National Aeronautics and Space Administration

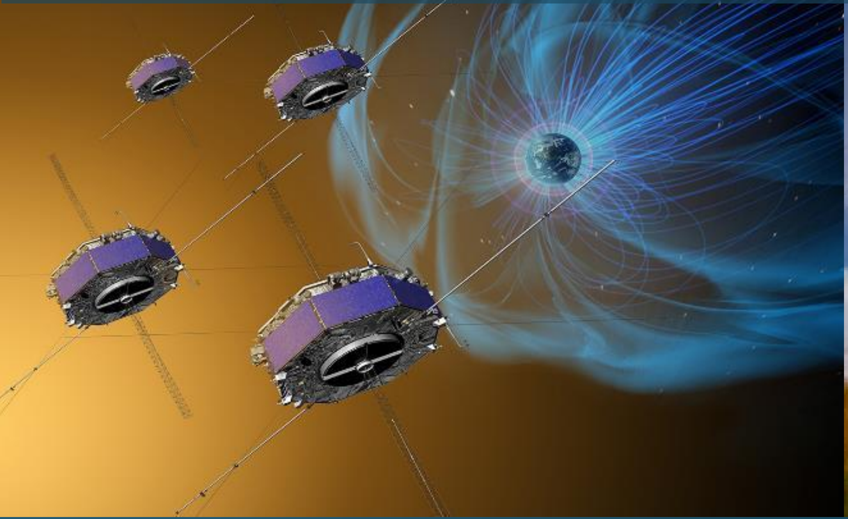
Lunar GNSS Utilization: From Vision to Reality

NASA PNT Update

Mr. Joel J. K. Parker, PNT Policy Lead
NASA Goddard Space Flight Center

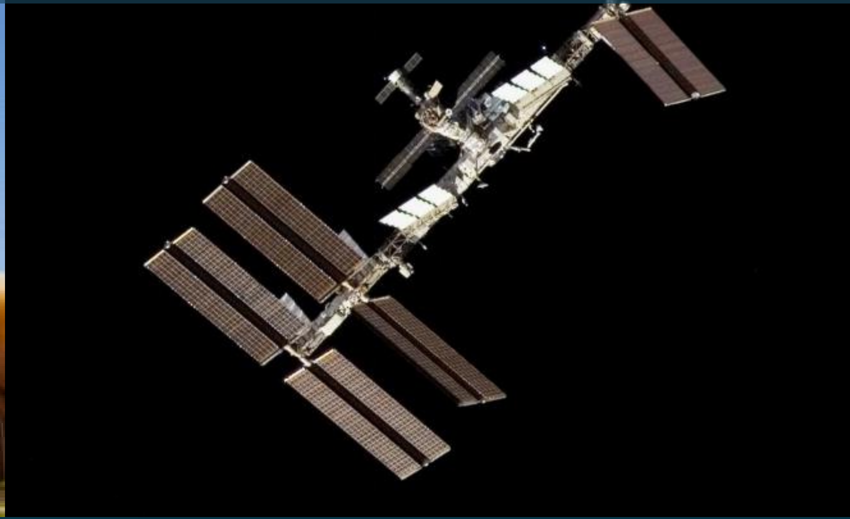
PNT Advisory Board Meeting
December 9, 2021

