NASA PNT Priorities to the Moon and Beyond

Joel J. K. Parker, NASA Goddard Space Flight Center, on behalf of
James J. Miller, Deputy Director, Policy and Strategic Communications,
NASA Space Communications and Navigation (SCaN)

63rd Meeting of the CGSIC
September 12, 2023

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

FY 2024 President's Budget Request
Moon to Mars Manifest

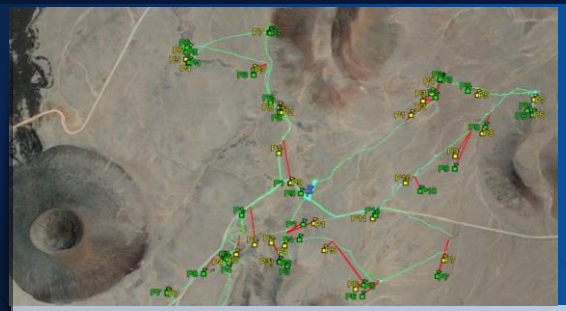
From HEO Committee of the NASA Advisory Council, May 15-16, 2023

CY	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
ESDMD	MISSION COMPLETE **Artemis I** (Nov. - Dec. 2022) Uncrewed Test Flight: SLS Block 1 / Orion / ML1 10 CubeSats Deployed		**Artemis II** (Nov. 2024) Crewed Test Flight SLS Block 1 / Orion / ML1 *HLS Uncrewed Lunar Demo*	**Artemis III** (Dec. 2025) Crewed Flight SLS Block 1 / Orion / ML1 HLS Crewed Lunar Demo xEVA Surface Suits *Gateway PPE/HALO Launch*	*Gateway PPE/HALO Arrival in NRHO*		**Artemis IV** (Sept. 2028) Crewed Flight SLS Block 1B / Orion / ML2 I-Hab to Gateway DSL to Gateway Sustaining HLS Crewed Lunar Demo xEVA Surface Suits *TBD Sustaining HLS Uncrewed Lunar Demo*	**Artemis V** (Sept. 2029) Crewed Flight SLS Block 1B / Orion / ML2 ESPRIT to Gateway DSL to Gateway Gateway External Robotics System TBD Sustaining HLS Crewed Lunar Demo xEVA Surface Suits LTV	**Artemis VI** (Sept. 2030) Crewed Flight SLS Block 1B / Orion / ML2 Airlock to Gateway DSL to Gateway TBD Sustaining HLS Services xEVA Surface Suits	**Artemis VII** (Sept. 2031) Crewed Flight SLS Block 1B / Orion / ML2 Gateway operations DSL to Gateway TBD Sustaining HLS Services xEVA Surface Suits Pressurized Rover
SOMD	DSN Upgrades (DLEU) **Completed** DSS-26 [Goldstone]	**Completed** DSS-36 [Canberra]	DSS-24 [Goldstone] DSS-56 [Madrid]	DSS-34 [Canberra] Lunar Communications Relay and Navigation Services (LCRNS) Increment Alpha	DLEU Overall Completion DSS-54 [Madrid]	Lunar Exploration Ground Sites 1-3 Increment Beta	Increment Charlie	Ongoing Science, Human Research Program, and Technology Development in LEO (ISS transition to CLD)		
SMD CLPS Flights Outlined	LRO Mars 2020:	TO 2-AB TO 2-IM	ESCAPADE TO 20A: VIPER TO 19D TO CP-11:	Artemis III Surface Science Instruments HERMES ready for integration ESA Lunar Pathfinder delivered for launch TO CP-12 TO CS-3	LRO continued ops TO CP-21 TO CP-22 TO CP-31	Mars Sample Return (MSR): Earth-Return Orbiter (ESA) TO CP-32 TO CP-41	Artemis IV Surface Science Instruments MSR Lander: Sample Retrieval Lander; Mars Ascent Vehicle TO CP-42 TO CP-51	Artemis V Surface Science Instruments Artemis LTV Science Instruments TO CP-52 TO CP-61 TO CP-62	Artemis VI Surface Science Instruments MSR: Mars Ascent Vehicle launch Mars 2020 Sample Delivery	Artemis VII Surface Science Instruments
STMD	MOXIE; MEDA LAUNCHED CAPSTONE LAUNCHED LOFTID	TO PRIME-1: Lunar Trailblazer; PRIME-1 Drill; Nokia LTE/4G Comm; IM Deployable Hopper CFM SpaceX TP Flight Demo	Surface Robotic Scouts (CADRE) Preliminary DRACO NTP Engine Design NEP Concept Vehicle Design PPE SEP qual. environ. complete CFM Eta Space TP Flight Demo	CFM Lockheed Martin TP Flight Demo CFM ULA TP Flight Demo	PSI Mini-Suite	TO CT-1: Lunar Surface Power Demo (i.e. RFC, VSAT, Wireless Charging); Lunar Surface Scaled Construction Demo 1; ISRU Pilot Excavator; ISRU Subscale Demo		SEP qual. complete	TO CT-2: Lunar Surface Scaled Construction Demo 2; Autonomous Robotics Demo; Deployable Hopper 2; ISRU Subscale Demo 2 Fission Surface Power demo delivered for launch	

