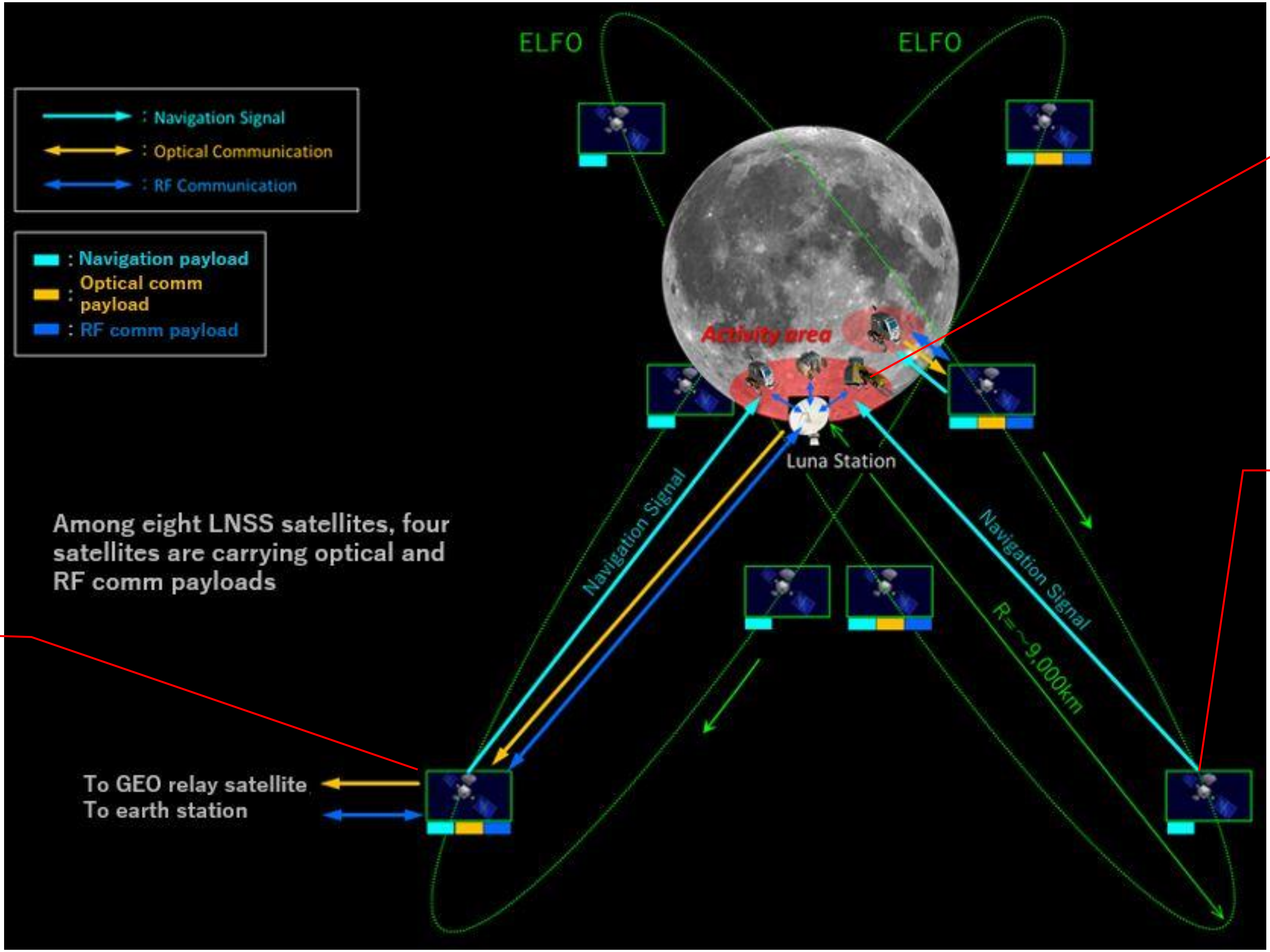
Japan, USA, EU, China plans for Lunar PNT and international collaboration

Masaya Murata (JAXA)

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

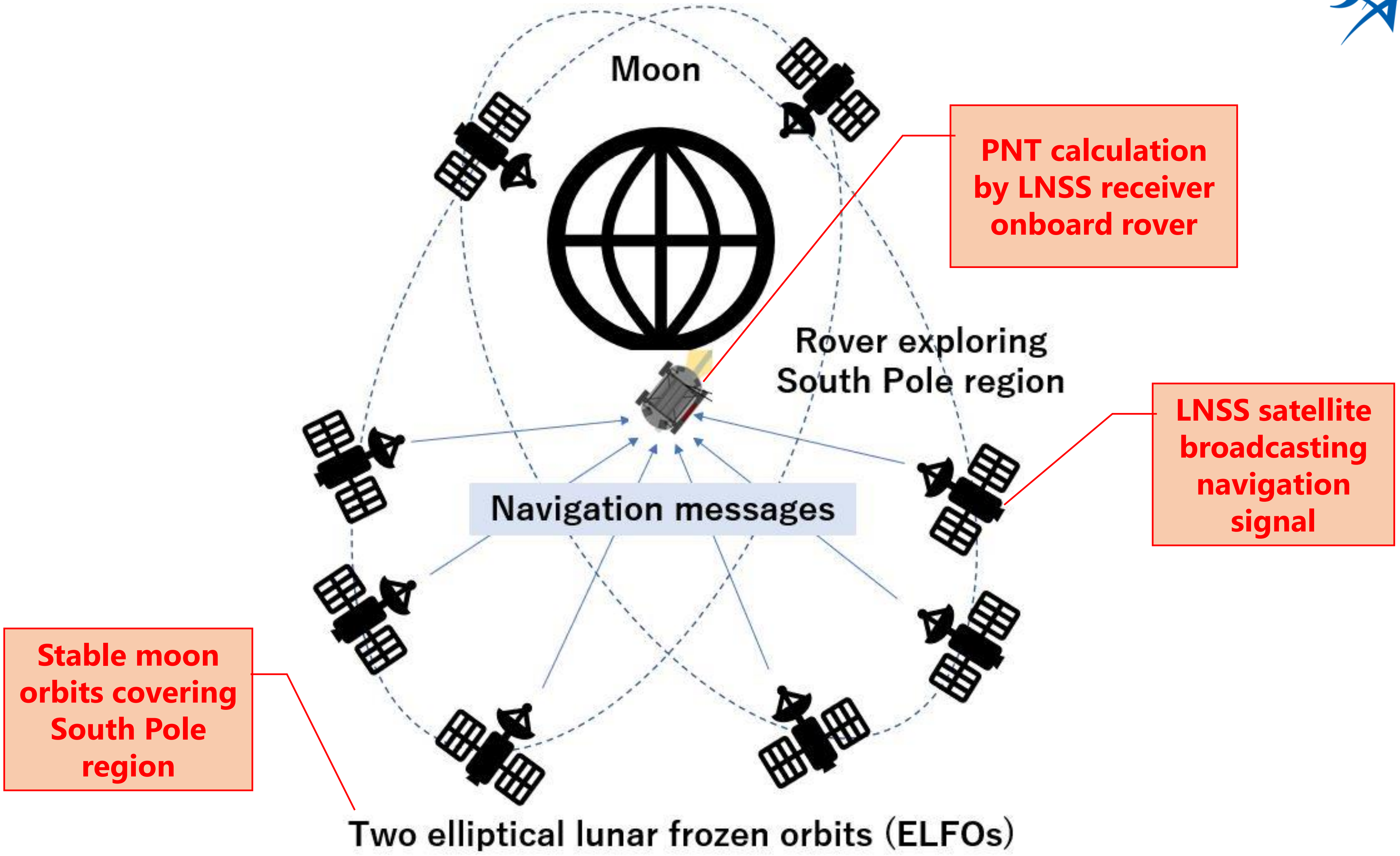


Target: South Pole region

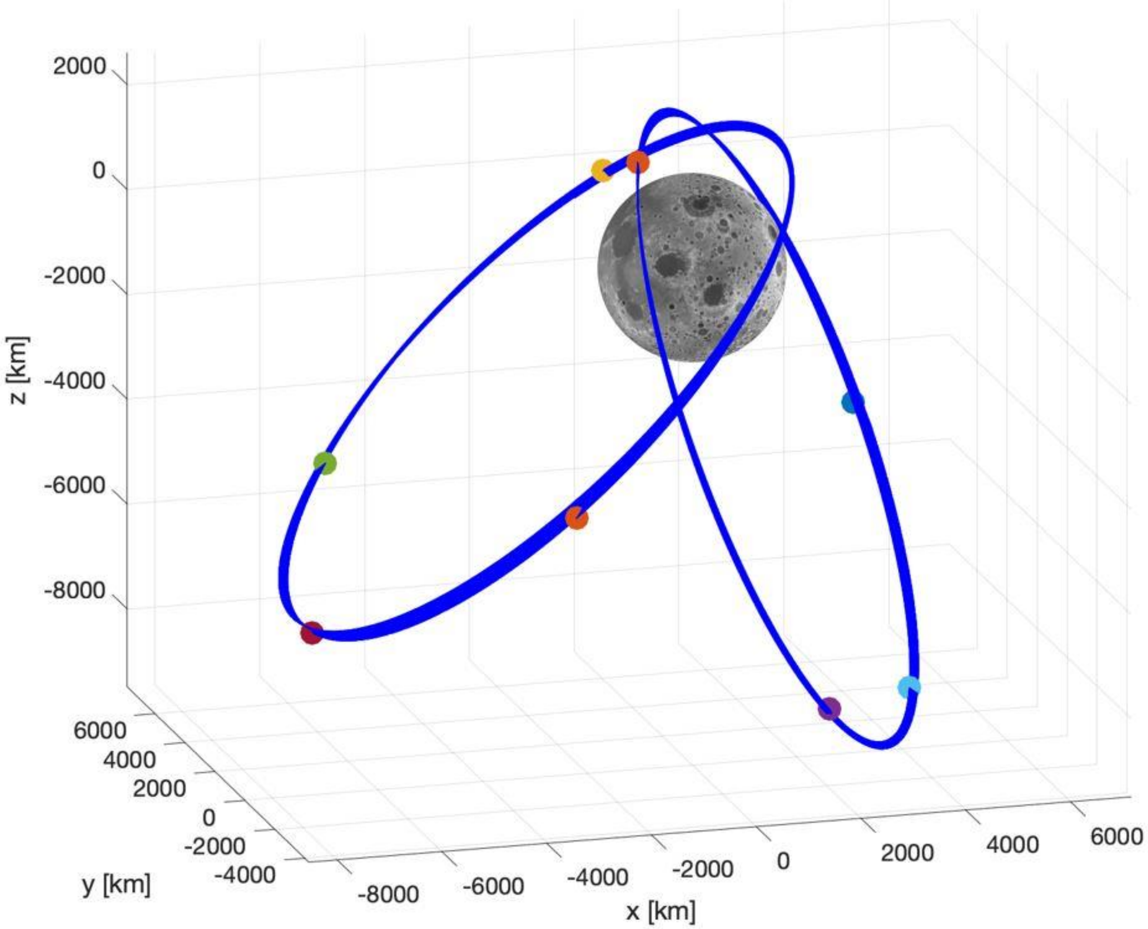
LNSS satellite functioning as data relay satellite

LNSS satellite broadcasting navigation signal

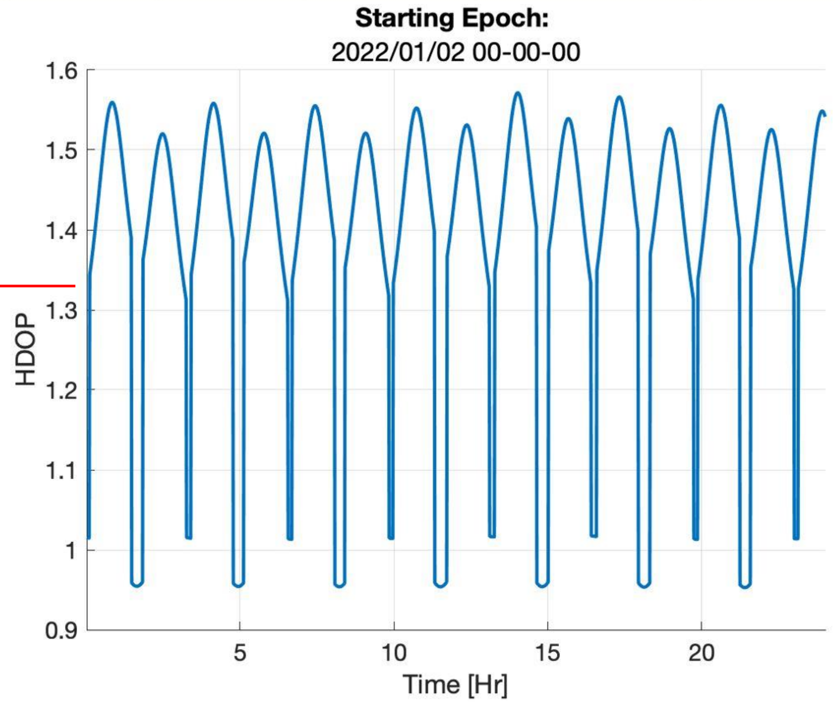
LNSS real-time PNT service at South Pole region



