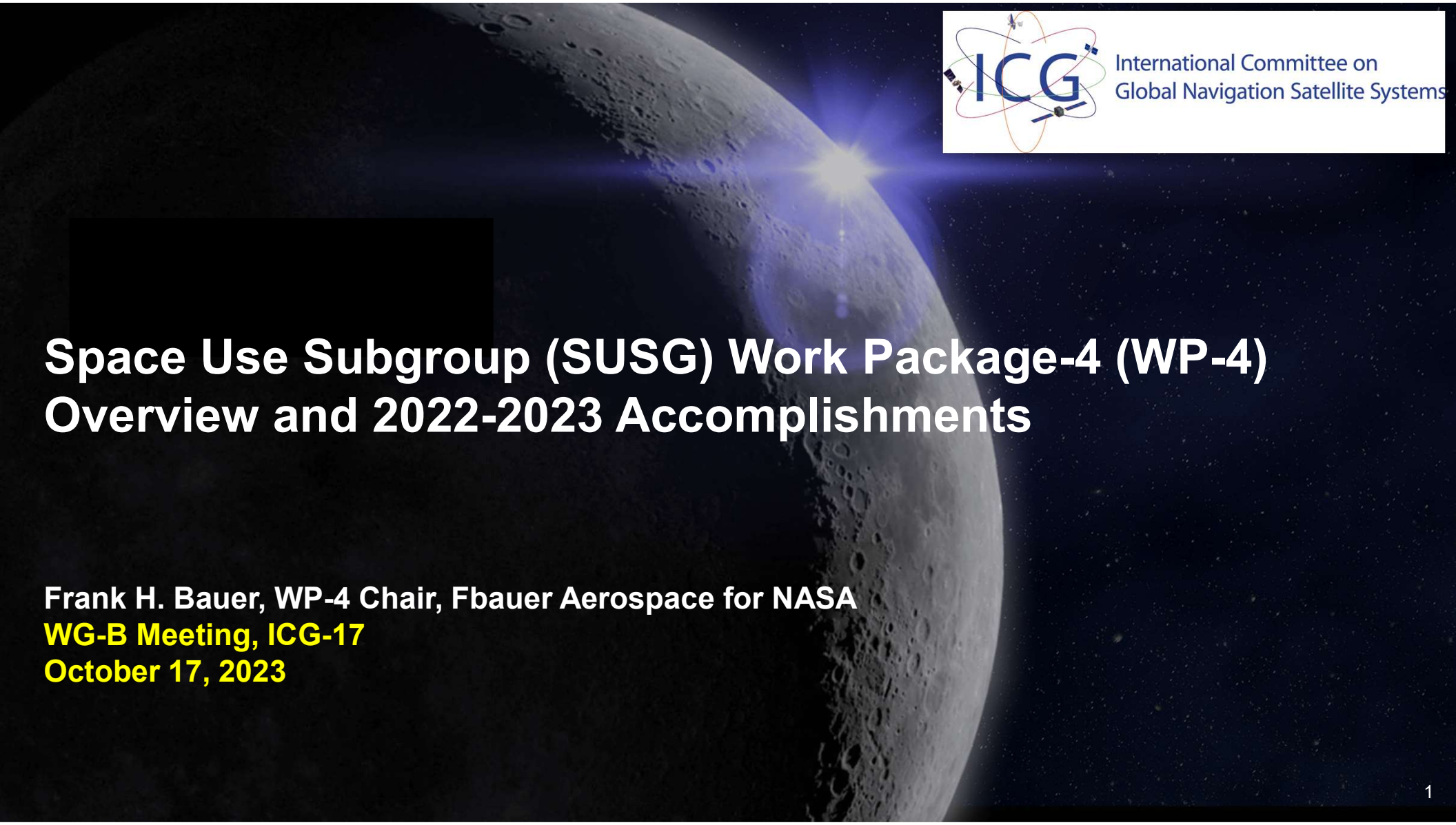

Space Use Subgroup (SUSG) Work Package-4 (WP-4) Overview and 2022-2023 Accomplishments

Frank H. Bauer, WP-4 Chair, Fbauer Aerospace for NASA

WG-B Meeting, ICG-17

October 17, 2023

Agenda

- Workplan and Accomplishments Overview
- ICG-16 Adopted Recommendation
- Lunar PNT: WP-4 Team Observations
- Status of International Lunar PNT Efforts
- Mission Profiles, Use Cases, PNT Architectures
- Lunar PNT Definitions
- ICG-17 Draft Recommendation

Space Use Subgroup Work Packages

Adopted 24 Sep 2021 at ICG-15

WP#	Activity	Lead	Participation
1	Public availability of provider antenna/signal technical data and requisite models	India	China Japan Europe USA
2	GNSS space user mission data and profile	China	USA Europe
3	GNSS space user timing requirement analysis and space user operations recommendations	Europe	USA China Japan India
4	GNSS SSV and lunar PNT systems to support lunar operations	USA	Russia China Japan Europe
5	GNSS space user Standards	Europe	Russia USA China India

WP-4: 2022-2023 Workplan (1 of 2)

Objective:

Work with GNSS providers and multilateral organizations, including the IOAG and SFCG, to ensure interoperability, compatibility, and availability of GNSS and lunar PNT systems that can be seamlessly employed together from the Earth to the Moon

Outcome:

Full attainment of an interoperable, compatible, and available GNSS/lunar PNT system of systems that can support the world's ever-expanding human and robotic space operations in transit, around and on the surface of the moon.