Icons are representative only, and may not reflect final configurations, not to scale | Icons represent the calendar year in which an event occurs | Based on FY 2024 President's budget request

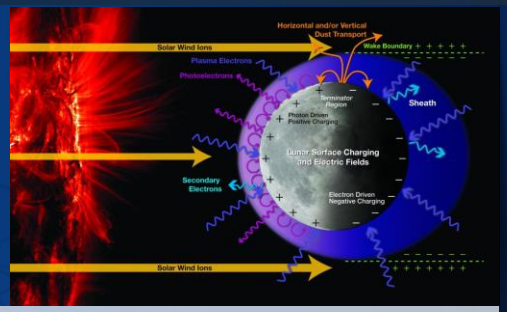
20230308

Lunar PNT **Challenges**



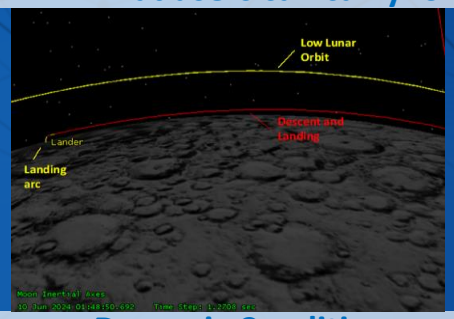
Orienteering Accuracy

Power / Mass / Volume – Constrain what users can carry for nav



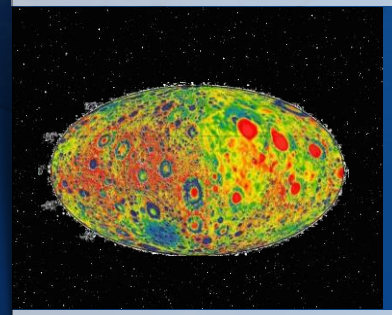
Surface Environment

Reference Time



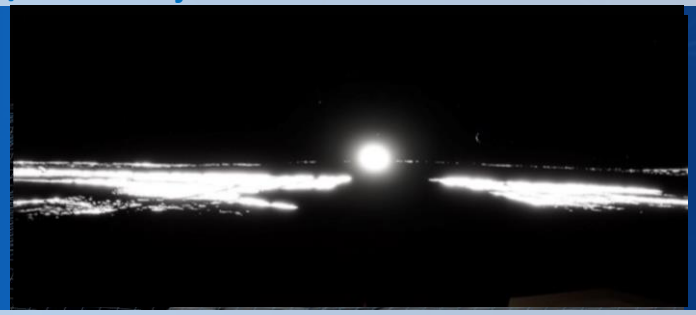
Dynamic Conditions – descent/ascent trajectories

Data/Sensor Fusion



Reference Geodetics

Interference



Stark Lighting – difficult for traditional cameras

Earth Occultation – limits Earth-based tracking

Fault tolerant autonomous systems providing PVT knowledge + situational awareness will be needed

Phased Expansion of Lunar PNT

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

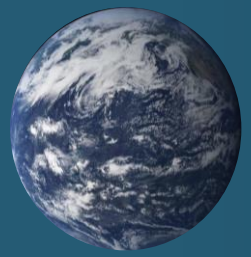
Relative use of signal sources

Terrestrial GNSS

Lunar PNT Services (e.g. LunaNet)

