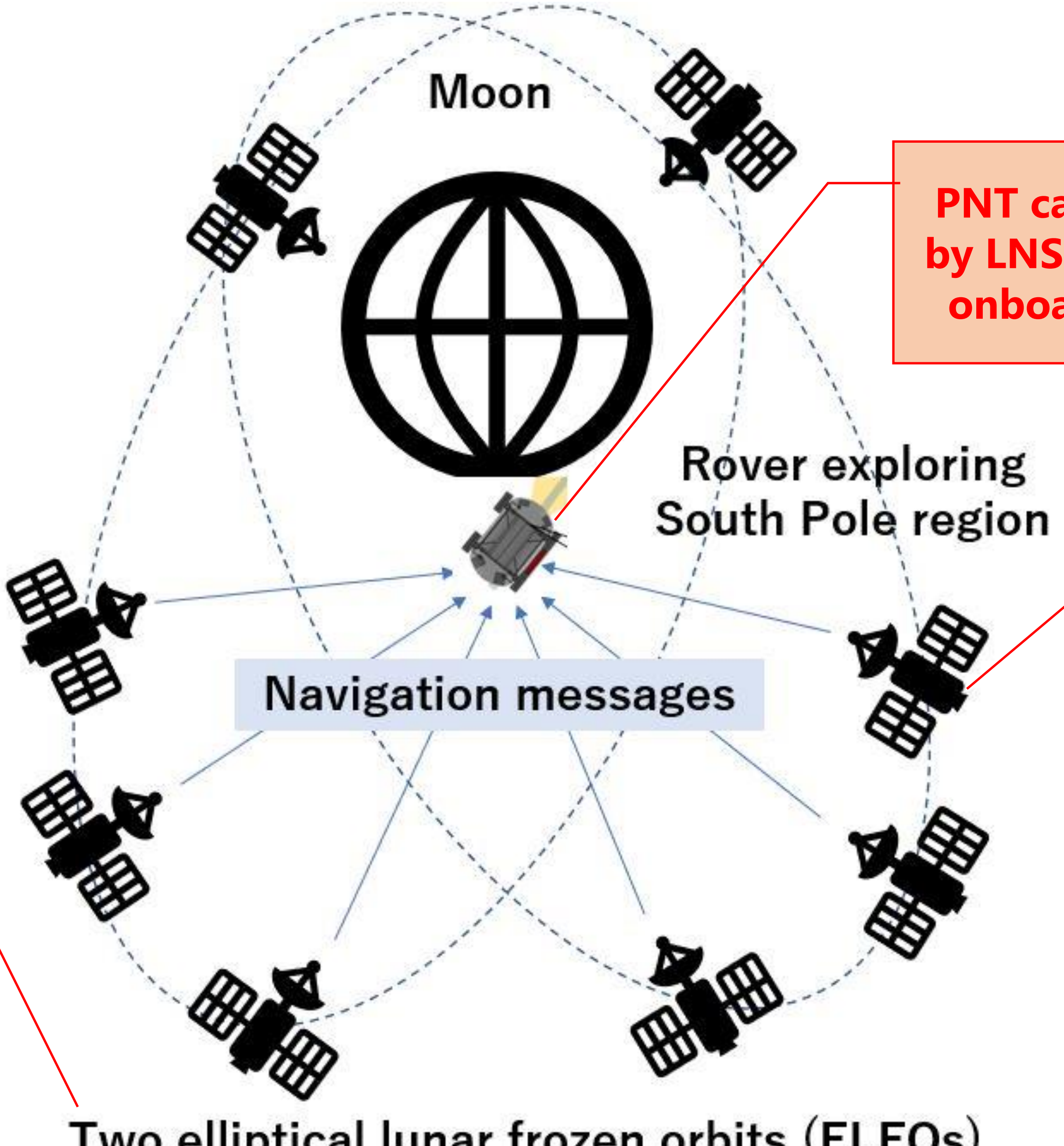
Earth data relay satellite

LNSS provides communication, positioning, navigation, and timing (CPNT) service



LNSS satellite functioning as data relay satellite

LNSS real-time PNT service at South Pole region

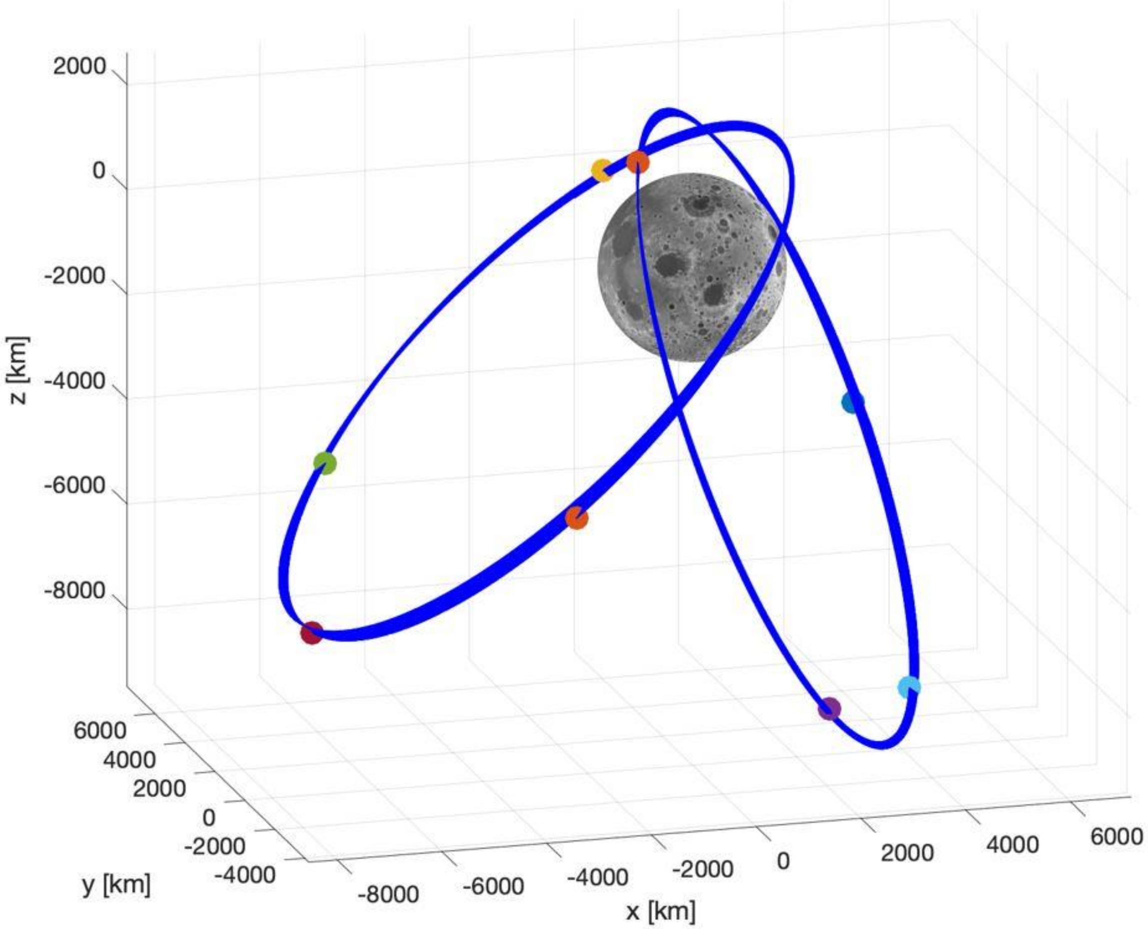


PNT calculation by LNSS receiver onboard rover

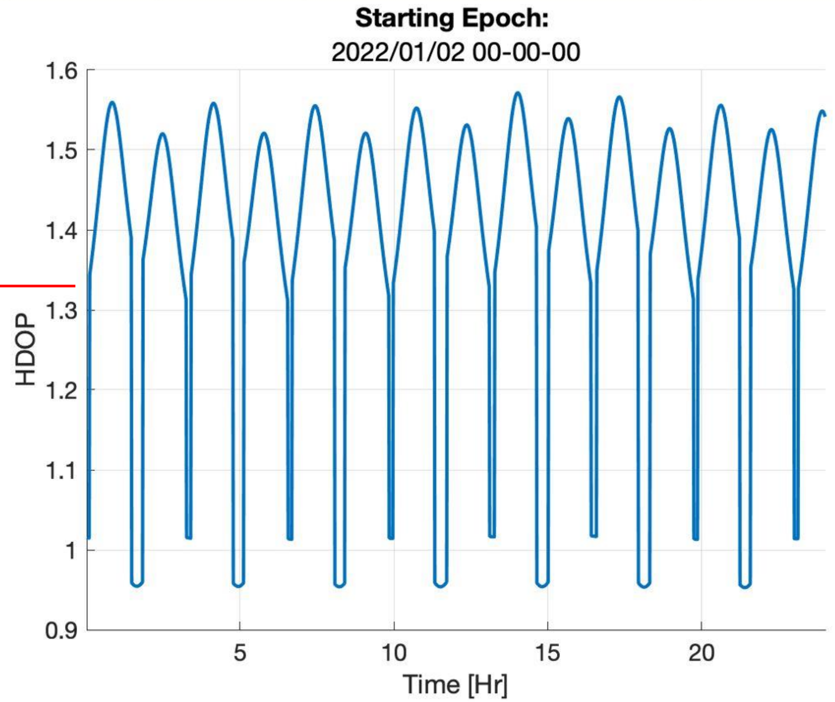
LNSS satellite broadcasting navigation signal

