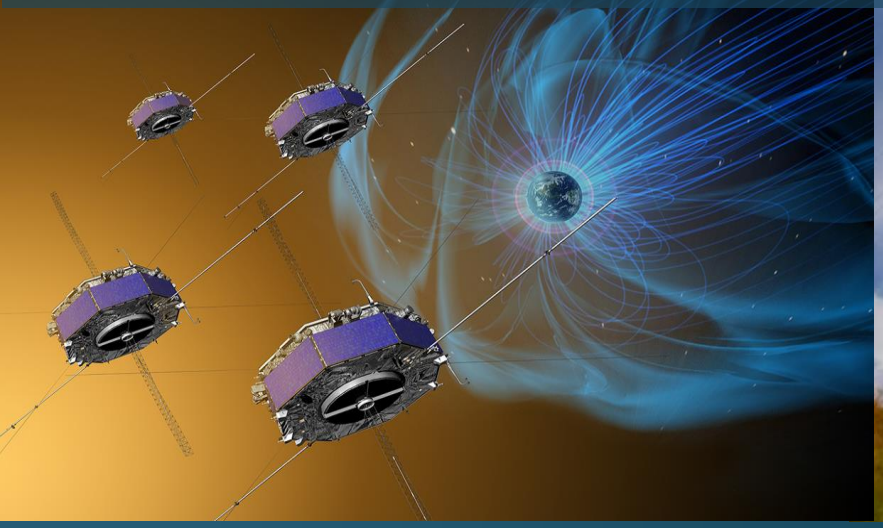
Lunar PNT Overview

Joel Parker, WG-B SUSG Co-Chair, NASA Goddard Space Flight Center

ICG-17 Plenary Session

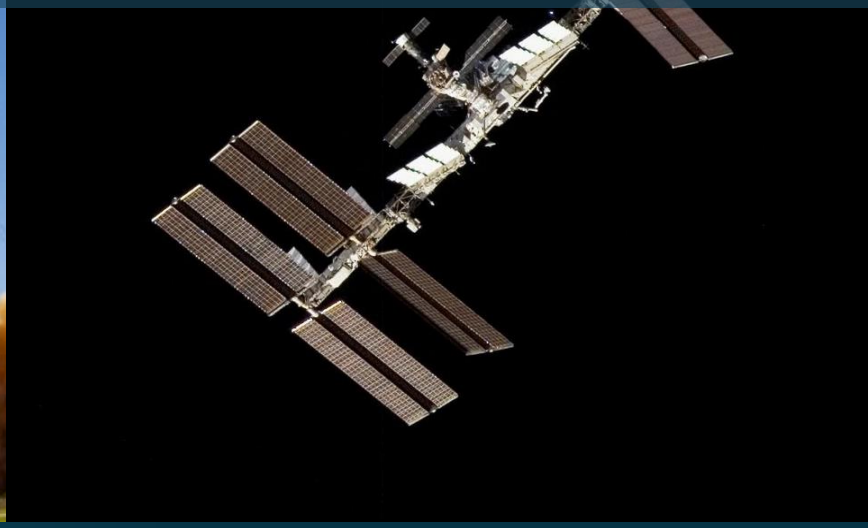
October 16, 2023

Active Space Uses of GNSS



Real-Time On-Board Nav

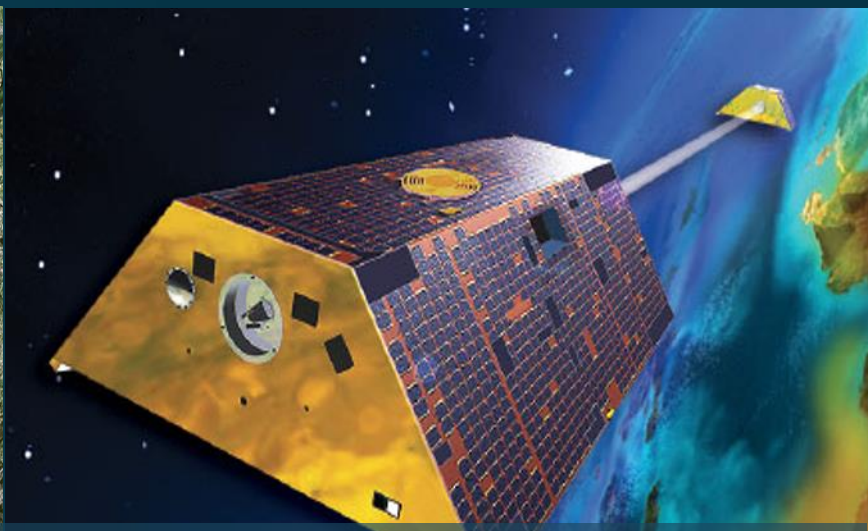
Launch Vehicle Range Ops



Attitude Determination