Real-Time On-Board PNT



Launch Vehicle Range Ops

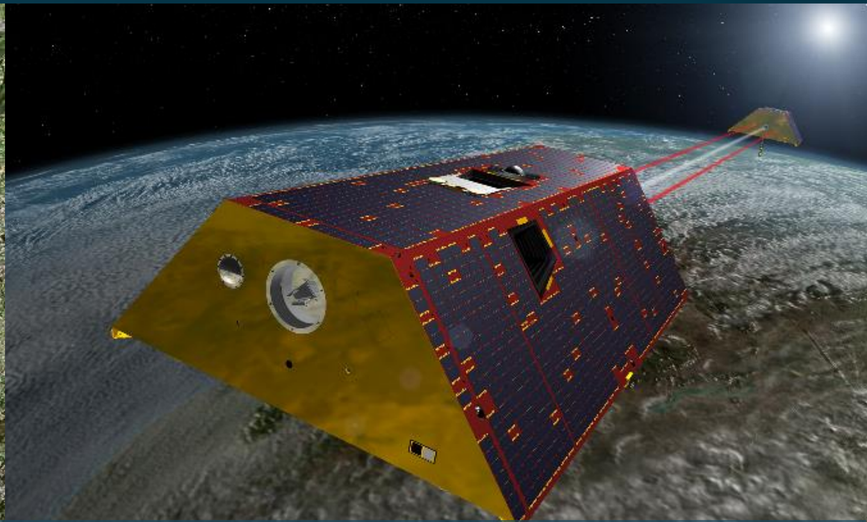
Attitude Determination



Active Space Uses of GNSS at NASA

Time Synchronization

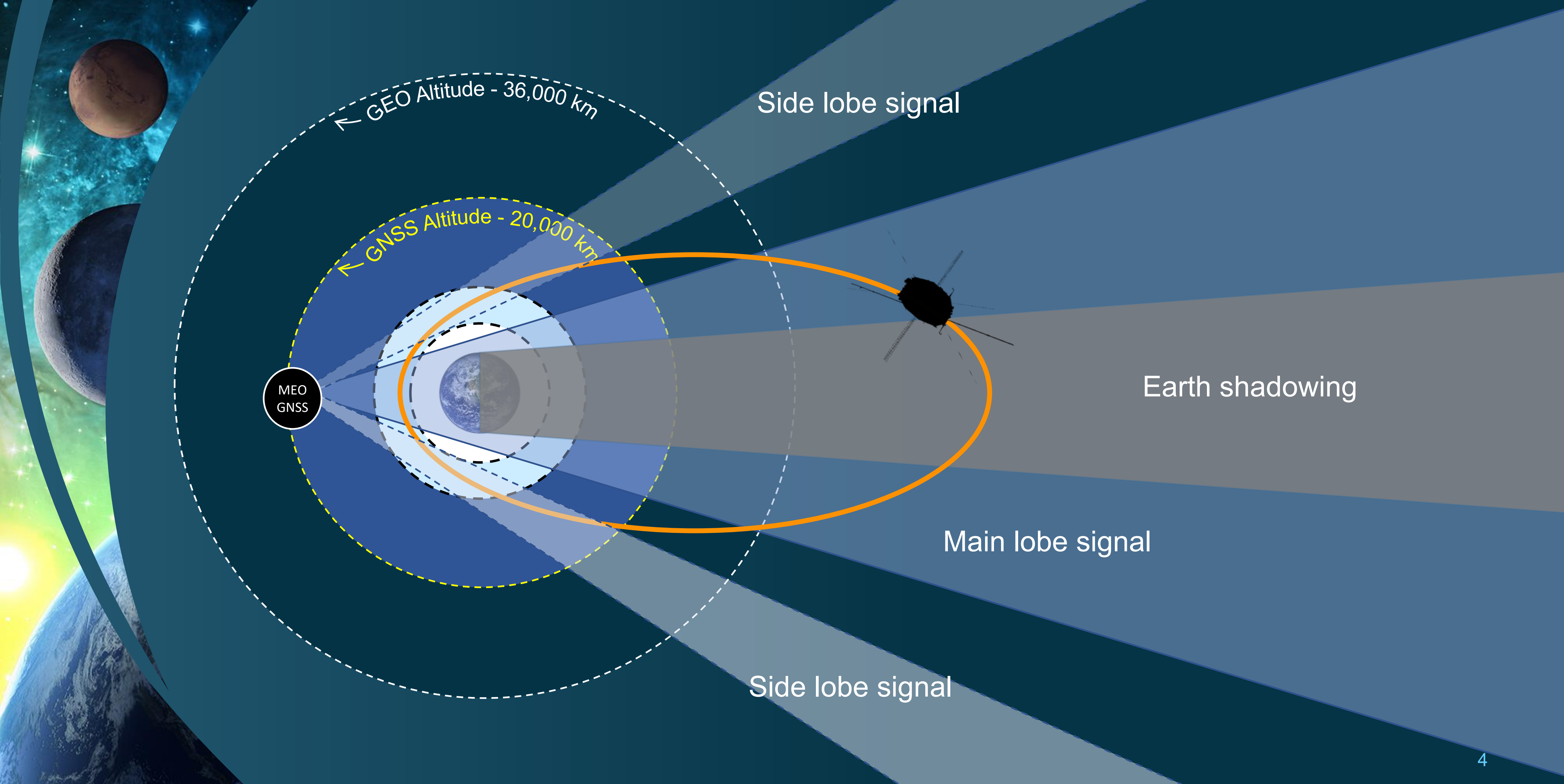
Earth Sciences



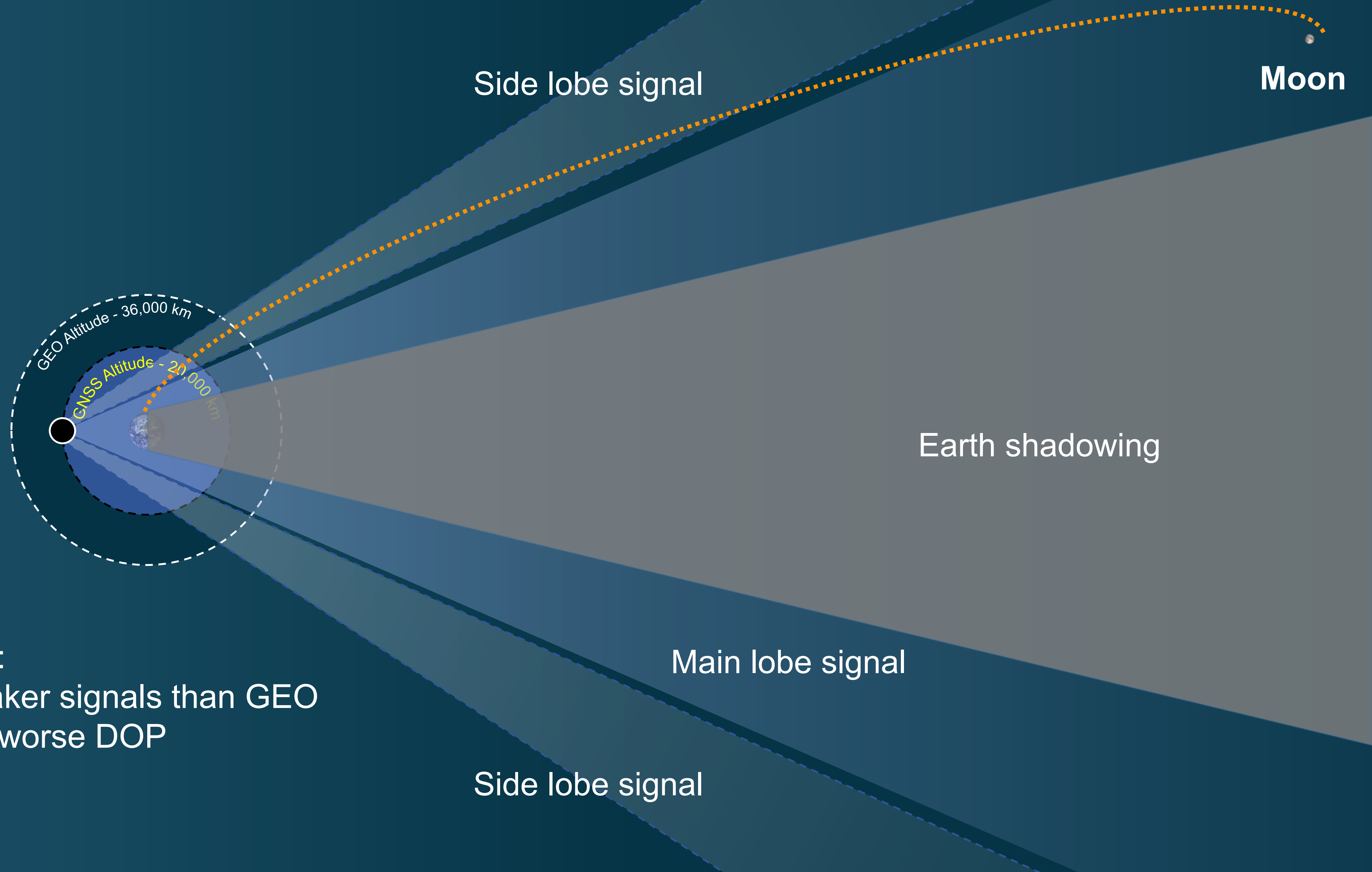
Precise Orbit Determination

GNSS for Lunar PNT:
Current Status and What's Next

Signal Reception in the Space Service Volume (SSV)