WP-4: 2022-2023 Workplan (2 of 2)

Approach:

- Establish necessary liaison roles with Space Frequency Coordination Group, ISECG, etc.
- Collect and document lunar use cases that require lunar GNSS or PNT
- Encourage and consolidate results of lunar flight experiments employing GNSS and lunar PNT systems
- Study and make recommendations to maximize compatibility, interoperability and availability of combined GNSS + lunar PNT “system of systems”, including:
  - Coordination of frequencies and codes
  - Lunar PNT definitions
  - Combined GNSS-lunar PNT architectures
  - Signal interoperability, compatibility and availability
  - Lunar reference frames and timing

WP-4 2022-2023 Accomplishments

- Developed recommendation, approved at ICG-16, encouraging GNSS and lunar PNT teamwork to ensure the future attainment of an **interoperable, compatible, and available** PNT system of systems for lunar human and robotic operations
- Reached consensus on several lunar PNT operations characteristics
- Teams from ESA, JAXA, NASA & China provided in-depth descriptions of current lunar PNT planning
- Documented comprehensive set of Lunar PNT Mission Profiles, Use Cases, and Architectures
- Developed/adopted key lunar PNT definitions: cislunar space and shielded zone of the moon
- Coordination started with IOAG and SFCG liaisons to ensure interoperability, compatibility and availability of PNT signals in and on the moon
- Developed ICG-17 draft recommendation to conduct a Joint ICG-IOAG multilateral Workshop on Cislunar PNT

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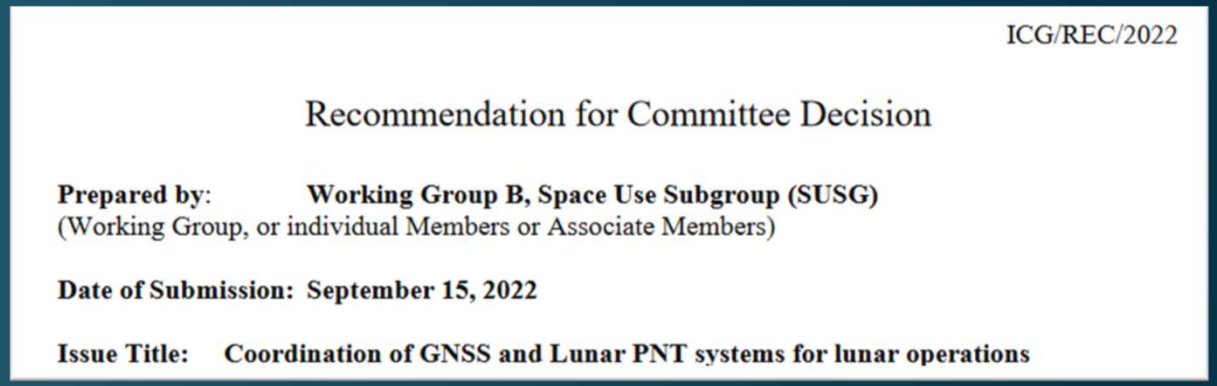
ICG-16 Recommendation—Adopted



ICG/REC/2022

Recommendation for Committee Decision

Prepared by: **Working Group B, Space Use Subgroup (SUSG)**
(Working Group, or individual Members or Associate Members)

Date of Submission: **September 15, 2022**

Issue Title: **Coordination of GNSS and Lunar PNT systems for lunar operations**

Recommendation

The ICG encourages international GNSS providers and lunar PNT developers to work together via the appropriate multilateral fora, such as the IOAG, to ensure the future attainment of an interoperable, compatible, and available PNT system of systems that can support the world's ever-expanding human and robotic space operations around and on the surface of the moon.

The collaborative efforts of the ICG, including the GNSS Space Service Volume initiative, should serve as a model for this promising international exploration initiative.

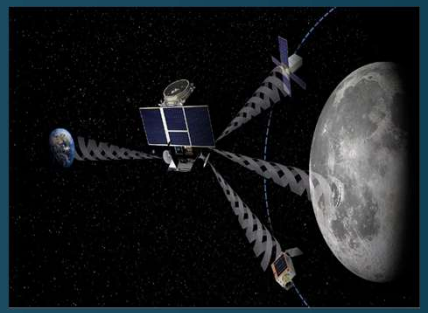
The ICG will analyze planned lunar PNT systems and their interactions with GNSS and propose recommendations that may be taken up by GNSS providers and lunar PNT developers.