Time Synchronization

Earth Sciences

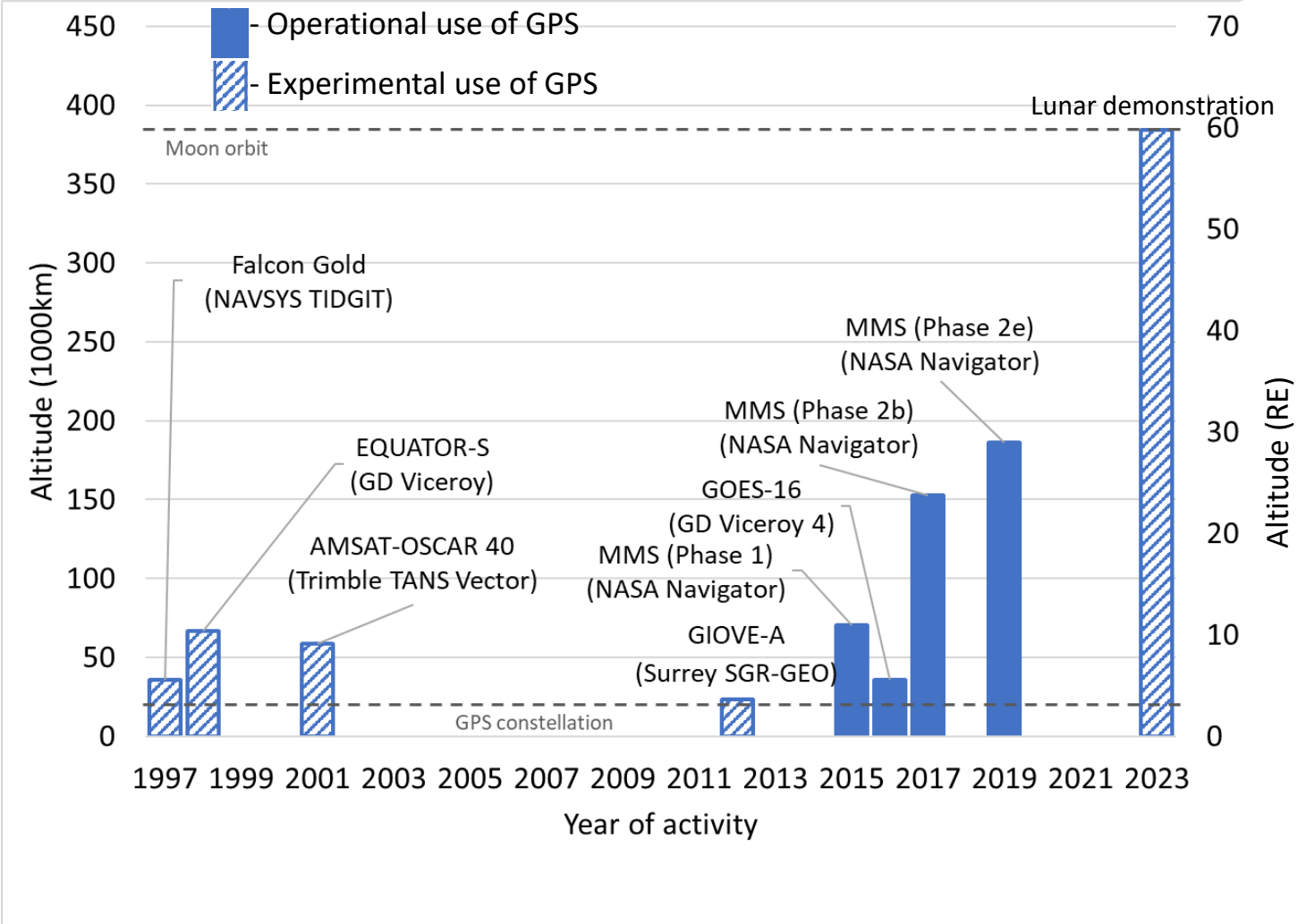


Precise Orbit Determination

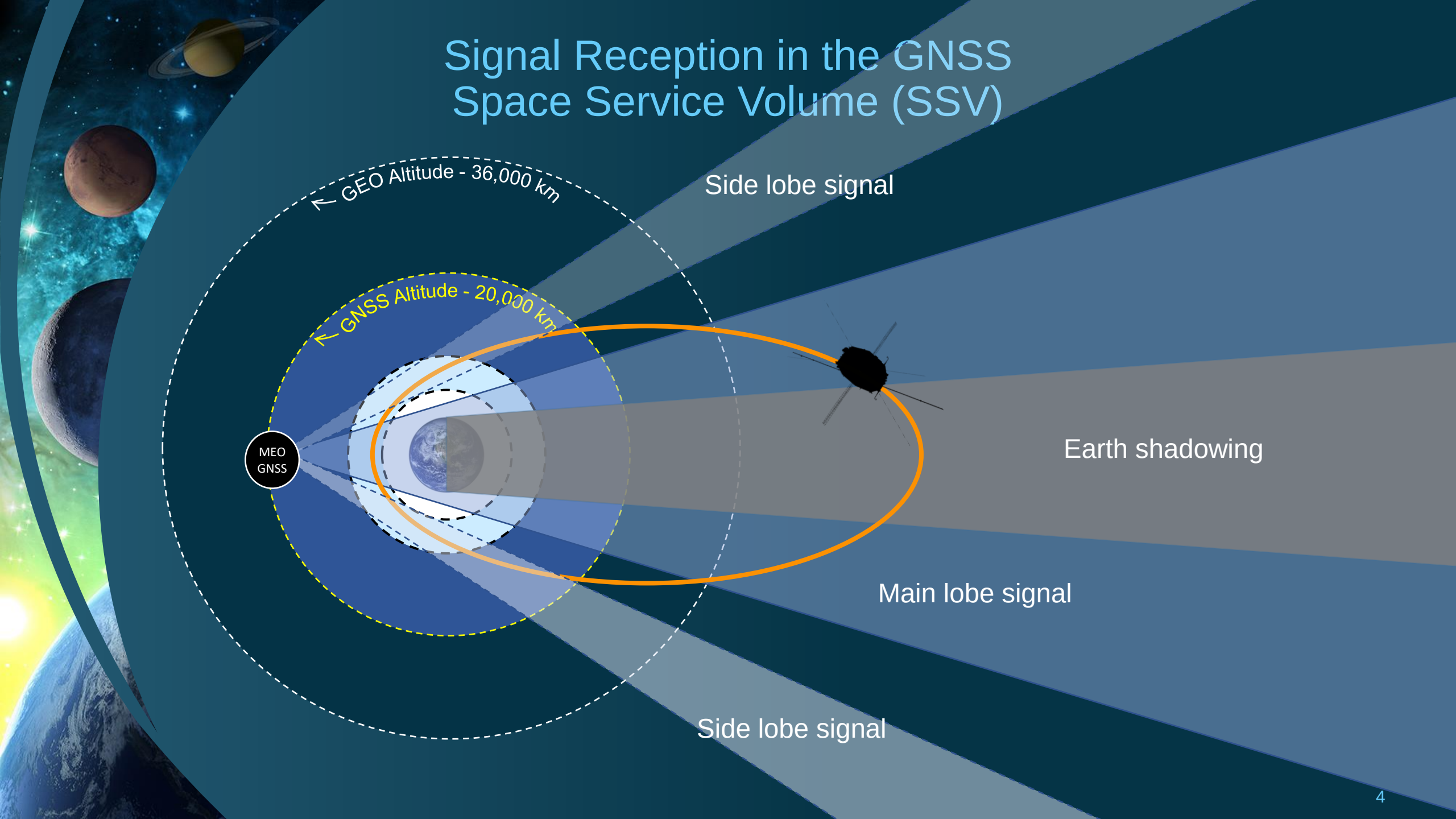
Development and Use of High Altitude GNSS

Transition from experimentation to operational use, and move into cislunar space:

- **1990s**: Early flight experiments—Equator-S, Falcon Gold
- **2000**: Reliable GPS at GEO w/ bent pipe architecture
- **2001**: AMSAT OSCAR-40 mapped GPS main and sidelobe signals
- **2015**: MMS employed GPS operationally at 76,000 km
- **2016–Present**: GOES-16/17/18 employs GPS operationally at GEO
- **2019**: MMS apogee raise to 50% lunar distance
- **2024 and beyond: Lunar demonstrations begin**



Signal Reception in the GNSS Space Service Volume (SSV)