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



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

The GNSS Lunar Vision—Circa 2004

NASA Goddard Space Flight Center

GPS Modernization: Implications for Space Users

Frank H. Bauer, Chief Engineer
Mike Moreau, Senior Engineer
Mission Engineering & Systems Analysis
NASA Goddard Space Flight Cente
August 25, 2004

NASA Goddard Space Flight Center

Genesis of Critical Comments to CDD

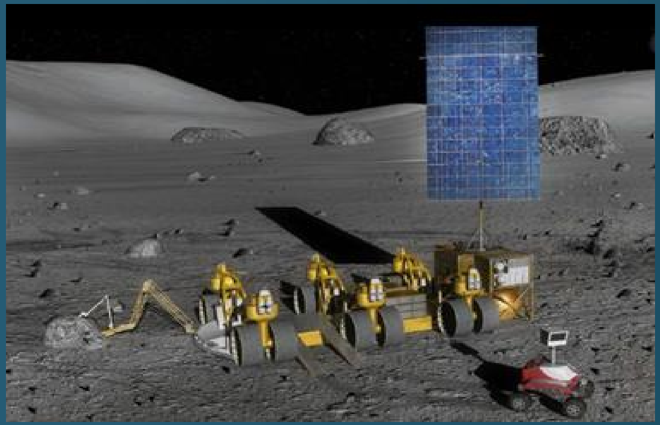
- Two significant shortcomings in the current CDD Space Service Volume power and availability requirements:
  - The power and availability numbers are significantly below levels provided by the current constellation
  - The current wording (power levels referenced to a specific angle with respect to the GPS transmitter) unnecessarily leads to a specific design solution
- **Desired Outcome:**
  - State threshold and objective requirements that will challenge the GPS III contractor teams to provide a level of service that is an improvement over current state of the art, but at a minimum results in no loss of performance over Block II.

NASA Goddard Space Flight Center

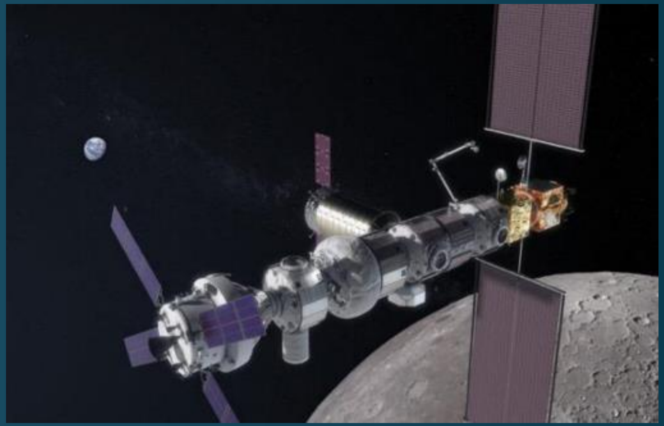
MEO/HEO GPS Current & Future Customers

- GOES Weather Satellites (NOAA)
- Commercial telecommunications satellites
- TDRSS (NASA)
- Military
- Earth Scientists
- Space Scientists
- Space Weather
- International satellites
- Lunar exploration (NASA and others)

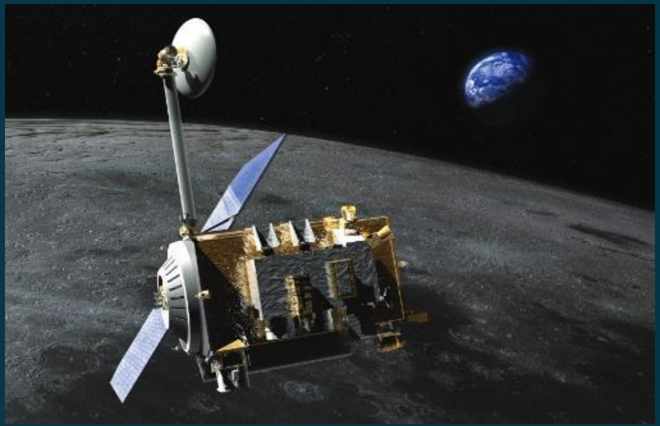
Lunar Exploration: Roles for GNSS



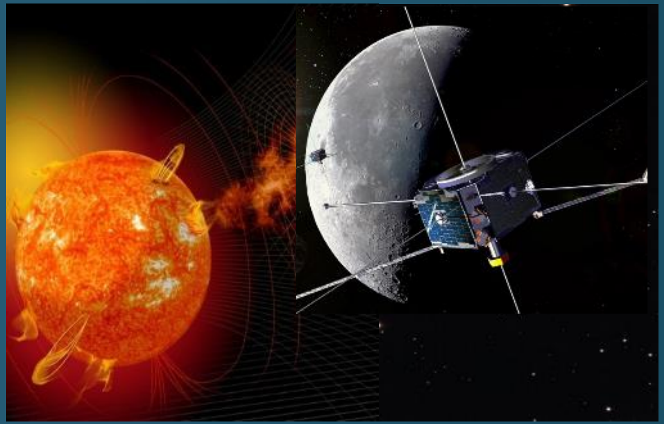
Lunar Surface Operations, Robotic Prospecting,& Human Exploration



Human-tended Lunar Vicinity Vehicles (Gateway)