Lunar PNT: WP-4 Team Observations

- Lunar PNT operations will rely on two PNT services:
  1) Earth-centric SSV employing GNSS
  2) Lunar-centric PNT capability
- Need a way to connect GNSS SSV and Lunar PNT services with a commonly-referred time-scale and reference frames to make navigation seamless: interoperable, compatible & available
- Lunar PNT services will likely employ orbital and lunar-surface augmentations to be used in conjunction with weak signal GNSS
- Lunar PNT transmissions may not be lunar-circular, like the GNSS SSV around Earth
- Lunar PNT transmissions (e.g. a lunar SSV architecture) will:
  - Evolve over time
  - Be dependent upon lunar reference frame and time developments, and
  - Be driven by lunar use-cases and associated requirements

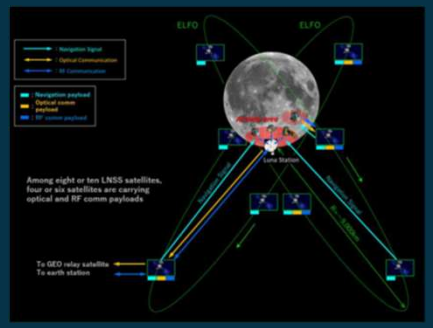
International Lunar PNT Efforts

WP-4 team received presentations from China, Europe, Japan and the USA on Lunar PNT demonstrations, requirements, architectures and systems being planned or in development including:



Lunar Pathfinder
(ESA demo)

LuGRE
(NASA Demo)



Lunar Navigation Satellite System (LNSS)
(JAXA Nav System)

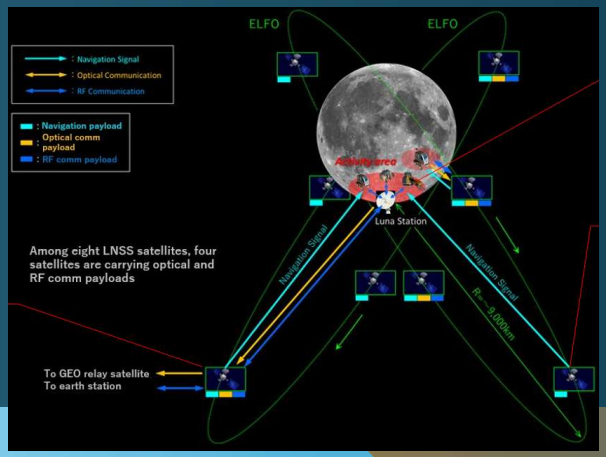
Lunar PNT Services (e.g. LunaNet)
(International Architecture)

Lunar Communication & Navigation Systems Proposed by USA, Europe, Japan, China

NASA LCRNS

ESA Moonlight LCNS

JAXA LNSS



China Queqiao

Initial Lunanet PNT System of Systems: Lunar Augmented Navigation System (LANS)

Augmented forward signal (AFS)

Augmented forward signal (AFS)

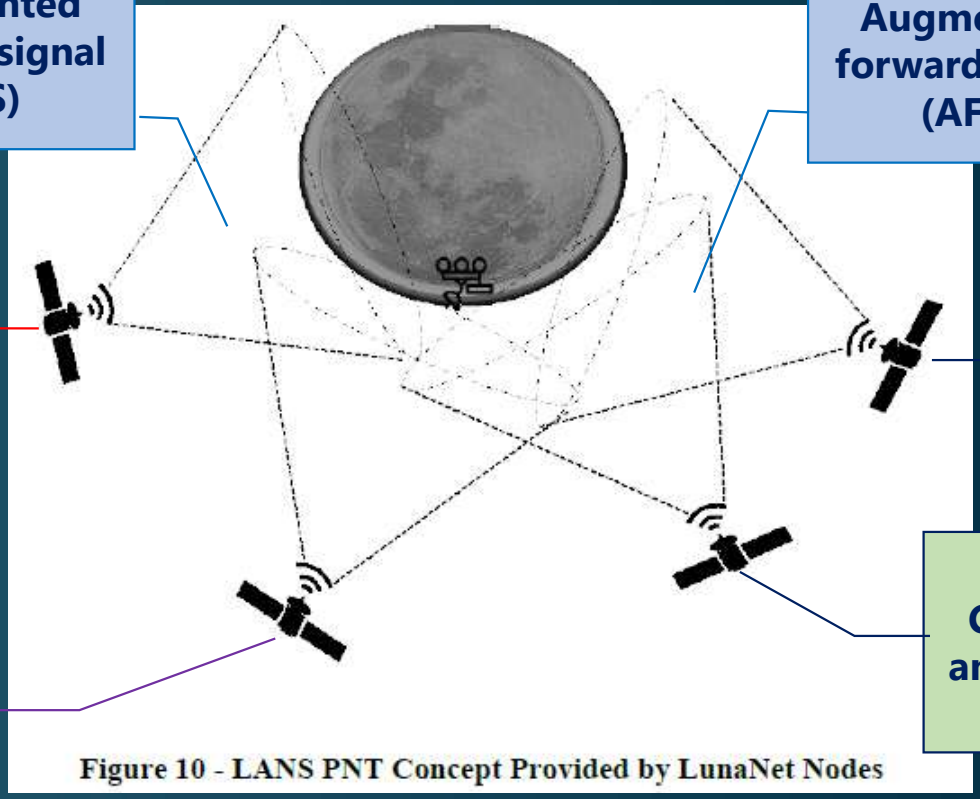


Figure 10 - LANS PNT Concept Provided by LunaNet Nodes

All broadcast a standardized AFS to form LANS, similar to GNSS around the Earth

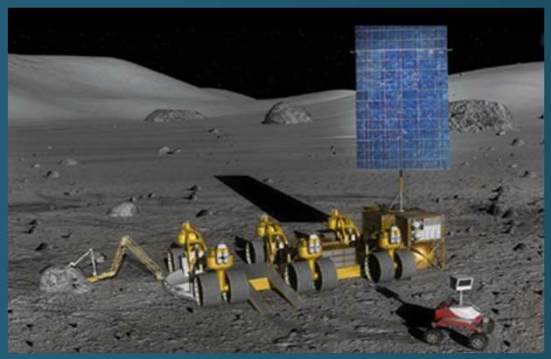
JAXA LNSS (Lunar Navigation Satellite System) satellite