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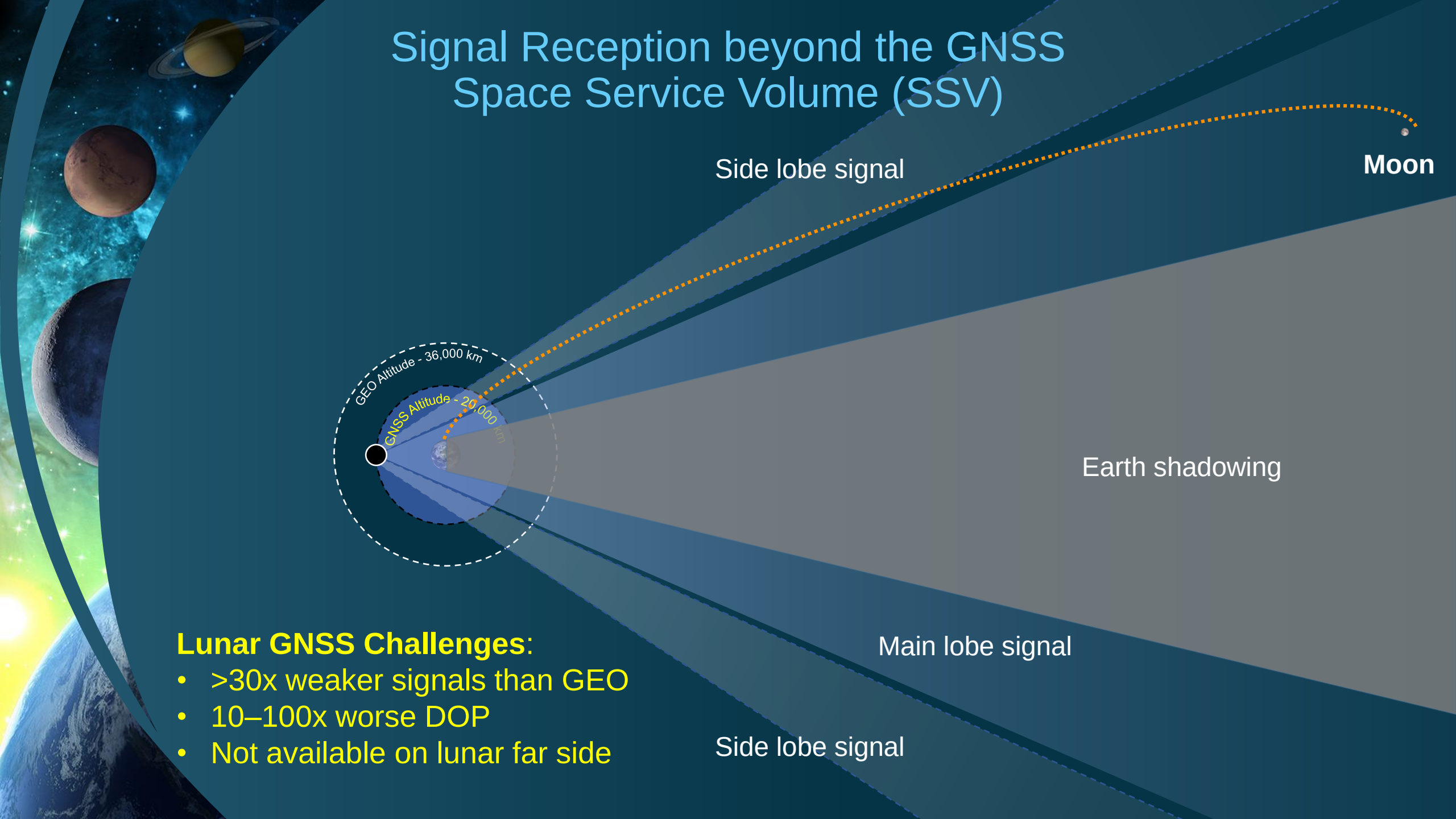


Lunar GNSS Challenges:

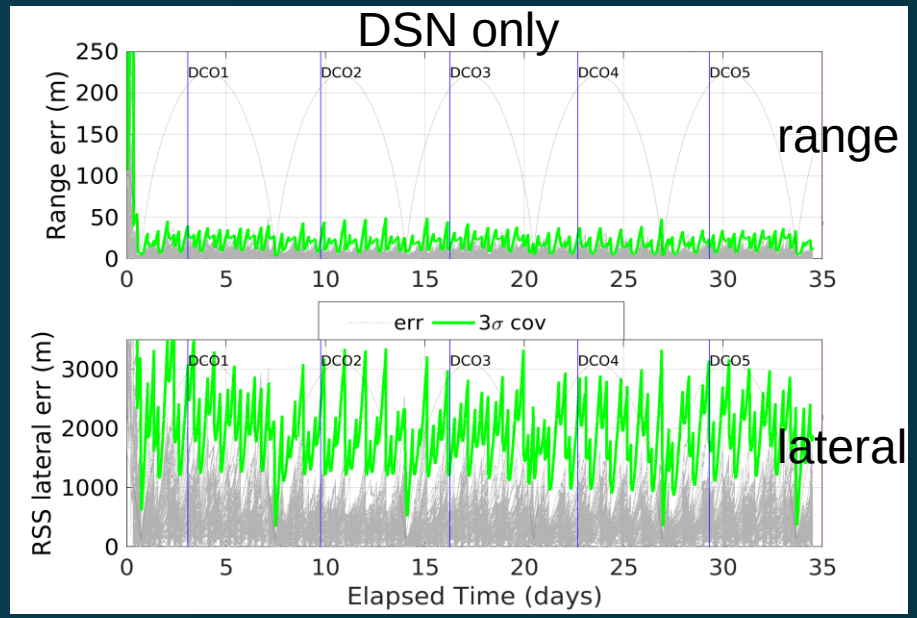
- >30x weaker signals than GEO
- 10–100x worse DOP
- Not available on lunar far side

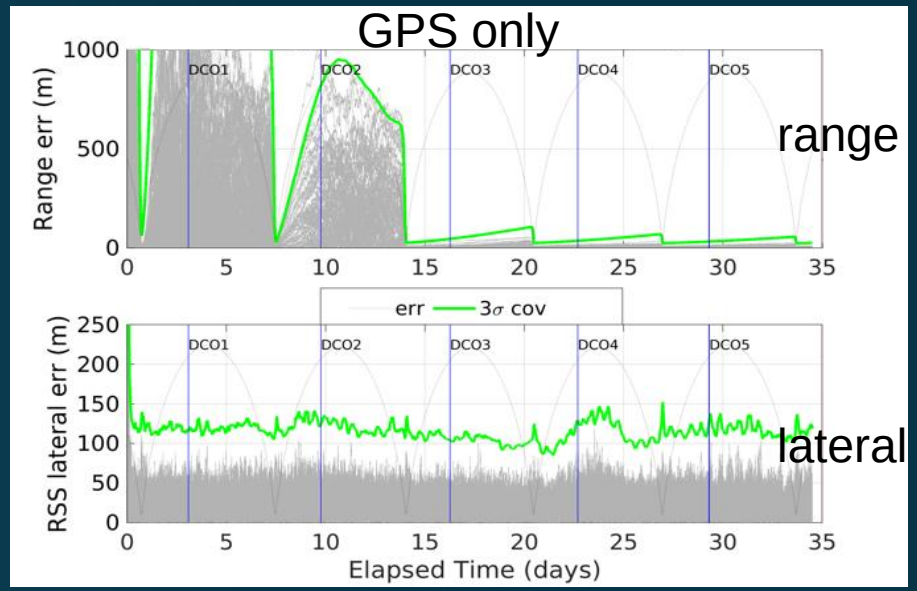
Lunar Gateway Study – Sep 2020
GPS Expected Performance