Today — Time

Transit use of GNSS and Lunar PNT Services



GNSS Use

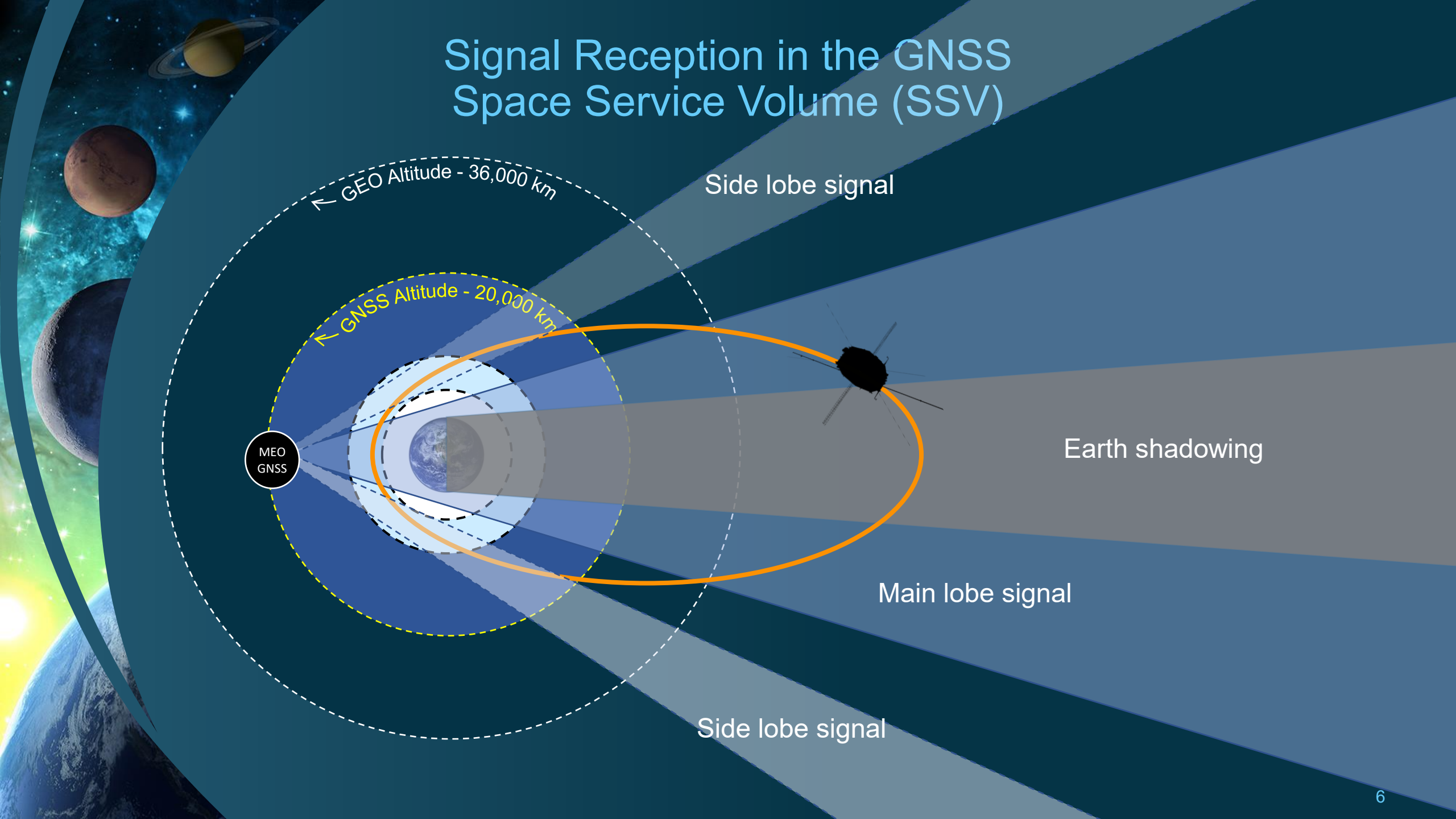
Lunar PNT Use

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.

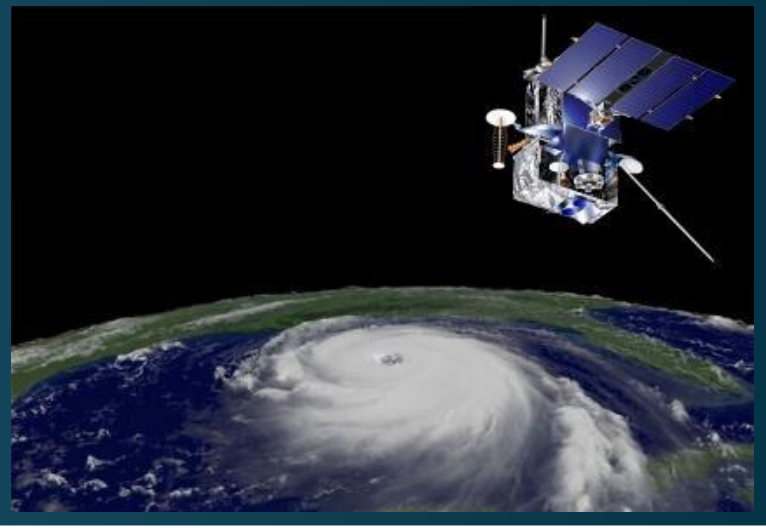
Signal Reception in the GNSS Space Service Volume (SSV)



Operational U.S. Missions Using GPS in the Space Service Volume & Beyond

GOES-R Weather Satellite Series:

- Next-generation U.S. operational GEO weather satellite series
- First series to use GPS for primary navigation
- GPS provides rapid maneuver recovery, enabling continual observation with <2 hour outage per year
- Introduction of GPS and new imaging instrument are **game-changers to humanity, delivering data products to substantially improve public and property safety**



GOES-16 GPS Visibility:

- Minimum SVs visible: 7
- DOP: 5–15

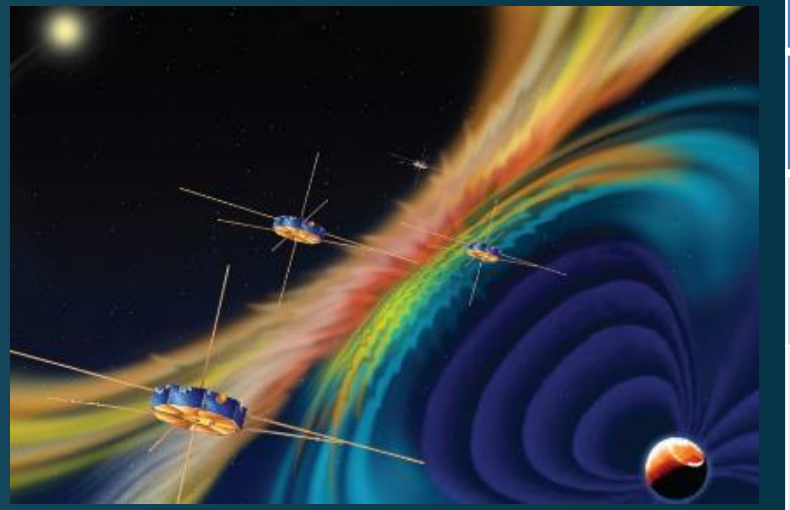
GOES-16 Nav Performance (3σ):

- Radial: **14.1 m**
- In-track: **7.4 m**
- Cross-track: **5.1 m**

- Compare to requirement: (100, 75, 75) m

Magnetospheric Multi-Scale (MMS) Mission:

- Four spacecraft form a tetrahedron near apogee for magnetospheric science measurements (space weather)
- Highest-ever use of GPS
  - Phase I: 12 Earth Radii (RE) apogee (76,000 km)
  - Phase 2B: 25 RE apogee (~150,000 km) **(40% lunar distance)**
  - Apogee raising beyond 29 RE **(50% lunar distance)** completed in 2019
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping



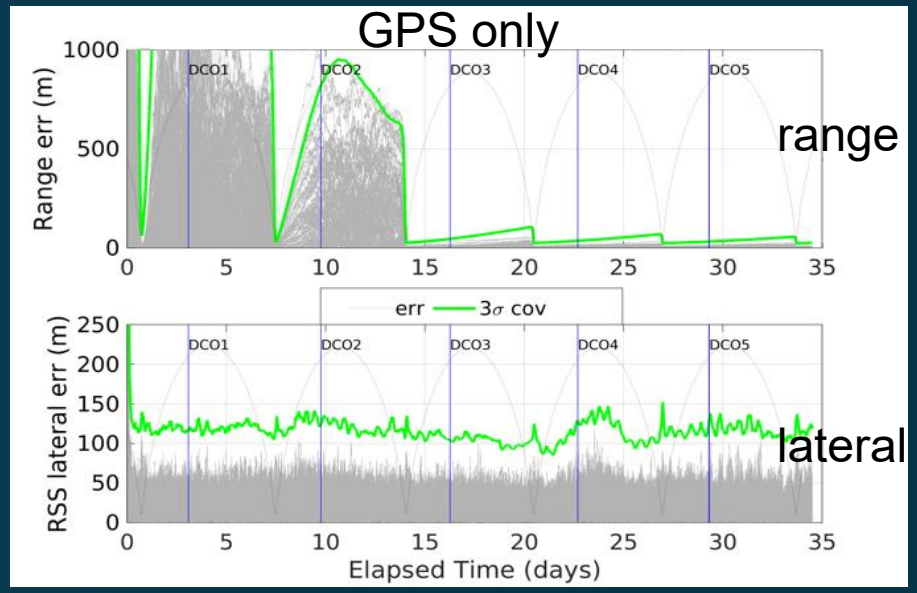
MMS Nav Performance (1σ)		
Description	**Phase 1**	**Phase 2B**
Semi-major axis est. under 3 R_E (99%)	2 m	**5 m**
Orbit position estimation (99%)	12 m	**55 m**

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

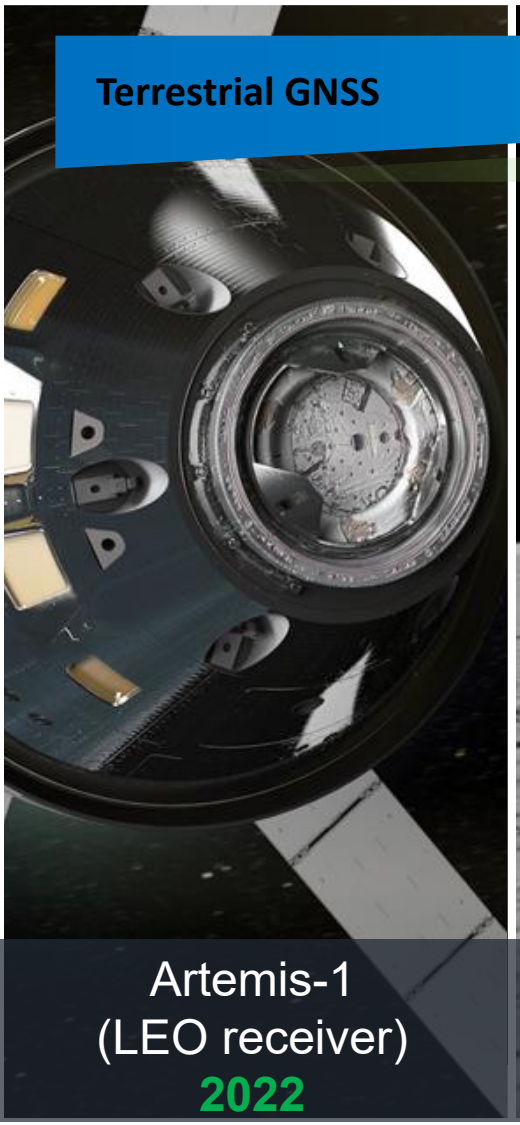
	Case	DCO	Apolune	Perilune	All
Position [m]	**DSN**	1469.7	1326.4	319.8	2353.6
	GPS	**60.4**	**84.5**	**73.0**	**118.7**
	DSN+GPS	57.7	81.7	107.0	117.4