LNSS satellite constellation for South Pole region

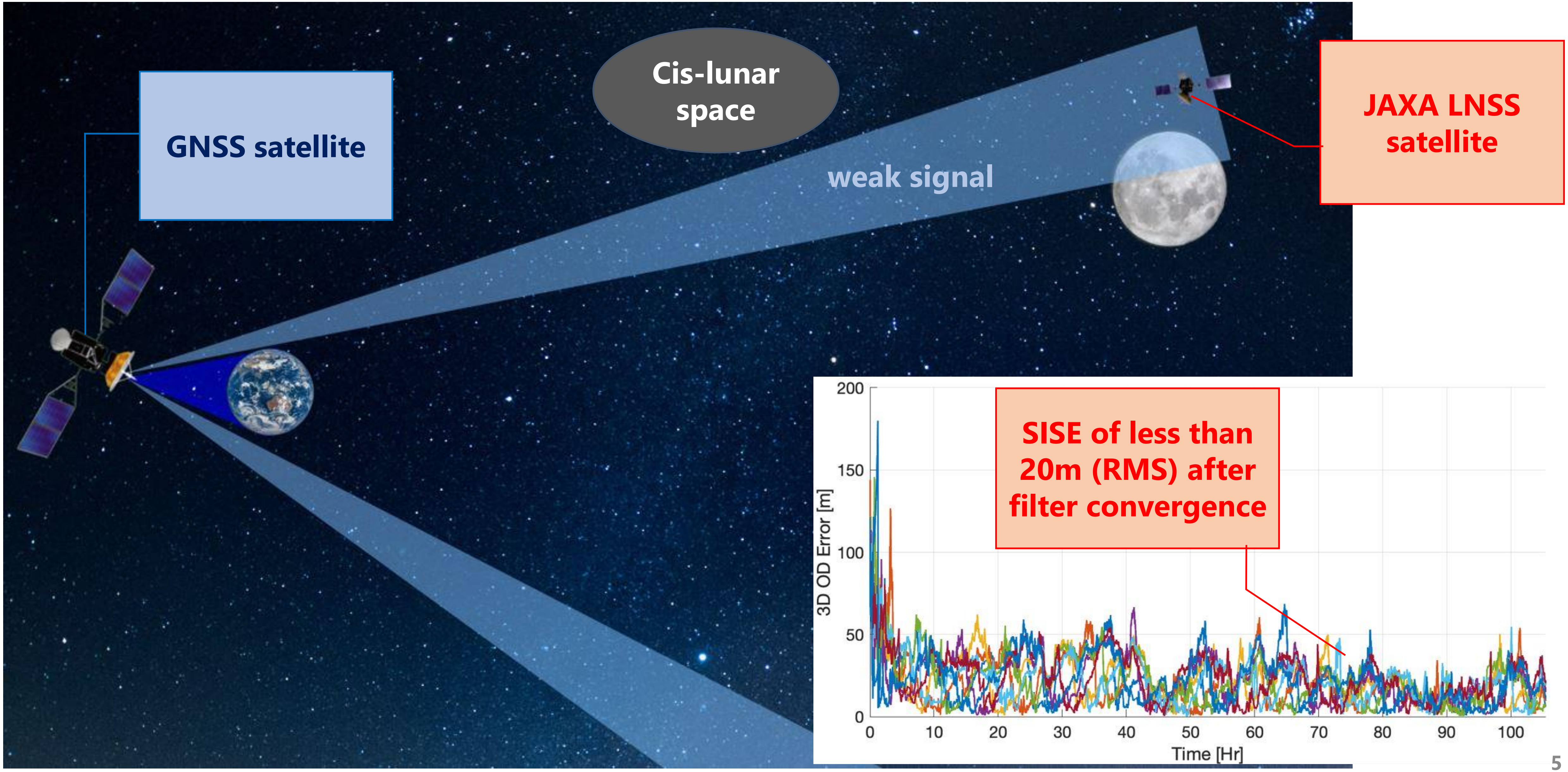


SV	A[km]	E	I[deg]	RAAN[deg]	AP[deg]	MA[deg]
ELFO11	6540	0.6	56.2	0	90	0
ELFO12	6540	0.6	56.2	0	90	90
ELFO13	6540	0.6	56.2	0	90	180
ELFO14	6540	0.6	56.2	0	90	270
ELFO21	6540	0.6	56.2	180	90	45
ELFO22	6540	0.6	56.2	180	90	135
ELFO23	6540	0.6	56.2	180	90	225
ELFO24	6540	0.6	56.2	180	90	315



HDOP of around 1.3 always at South Pole region

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



Expected single point positioning (SSP) accuracy at the South Pole
(Our requirement is < 40m in terms of the horizontal (2D) positioning accuracy)

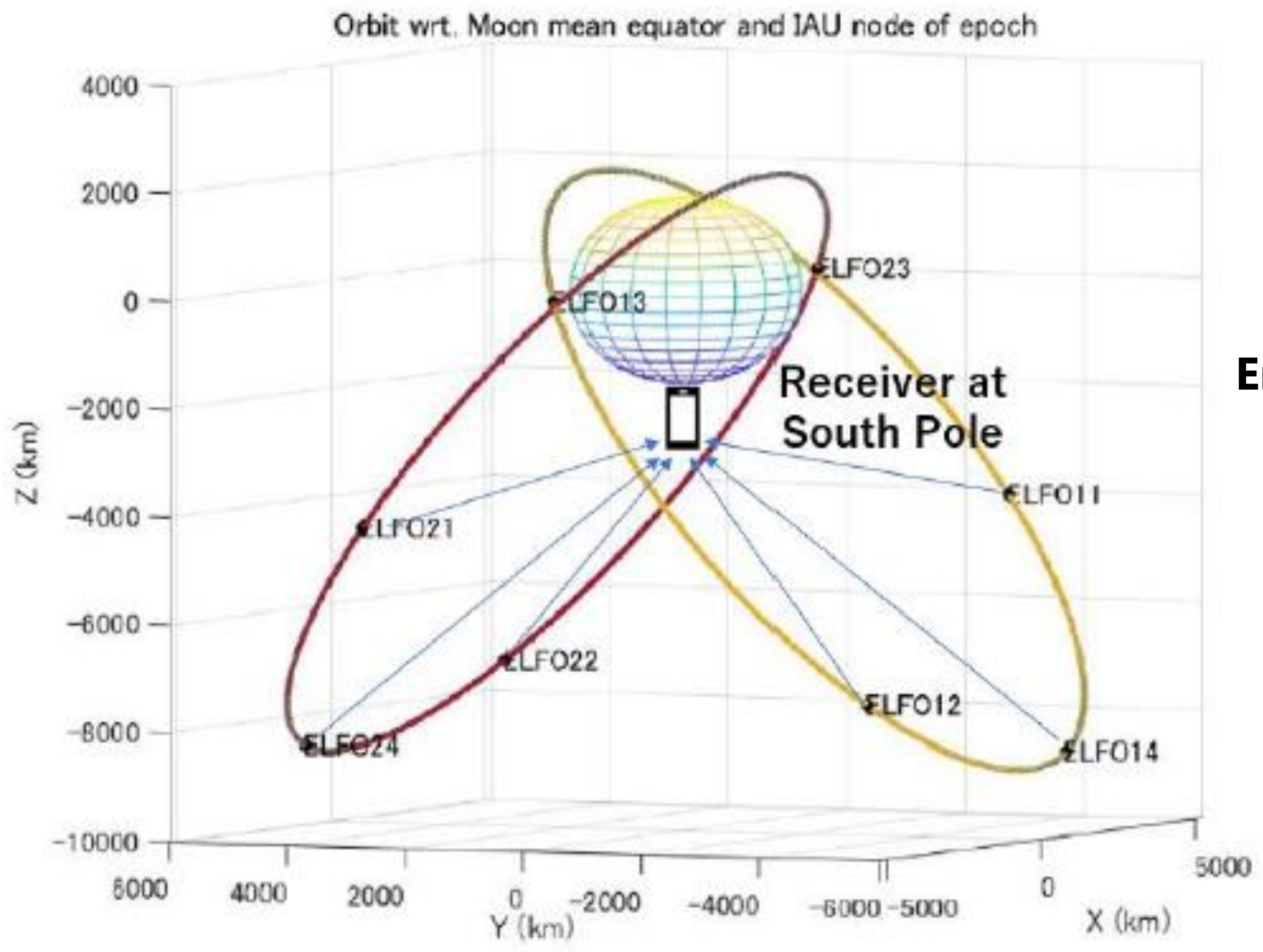
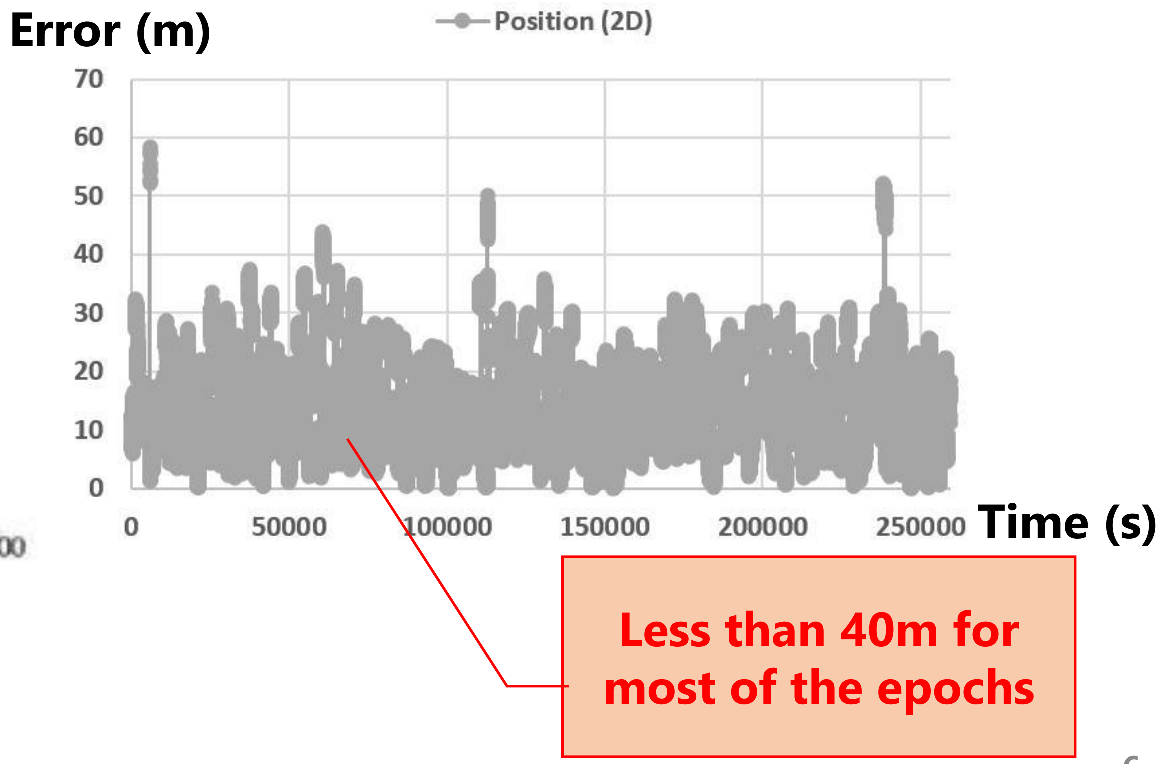


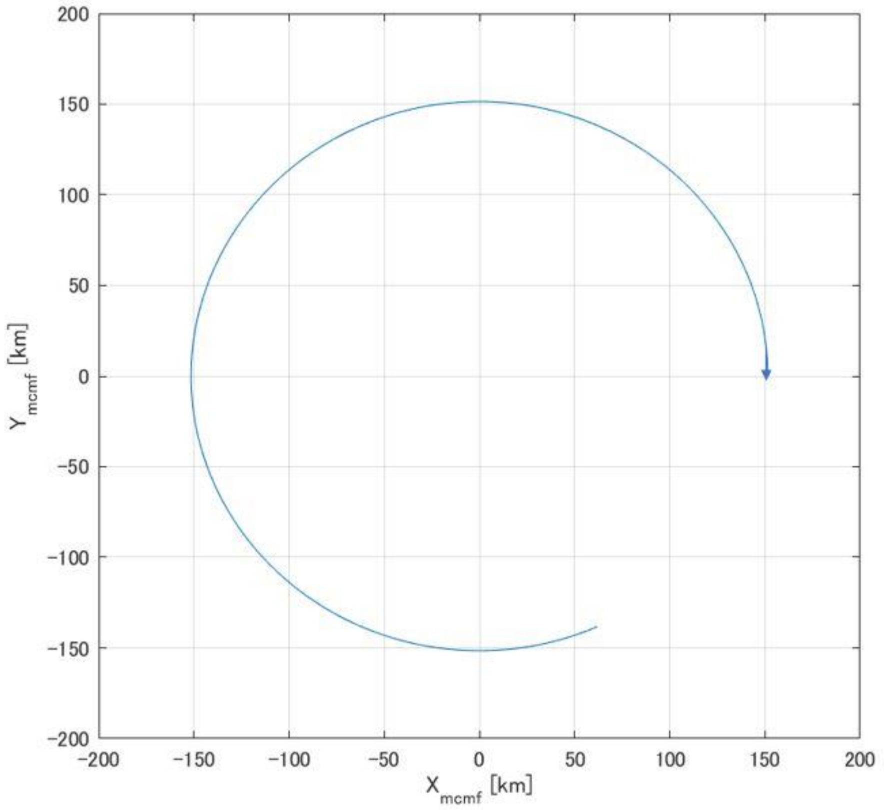
Figure 2: LNSS satellite constellation and receiver at South Pole.

- Average SSP errors:

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



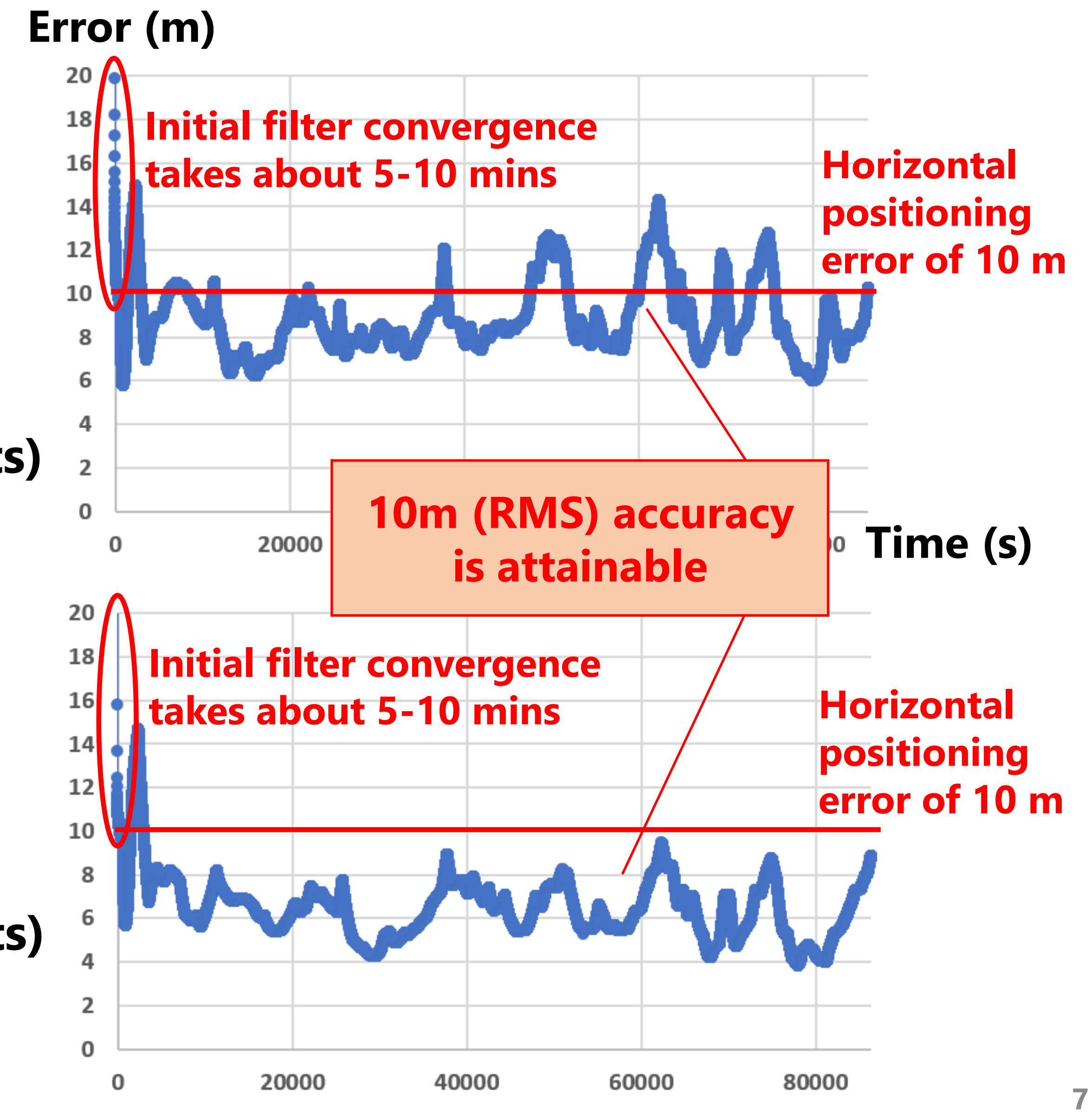
Expected navigation accuracy for moving object such as pressurized rover (Our requirement is < 10m in terms of the horizontal (2D) positioning accuracy)