- Update to Feb 2019 preliminary study
- Position and velocity goals: 10 km and 10 cm/s, respectively
- Analyzed max OD error at the Data Cutoff (DCO) and at the final two perilunes and apolunes
- Observations:
  - GPS can provide greatly improved performance vs. DSN
  - GPS is real-time, on-board, without reliance on ground-based assets.

Max steady-state errors, crewed assumptions

	Case	DCO	Apolune	Perilune	All
Position [m]	**DSN**	1469.7	1326.4	319.8	2353.6
	GPS	**60.4**	**84.5**	**73.0**	**118.7**
	DSN+GPS	57.7	81.7	107.0	117.4



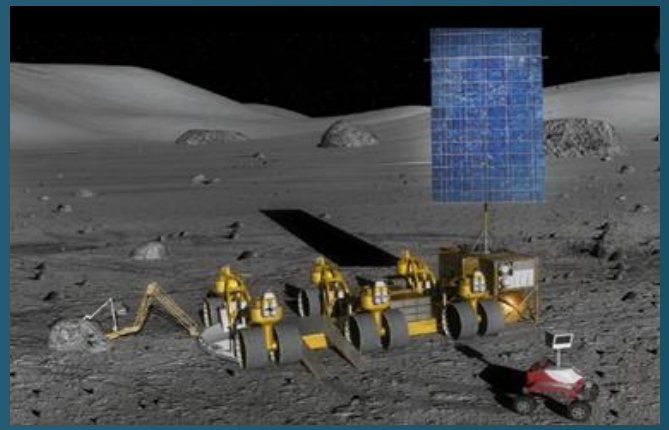


Ref: https://ntrs.nasa.gov/citations/20210014049

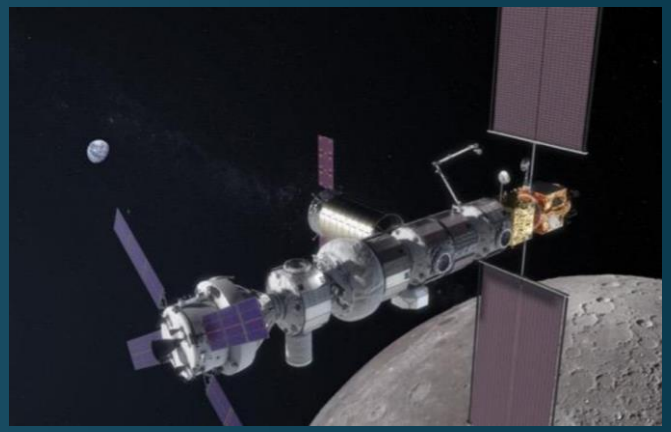
Lunar Exploration

- The Moon is now an international space exploration priority
- Current lunar exploration efforts more diverse and collaborative
  - >80 national space agencies
  - numerous private companies and partnerships
- 28 nations have signed the Artemis Accords to cooperate in the exploration and use of the Moon
- International Space Exploration Coordination Group (ISECG) currently comprised of 27 international space agencies
  - Global Exploration Roadmap (GER) identified 14 planned Moon missions
  - 100-m performance target for precision landing
- GNSS will play a meaningful role in Lunar PNT
- International space agencies are developing lunar PNT capabilities **now**; we need to ensure these are interoperable, compatible and available to all