NASA LCRNS (Lunar Communications Relay and Navigation Systems) satellites

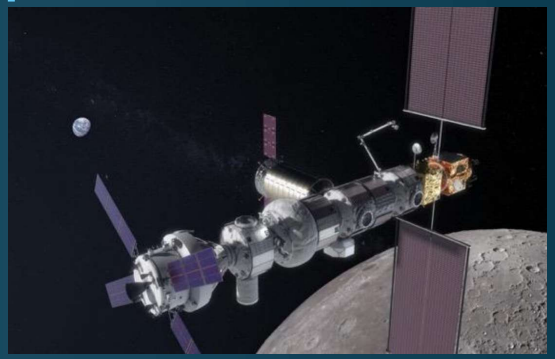
ESA Moonlight LCNS (Lunar Communications and Navigation Services) satellite

Figure is copied from the LunaNet Interoperability Specification (LNIS) and Modified with Planned Space Agency Constellations

Mission Profiles, Use Cases, PNT Architectures
Lunar Exploration: Roles for GNSS

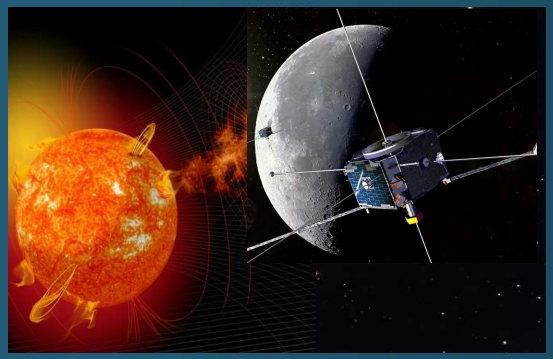


Lunar Surface Operations, Robotic Prospecting,& Human Exploration



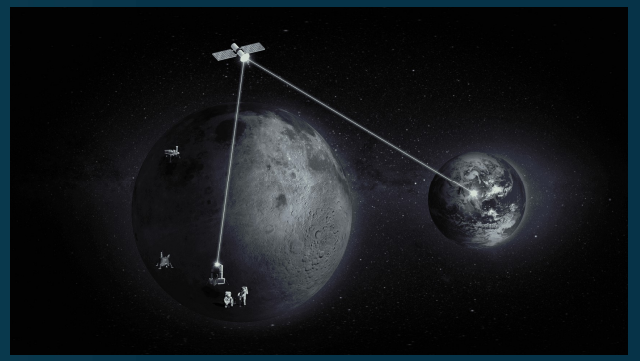
Human-tended Lunar Vicinity Vehicles (Gateway)

Robotic Lunar Orbiters, Resource & Science Sentinels



Earth, Astrophysics, & Solar Science Observations

Satellite Servicing



Lunar Exploration Infrastructure

Mission profiles that could benefit from Lunar PNT services

- Space Stations in NRHO (Gateway)
- Moon transit spacecraft (Artemis I & II)
- Low Lunar Orbit (LRO)
- South pole landers (Artemis III, LEAD)
- Lunar equatorial landers (LuGRE, CLPS, etc)
- Lunar comm/nav relay (Queqiao-2, Lunar Pathfinder, LNSS, LCRNS, Moonlight)
- L2 relay satellite (Queqiao-1)
- Surface Roving (LTV, JAXA Rover)
- Combined mission: Far Side Lander, Jumper, Orbiter (CE-7)
- Science observations, highly elliptical Earth orbiter (MMS, TESS, Proba-3)
- L1/L2 science observations (Themis/Artemis constellation)
- Gravitational observations (GRAIL)
- Impactors (LCROSS)
- In-Situ Resource Utilization (ISRU) and Mining

Encompasses human and robotic missions

Lunar PNT Use Cases

- Satellite servicing
- Real-time on-board nav/orbit determination
- On-board timing/clock synchronization
- Transit maneuver planning and calibration
- Surface navigation
- Autonomous rendezvous and docking
- Radiometric science
- Lunar reference frames and lunar time systems ("Lunar Geodesy")
- Collision avoidance
- VLBI (support)
- Formation flying
- Search and Rescue

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Lunar PNT
Planned Architectures and Augmentations

PNT Architectures

- Moonlight—ESA
- Lunar Communications Relay and Navigation System (LCRNS)—NASA
- Lunar Navigation Satellite System (LNSS)—JAXA
- Queqiao-DSEL
- GNSS

Augmentations

- Lunanet compatible services
- Satellite Laser Ranging (SLR)
- Lunar Laser Retroreflectors
- Commercial and government ground networks

Cislunar Space Definition

For the purposes of considering interoperability, compatibility, and availability of GNSS and other PNT services in cislunar space, the following definition will be used:

- *Cislunar space is a volume around the Earth extending from the edge of the current SSV definition (at GEO orbit) to ~524,000 km from the Earth's center*
- *The combined Earth SSV and Cislunar space definition support PNT operations from the Earth to the moon and beyond.*