Circular movement with a velocity of 3m/s at the south latitude of 85°

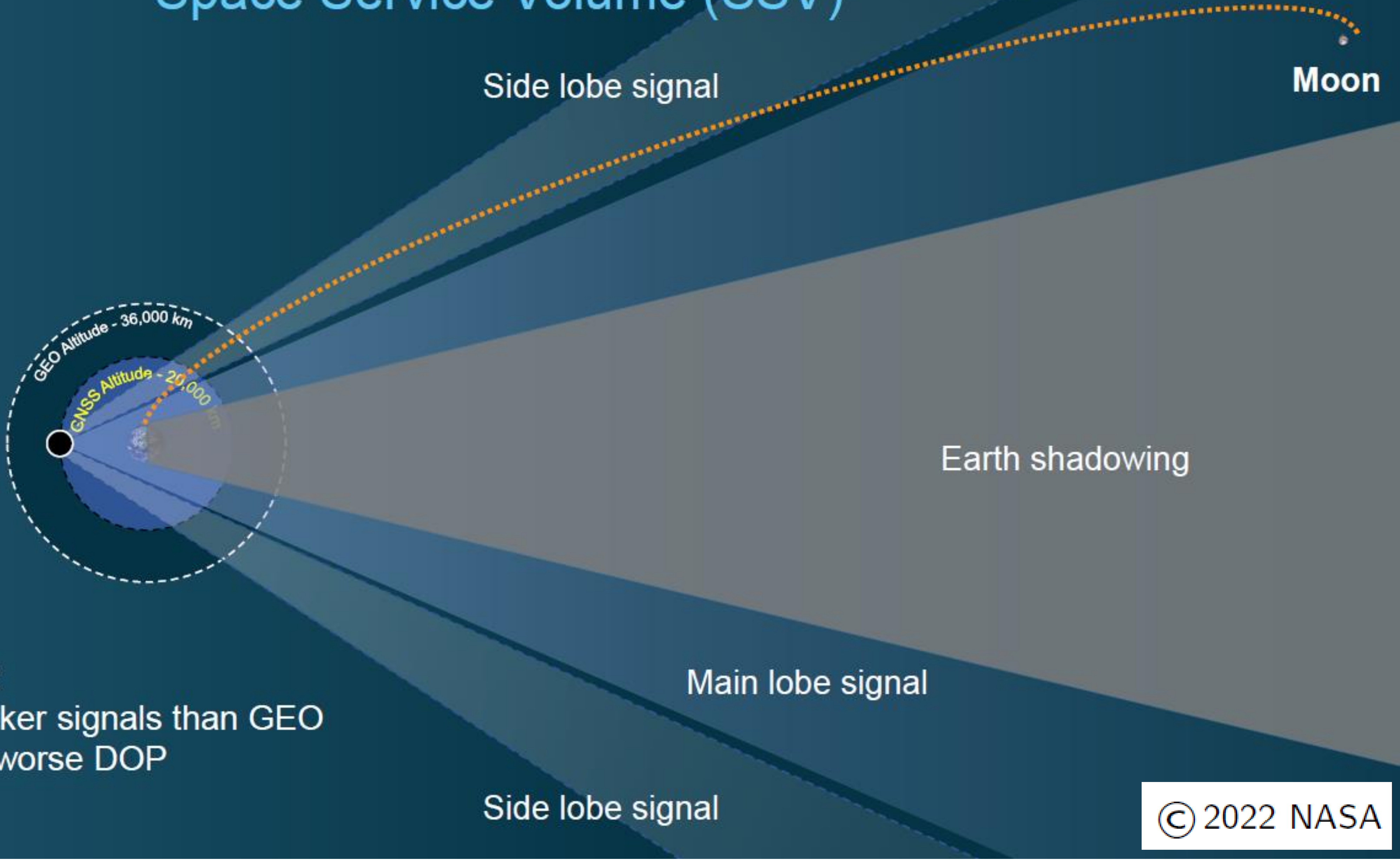
LNSS + high-grade IMU (1Hz measurements)

LNSS + high-grade IMU (10Hz measurements)



NASA Status

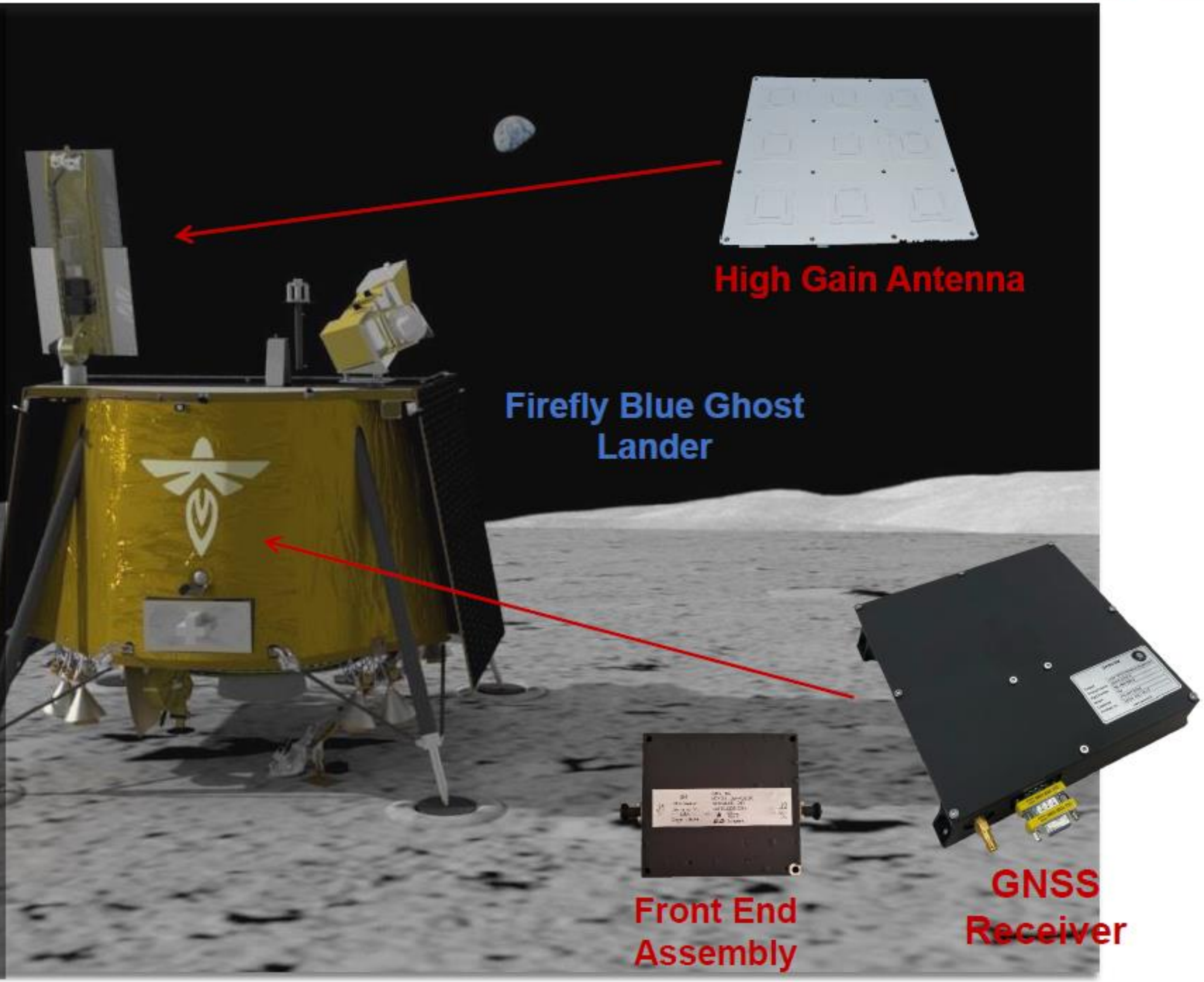
Signal Reception **beyond** the GNSS Space Service Volume (SSV)



Challenges:
- >30x weaker signals than GEO
- 10–100x worse DOP

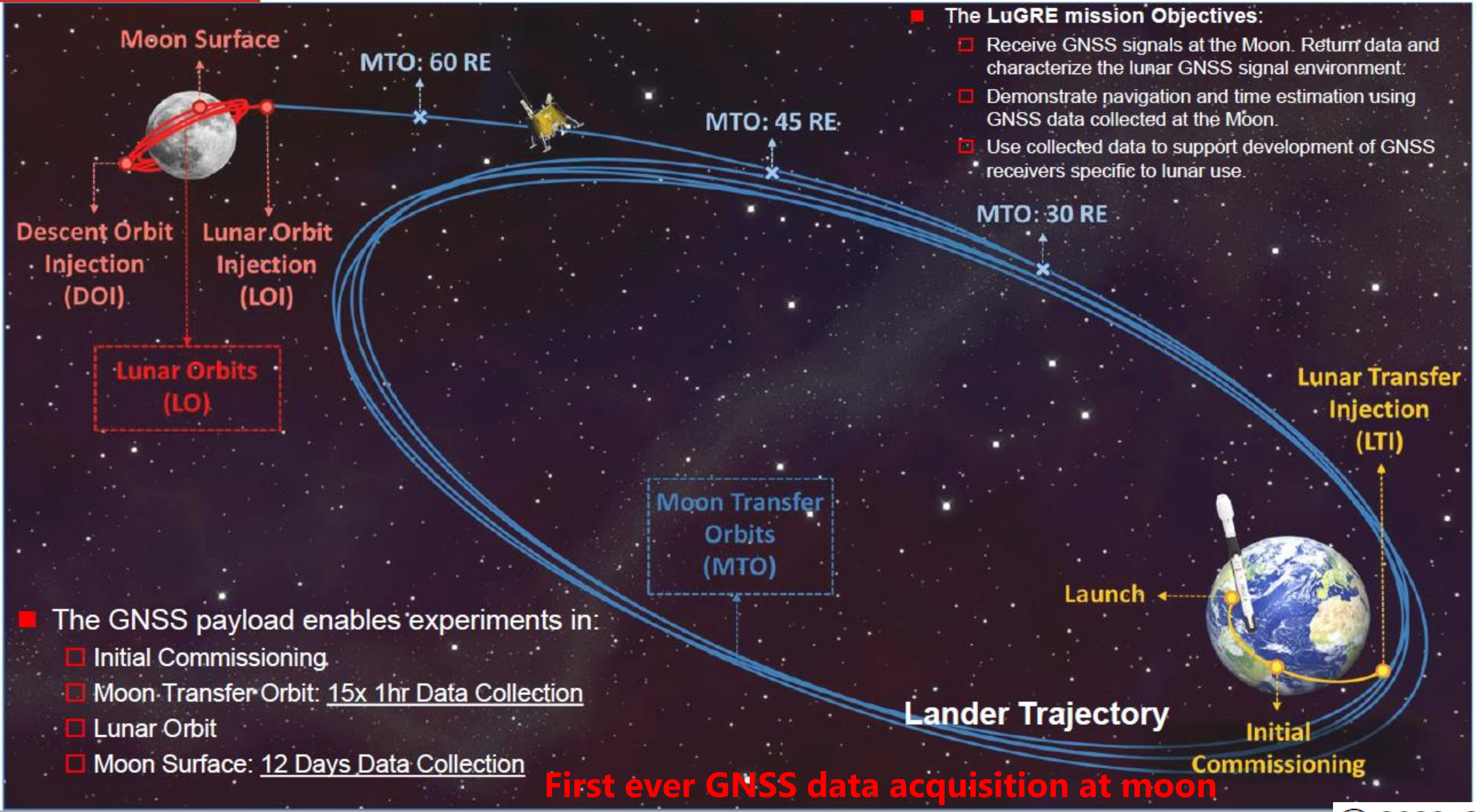
LuGRE Payload

- Qascom is the provider of the GNSS Payload for the **Lunar GNSS Receiver Experiment (LuGRE),** under a NASA-Italian Space Agency (ASI) initiative in the frame of the **Commercial Lunar Payload Services (CLPS)**
- The Payload will fly and land to the Moon (Mare Crisium 18°N, 62°E) in 2024, on board the Firefly Blue Ghost Mission 1 (BGM1)
- The GNSS payload is a Moon customized version of Qascom QN400-Space SDR receiver (GPS/GAL, L1/L5).
- The main challenges of the Development have been:
  - Maximize GNSS Data Collection according to LuGRE Mission Operational Concept
  - Deliver a Payload matching the schedule of the BGM1 Commercial Mission
  - Improve the Robustness of the Receiver for the Lunar Radiation Environment
  - Upgrade the Receiver High Sensitivity Processing and Positioning for Moon scenarios
- To date, the GNSS Payload Flight Model is undergoing Acceptance Testing



Qascom
Trust is Nice, Control is Better.

LuGRE Operational Concept



- The **LuGRE mission Objectives**:
  - Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
  - Demonstrate navigation and time estimation using GNSS data collected at the Moon.
  - Use collected data to support development of GNSS receivers specific to lunar use.