Lunar Exploration: Roles for GNSS

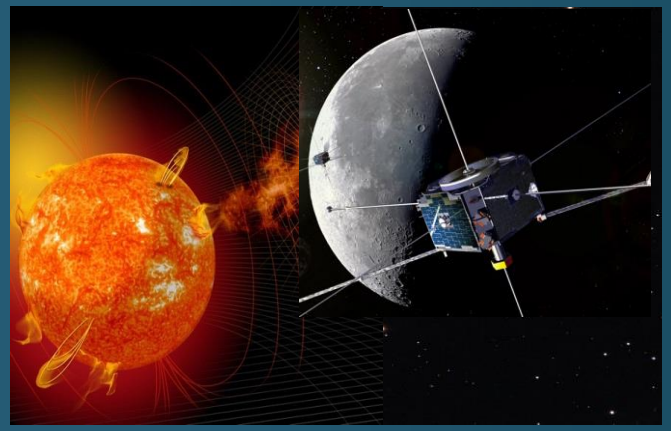


Lunar Surface Operations, Robotic Prospecting,& Human Exploration

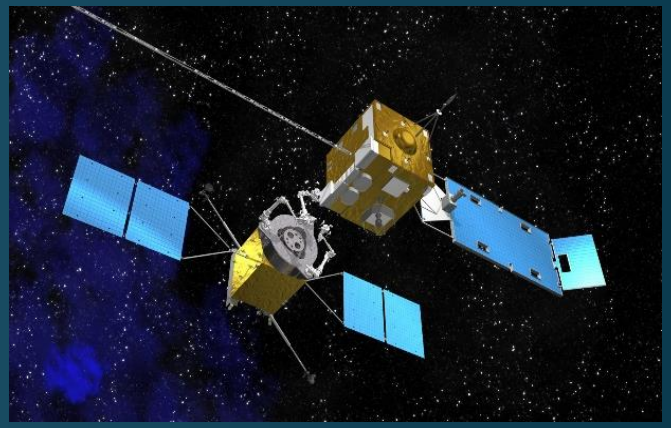


Human-tended Lunar Vicinity Vehicles (Gateway)

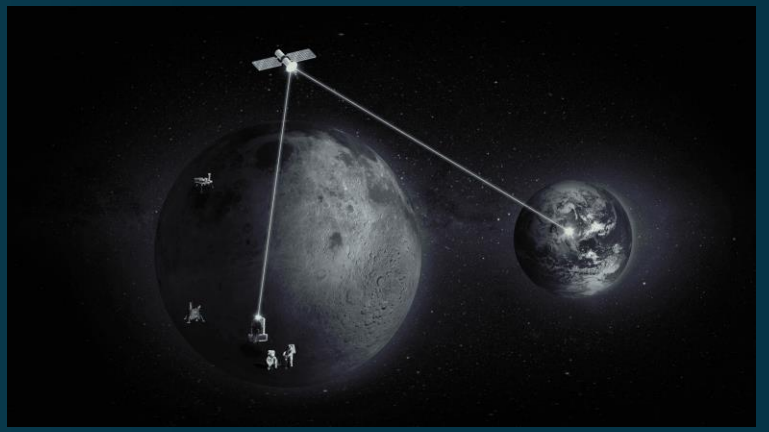
Robotic Lunar Orbiters, Resource & Science Sentinels



Earth, Astrophysics, & Solar Science Observations



Satellite Servicing



Lunar Exploration Infrastructure

Phased Expansion of Lunar PNT

GNSS-only Lunar demonstrations → GNSS Lunar Operations → GNSS + Lunar PNT Service Demos → Broad Infusion

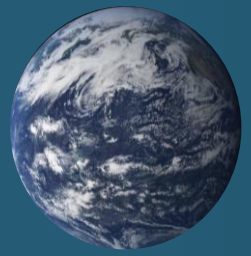
Relative use of signal sources

Terrestrial GNSS

Lunar PNT Services (e.g. LunaNet)

Today → Time

Transit use of GNSS and Lunar PNT Services



GNSS Use

Lunar PNT Use

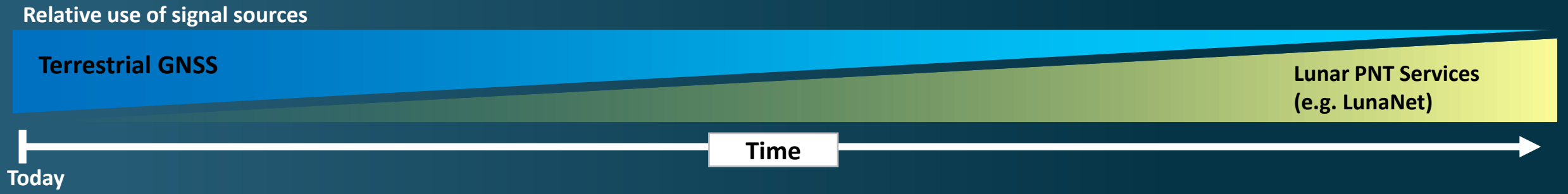
Lunar PNT Services (e.g. LunaNet)

Transit Distance

Use of GNSS and lunar PNT services are considered as a key part of the broader navigation ecosystem including ground-based on on-board sources.

Phased Expansion of Lunar PNT

GNSS-only Lunar demonstrations → GNSS Lunar Operations → GNSS + Lunar PNT Service Demos → Broad Infusion