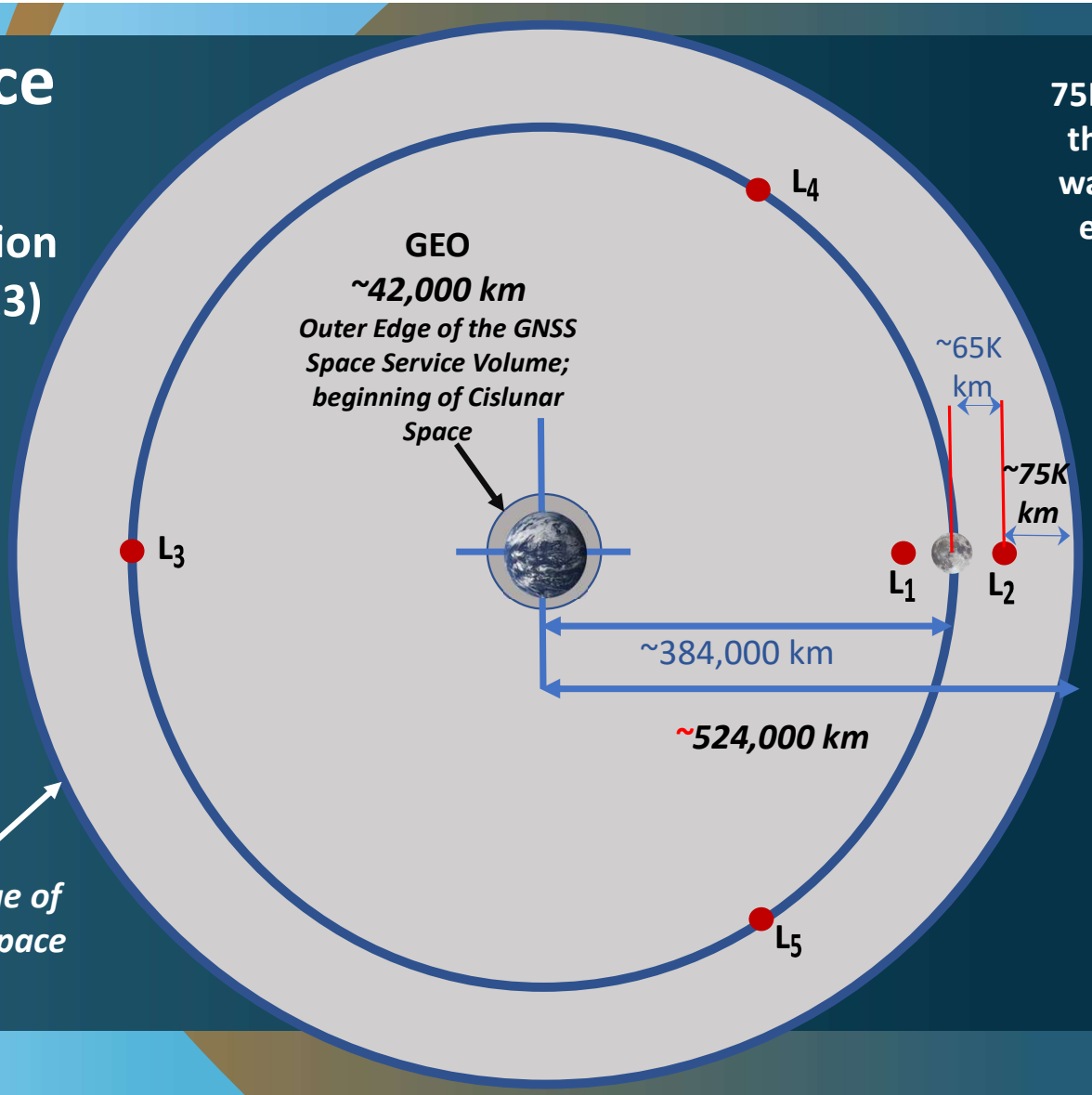
Rationale:

Encompasses users in Earth orbit beyond GEO, in lunar orbit, and within a 75,000 km radius surrounding each of the five Lagrange points, of which L1 and L2 are of particular interest.

This definition will be subject to change as use cases and mission types are better understood and as infrastructure evolves

Cislunar Space Depiction

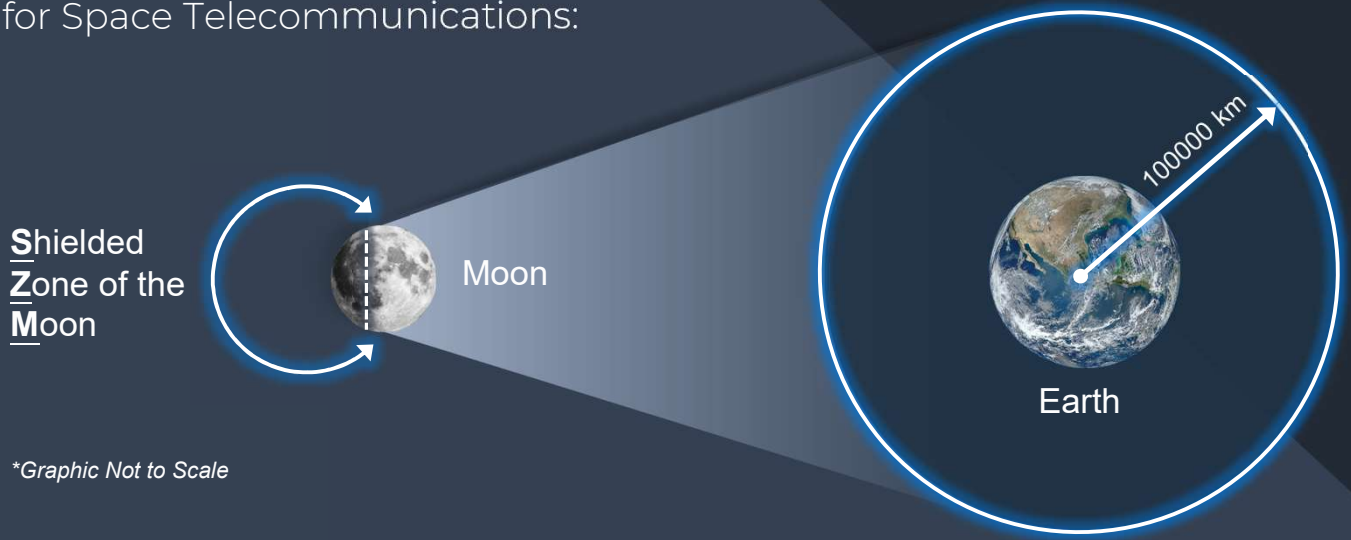
SUSG WP-4 Definition (September 7, 2023)