- The GNSS payload enables experiments in:
  - Initial Commissioning
  - Moon Transfer Orbit: 15x 1hr Data Collection
  - Lunar Orbit
  - Moon Surface: 12 Days Data Collection

First ever GNSS data acquisition at moon

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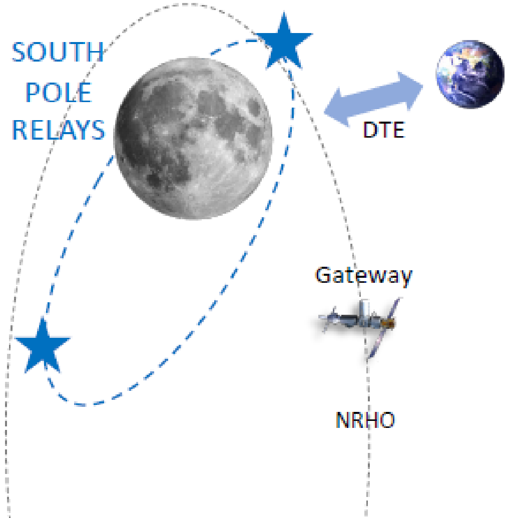
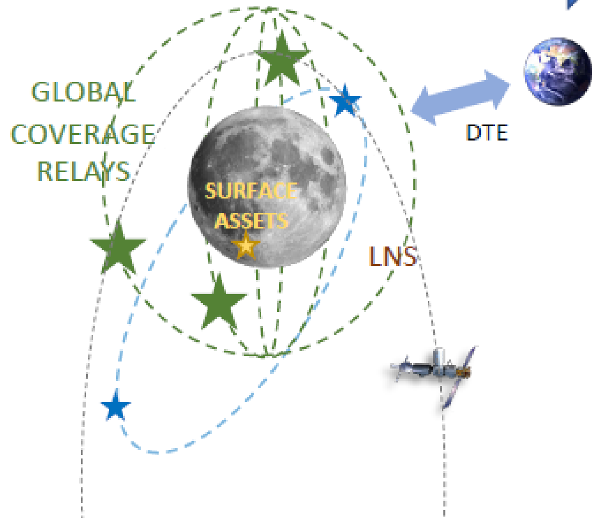
Overview of Architecture Evolution

Initial Phase: By 2024-2026



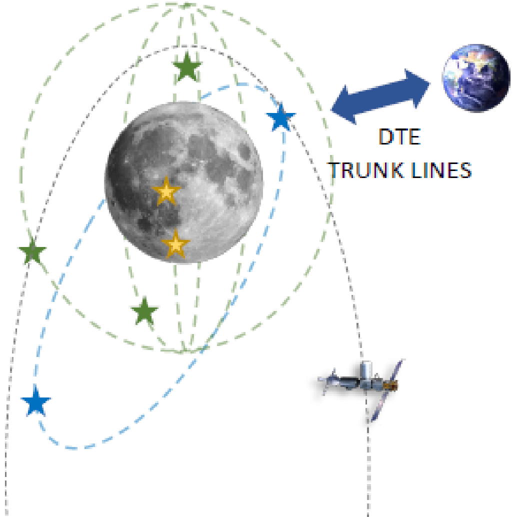
- *DTE service for Near Side, lunar orbiters and surface missions*
- *Intensive relay service for South Pole and a selected area of the Far Side*
- *Initial PNT service and lunar surface networks*
- *LunaNet interoperability established from the beginning*

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

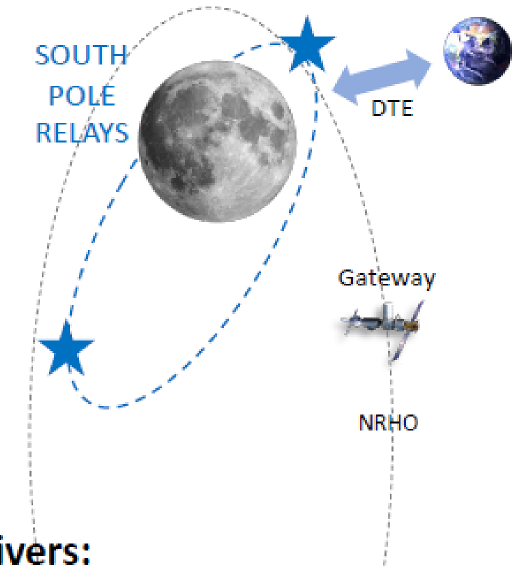


- *Satellite constellations with multiple operators functioning as cooperative set of networks*
- *Intensive coverage of specific regions and regular coverage of all regions*
- *Optical trunk line links*
- *Surface network assets in multiple locations*

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.

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.

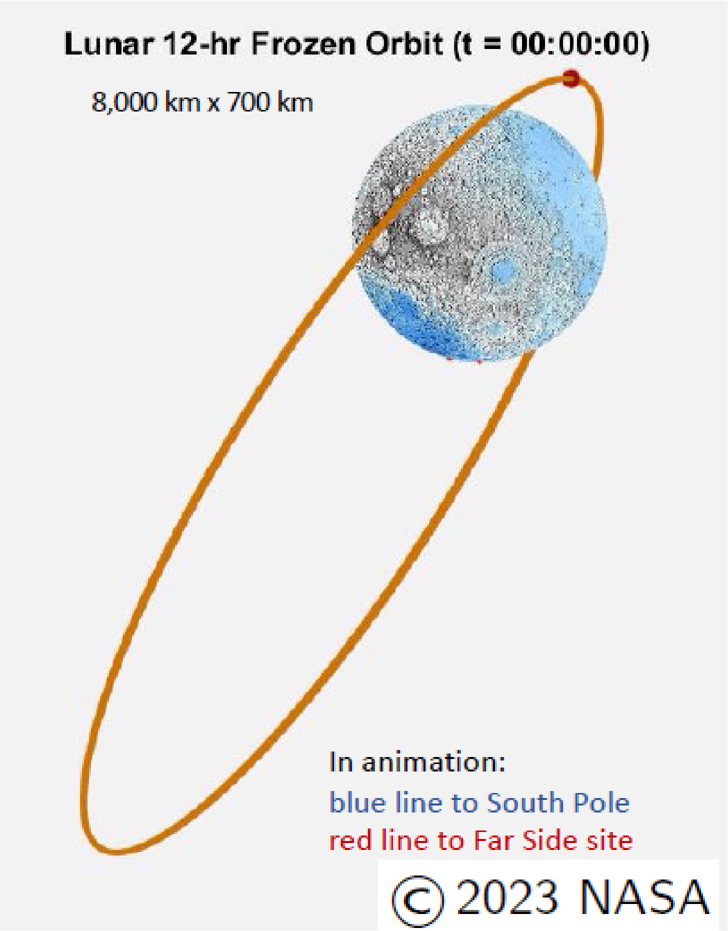
Initial Relay Concept

Lunar Communications Relay and Navigation Systems (LCRNS), Lockheed Martin's Parsec to be launched in 2025

Reference Relay Concept

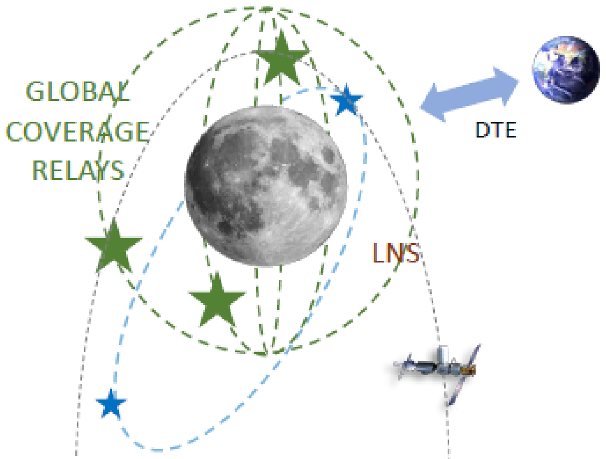
For the initial architecture, coverage of South Pole and southern region of the Far Side is needed

- 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.



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.

Their IOC will potentially split into three phases: Inc-Alpha, Inc-Bravo, Inc-Charlie

Initial Operating Capability Increments

	Increment-Alpha	Increment-Bravo	Increment-Charlie
Effectivity	2025	2027	2028
Capabilities	•Communication support •RF and waveform compatibility with LNIS •AFS	•Enhanced communications support •RF and waveform compatibility with LNIS •Multiple AFS	•Full set LCRNS SRD IOC requirements
% of SRD IOC RQMTS	75%	83%	100%

LNIS: LunaNet Interoperability Specification; AFS: Augmented Forward Signal (PNT);

Phase-Increment	Inc-Alpha			Inc-Bravo				Inc-Charlie		
Service Type	Ka-band	S-band	AFS	Ka-band	S-band	AFS		Ka-band	S-band	AFS/ LANS
Number of simultaneous links	1	1	1	1	1	2	3	2	2	4
Forward/ Return Link	R only	F+R	F only	F+R	F+R	F only	F only	F+R	F+R	F only
Service Volume	SV1			SV1				SV2		
Min. % Coverage of an Earth Day	70% (TBR)			75%	90%	70%	40%	75%	90%	40% (with max. spatial GDOP<6)

Their on-orbit service testing is in 2025 and service validation is in 2028

Validation Milestone	*Milestone Title*	*Potential Timeframe*
M1	Service Concept	2023
M2	Service Requirements	
M3	Service Design	2024
M4	Service Integration	
M5	On-Orbit Service Testing	2025
M6	On-Orbit Service Verification	2027
M7	On-Orbit Service Validation	2028

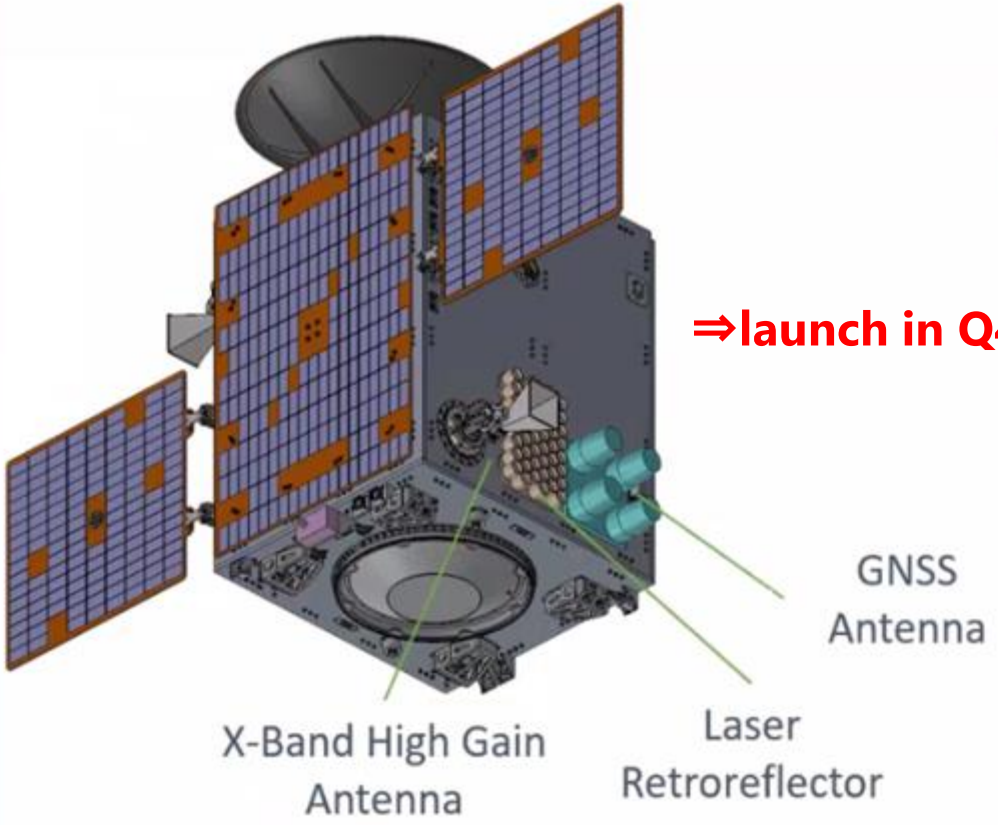
A possibility that there will be four NASA (LCRNS) satellites in 2028