Robotic Lunar Orbiters, Resource & Science Sentinels



Earth, Astrophysics, & Solar Science Observations

Satellite Servicing

Lunar Exploration Infrastructure

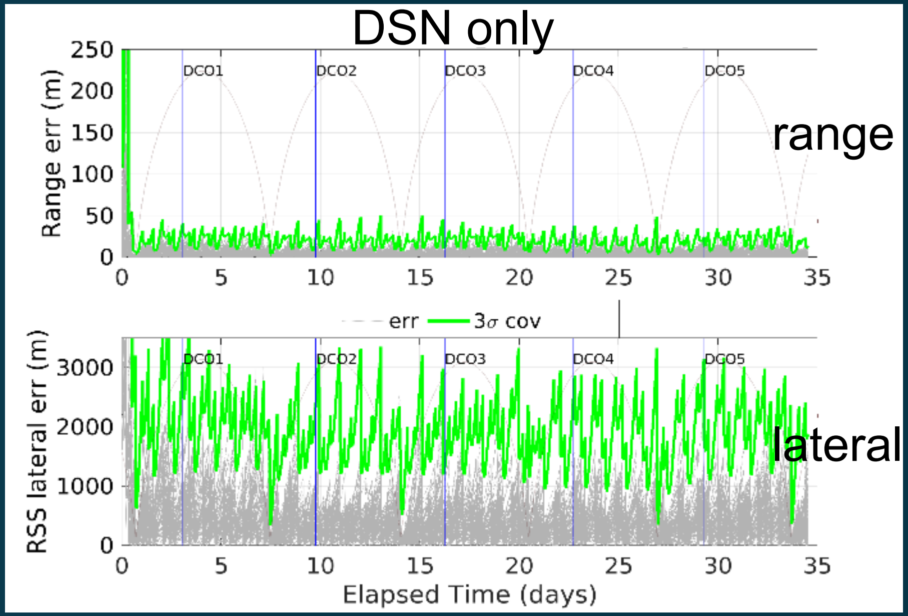
Lunar Gateway Study – Sep 2020

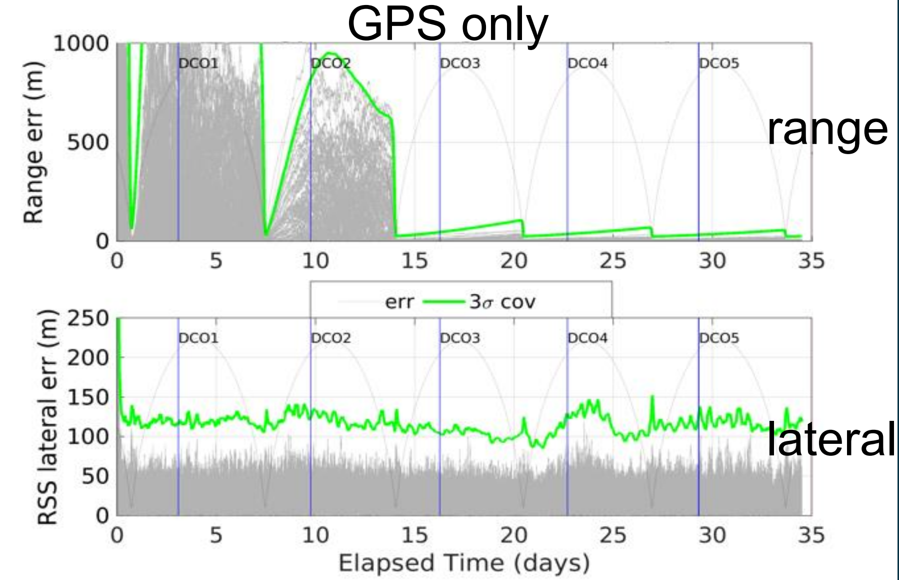
GPS Expected Performance

- 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





Lunar GNSS Phased Approach

Initial demonstrations

- Demonstrate lunar reception
- Opportunistic flights/technology
- Return evidence of performance
- Return raw data, lessons learned

- GNSS-only baseline demonstrations

We are here

First operational capability

- High-reliability unit
- High-accuracy clock
- Integrated into vehicle avionics
- Leverage demo data & lessons

- Utilize initial lunar PNT services

Commercialization

- Foster lunar UE commercial base
- Diversity of UE classes:
  - Flagship receivers
  - CubeSat/reduced SWaP
  - Integrated chipsets

- Leverage PNT signal compatibility: Earth-based GNSS + lunar PNT services

Broad Infusion

- GNSS is standard equipment
- Established, diverse UE base
- Part of diverse PNT solution

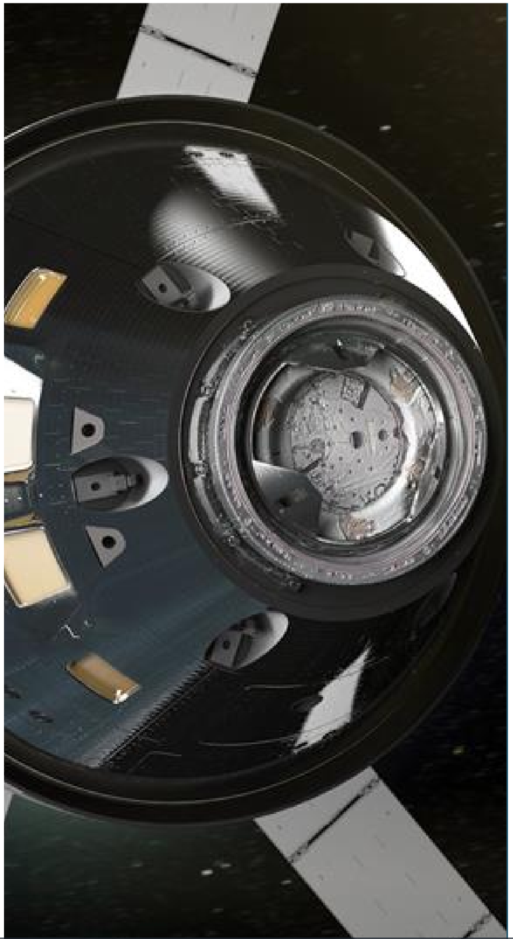
- Robust global PNT signal coverage from all sources