75K distance from E-M L2 to the edge of cislunar space was defined to support the expected scope of lunar PNT use cases

Shielded Zone of the Moon (SZM) Definition

- Protection of the Shielded Zone of the Moon (SZM) was a decision by the 1971 World Administrative Radio Conference for Space Telecommunications:



**Graphic Not to Scale*

- The SZM is isolated from radio emissions from the Earth as well as satellites orbiting the Earth, making this region a desirable location from which to make observations in a very low-noise environment, and in particular, to enable science in frequencies which observations are not possible from the Earth/Earth orbits.
- ITU Radio Regulations Article 22 protection extends to the entire radio spectrum; however, specific frequencies are permitted in support of space research data communications.

ICG-17 Proposed Recommendation: ICG-IOAG Joint Multilateral Cislunar PNT Workshop (Chart 1 of 3)

Issue Title: Joint ICG-IOAG organization of multilateral workshop on cislunar PNT

Background/Brief Description of the Issue:

USA, Europe, China, and Japan plan to deploy satellites in lunar orbits to provide real-time Positioning, Navigation and Timing (PNT) services for missions on the lunar surface, in low lunar orbits, and within the Earth-Moon L2 Lagrange point. According to tentative timelines outlined in presentations and papers, initial operational capabilities (IOCs) of some of these PNT services are being planned for around 2028. With these initial system developments underway, it is critically important for these systems to be interoperable, compatible and available with each other to maximize their utility for lunar space users.

LunaNet represents a US-led framework for the standardization of lunar PNT, communications and other services. The LunaNet framework is being documented in a standardization document called the LunaNet Interoperability Specification (LNIS). The LNIS is currently being developed by teams from Europe and the USA.

At the recent Interagency Operations Advisory Group (IOAG) IOP-5 meeting, held June 20th-22nd, 2023, the IOP adopted a plan for the IOAG and ICG to jointly organize a multilateral forum for the coordination of cislunar PNT systems. The next step is for the ICG to adopt this multilateral coordination plan via this recommendation.

ICG-17 Proposed Recommendation: ICG-IOAG Joint Multilateral Cislunar PNT Workshop (Chart 2 of 3)

Discussion/Analyses:

Some elements of various lunar PNT systems architectures have been discussed in the following international coordination groups: the ICG, the IOAG, CCSDS, the International Space Exploration Coordination Group (ISECG) and the Space Frequency Coordination Group (SFCG). But a full understanding of cislunar PNT development plans, specifications, planned reference frames and timing architectures, across international space agencies and commercial entities, is currently not known. To maximize interoperability, compatibility and availability of lunar PNT signals, a multilateral communication of cislunar PNT plans and developments—early and often—is crucial. Leveraging the outstanding GNSS coordination performed by the ICG, a similar international effort, through workshops and international delegates meetings, should be performed for Lunar PNT. This multilateral cislunar PNT coordination should be co-led by the ICG and the IOAG. To kickoff this coordination effort, a proposed ICG-IOAG multilateral workshop, called the multilateral cislunar PNT workshop, should be held in the mid-2024, after the completion of NASA, ESA and Japan sensitive service procurement activities of their respective lunar PNT systems. This workshop aims to encourage multinational participation, not only from LunaNet service providers, but also from other countries working on their respective lunar PNT systems. Therefore, this workshop will provide the first-ever multilateral discussion and coordination venue on lunar PNT domains.