Stable moon orbits covering South Pole region

LNSS satellite constellation for South Pole region

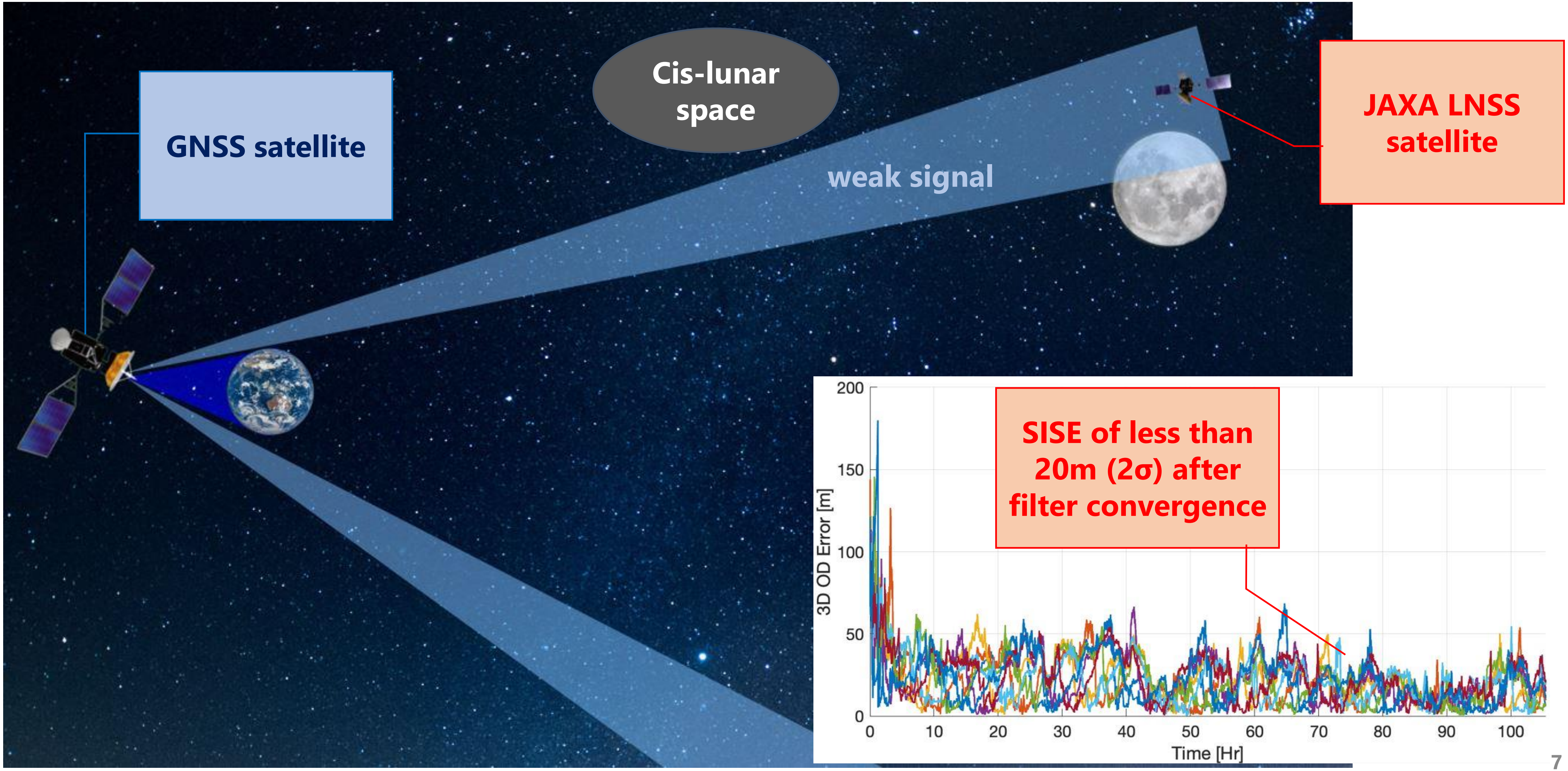


SV	A[km]	E	I[deg]	RAAN[deg]	AP[deg]	MA[deg]
ELFO11	6540	0.6	56.2	0	90	0
ELFO12	6540	0.6	56.2	0	90	90
ELFO13	6540	0.6	56.2	0	90	180
ELFO14	6540	0.6	56.2	0	90	270
ELFO21	6540	0.6	56.2	180	90	45
ELFO22	6540	0.6	56.2	180	90	135
ELFO23	6540	0.6	56.2	180	90	225
ELFO24	6540	0.6	56.2	180	90	315



HDOP of around 1.3 always at South Pole region

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



Simulation setting

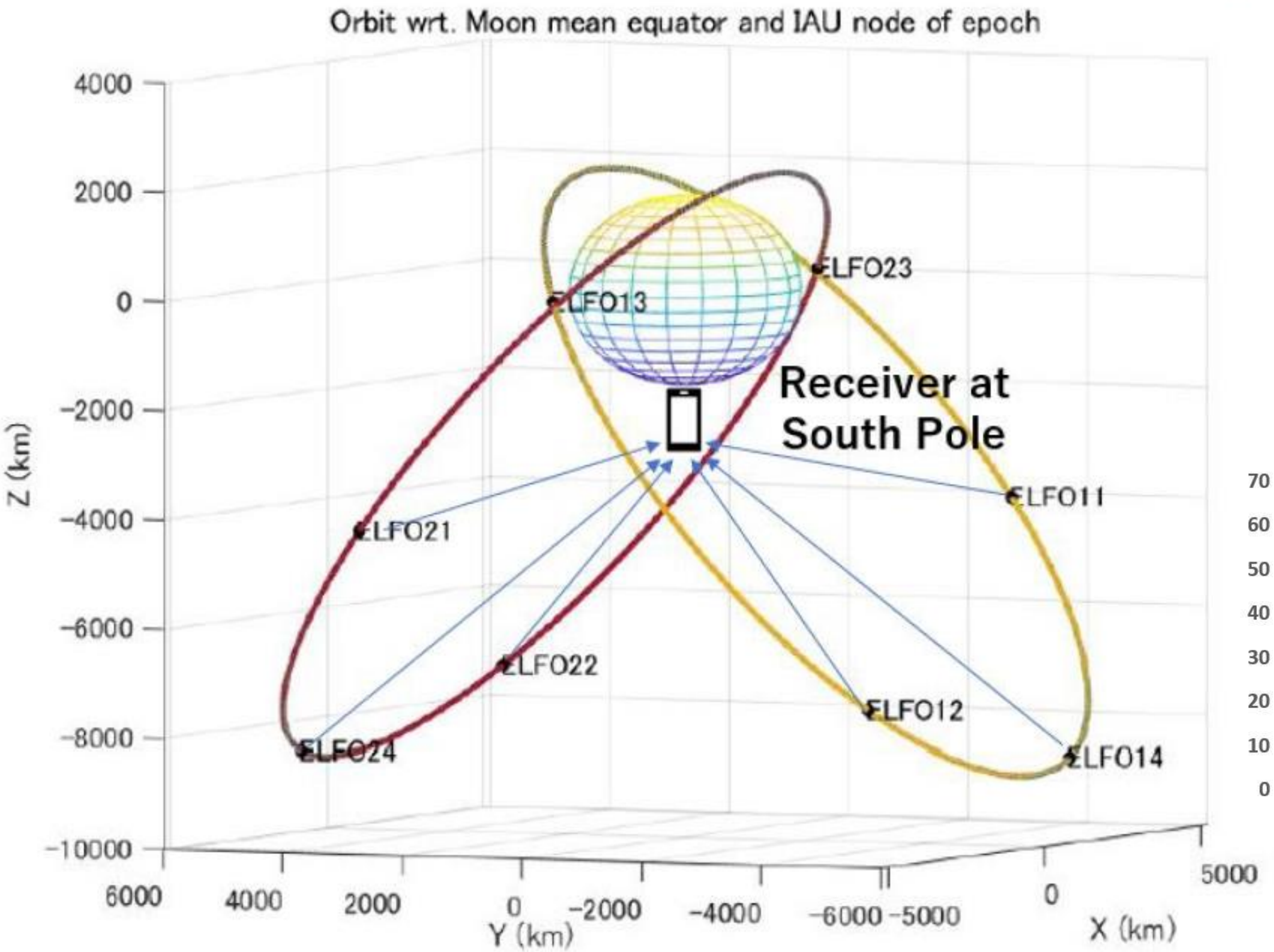
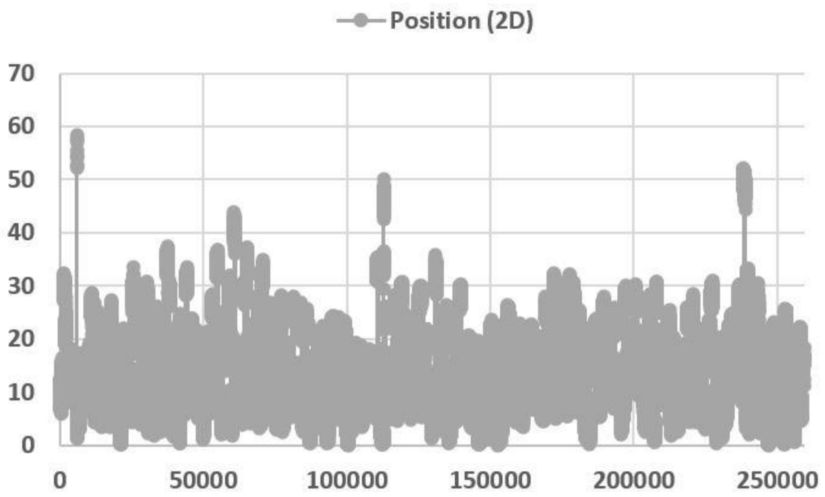


Figure 1. LNSS satellite constellation.