Relative use of signal sources

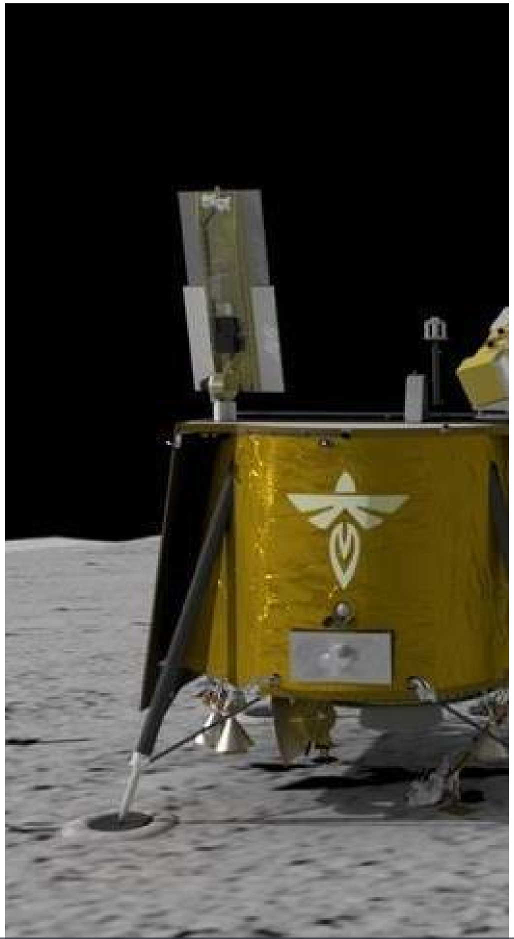
Terrestrial GNSS

Lunar PNT Services
(e.g. LunaNet)