Evolutionary Milestones in Lunar PNT

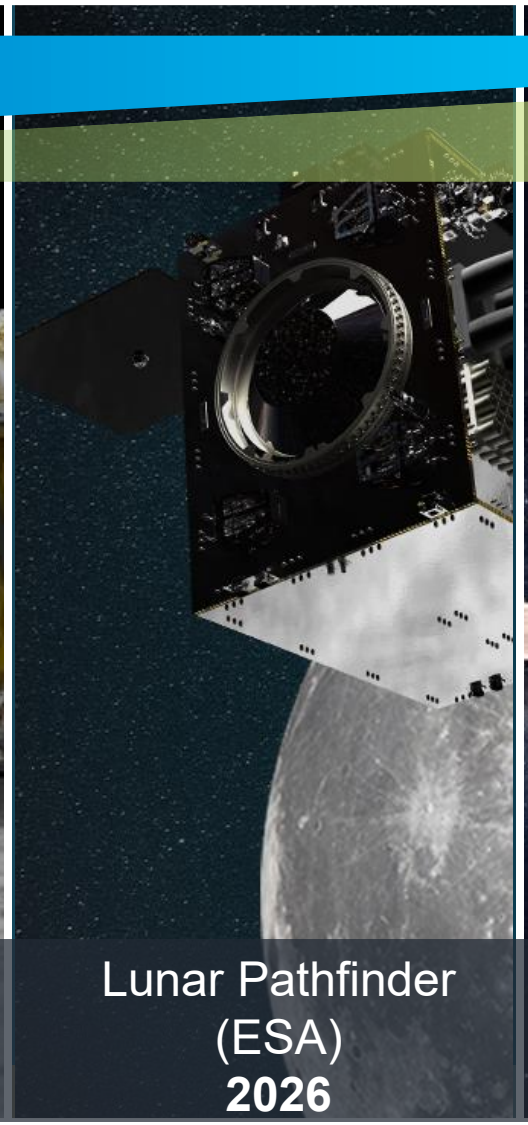
Terrestrial GNSS

Lunar PNT Services (e.g. LunaNet)



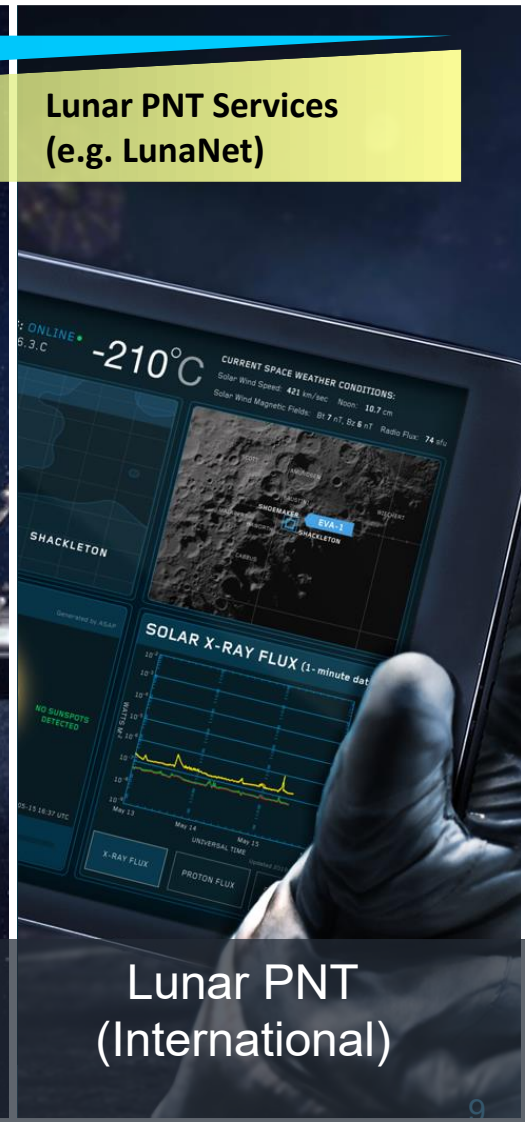
Artemis-1
(LEO receiver)
2022

LuGRE
(NASA)
2024



Lunar Pathfinder
(ESA)
2026

Gateway
(International)