ESA Status

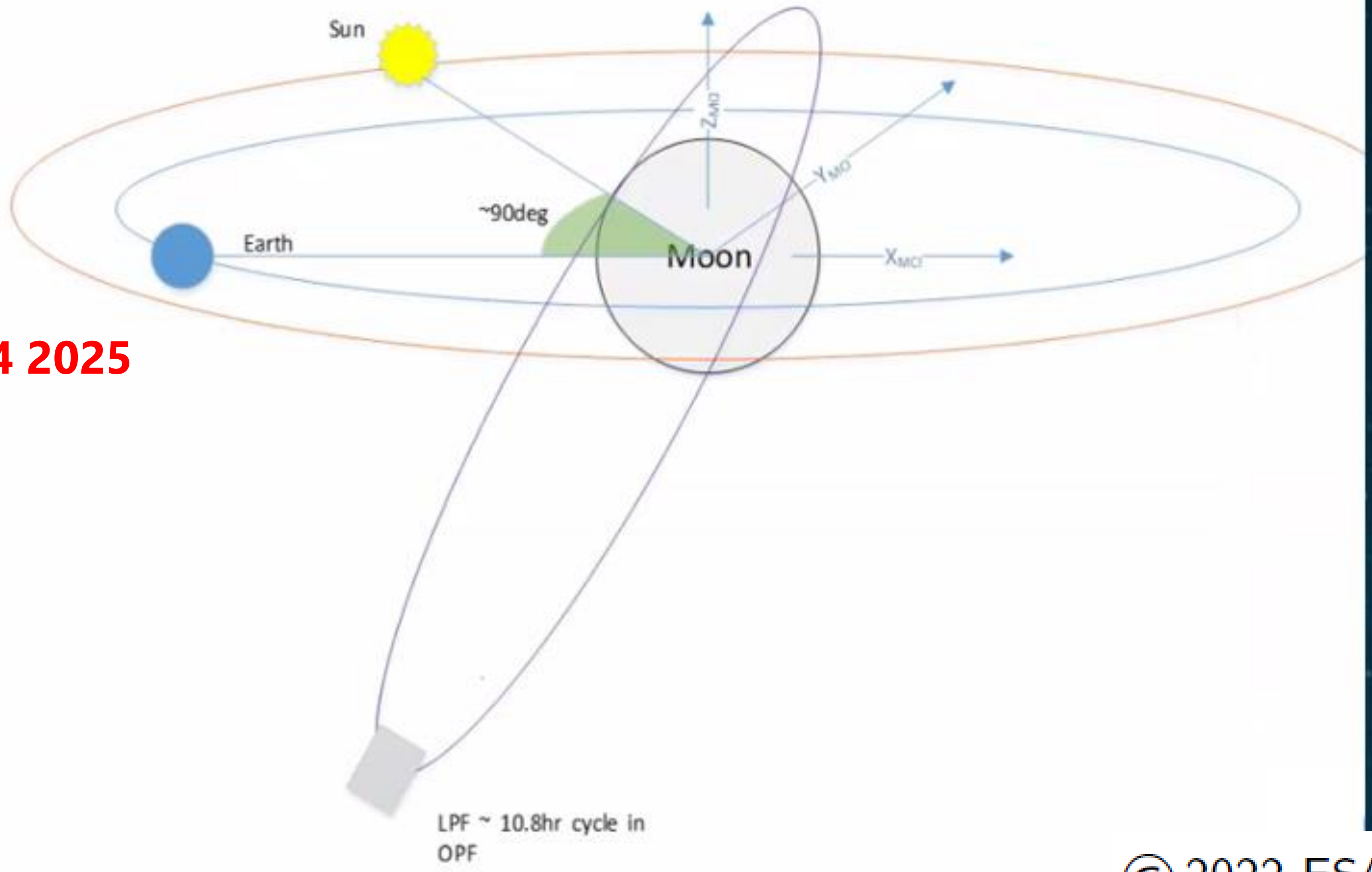
Roadmap

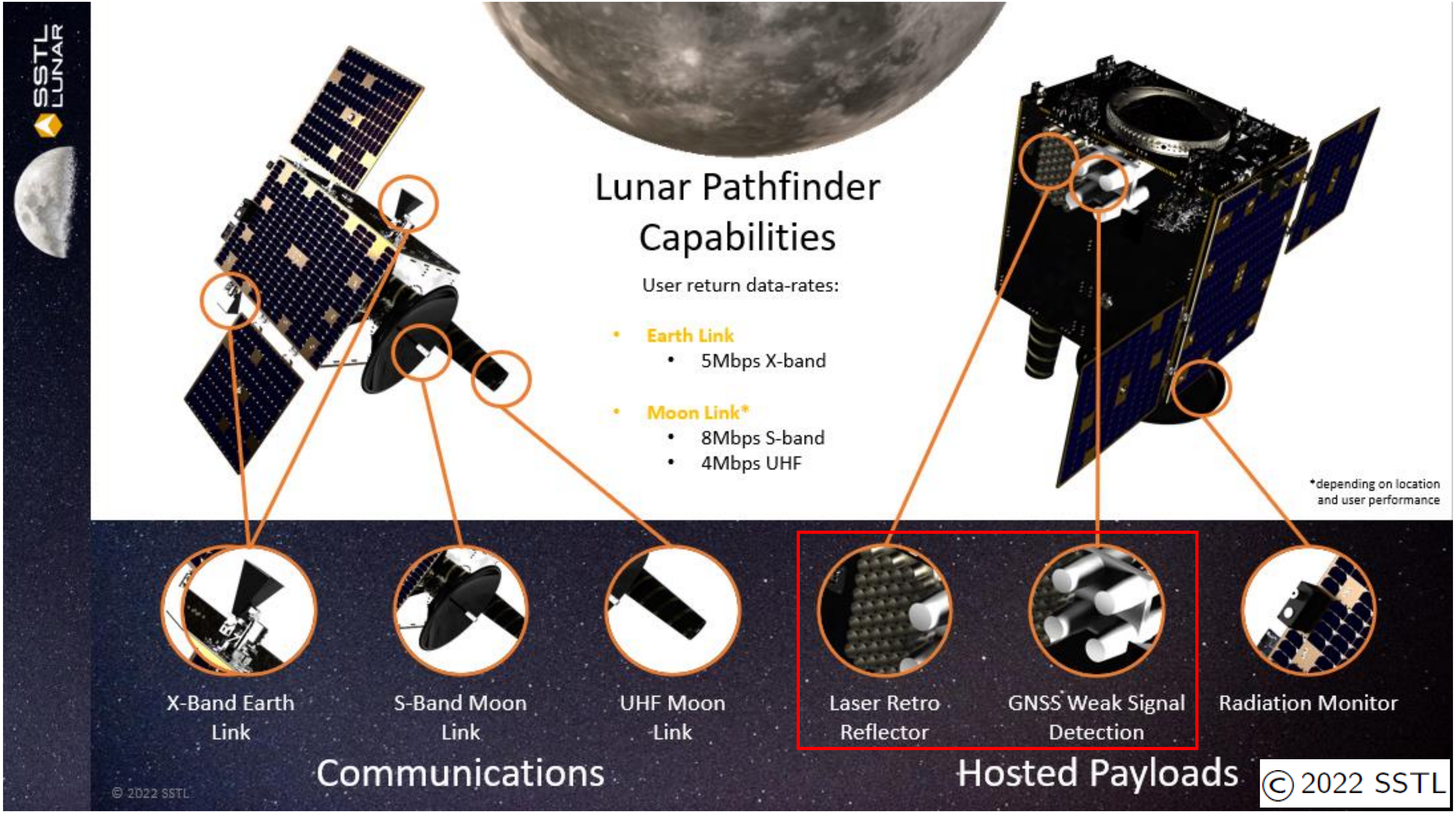

STEP 1: LUNAR PATHFINDER
Low-rate satellite communications service + Moon GNSS Receiver
Development
Pathfinder Service
⇒Q4 2025
STEP 2: MOONLIGHT CONSTELLATION
High-data rate satellite communications and navigation service
Design
Development
IOC
FOC
2020
2021
2022
2023
2024
2025
2026
2027
2028
2030

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



⇒launch in Q4 2025

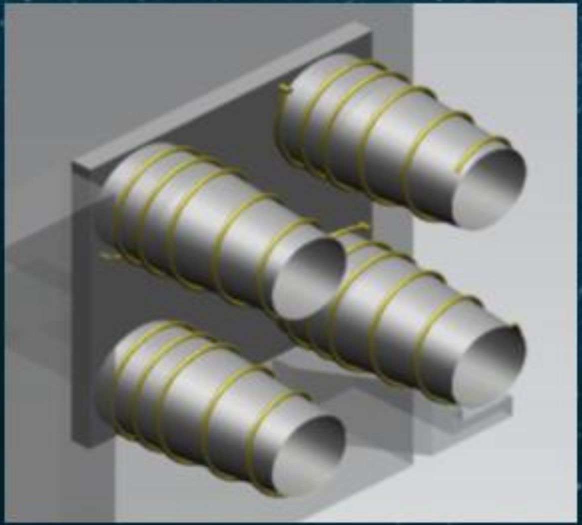



SSTL LUNAR
Lunar Pathfinder Capabilities
User return data-rates:
Earth Link
5Mbps X-band
Moon Link*
8Mbps S-band
4Mbps UHF
*depending on location and user performance
X-Band Earth Link
S-Band Moon Link
UHF Moon Link
Laser Retro Reflector
GNSS Weak Signal Detection
Radiation Monitor
Communications
Hosted Payloads
© 2022 SSTL

Lunar Pathfinder experiment – GNSS receiver

Parameter	Value
Acquisition sensitivity	15dBHz
Tracking sensitivity	15dBHz
3D Position accuracy	< 100m RMS
3D Velocity accuracy	< 0.1 m/s RMS
Mass	1.3 Kg
Size	24x12x7cm
Power	< 12W
Constellations	GPS / Galileo L1/E1/L5/E5

SpacePNT NaviMoon Receiver Specifications



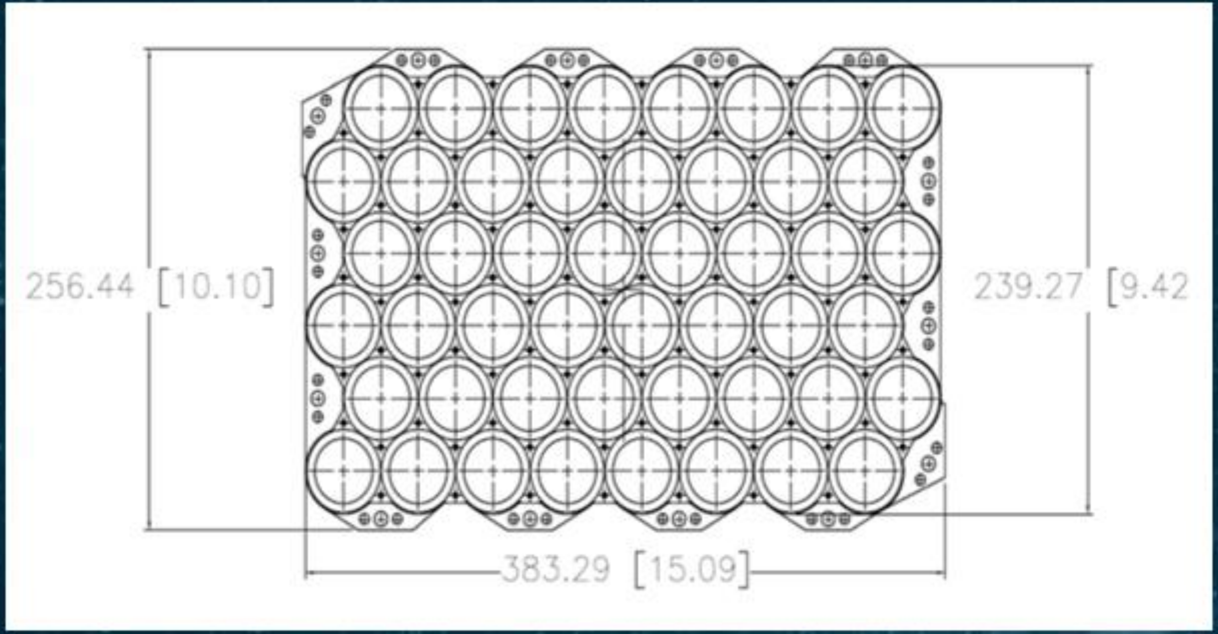
Parameter	Value
L1 boresight gain	15 dBi
L5 boresight gain	12 dBi
Polarization	RHCP
Mass	~2Kg
Size	26x26x28cm

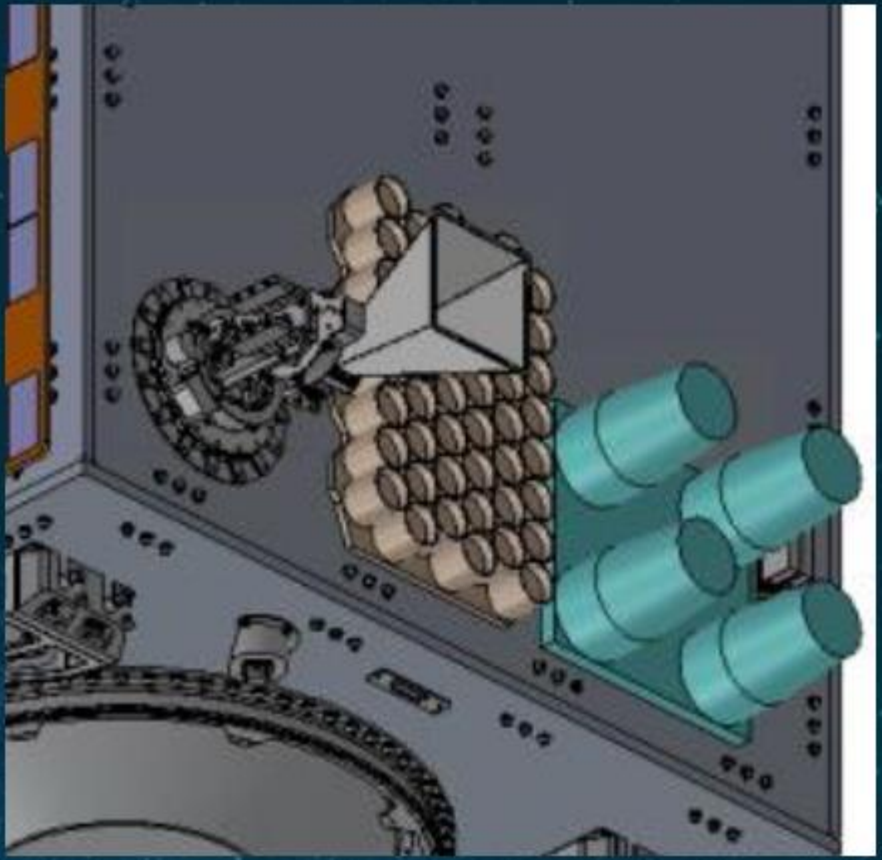
MDA Antenna Specifications

First ever demonstration of GNSS reception on Lunar orbit.

LRR Developed by NASA

esa





Technical Description:

- LRR is composed of 48 reflector cubes (1.6” diameter), based on the technology developed and flown by NASA on the Lunar Reconnaissance Orbiter (LRO) - Mass < 4 kg (TBC)

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

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%

Long term - Moonlight FOC

esa

- 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)

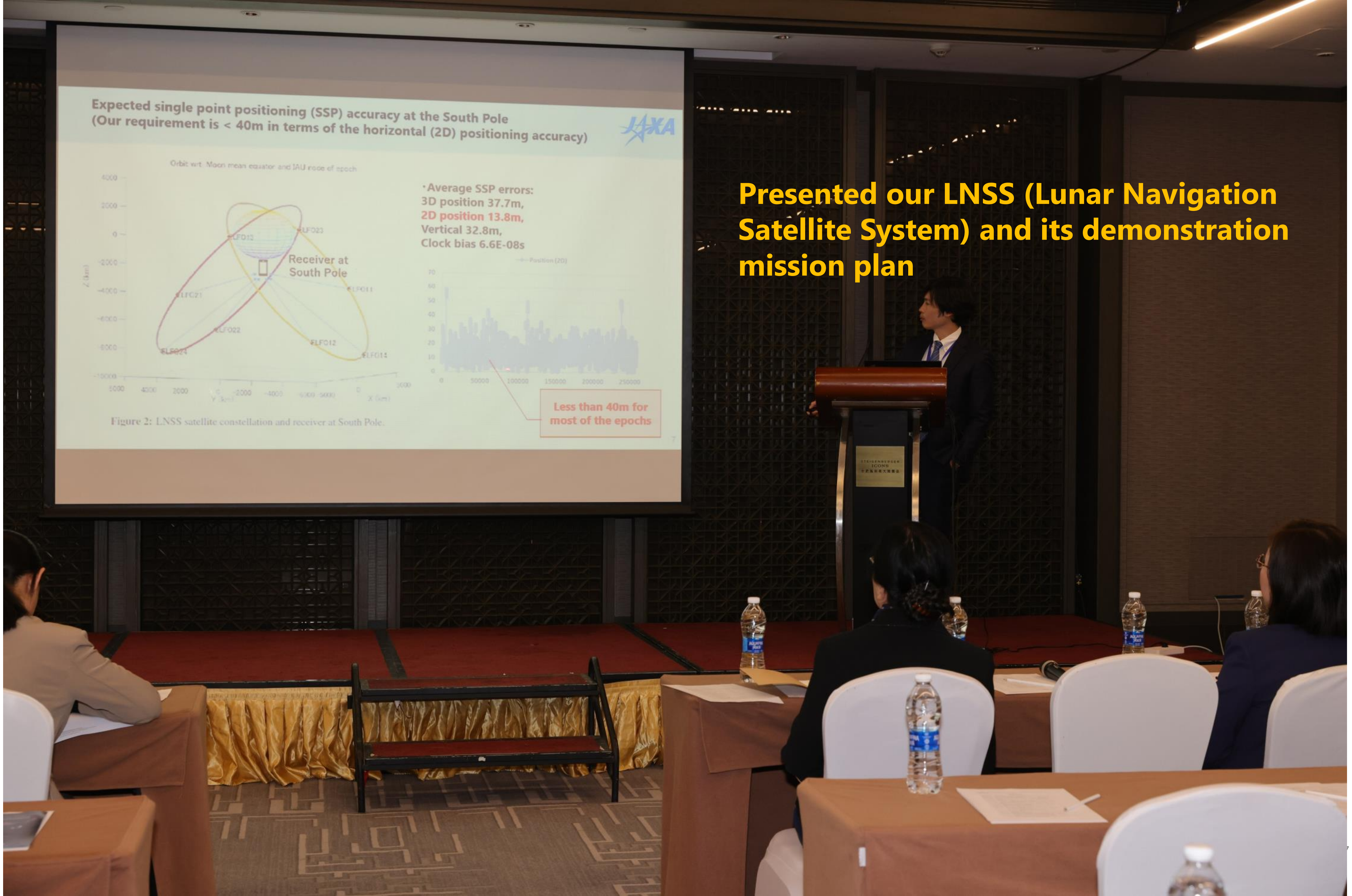
[redacted]

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

China Status


DSEL
DEEP SPACE EXPLORATION LAB
深空探测实验室
2023 International
Conference of Deep Space
Sciences
22-27 April 2023, Hefei, China
Home
Important dates
Program
Registration
22-27 April 2023


Beijing
北京
唐山市
天津
河北
大连市
西
济南市
青岛市
山东
中華人民
共和国
西安市
Xi'an
河南
2-3 hours by
express train
Hefei
江苏
合肥融创
Shanghai
上海
苏州市
湖北
武汉市
安徽
杭州市
成都市
四川
Chengdu
重庆
浙江
Google



Presented our LNSS (Lunar Navigation Satellite System) and its demonstration mission plan

Queqiao (QQ)-Net plan

China's lunar comm&nav system called Queqiao（鵲橋）

～2030
50Mbps return, 100m positioning accuracy

2030～2040
1～10Gbps return, 50m positioning accuracy

2040～2050
>10Gbps return, 10m positioning accuracy

Photos taken from "Report 3: Global Call & Competition for QQnet Constellation Solution", Tiandu Forum, Apr. 25, 2023.