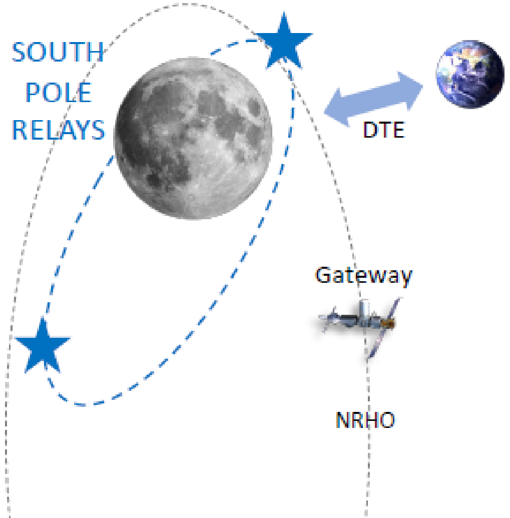
・単独測位平均精度
（エポック毎の推定精度）
位置（3次元）37.7m
水平 13.8m、
垂直 32.8m、
クロック6.6E-08s



NASA Status

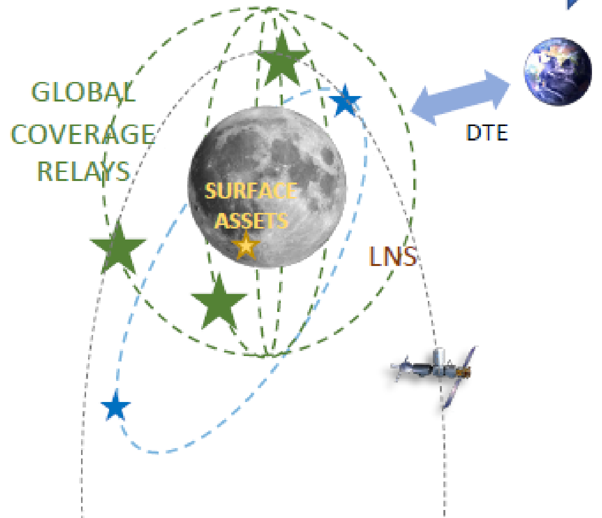
Overview of Architecture Evolution

Initial Phase: By 2024-2026



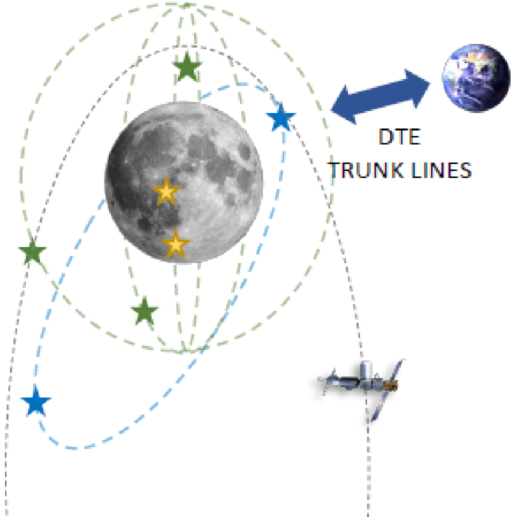
- *DTE service for Near Side, lunar orbiters and surface missions*
- *Intensive relay service for South Pole and a selected area of the Far Side*
- *Initial PNT service and lunar surface networks*
- *LunaNet interoperability established from the beginning*

Growth Phase: 2027-2030



- *Continued DTE service for Near Side*
- *Expanded relay service for South Pole and multiple Far Side regions*
- *Limited relay service for other globally-dispersed locations and orbiters*
- *Lunar Navigation Service for PNT*
- *Surface networking*
- *Introduction of optical links*

Desired Future State: 2030 + Beyond



- *Satellite constellations with multiple operators functioning as cooperative set of networks*
- *Intensive coverage of specific regions and regular coverage of all regions*
- *Optical trunk line links*
- *Surface network assets in multiple locations*

The implementation described is not intended to be prescriptive but to indicate a means to achieve the required services. Other implementations that would meet the same intent should be considered.

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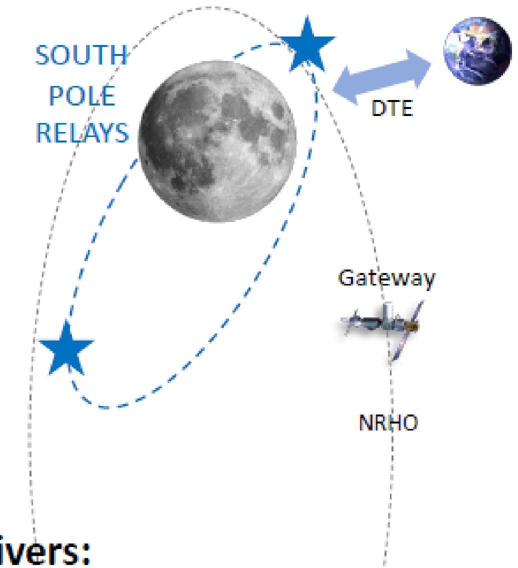
Initial Phase Architecture

Initial Phase: By 2024-2026



Mission Drivers:

- Multiple spacecraft, orbiting and landed, requiring DTE service
- Far-side robotic users and human exploration at the South Pole
- High-rate services up to 50 Mbps return and 10 Mbps forward
- PNT knowledge for landed spacecraft to within 100 meters

Implementation:

- **LEGS** assets supplemented by DSN when necessary for DTE service needs
- **At least two Relay satellites** in an elliptical orbit to provide service to the South Pole and a portion of the Far Side.
- As possible, additional relay satellites added for greater capacity and redundancy.
- Relay satellite systems comply with established **interoperability standards**
- **PNT service** from relay satellites to include, as a minimum, range and range rate service as part of communications link and incorporation of Earth-orbit-based GNSS reception and precise on-board time reference for position knowledge
- As possible, relay satellites should incorporate capabilities for direct links between lunar users and **intersatellite links** between relay satellites.
- **Gateway** and ESA **Lunar Pathfinder** may also contribute to relay capabilities.

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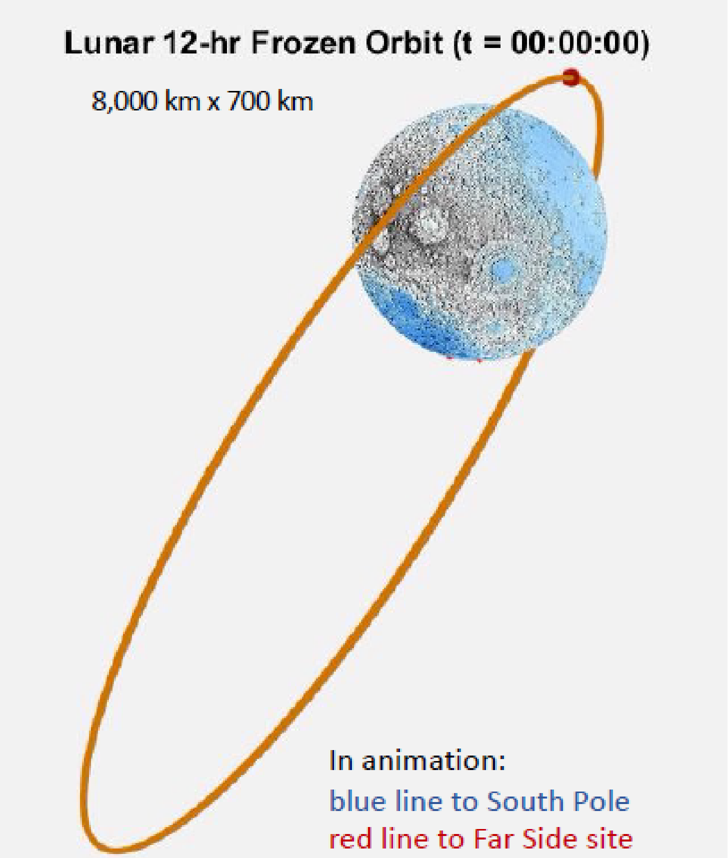
Initial Relay Concept

Lunar Communications Relay and Navigation Systems (LCRNS)

For the initial architecture, coverage of South Pole and southern region of the Far Side is needed

- There is a family of elliptical orbits that require minimal orbit maintenance and provide long dwell times over the South Pole
  - A single relay satellite in a 12-hour elliptical orbit can provide 8 to 9 hours of coverage of South Pole and Schrodinger Basin (Far Side reference site) in each orbit - yielding about 75% coverage time
  - With only two properly phased relays in this type of orbit, South Pole coverage could be continuous, independent of Gateway.
- Small spacecraft – as low as 150-300 kg could be adequate for the service needed. These could be delivered as rideshare payloads.
- Relays would link to Earth ground stations – assuming 18-meter class antennas.
- Gateway, when present, will provide substantial relay service to HLS missions
- ESA Lunar Pathfinder may provide service to NASA robotic science missions.
- Over time, more satellites can be added in order to augment redundancy, increase capacity for more users, and expand to global coverage.