Lunar PNT
(International)

Early Lunar Communications and Navigation Architecture Concept

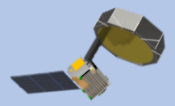
Gateway

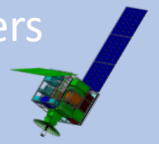
Additional relay capability

Orbital Relays

LINKING LUNAR USERS TO EARTH & TO EACH OTHER

Diverse, evolving constellation with multiple users and providers





LunaNet

Framework of standards for open, interoperable networks - Data, PNT & other services

Earth Stations

Upgraded DSN and other assets including commercial stations

Orbiting Spacecraft Users

SOUTH POLE

Artemis surface missions

Far Side missions

Other robotic missions

Surface communications and navigation assets

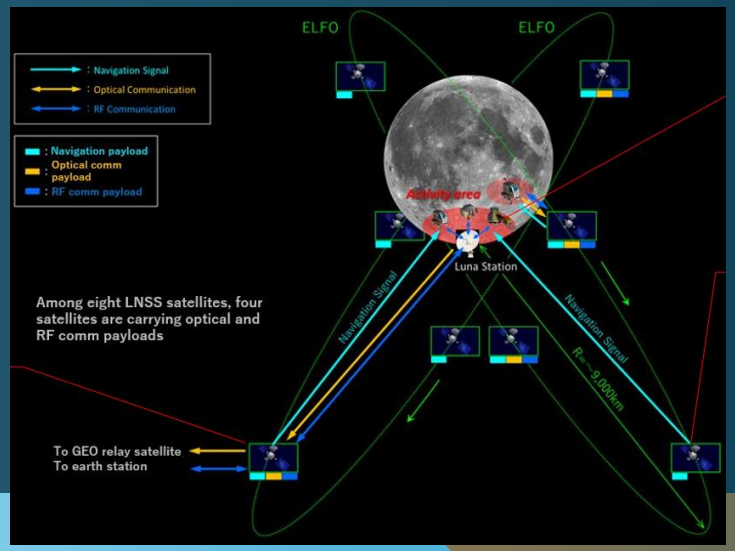
Communication and navigation infrastructure lowers the barriers to entry for new missions and capabilities and supports expanding robotic and human activities on the Moon.

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 Service (LANS)

Augmented Forward Signal (AFS)

Augmented Forward Signal (AFS)