ICG-17 Proposed Recommendation: ICG-IOAG Joint Multilateral Cislunar PNT Workshop (Chart 3 of 3)

Recommendation of Committee Action:

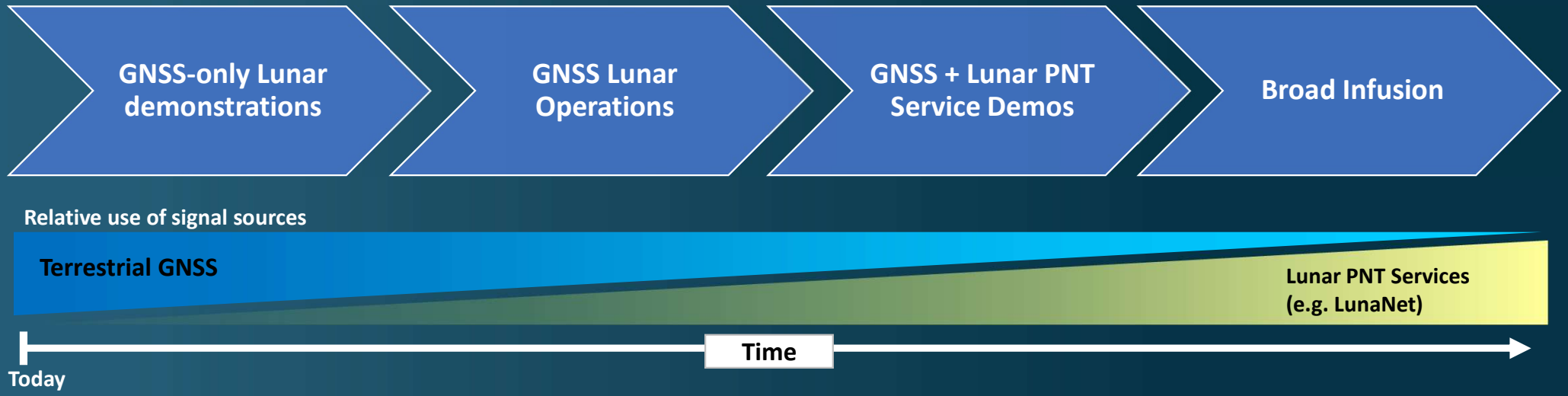
The ICG encourages the organization of a joint ICG-IOAG multilateral cislunar PNT workshop to be performed in the mid-2024 timeframe. The workshop shall: (1) serve as a mechanism to better understand the scope and depth of lunar PNT systems being developed, (2) propose architectural recommendations that may be taken up by international lunar PNT developers, and (3) facilitate refinement of interoperable, compatible, and available lunar PNT systems of the future. The workshop co-leaders shall also seek the collaboration of other international bodies such as the ISECG, CCSDS, and SFCG to strengthen the international coordination and standardization of lunar PNT systems. This recommendation represents a specific action from the more general recommendation approved at ICG-16 (ICG/REC/2022) entitled "Coordination of GNSS and Lunar PNT systems for lunar operations."

Thank You!

- Thanks to WG-B, SUSG and the WP4 team for outstanding teamwork and collaborative support over the past year
- WP-4 outcomes in 2022-2023 would not be possible without your collaboration and leadership