Reference Relay Concept



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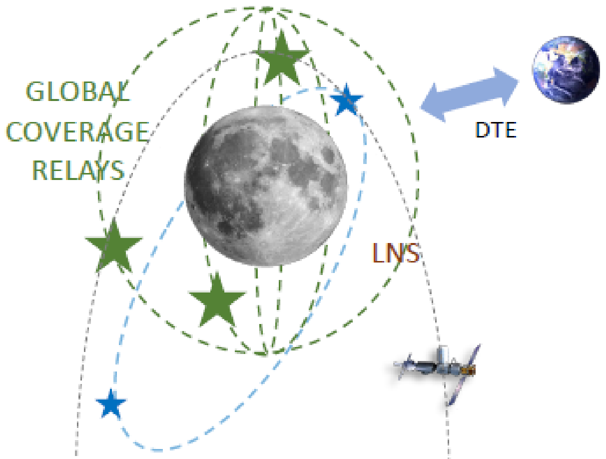
Growth Phase Architecture

Growth Phase: 2027-2030



Mission Drivers:

- Growth in assets and missions – multiple surface elements (e.g., LTV) and operations continue even when crew are not present
- Data rate growth to 150 Mbps and greater, and lower latency services for real-time telerobotic operations
- Growth in mobility operations – distance and durations
- More diversity in mission location across a range of far side and polar regions with longer durations
- Science missions and EVA crew will require very precise position information and on-demand location service
- Lunar orbiting spacecraft demand is likely to increase substantially, including many small satellites

Implementation:

- Maintain relay service in elliptical orbit over South Pole with **addition and/or replenishment of satellites**, as needed. Capacity of individual relay satellites or combined capacity of multiple satellites increase.
- Establish **3GPP/5G surface communications and navigation** assets to maintain contact between surface elements and between mobile elements and orbiting relays or Earth.
- Add relay satellites to provide **globally-distributed coverage**.
- DTE service needs will peak as lunar relay satellites and surface relays will **aggregate data and provide trunk lines to Earth**.
- Coherent **Optical links** might be introduced: 1) for trunk lines between lunar relays and Earth stations, 2) for intersatellite links between relays, and 3) between lunar relays and lunar users.
- Comprehensive PNT services with the introduction of "**Lunar Navigation Service**" (LNS) comparable to the Earth-based GNSS.
- Additional ground station capacity via commercial service contracts and international partner contributions.

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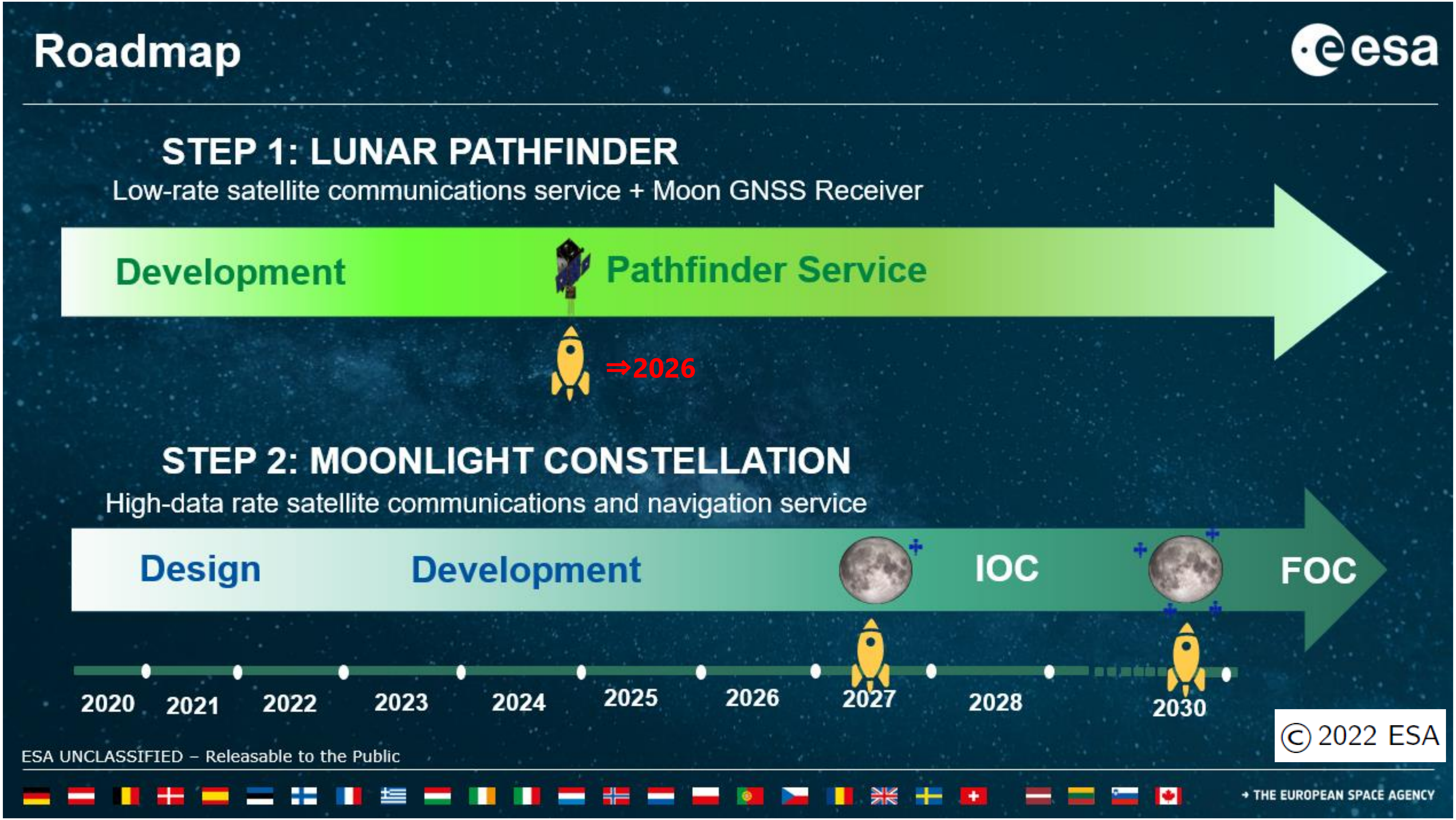
ESA Status


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

- 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%

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Long term - Moonlight FOC

- Moonlight FOC phase will start by end of 2030
- PVT service has to be provided so LCNS should have around 4 satellites 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)

[redacted]

LCNS NAV service Main requirements	
Requirement	Value
Geographic coverage	South Pole
Temporal availability	15h/24h
PVT availability	> 95%

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LunaNet Interoperability Specification

Published by NASA and ESA

Lunanet Interoperability Specification - to define a framework of mutually agreed-upon standards to be applied by users and service providers in a cooperative network supporting missions on and around the Moon.

Applies to communication transmission services for science, exploration and commercial operations, distribution of navigation and timing references, and sharing of information such as space weather alerts.