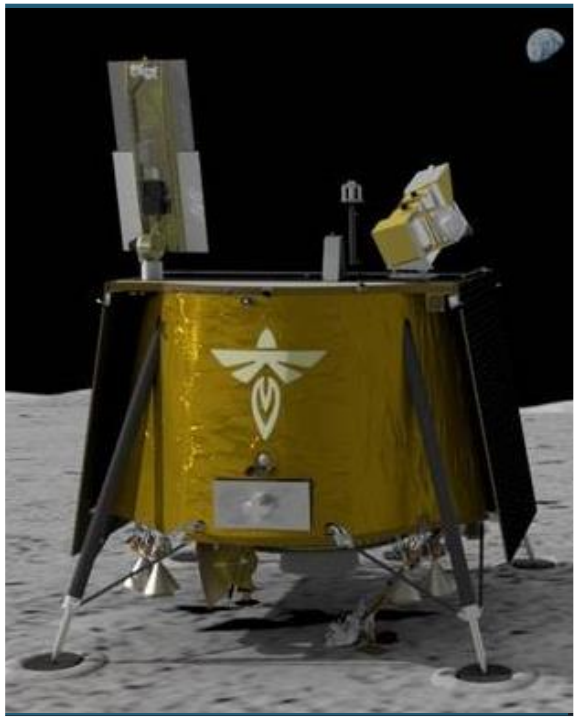


Transit use of GNSS and Lunar PNT Services

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

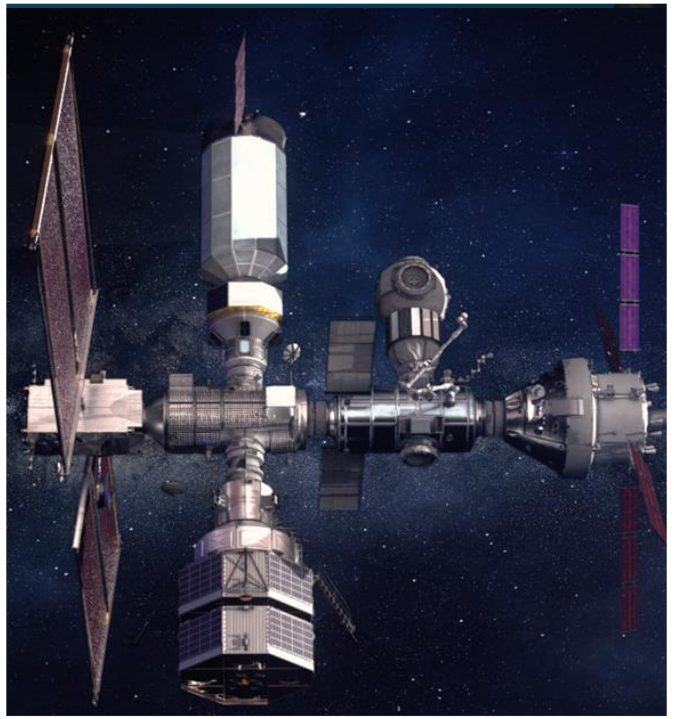
PNT Evolution: Demonstrations to Flight Operations

Selected Examples



LuGRE
(NASA 2024)

Lunar Pathfinder
(ESA 2026)



Gateway Payloads
(NASA, ESA & JAXA)

Lunar PNT Services
(International)

Relative use of signal sources

Terrestrial GNSS

Lunar PNT Services (e.g. LunaNet)

Today

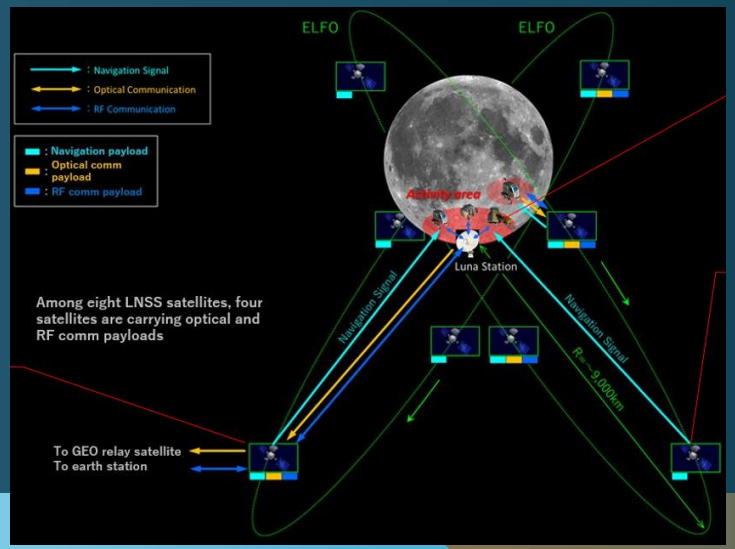
Time

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

NASA LCRNS

ESA Moonlight LCNS

JAXA LNSS



China Queqiao

Interoperable International Lunar Communications & Navigation Architecture: LunaNet

Networking Services
(Data Transmission)

Data transmitted to Earth in real time or aggregated and transmitted in store-and-forward mode

Data exchange among lunar users (avoid transfer to and from Earth)

Multiple relays used interchangeably, as needed

PNT Services
(Position, Navigation, Timing)

LunaNet nodes generate and exchange PNT information

Nodes can share PNT data to support and enhance their operations

Messages, Alerts, Radio/Optical Science

LunaNet nodes can host sensors and disseminate space weather alerts conjunction alerts and science measurements

Version 5 of the LunaNet Interoperability Specification is out for comment now (through end of Nov 2023):
https://www.nasa.gov/directorates/somd/space-communications-navigation-program/lunanet-interoperability-specification/

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

Augmented Forward Signal (AFS)