What’s Next

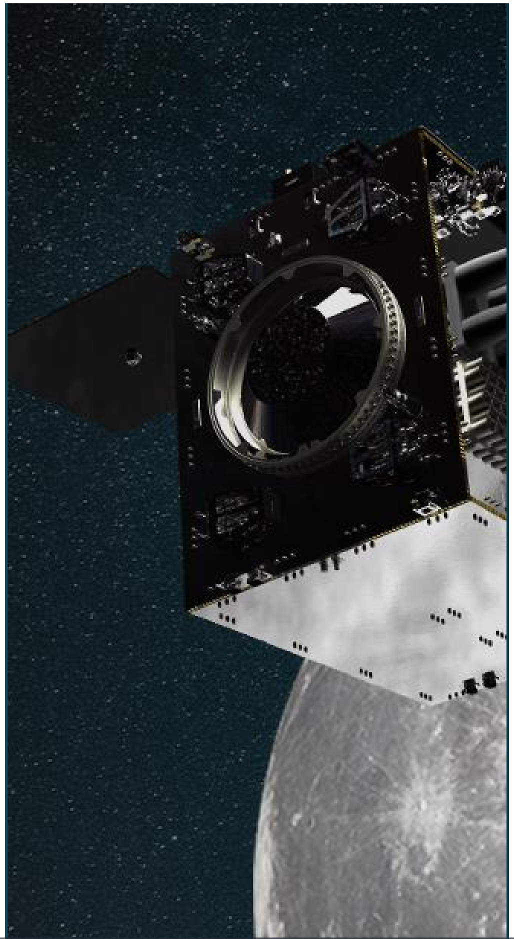


Artemis-1
(LEO receiver)
2022

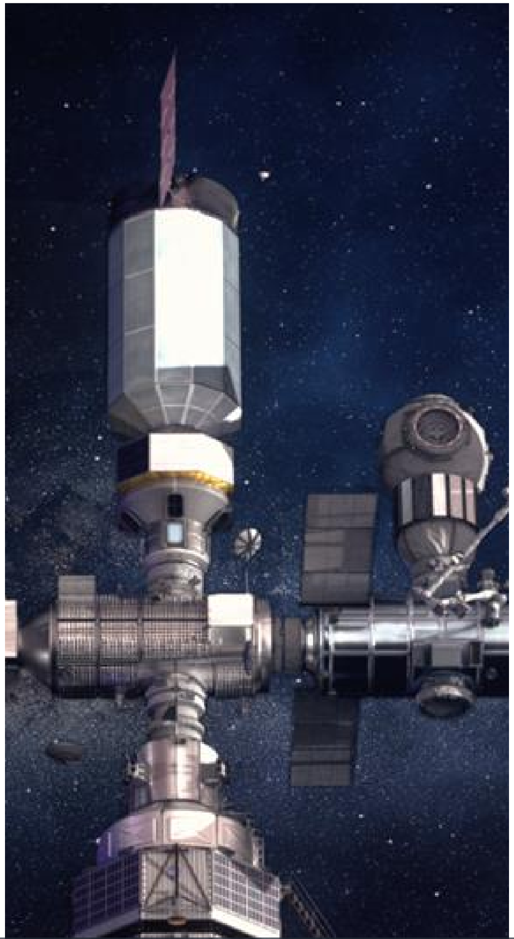


LuGRE

2023

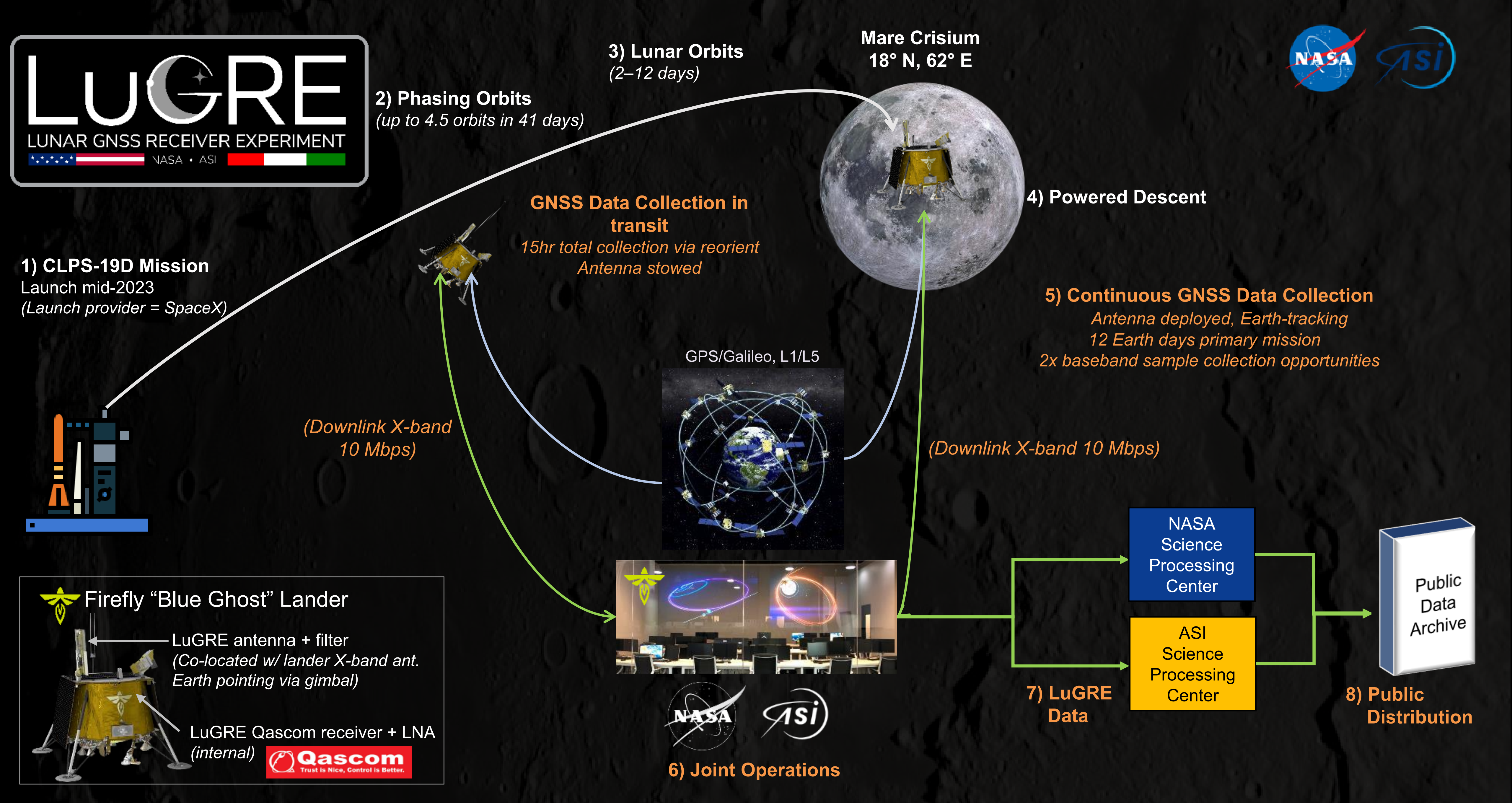


Lunar Pathfinder
(ESA)
2024



Gateway Payloads

LunaNet



LuGRE will demonstrate GNSS-based PNT in flight to the Moon, and on the lunar surface.

LuGRE Outcomes

Characterize the GNSS signal environment

- GPS+Galileo, L1+L5, E1+E5a
- Signal availability
- DOP
- C/N_0
- Observables
  - Pseudorange
  - Carrier phase
  - Doppler
- Raw baseband I/Q samples
- Transmit antenna patterns
- Multipath, surface environment

Characterize navigation performance

- Point solutions
- Onboard Kalman filter states
- Time to first position fix
- Formal errors, convergence
- Comparison to independent sources (lander, LRR)
- Application of GGTO

Share collected data

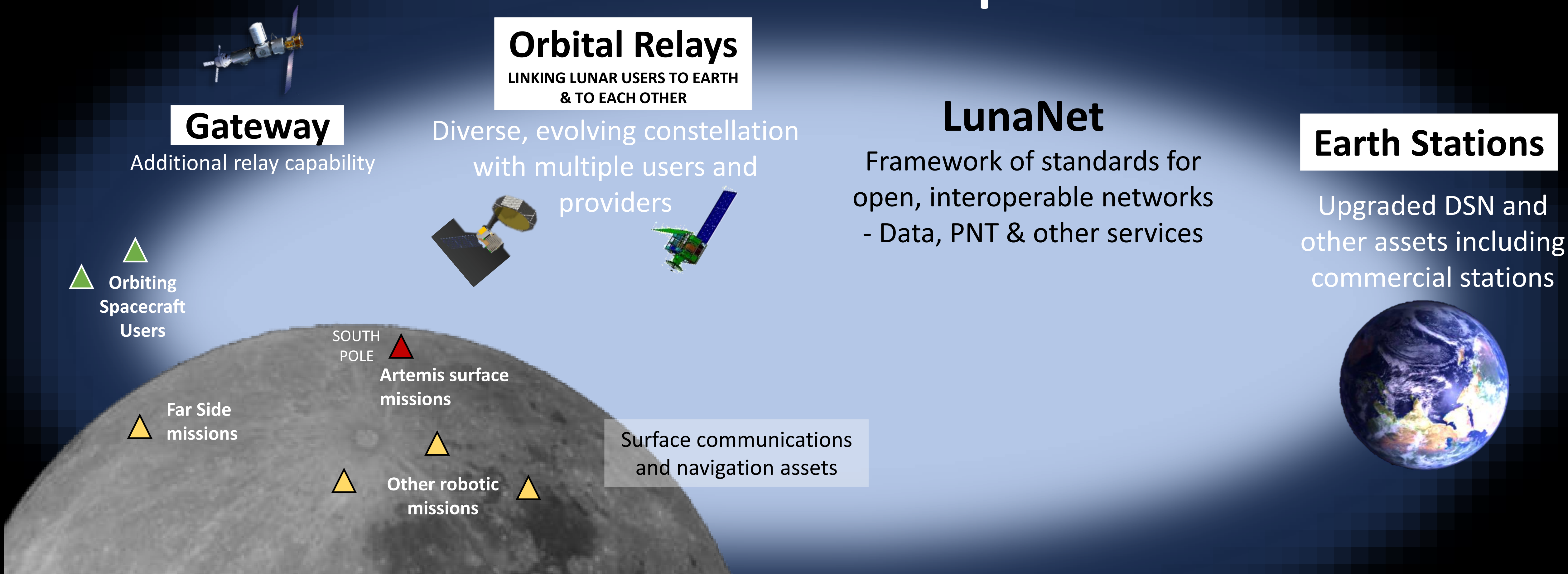
- GNSS receiver developers
- LuGRE science partners
- NASA missions (Artemis, Gateway, science)
- Commercial landers
- International space agencies
- GNSS community
- Science community
- Public