Seeking input from all potential service providers and users

Draft Version 1 – September 2021

Version 2 – April 2022

Version 3 – July 2022

Version 4 – September 2022 https://go.nasa.gov/3wtefEv

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According to the LunaNet Interoperability Specification (LNIS), Lunar augmented navigation system (LANS) is the GNSS-like system for the moon

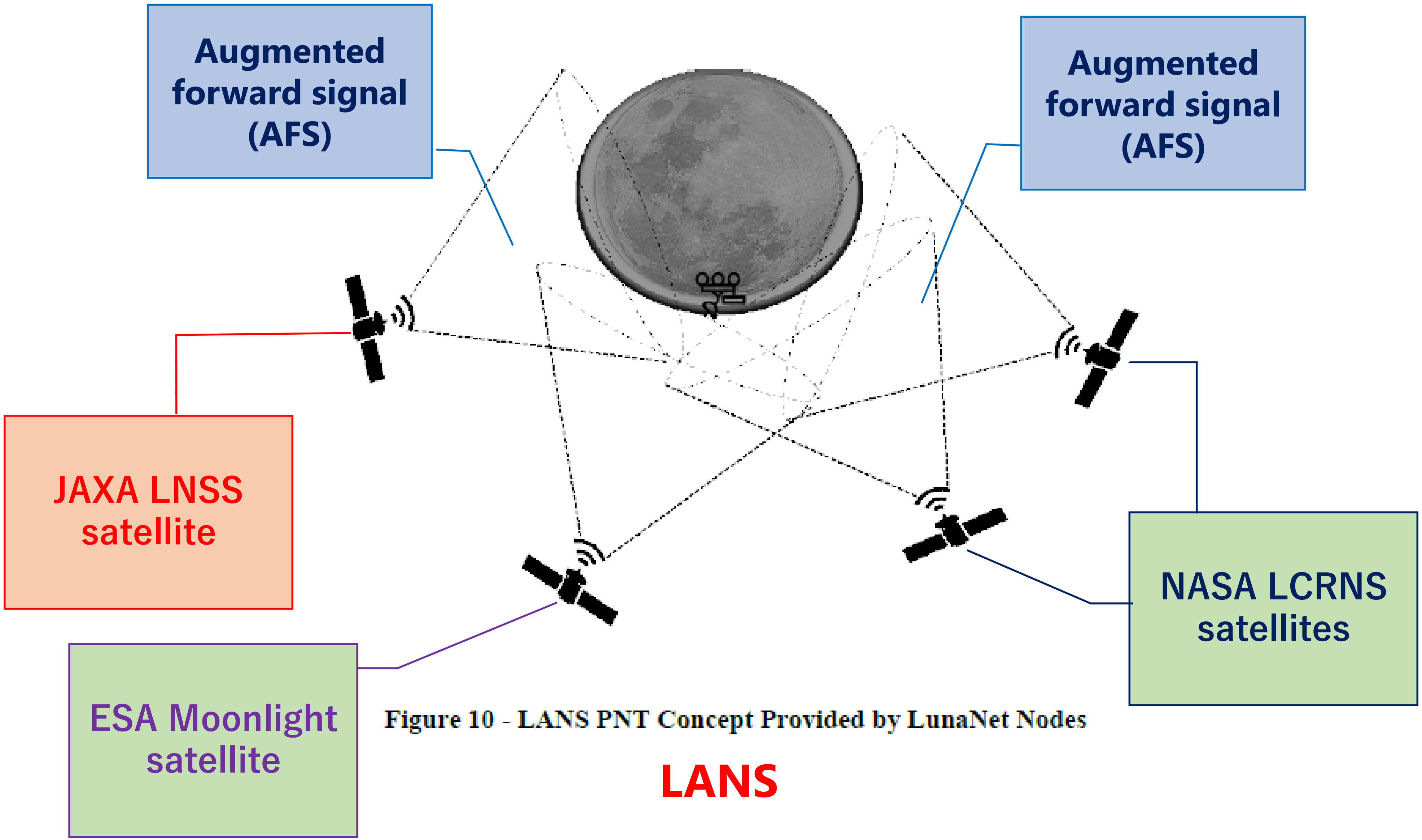

Figure 10 - LANS PNT Concept Provided by LunaNet Nodes

LANS

The AFS structure is called PFS5 having the following message titles:

Table 5 - Message ID and Titles

Message ID	Message Title
MSG-G1	LunaNet Network Access Information
MSG-G2	Health and Safety
MSG-G3	MAntennaProperties
MSG-G4	SOrbit Ephemeris+Clock correction
MSG-G5	MOrbit Almanac
MSG-G6	SOrbit Almanac
MSG-G7	SOrbitState /Location
MSG-G8	Time and Frequency Synchronization (fine)
MSG-G9	Time and Frequency Synchronization (frame)
MSG-G10	Maneuver
MSG-G11	SAttitude State/Ephemeris
MSG-G12	MAttitudeEphem
MSG-G13	Observations
MSG-G14	Conjunction
MSG-G15	Maplet
MSG-G16	Map Comprehensive
MSG-G17	Ancillary info
MSG-S18	Search and Rescue Alert
MSG-S19	Acknowledge- of SAR - LvL1
MSG-S20	Acknowledge- of SAR - LvL2
MSG-G21	User Message Request
MSG-G22	Acknowledge- of non-SAR MSG
MSG-G23	GNSS Augmentation
MSG-G24	Detection Alert
MSG-G25	Science
MSG-G26	UIS Request
MSG-G27	UIS Response
MSG-G28	User Schedule Notice
MSG-G29	FF Commands

Frequency: **The signal will be broadcasted in the 2483.5-2500 MHz frequency range (S-band)**

Modulations: **Modulations adopted will be in line with current GNSS signals, by utilizing Bi-Phase Shift Keying (BPSK) and/or Binary Offset Carrier (BOC) modulations**

In the AFS, GNSS information such as the ephemeris is also sent to lunar users

Table 5 - Message ID and Titles

Message ID	Message Title
MSG-G1	LunaNet Network Access Information
MSG-G2	Health and Safety
MSG-G3	MAntennaProperties
MSG-G4	SOrbit Ephemeris+Clock correction
MSG-G5	MOrbit Almanac
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MSG-G7	SOrbitState /Location
MSG-G8	Time and Frequency Synchronization (fine)
MSG-G9	Time and Frequency Synchronization (frame)
MSG-G10	Maneuver
MSG-G11	SAttitude State/Ephemeris
MSG-G12	MAttitudeEphem
MSG-G13	Observations
MSG-G14	Conjunction
MSG-G15	Maplet
MSG-G16	Map Comprehensive
MSG-G17	Ancillary info
MSG-S18	Search and Rescue Alert
MSG-S19	Acknowledge- of SAR - LvL1
MSG-S20	Acknowledge- of SAR - LvL2
MSG-G21	User Message Request
MSG-G22	Acknowledge- of non-SAR MSG
MSG-G23	GNSS Augmentation
MSG-G24	Detection Alert
MSG-G25	Science
MSG-G26	UIS Request
MSG-G27	UIS Response
MSG-G28	User Schedule Notice
MSG-G29	FF Commands

GNSS augmentation: Provision for LunaNet to distribute ephemeris information for Earth-centric GNSS constellations to support the use of the GNSS weak signals by GNSS sensitive receivers in cislunar.

Each LunaNet service providers (LNSP) shall ensure the AFS maintains Signal-In-Space-Errors (SISE) within the requirement specified in Table C-1

Table C-1 LNSP SISE

Error	Value
SISE pos	≤TBD m (99%) - Calculated as the 99th percentile of the time series of instantaneous SISE values over a TBD hours period.
SISE vel	≤TBD m/s (99%) - Calculated as the 99th percentile of the time series of instantaneous SISE values over a TBD hours period.

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

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

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):