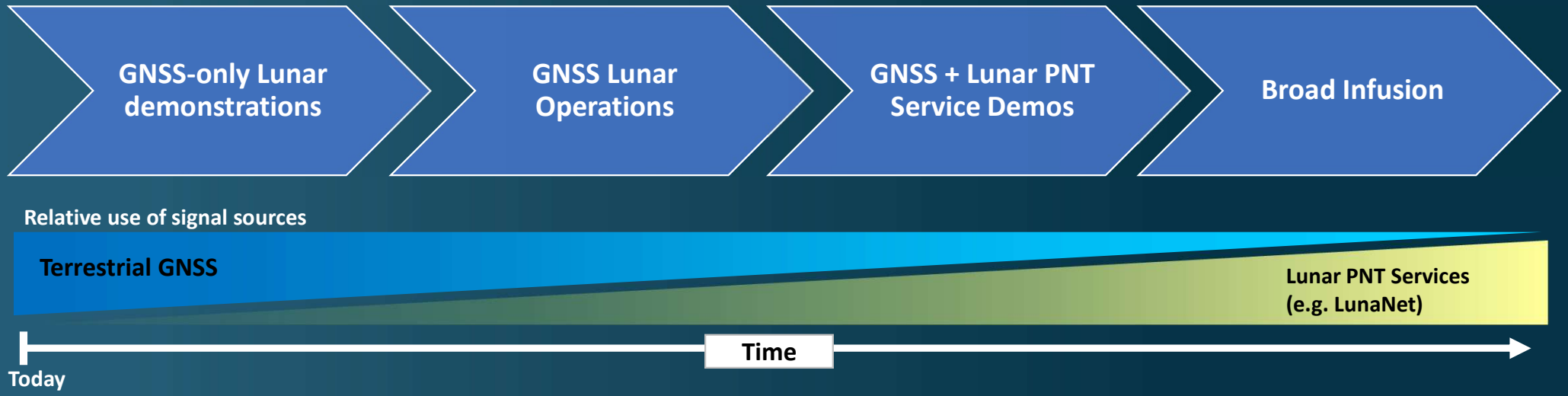
Backup

Phased Expansion of Lunar PNT



Transit use of GNSS and Lunar PNT Services

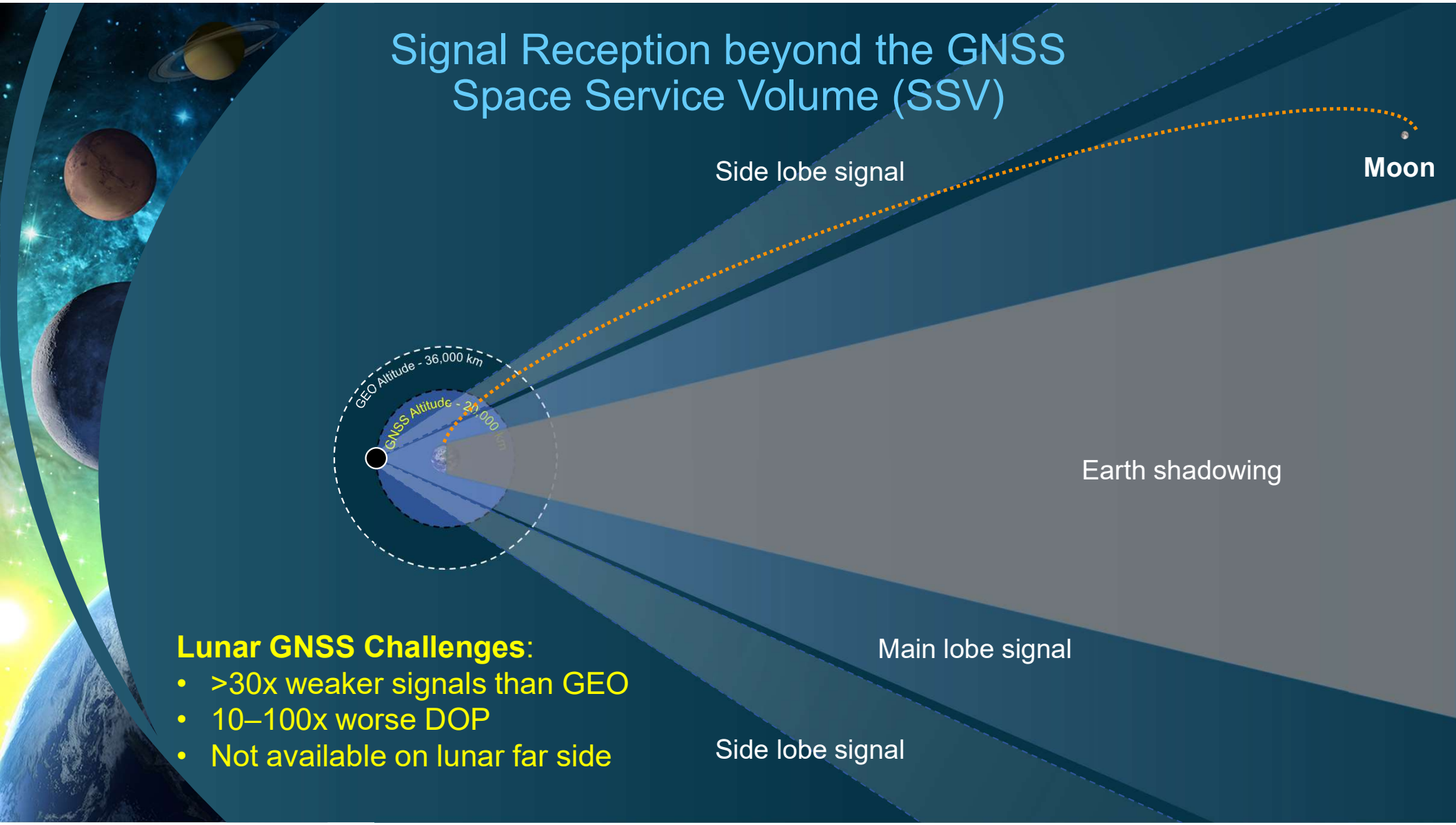
Phased Expansion of Lunar PNT



Transit use of GNSS and Lunar PNT Services

Combined use of GNSS and Lunar PNT will be crucial for Earth-Lunar Transit

Signal Reception beyond the GNSS Space Service Volume (SSV)



Lunar GNSS Challenges:

- >30x weaker signals than GEO
- 10–100x worse DOP
- Not available on lunar far side

2022-2023 WP-4 Workplan

Title	Objective	Proposed Approaches	Outcome
GNSS SSV and lunar PNT systems to support lunar operations	Work with GNSS providers and multilateral organizations, including the IOAG and SFCG, to ensure interoperability, compatibility, and availability of GNSS and lunar PNT systems that can be seamlessly employed together from the Earth to the Moon.	**a. Lunar PNT Frequency and Code Coordination**: Work with the Space Frequency Coordination Group (SFCG) to coordinate use of existing Earth-based GNSS L-band receive frequencies and transmit bands/frequencies and planned signal codes for proposed Lunar-based PNT systems, beacons and augmentations **b. Lunar Use Cases**: Collect international cislunar and lunar PNT use cases and develop initial set of user performance needs. **c. Lunar PNT Definitions**: Develop definitions that facilitate and clarify cislunar and lunar use of GNSS and other lunar PNT definitions, including an extension of the GNSS SSV concept. Coordinate definitions with multilateral organizations including the IOAG. **d. Lunar PNT Flight Experiments**: Encourage lunar flight experiments employing Earth-based GNSS and/or lunar PNT capabilities to gain an understanding of the performance and limitations of these systems; disseminate results and lessons learned **e. Lunar PNT Architectures**: Research, analyze and recommend PNT system architectures, employing Earth-based GNSS and Lunar PNT capabilities, that are interoperable, compatible, available and support current and future user needs; highly leverage already performed work **f. Lunar Reference Frame**: Work with international organizations to develop and coordinate international lunar reference frames	Full attainment of an interoperable, compatible, and available GNSS/lunar PNT system of systems that can support the world's ever-expanding human and robotic space operations in transit, around and on the surface of the moon.