Facilitate adoption of capability

- Raw data availability
- LuGRE team reports + papers
- Calibration of lunar GNSS simulation models
- Application to future mission navigation studies
- Lessons learned to GNSS hardware and software developers

*Specific investigations are coordinated via LuGRE Science Team

Early Lunar Communications and Navigation Architecture Concept



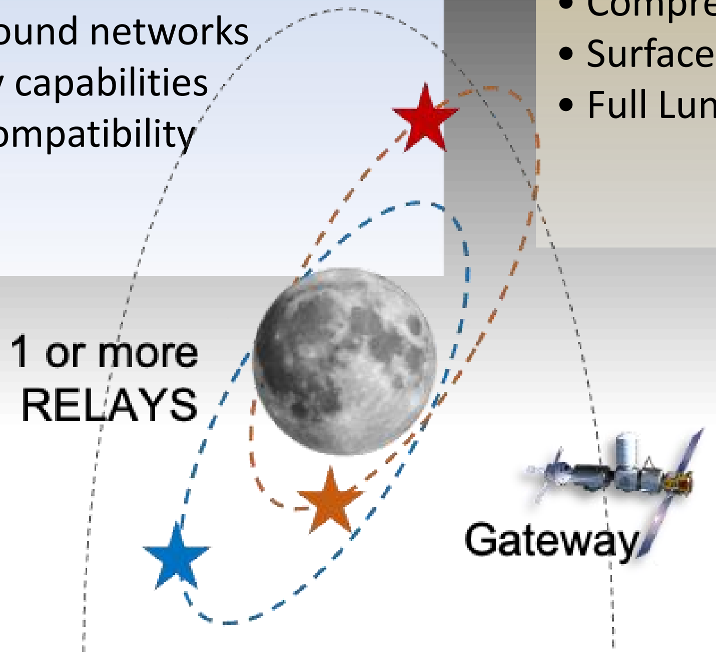
Communication and navigation infrastructure lowers the barriers to entry for new missions and capabilities and supports expanding robotic and human activities on the Moon.

Lunar Communications & Navigation Evolution

Near-Term

NEEDS
- Far Side science mission
- South Pole human exploration
- PNT services

IMPLEMENTATION
- Existing ground networks
- Initial relay capabilities
- LunaNet compatibility



Medium-Term

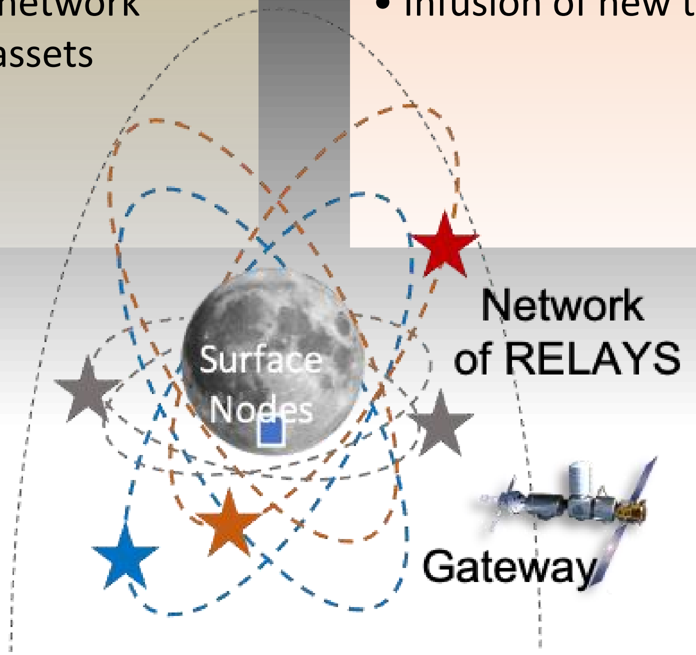
NEEDS
- Global coverage
- Longer, more complex missions, greater mobility

IMPLEMENTATION
- Comprehensive relay network
- Surface comm & nav assets
- Full LunaNet services

Far-Term

NEEDS
- Sustained surface and orbital presence

IMPLEMENTATION
- Evolution of infrastructure
- Infusion of new technology



Provider Collaborative Accomplishments via the International Committee on GNSS (ICG)

International Committee on GNSS (ICG)

- The ICG emerged from 3rd UN Conference on the Exploration and Peaceful Uses of Outer Space in July 1999
- The ICG brings together all six GNSS providers (United States–GPS, European Union–Galileo, Russia–GLONASS, China–BeiDou, India–NavIC and Japan–QZSS), as well as other members and observers to:
    - *Promote the use of GNSS and its integration into infrastructures*
    - *Encourage compatibility and interoperability among global and regional systems*
- Observers: International organizations and associations (BIPM, IOAG, ITU, IGS, etc.,)

https://www.unoosa.org/oosa/en/ourwork/icg/icg.html

International Committee on GNSS (ICG)

The ICG consist of the GNSS Service Providers Forum and four Working Groups (WG-S, WG-B, WG-C and WG-D).