Chang’e (嫦娥)- 6 in 2024 Chang’e 7 in 2026 Chang’e 8 in 2028

International Lunar Research Station (ILRS)

Moon exploration

Planet exploration

Sun exploration

Photos taken from “Report 3: Global Call & Competition for QQnet Constellation Solution”, Tiandu Forum, Apr. 25, 2023. © 2023 CASC

Queqiao-2 will be launched in early 2024 to support Chang'e-6, 7, and 8

Tiandu (天都)-1, 2 will be launched together with Queqiao-2 for comm&nav experiment

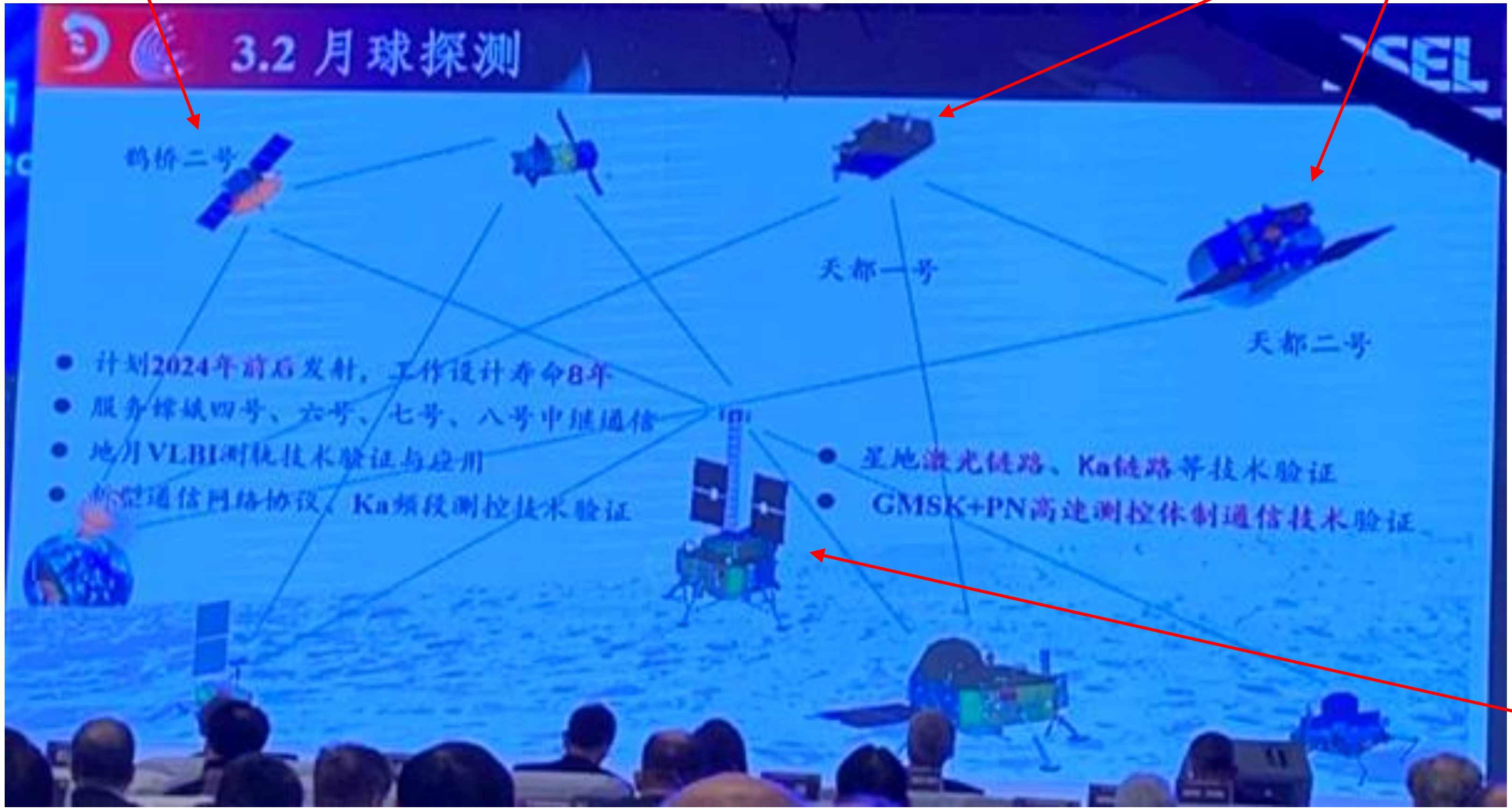
Queqiao-3 under planning

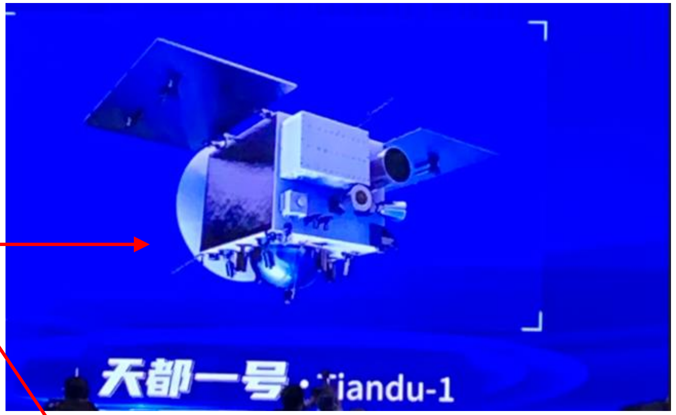
Reminding that ESA Lunar Pathfinder is currently scheduled in Q4 2025, Queqiao-2 is faster. Their schedule is as fast as NASA, showing USA and China are now in space race for the moon

Photos taken from "Report 3: Global Call & Competition for QQnet Constellation Solution", Tiandu Forum, Apr. 25, 2023. © 2023 CASC

Queqiao-2

Tiandu-1, 2

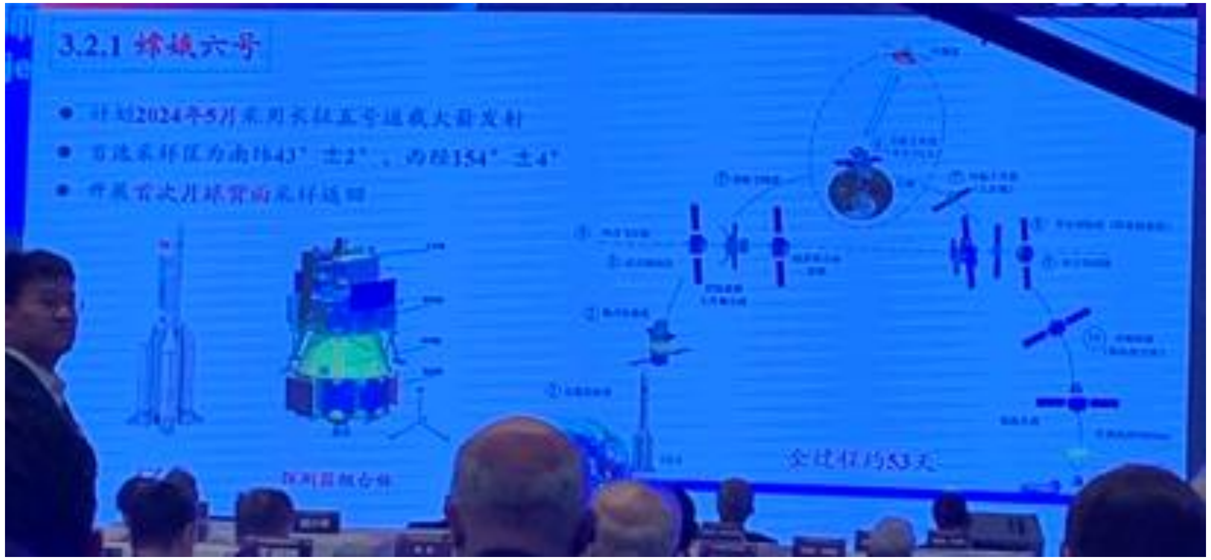




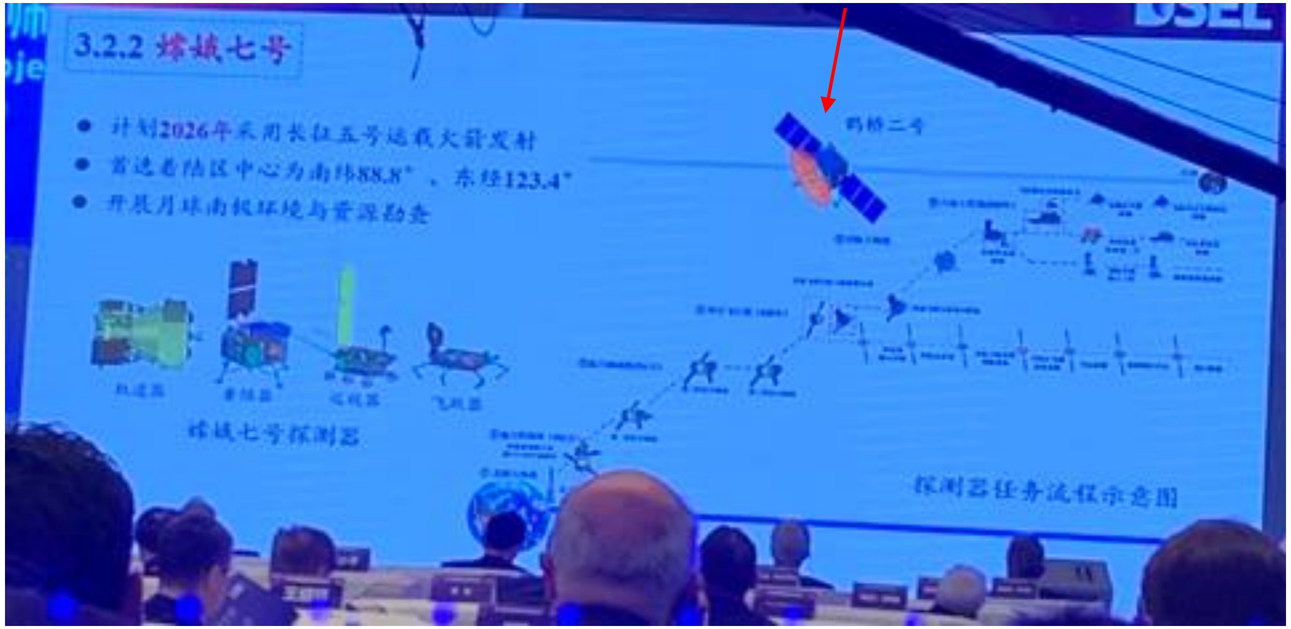
Chang'e 6 (in 2024), 7 (in 2026) and 8 (in 2028) robotic lunar missions

Photos taken from "Report 3: Global Call & Competition for QQnet Constellation Solution", Tiandu Forum, Apr. 25, 2023. © 2023 CASC

Chang’e 6 in May 2024

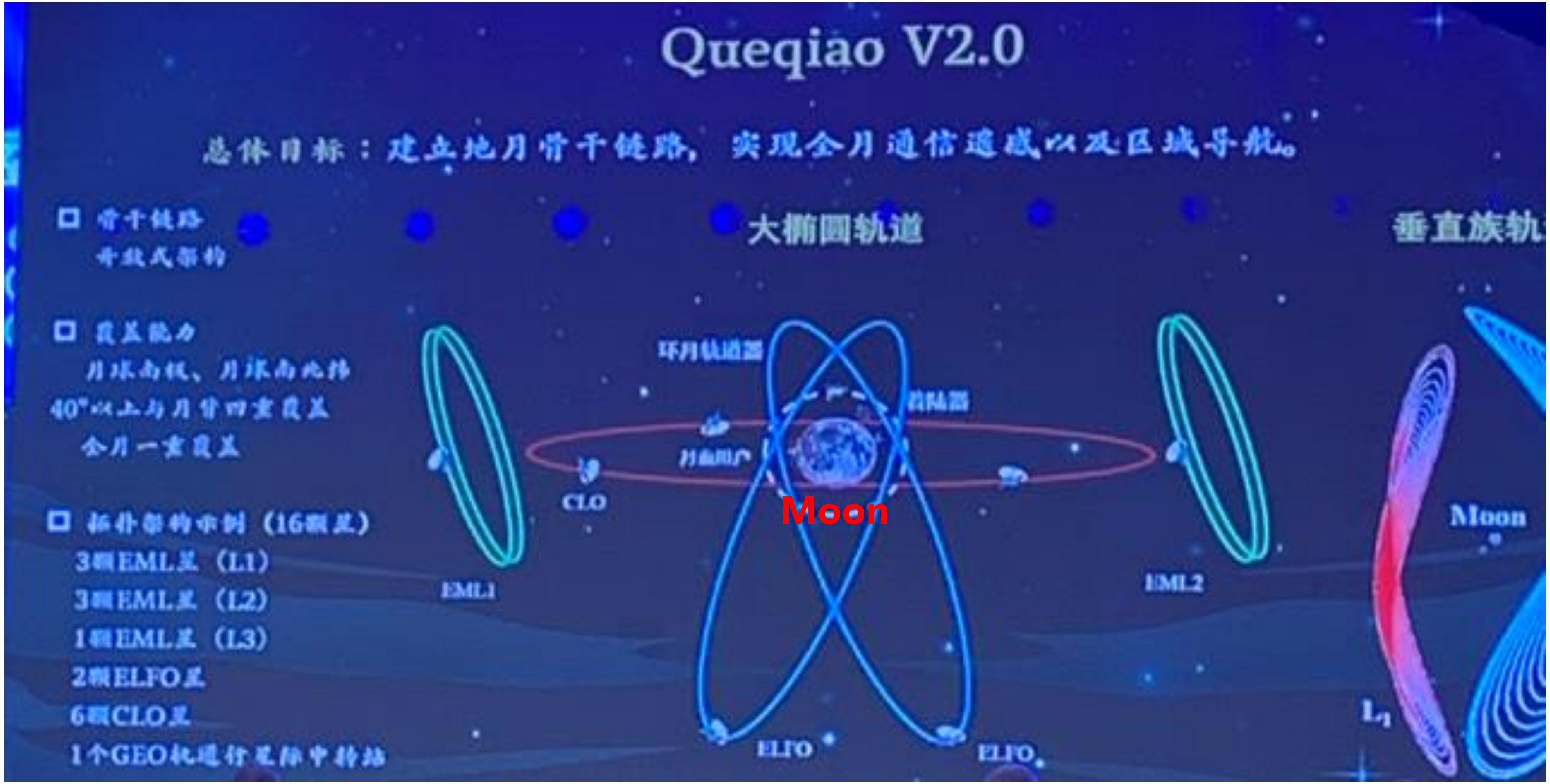


Chang’e 7 in 2026 and Queqiao-2

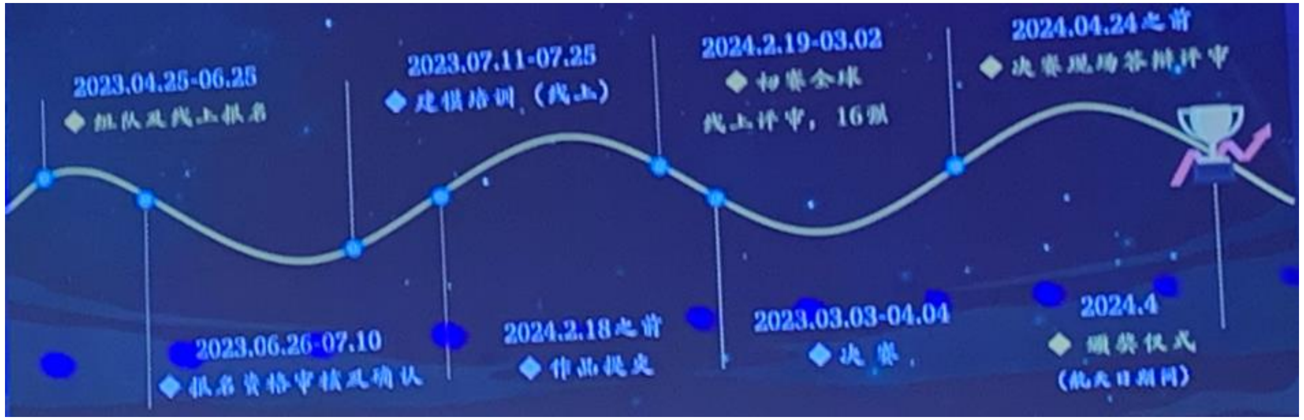


Chang’e 8 in 2028 and International Lunar Research Station (ILRS) construction

Photos taken from “Report 3: Global Call & Competition for QQnet Constellation Solution”, Tiandu Forum, Apr. 25, 2023.