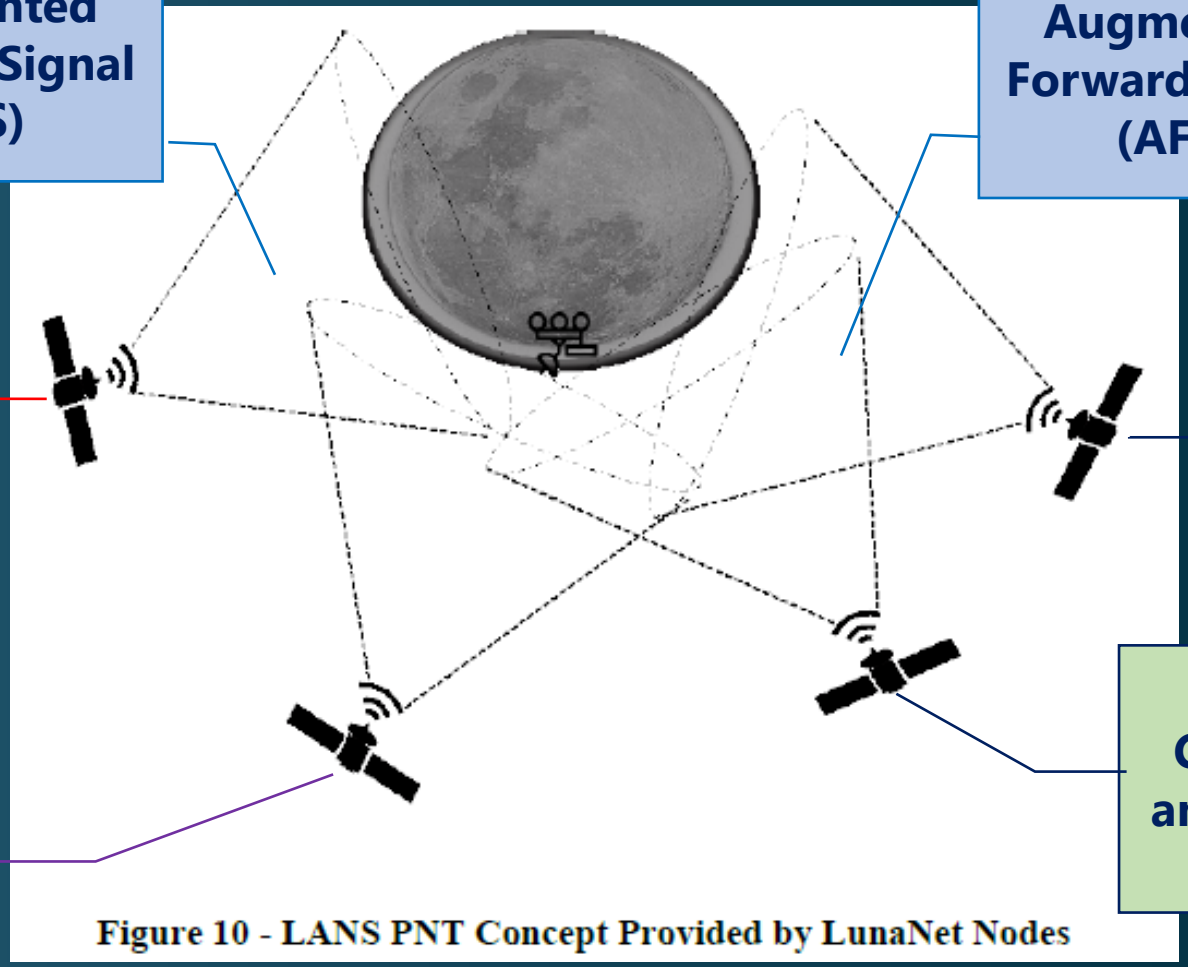


Figure 10 - LANS PNT Concept Provided by LunaNet Nodes

JAXA LNSS (Lunar Navigation Satellite System) satellite

ESA Moonlight LCNS (Lunar Communications and Navigation Services) satellite

NASA LCRNS (Lunar Communications Relay and Navigation Systems) satellites

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

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

Enabling Lunar PNT:
GPS Initiatives

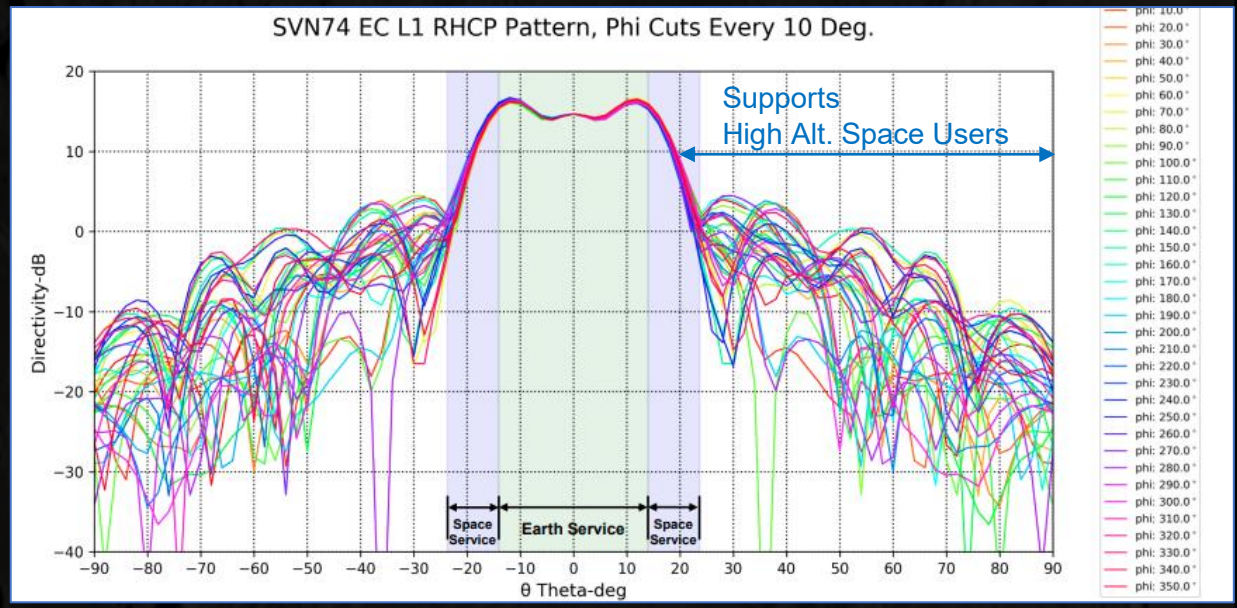
Background

- Knowledge of GNSS transmit antenna patterns is critical to support high-accuracy applications & use of GNSS signals within the Space Service Volume (SSV) and beyond into Cislunar Space