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

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

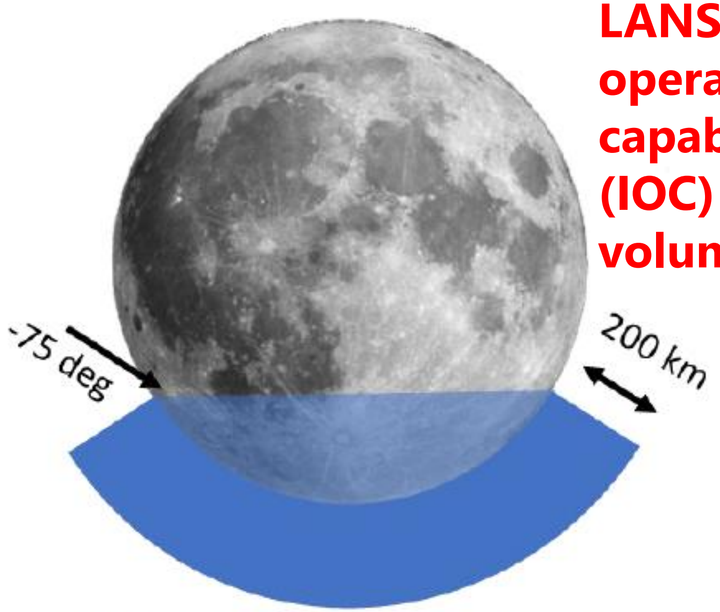


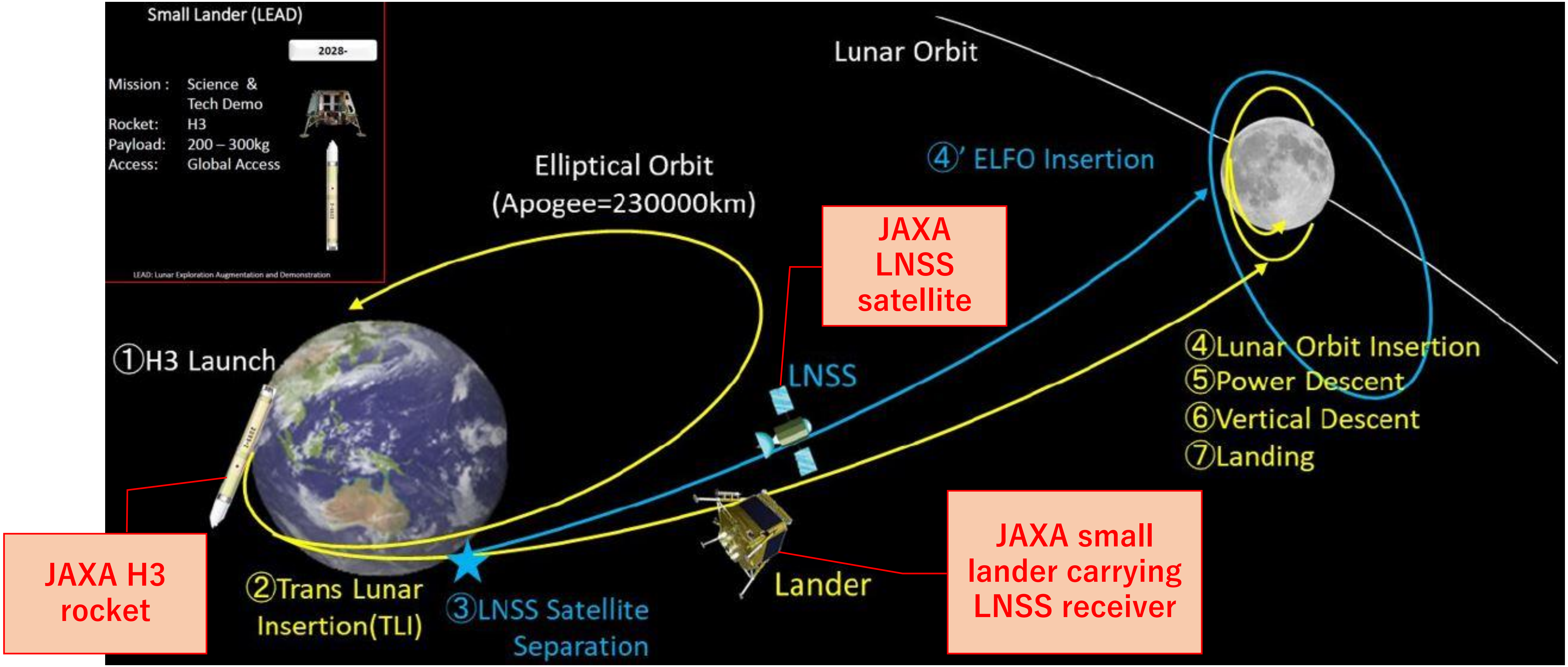
Figure 11 - LANS IOC Service Coverage and Performance Volume

LANS initial operations capability (IOC) service volume

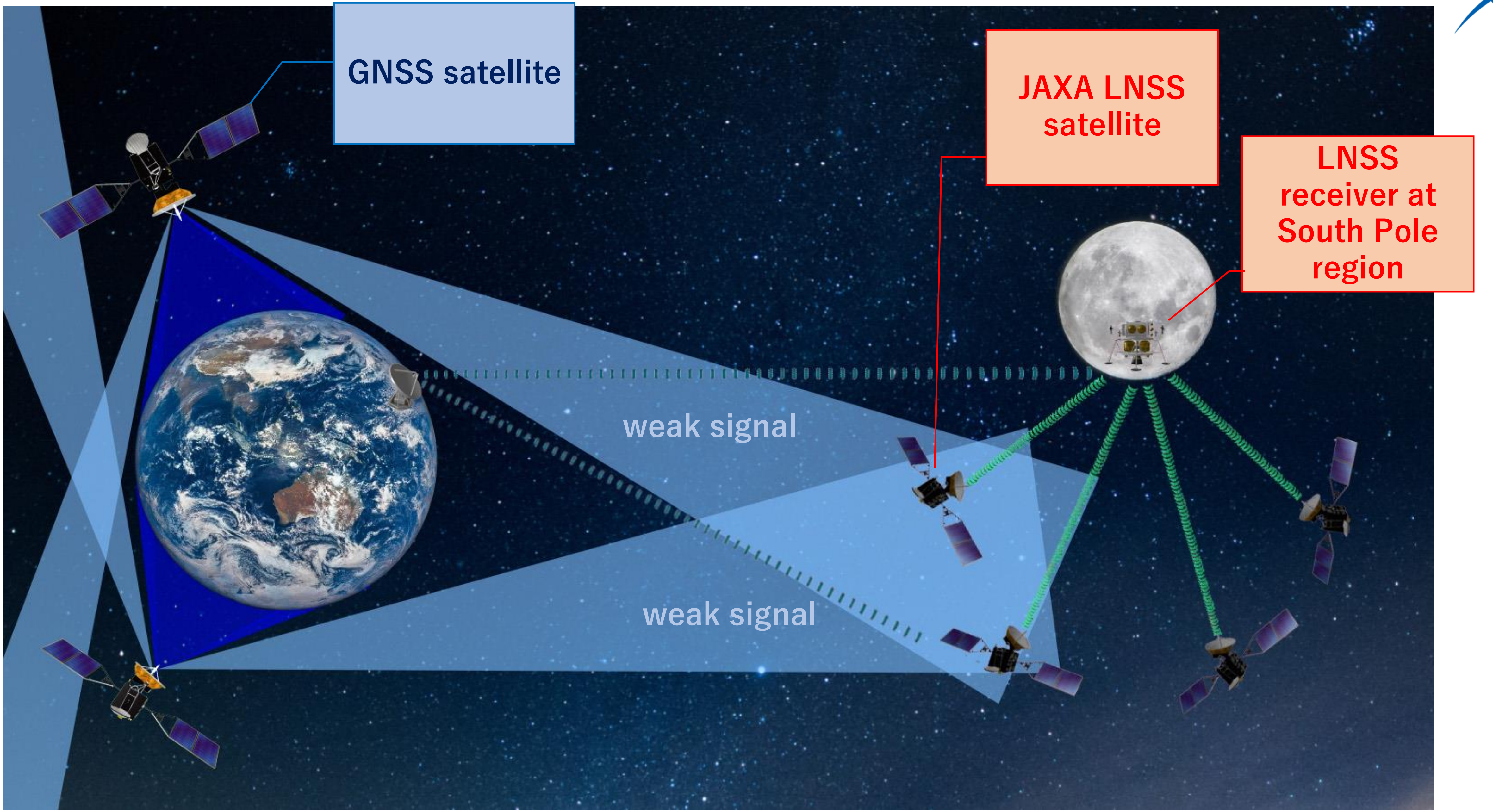
Both based on lunar reference frame and time, which will be defined in the applicable documents called Lunar Reference Frame Standard and Lunar Time System Standard

LNSS demonstration mission targeting around 2028

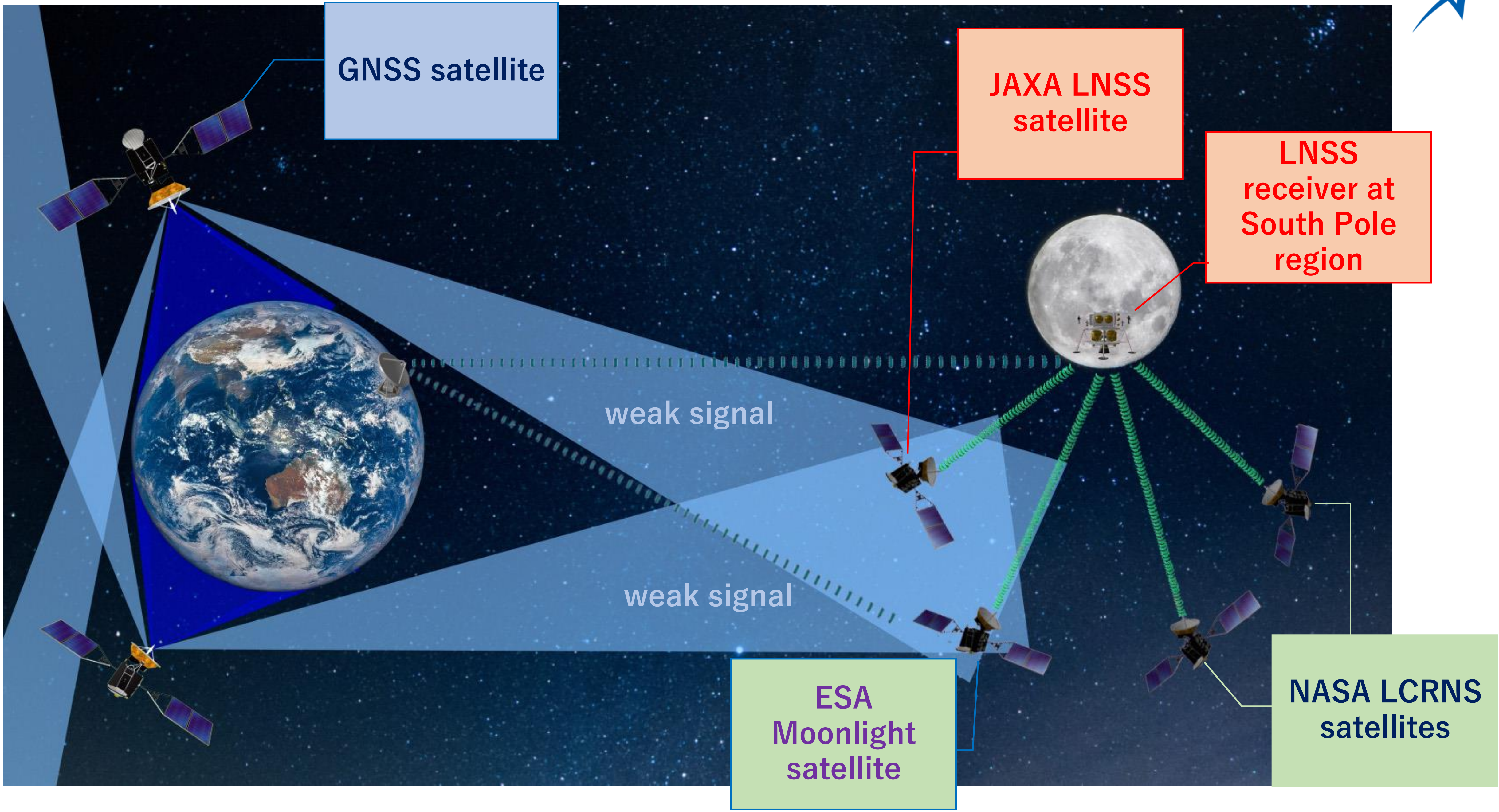
LNSS demonstration mission under planning