Augmented Forward Signal (AFS)

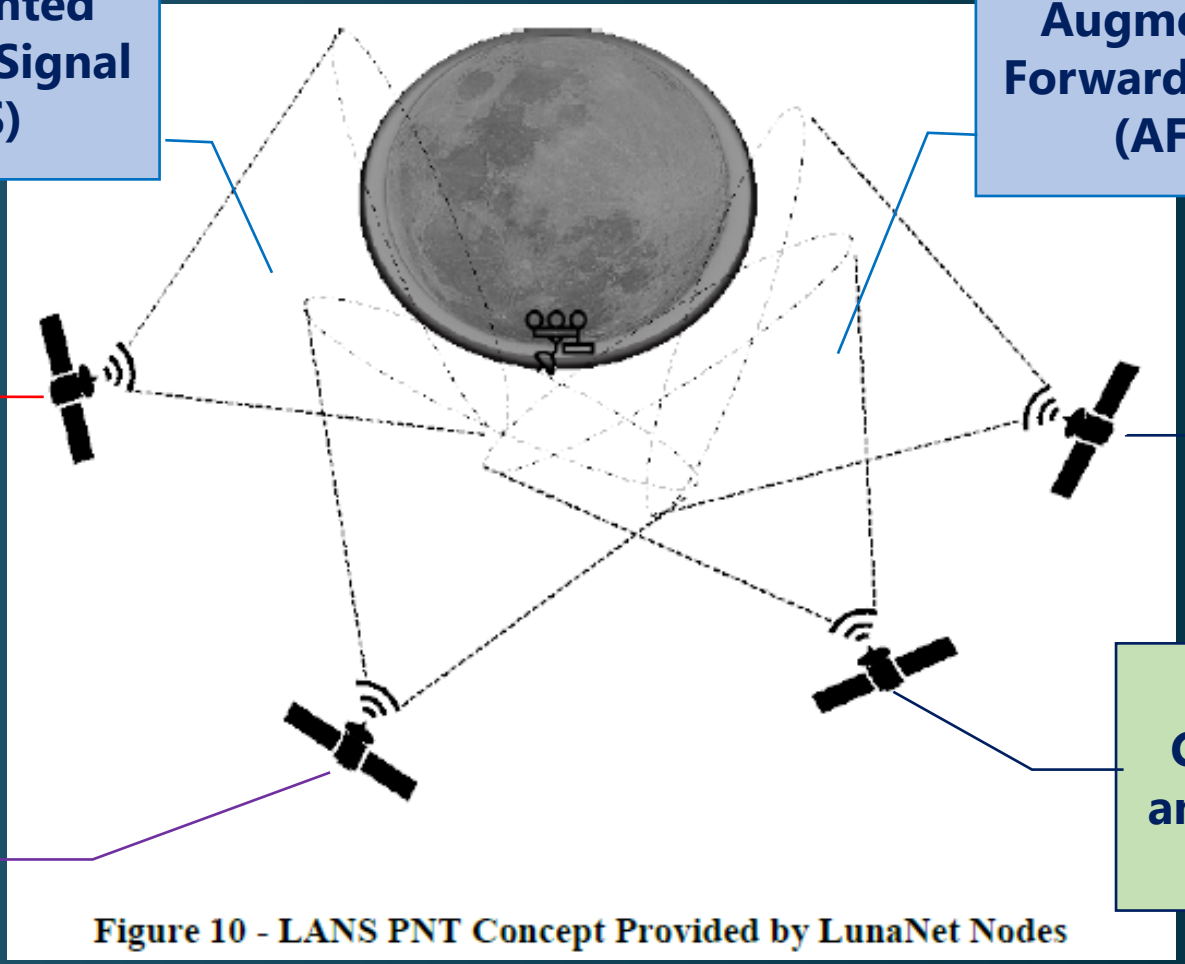


Figure 10 - LANS PNT Concept Provided by LunaNet Nodes

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

Summary of ICG Lunar PNT Activities

- WG-B Space Use Subgroup (SUSG) established Work Package 4 (WP-4) in 2021 with lunar focus.
  - 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
- ICG-16 (2022): Recommendation encouraging collaboration between Lunar PNT and GNSS teams
- ICG-17 (2023): Proposed recommendation to conduct a joint ICG-IOAG multilateral Workshop on Cislunar PNT

Necessary focus areas across ICG working groups

- Frequency coordination
- Time/reference frame coordination
- Performance enhancements by GNSS providers to support lunar users

Conclusions

- The Moon is the next frontier for in space use of GNSS and other PNT services
- All need to pursue multiple open, collaborative PNT capabilities to open-up cislunar space for government and commercial exploration and use
- The first lunar GNSS demonstrations, such as LuGRE and Lunar Pathfinder, are around the corner
- New lunar PNT architectures, like LCRNS, Moonlight, LNSS and Queqiao are being devised
- Teams, encompassing the ICG, IOAG, space agencies and GNSS service providers, are working to enhance the use of GNSS services in the lunar environment and to develop and expand lunar PNT capabilities that are **available** to all users and **interoperable and compatible** with all region-developed PNT systems