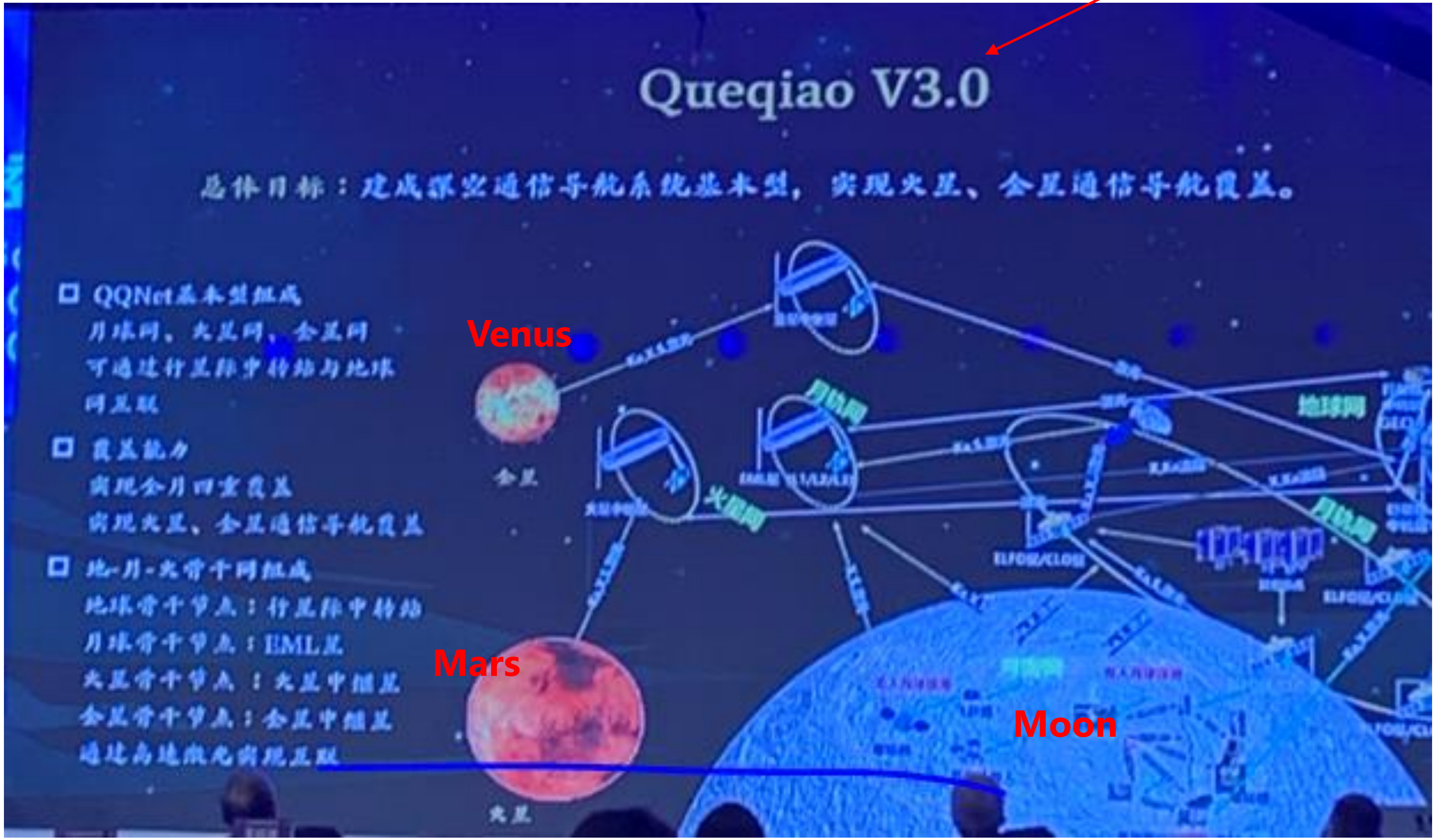
Concept of QQ-Net under study (to be deployed before 2040)



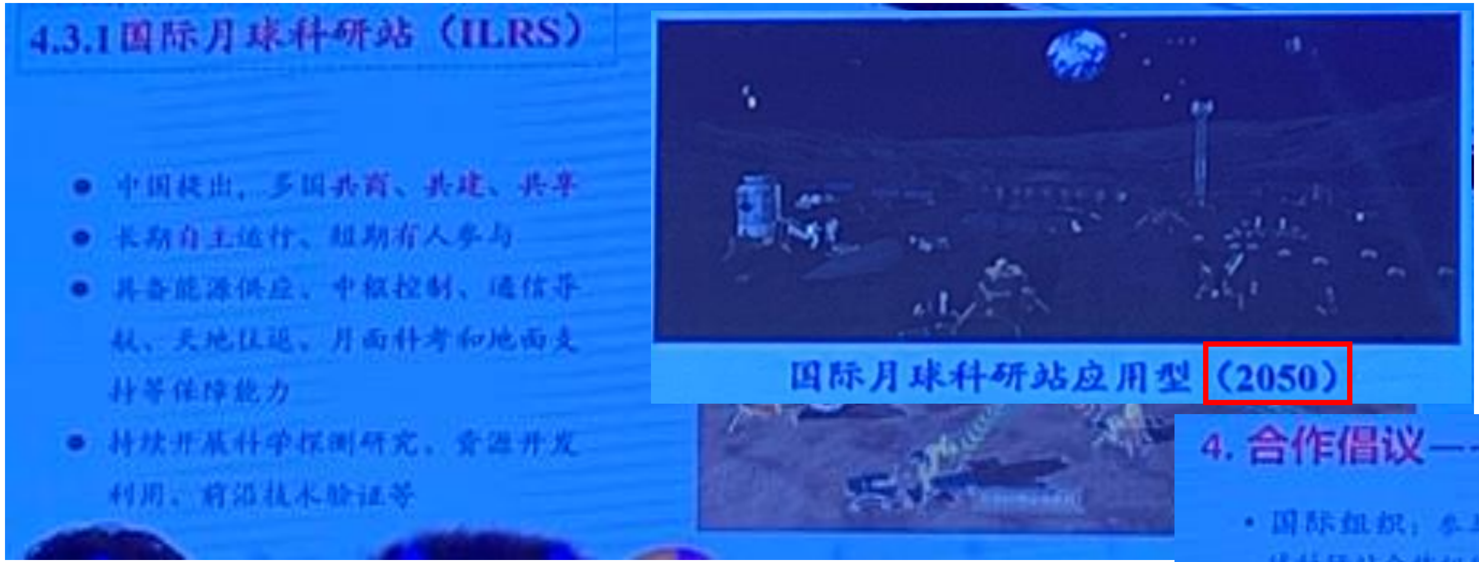
They are now in the one-year competition study phase for the QQ-Net (2023.4-2024.4)

Photos taken from "Report 3: Global Call & Competition for QQnet Constellation Solution", Tiandu Forum, Apr. 25, 2023.

Expansion to Mars, Venus, … to be realized before 2050

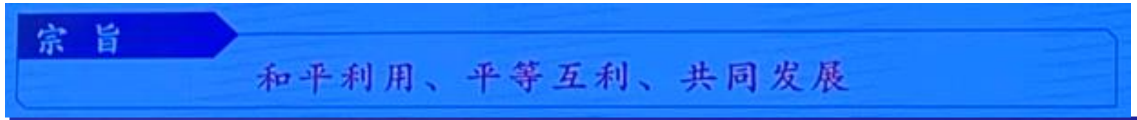


International Lunar Research Station (ILRS) under planning by China and Russia.
Construction starts from 2028 (by Chang'e 8) and basic model completed by 2030



ILRS Cooperation Organization (ILRSCO) that is analogous to the U.S.-led Artemis program and its political underpinning, the Artemis Accords

For peaceful use, equal right, collaborative development



Photos taken from "Report 3: Global Call & Competition for QQnet Constellation Solution", Tiandu Forum, Apr. 25, 2023.

We join LunaNet and its Lunar Augmented Navigation System (LANS) with NASA and ESA

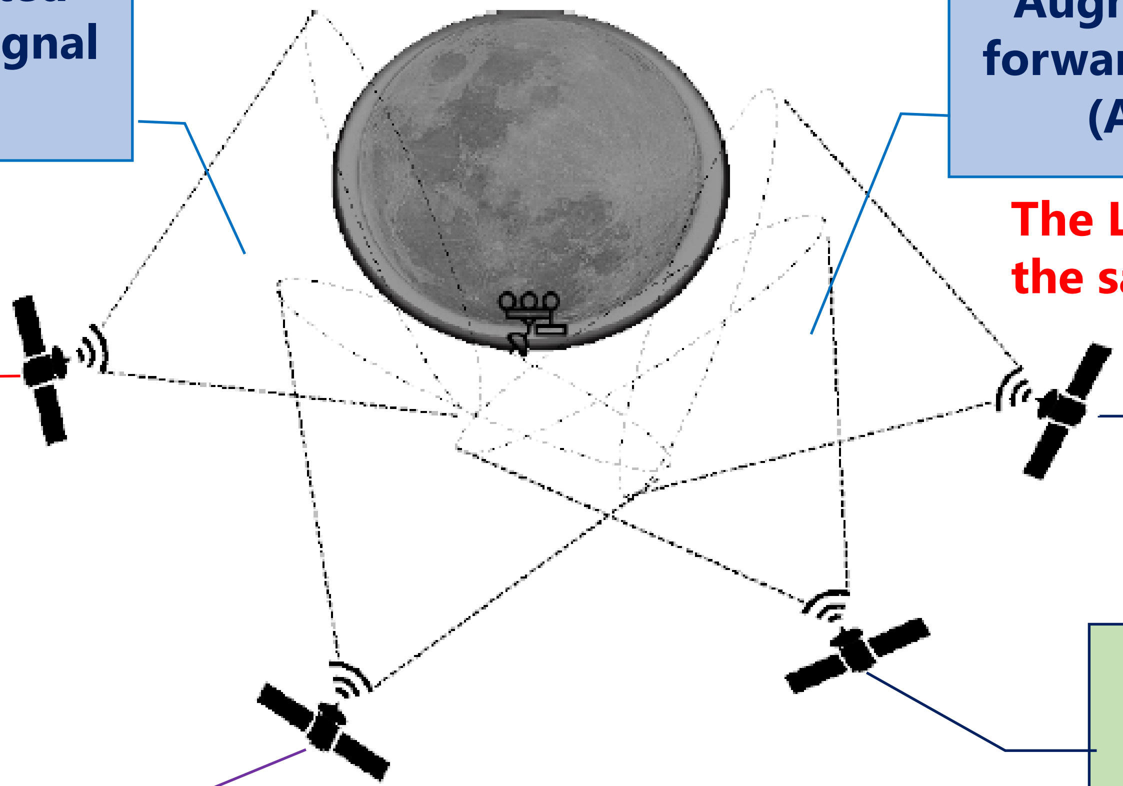
The Lunar augmented navigation system (LANS) is the GNSS-like system for the moon

Augmented forward signal (AFS)

Augmented forward signal (AFS)

The LANS satellites all broadcast the same navigation signal (AFS)

JAXA LNSS satellite



NASA LCRNS (Lunar Communications Relay and Navigation Systems) satellites

ESA Moonlight satellite

Figure 10 - LANS PNT Concept Provided by LunaNet Nodes

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

LunaNet Interoperability Specification (LNIS)

LunaNet Interoperability Specification Document

Published by NASA and ESA

Version 4

Version 4 – September 2022

LN-IS V004 September 12, 2022 1

The LNIS includes:

- The message format of the AFS, signal frequency, power, etc.
- The LANS Initial Operations Capability (IOC) and Enhanced Operations Capability (EOC)
- Accuracy specification (Signal-In-Space-Errors) for the LunaNet Service Providers (LNSP)
- Lunar Reference Frame Standard and Lunar Time System Standard

JAXA LNSS complies with the LNIS to be compatible and interoperable with the other LNSP such as ESA and NASA

Each LNSP shall ensure that the AFS maintains Signal-In-Space-Errors (SISEs) within the requirement specified in Table C-1 at the defined service volume

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)

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

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.