We deploy one LNSS satellite and one LNSS receiver at South Pole region



Proposing first-ever lunar PNT and interoperability demonstration



Challenge （航法メッセージの精度/SISURE解析）

- The accuracy of the navigation signal is evaluated based on the following pseudo range equation:

疑似距離の観測モデル

$$PR = ||r^{\mathrm{LNSSsat}} - r^{\mathrm{receiver}}|| + c^{\mathrm{receiver}} - c^{\mathrm{LNSSsat}} + \omega \quad (1)$$

Here, PR stands for the pseudo range measurement, $(r^{\mathrm{LNSSsat}}, c^{\mathrm{LNSSsat}})$ are the LNSS satellite position and clock bias, $(r^{\mathrm{receiver}}, c^{\mathrm{receiver}})$ are the surface receiver position and clock bias, and ω is the measurement noise, respectively

- Because the estimate of $(r^{\mathrm{LNSSsat}}, c^{\mathrm{LNSSsat}})$ is obtained from the ephemeris, we can compare the measured PR and the calculated PR if and only if $(r^{\mathrm{receiver}}, c^{\mathrm{receiver}})$ is known
- Therefore, the key issue of this demonstration mission is the precise determination of $(r^{\mathrm{receiver}}, c^{\mathrm{receiver}})$

南極域受信機の位置・クロックバイアス値が必要

Simulation setting

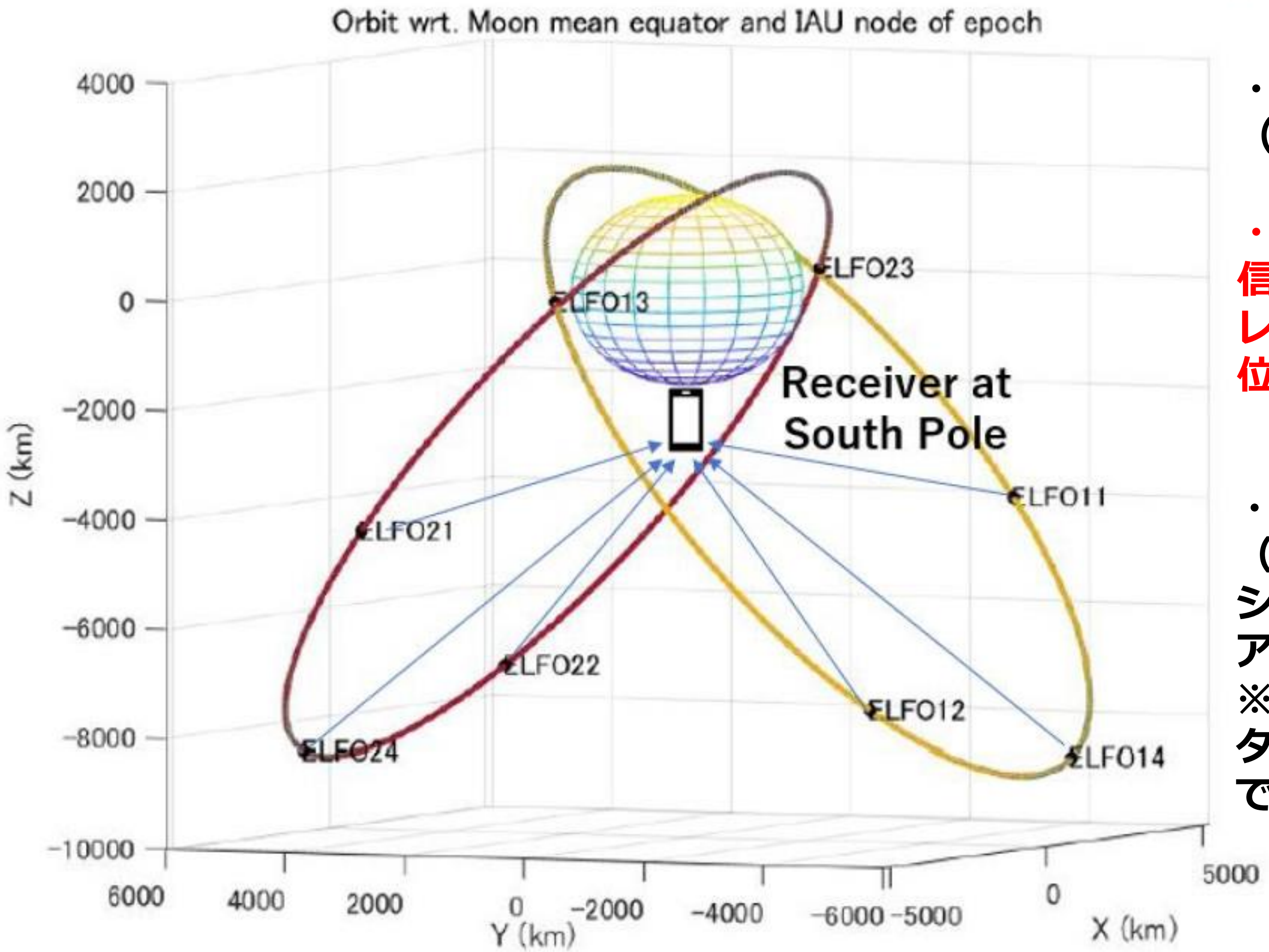


Figure 1. LNSS satellite constellation.

・単独測位の平均水平精度は20m以下（エポック毎の推定精度）

↓

・実証ミッションにおいて、南極域受信機の位置及びクロックを数m、数nsレベルで決定する必要がある。単独測位ではなく、フィルタの推定精度は？

・フィルタ推定とはLNSSの観測値（疑似距離や搬送波位相）をシーケンシャルに処理して推定精度を高めるリアルタイム推定（例、GPS航法）
※MoonlightやLCRNSではこのフィルタ推定が前提になっている（特にIOCでは機数が少ないため）