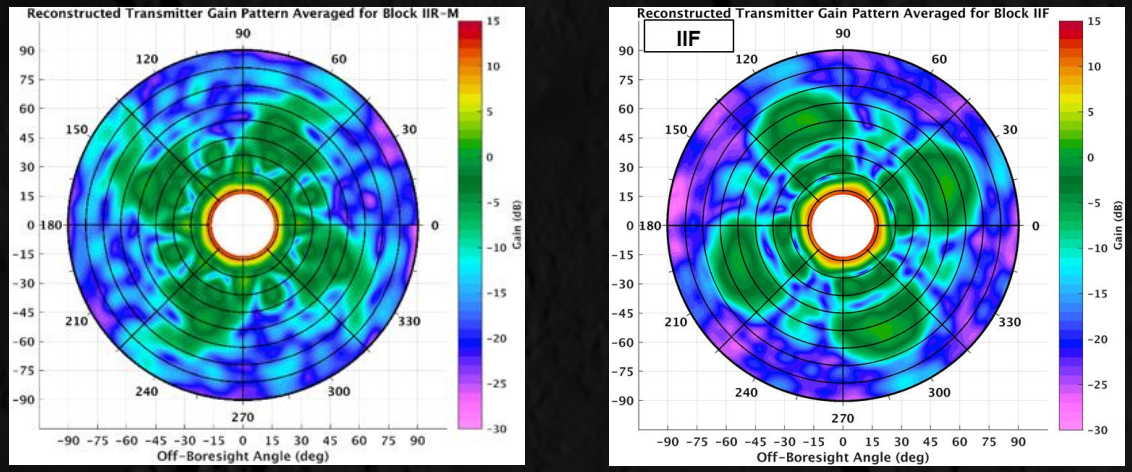
GPS data availability

- 2001: AO-40 initial gain pattern measurements
- 2015: Initial IIR/IIR-M antenna gain pattern data release
- 2018: GPS ACE flight-measured patterns released by NASA
- 2020: IIR/IIR-M antenna gain pattern data (re-release)
- 2022: Public release of GPS III antenna gain patterns
- 2023: Public release of GPS-IIF antenna gain patterns
- **The antenna patterns of all active GPS satellites are now available at the NAVCEN GPS portal:**

  https://www.navcen.uscg.gov/gps-technical-references



GPS Block III, SVN-74
L1 Antenna Pattern



NASA GPS ACE Reconstructed Patterns for Block IIR-M (left) and IIF (right)
Source: https://doi.org/10.1002/navi.361

National Space Council (NSpC) Users' Advisory Group (UAG)

Authority

- The NSpC is authorized under *Title V of Public Law 100-685*, to advise / assist President on national space policy & strategy
- UAG required by *Executive Order 14056 on the NSpC (dated 1 Dec 2021),* and governed by *Federal Advisory Committee Act (FACA), Public Law 92-463, as amended (5 U.S.C. App 2)*

Organization

- Reports to the Vice President's Office. The VP is also Chair of the NSpC
- Managed by SCaN since 2019. Charter signed Dec. 3, 2021, by NASA Administrator.
- Six public meetings held-to-date, where the UAG deliberates on findings / recommendations

Activities

- Gen Lester Lyles (USAF, ret.) appointed Chair on Sep. 8, 2022
- Board members for 2023-2025 term appointed/ reappointed on Jan. 26, 2023
- First public meeting under Biden-Harris Admin held Feb. 23, 2023, in D.C., followed by meeting with VP Harris at White House
- Next public meeting planned on Oct. 6.

Established in 2017 to ensure that the interests of industry, non-federal entities, & persons involved in aeronautical & space activities are represented at the National Space Council

https://www.nasa.gov/content/national-space-council-users-advisory-group

National Space-Based **PNT Advisory Board**

Organization

- Established under presidential authority & operates per FACA provisions
- Provides independent technical and policy counsel to PNT EXCOM
- Members nominated by EXCOM depts/agencies, approved by EXCOM Co-Chairs, and appointed by NASA Administrator
- Charter allows establishment of ad-hoc task forces & subcommittees
- Managed by SCaN since 2007 & currently chaired by ADM Thad Allen (USCG, ret.)

Recent Activities

- 27th session held Nov. 16-17, 2022, in Redondo Beach, CA
- Chair Recommendations Memo submitted to EXCOM Co-Chairs on Jan 27, 2023
- Charter renewed by NASA Administrator on Apr. 25, 2023
- 28th session held May 3-4, 2023, in Annapolis, MD

Upcoming

- **29th session to be held Dec. 6-7, 2023, in Houston, TX**

Established in 2007 to provide independent counsel to the National Space-Based PNT EXCOM
https://www.gps.gov/governance/advisory/

International Committee on GNSS (ICG) Space Use Subgroup (SUSG) Work Package 4: GNSS SSV and lunar PNT systems to support lunar operations

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.

Conclusions

- The Moon is the next frontier for in space use of GNSS and other PNT services.
- The first lunar GNSS demonstrations, such as LuGRE and Lunar Pathfinder, are around the corner.
- New lunar PNT architectures, like LunaNet, 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.
- Technical and policy coordination is essential to develop an efficient robust lunar PNT architecture.