LANS initial operations capability (IOC) service volume

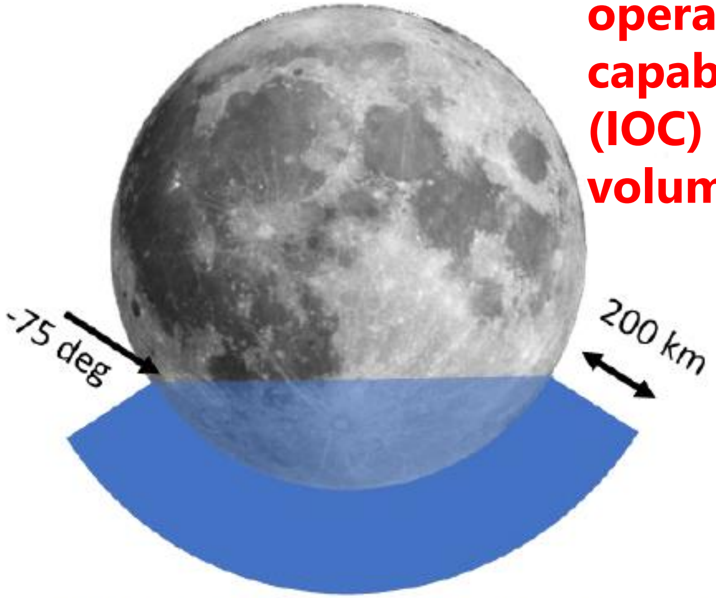
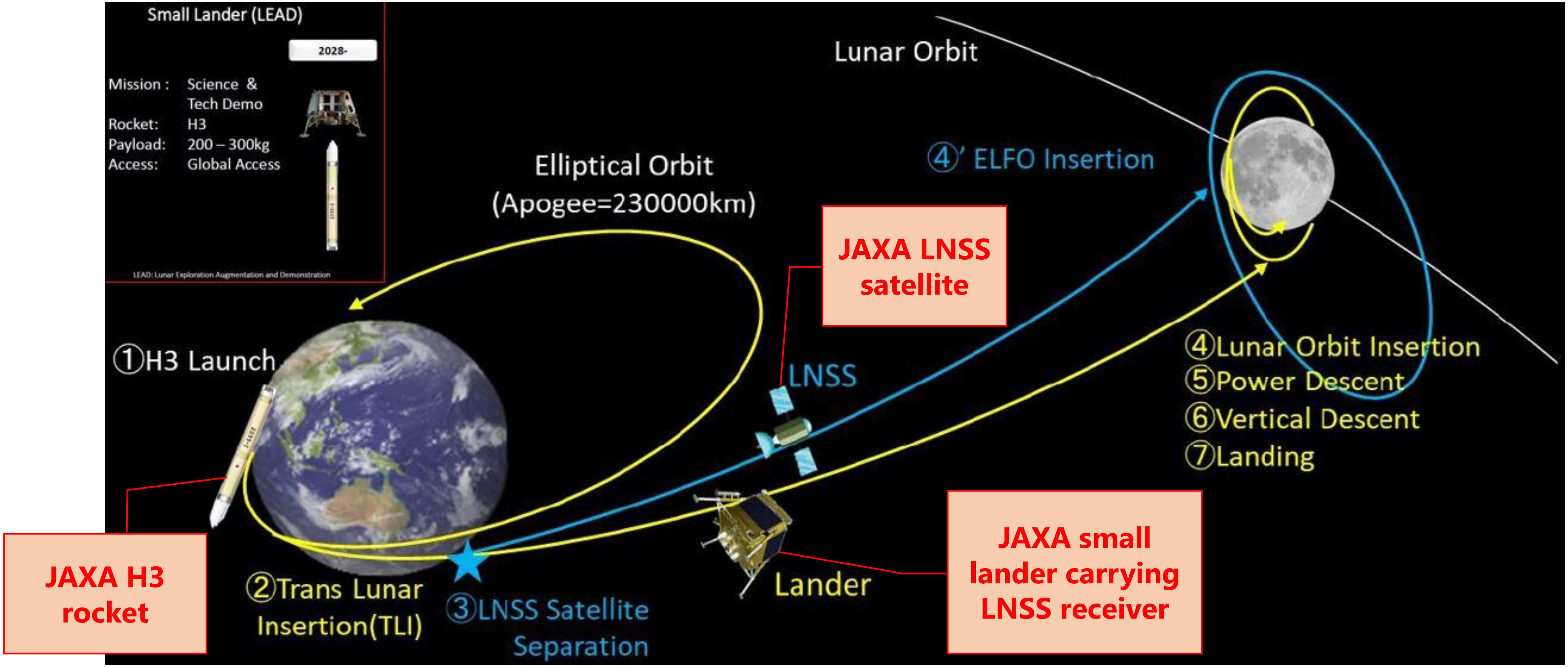


Figure 11 - LANS IOC Service Coverage and Performance Volume

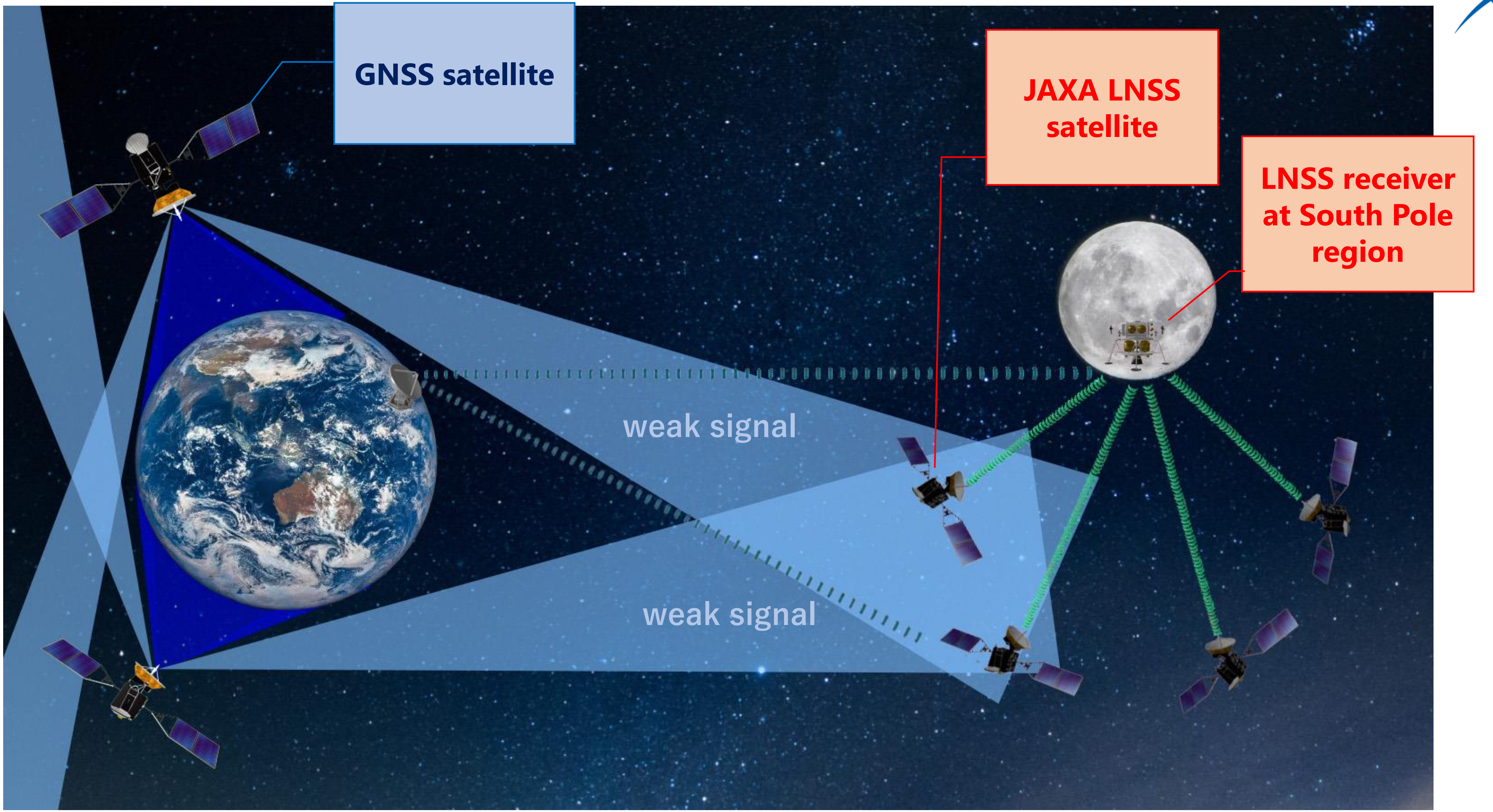
Both SISEs are based on lunar reference frame and time, which will be defined in the applicable documents to the LNIS called <u>Lunar Reference Frame Standard</u> and <u>Lunar Time System Standard</u>

Our LNSS Demonstration Mission Under Planning

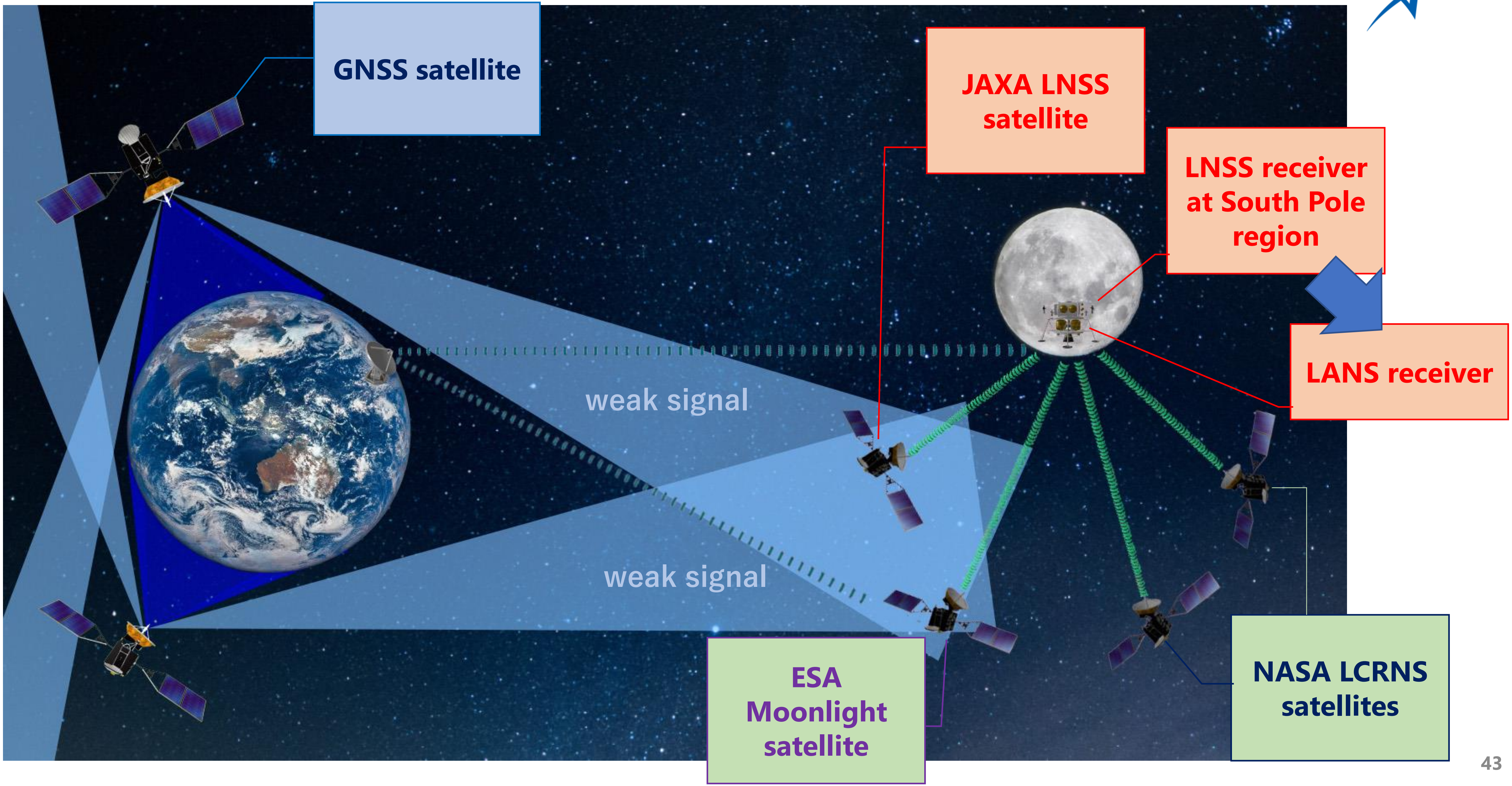
LNSS demonstration mission targeting around 2028



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



Proposing first-ever lunar PNT SISE evaluation and interoperability demonstration



Conclusions

・The JAXA LNSS will comply with the LunaNet Interoperability Specification (LNIS) and join the Lunar Augmented Navigation System (LANS) that becomes the moon GNSS.

・We are planning our demonstration mission around 2028 and our receiver to be located at South Pole region will be interoperable so that all LunaNet Service Providers (LNSPs) Augmented Forward Signals (AFSs) will be received.

・I believe this demonstration mission will contribute to the SISE evaluation for all LNSPs such as NASA, ESA, and JAXA joining the LANS. Related collaboration discussion has been already ongoing both bilaterally and multilaterally.

Discussion ongoing with foreign colleagues

ICG International Committee on Global Navigation Satellite Systems

NASA | esa European Space Agency | ROSCOSMOS | CASC | JAXA | इसरो isro

NASA GNSS Activities Update; *Joel PARKER, NASA/United States*
Lunar Navigation Satellite System (LNSS) and its Demonstration Mission; *MASAYA Murata, JAXA/Japan*
The Envision of Earth-Moon Communication-Navigation System; *Xiongwen HE, CAST/China*
ESA Lunar Navigation Plans: Lunar Pathfinder & Moonlight; *Javier VENTURA-TRAVESET, ESA*

Lunar PNT presentation from NASA, ESA, JAXA, CAST
(On respective space agency's lunar PNT system)

IOAG Interagency Operations Advisory Group

Committee for the Study of LunaNet Governance

Lunar Communications & Navigation Working Group (LCNWG)

Members

ASI Agenzia Spaziale Italiana | cnes CENTRE NATIONAL D'ÉTUDES SPATIALES | CSA ASC | DLR | esa | JAXA Explore to Realize | NASA | UK SPACE AGENCY

This year's ION GNSS+2023 lunar PNT panel

https://www.ion.org/gnss/sessions.cfm?sessionID=1596

Session F5b: PANEL: International Civilian Agency Lunar PNT Systems

RETURN TO SESSION LIST

Date: Friday, September 15, 2023

Time: 10:35 a.m. - 12:15 p.m.

ON DEMAND This session will recorded, and will become available for viewing by registered attendees within 24 hours.

Session Chairs

Dr. Evan Anzalone
NASA

Giuseppe D'Amore
Agenzia Spaziale Italiana

Track Chair

Dr. Seebany Datta-Barua
Illinois Institute of Technology

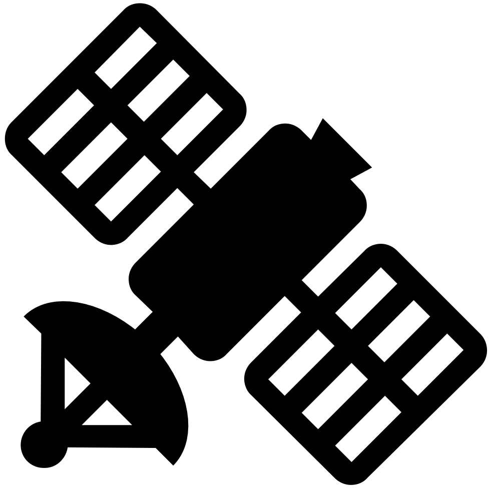
Panel Members:

- Dr. Javier Ventura-Traveset, European Space Agency (ESA)
- Cheryl Gramling, National Aeronautics and Space Administration (NASA)
- Dr. Masaya Murata, Japan Aerospace Exploration Agency (JAXA) (invited)

ESA Moonlight
NASA LCRNS
JAXA LNSS

We are partners, working together towards the moon GNSS (LANS)

Thanks!



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