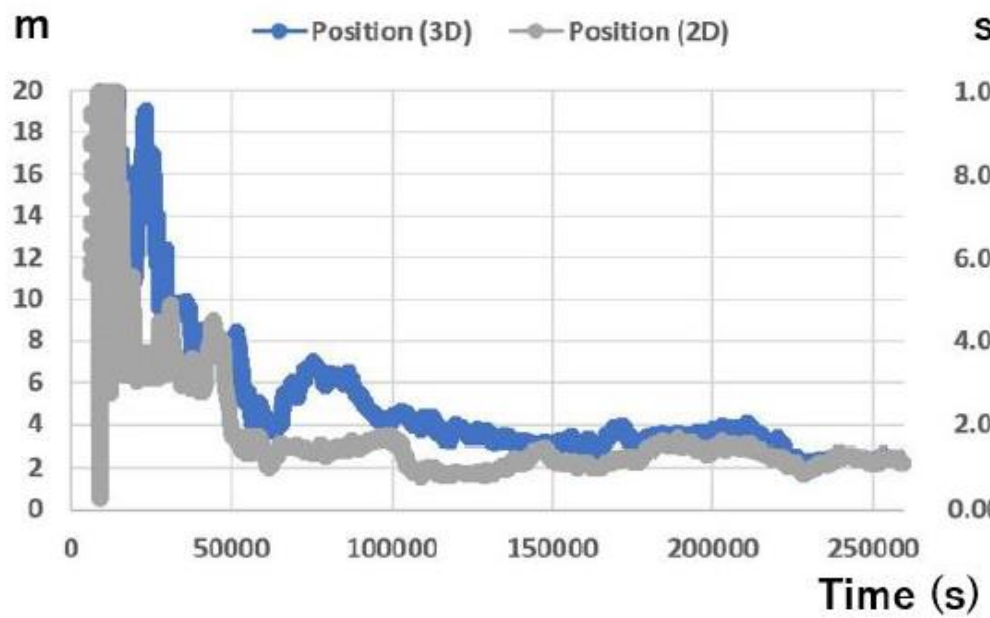
PPP using two LNSS satellites

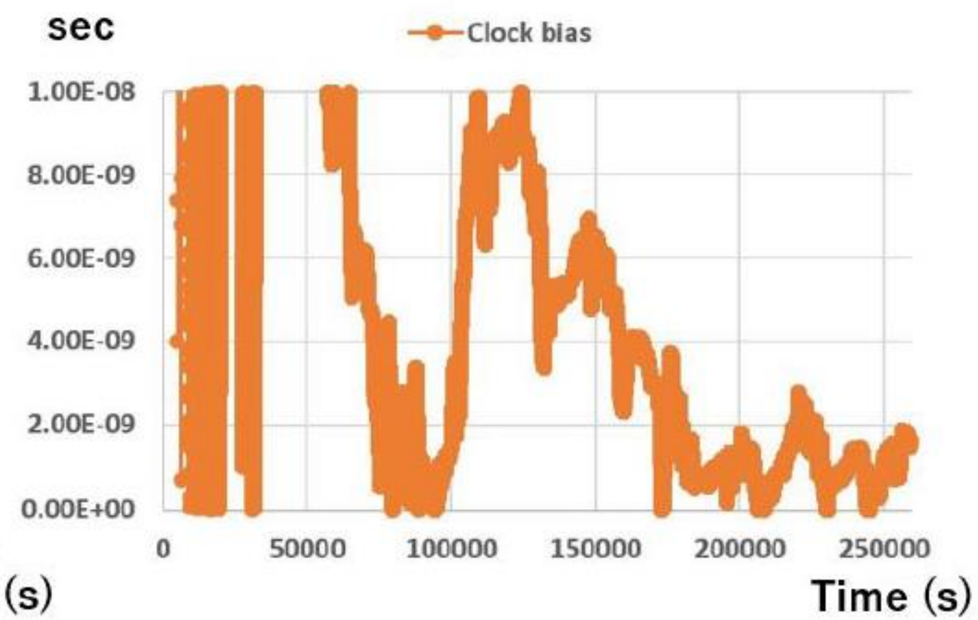
（LNSS2機を用いた南極点受信機の精密測位）

- The following PPP results are obtained when using the two satellites shown below. The results show that a few meter and nanosecond level estimation is possible even for the two satellite case

SV	A[km]	E	I[deg]	RAAN[deg]	AP[deg]	MA[deg]
ELFO12	6540	0.6	56.2	0	90	180
ELFO21	6540	0.6	56.2	180	90	0

フィルタの収束後は数mの精度





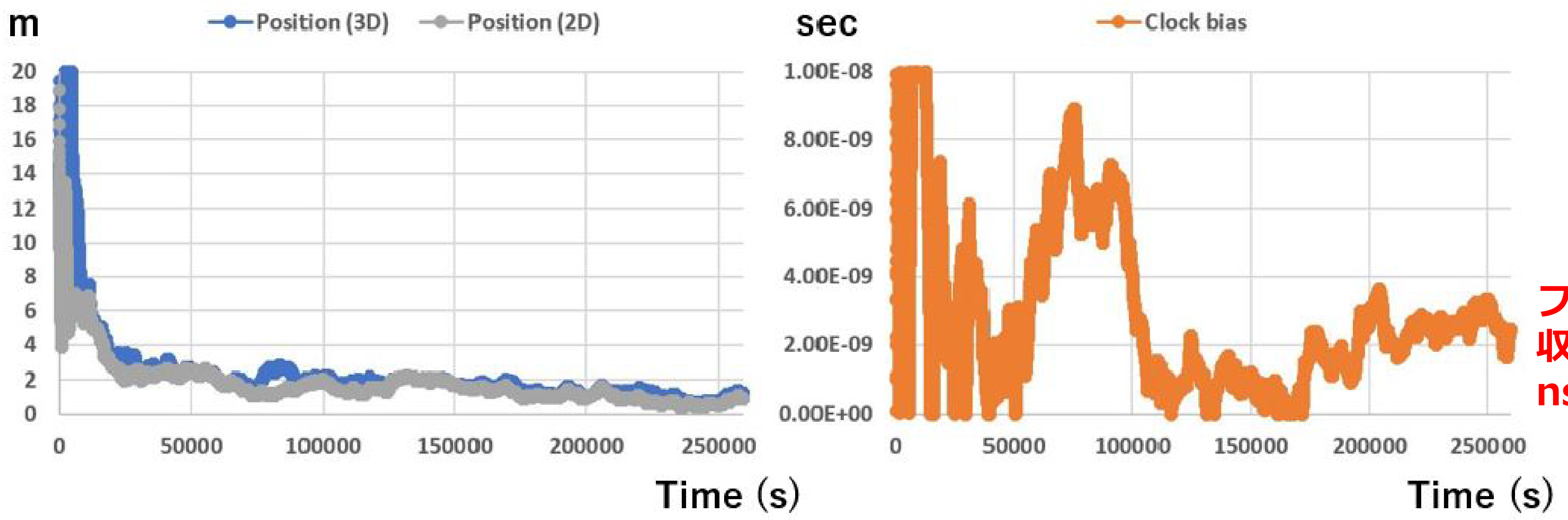
フィルタの収束後は数nsの精度

PPP using eight LNSS satellites

（参考：LNSS8機を用いた南極点受信機の精密測位）

- As expected, the PPP using our full constellation (eight-satellite constellation) shows the fastest convergence

収束が早くなり、フィルタの収束後は1m級の精度



フィルタの収束後は数nsの精度

After the filter convergence, the 3D and horizontal positioning accuracy reach about 1m and the clock bias estimation accuracy is about $2.5 \cdot 10^{-9}$s, respectively

・機数が多くなればフィルタの収束性・推定精度共に高くなる。2028年にはLNSS1機、Moonlight1機、LCRNS2機が期待されるため、シミュレーションによると南極域受信機の位置・クロック推定は数m、数nsレベルで実行可能

・南極域受信機の位置・クロックの真値相当データが取得できれば、航法メッセージのSISURE評価が可能に。つまり、本実証ミッションでLNSSのみならず、LANSを構成する各国システムの精度評価に貢献することができる

・MoonlightのIOCは2027年、FOCは2030年、LCRNSは2024～2026年という状況の中で、LNSS実証ミッションを2028年に達成することで日本の存在感を示す

・受信機の相互運用性（interoperability）が大前提（LNISに準拠すること）。また、International Committee on GNSS (ICG)やInteragency Operations Advisory Group (IOAG)といった国際会議・調整の場で、LNSSを積極的にアピールし続けることも重要

China Status

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中国も欧米並みのスピードで取り組んでいる模様。
以下最近のSPACENEWSの記事 (Jan. 18th, 2023)

News

China to launch relay satellite next year to support moon landing missions

Andrew Jones January 18, 2023

鵲橋（じゃっきょう、英語: Queqiao）

HELSINKI — China will launch its Queqiao-2 communications relay satellite in 2024 to support upcoming robotic landing missions at the lunar south pole and far side of the moon.

Wang Qiong of the Lunar Exploration and Space Engineering Center under the China National Space Administration (CNSA) told press Jan. 17 that Queqiao-2 would launch in early 2024, ahead of the Chang'e-6 mission which is currently scheduled to launch in late 2024 or early 2025.

嫦娥（英語ではChang'e）

Queqiao-2, which means "Magpie Bridge-2" and is taken from Chinese mythology, will enter a distant retrograde orbit (DRO) to support Chang'e-6, according to the report,

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The satellite and its 4.2-meter-diameter parabolic antenna will also serve the Chang'e-7 and Chang'e-8 missions to the lunar south pole as part of China's growing lunar ambitions.

This will likely require Queqiao-2 to change its orbit, with an inclined highly elliptical frozen orbit the possible choice, according to earlier reports. This orbit would allow communication links for over 8 hours of a roughly 12-hour-period orbit.

このELFOはNASA LCRNS, ESA Lunar Pathfinder, JAXA LNSSのELFOと類似

Chang'e-7 will launch around 2026 and consist of an orbiter, lander, rover and "mini flying detector," to study the lunar topography, material composition and environment, with the latter spacecraft to look for the presence of water-ice, while Chang'e-8, targeted for launch around 2028, will be an in-situ resource utilization and 3D-printing technology test mission.

このニュースによると、Queqiao-2はESA Lunar Pathfinder並みの線表。欧米だけでなく、中国の動向も注視する必要がある

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