WG-S
Systems, Signals and Services

Major Topics
- Spectrum compatibility
- Interference detection & mitigation
- Service interoperability
- Performance standards & monitoring

WG-B
Enhancement of GNSS
Performance, New Services and Capabilities

Major Topics
- Development of interoperable, multi GNSS SSV
- GNSS hosted search and rescue payloads
- Space weather and atmosphere modelling

Applications Subgroup

Space Use Subgroup

The WG-B Space Use Subgroup (SUSG) is dedicated to representing needs of space users within ICG

WG-C
Information Dissemination and Capacity Building

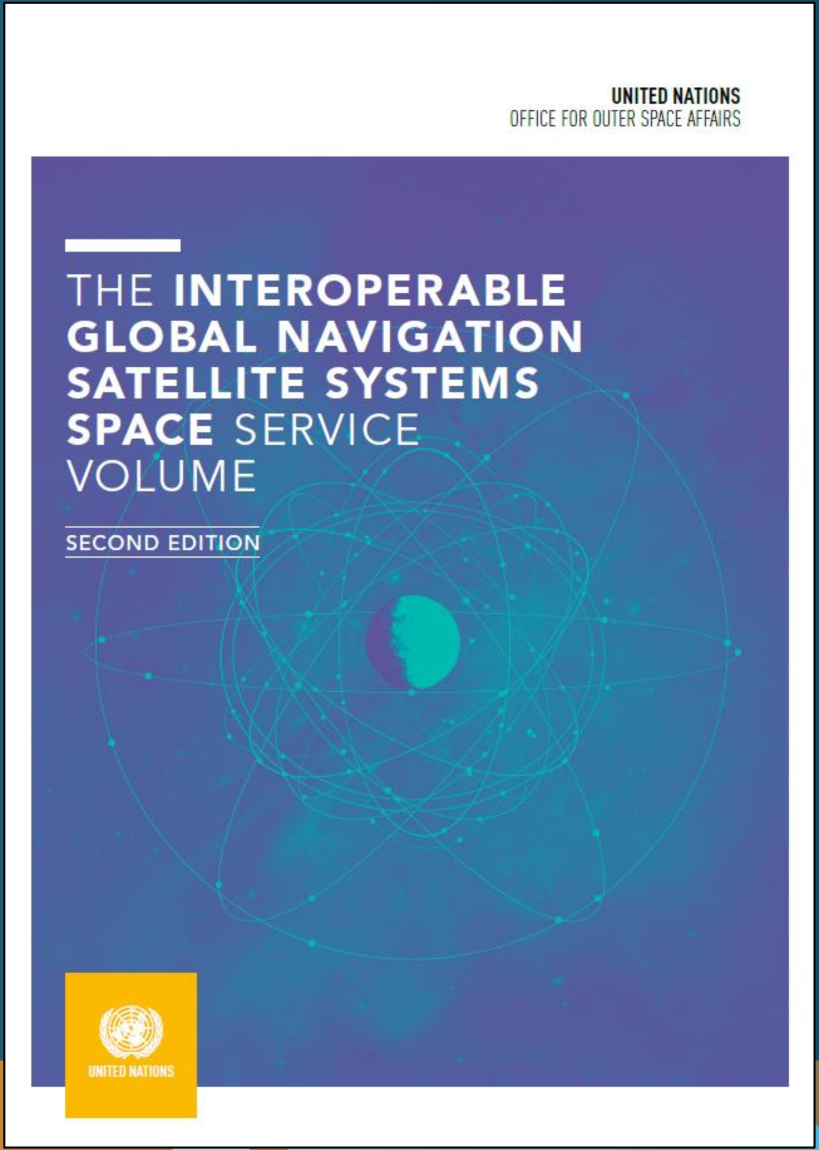
Major Topics
- Training and Seminars
- Information Material

WG-D
Geodetic Reference, Time Reference and Applications

Major Topics
- ITRF, geodetic reference frame
- Time standards & multi constellation time offsets
- High Accuracy applications (PPP)

(Subgroups of WG-S, WG-D, WG-C not shown.)

ICG SUSG Product:
"The Interoperable GNSS SSV", 2nd Edition



- Product of 3 years of work by ICG WG-B Space Use Subgroup
- Series is "one stop shop" for SSV data for all GNSS constellations
- 2nd Edition thoroughly updated throughout:
  - Latest GNSS constellation data
  - Expanded analysis of geometric aspects in SSV
  - Addition of profiles of five real-world SSV and multi-GNSS missions
- Available at: https://undocs.org/ST/SPACE/75/REV.1

ICG SUSG Product: Space Service Volume Video

Sponsors:

NASA

SPACE-BASED POSITIONING NAVIGATION & TIMING
NATIONAL COORDINATION OFFICE

- Four-minute outreach tool for all audiences
- Conveys utility & benefits of a multi-GNSS SSV, describes its transformative use to navigate in space and shows how it will impact humanity—in space and on Earth
- Available on YouTube: https://youtu.be/-1ngun6OfgQ?t=13

SUSG Work Plan 2021-2022

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

WP4: Expansion of GNSS SSV to support lunar operations

Objective: Expand interoperable GNSS SSV to support Lunar transit, surface, Earth-Moon Lagrange points and orbital operations (cis-lunar region); develop a formal definition of the expanded SSV

Approach:

1. Lunar frequency and code signal coordination
2. User needs assessment
3. Draft lunar SSV definition
4. Recommend/support lunar GNSS flight experiments; publish results and lessons learned
5. Leverage publicly available trade studies and performance analyses; if necessary, perform narrow analyses/trades via ICG region study team(s)
6. Recommend updated provider requirements and/or augmentations as needed
7. Publish results in future editions of SSV Booklet, technical journals and press articles

Enabling Activities and Current Needs

GPS Enabling Activities

- **NASA-USAF Memorandum of Understanding**
  - Signed in 2017 to ensure SSV signal continuity for future space users
  - Provides for release of antenna data + NASA representative in the GPS IIIF procurement cycle

- **GPS data availability**
  - Late 2020: IIR/IIR-M antenna gain pattern data (re-release)
  - Late 2020: GPS III SVN 74-77 phase center, group delay, and inter-signal bias data
    - Response to request from ICG IGMA Task Force
  - Remaining need: Release of GPS III antenna gain pattern data
    - Subject of NASA/USSF discussion, Nov 2019
    - Direct release is only available data source; NASA GPS ACE reconstruction does not cover GPS III

https://www.navcen.uscg.gov/?pageName=gpsTechnicalReferences

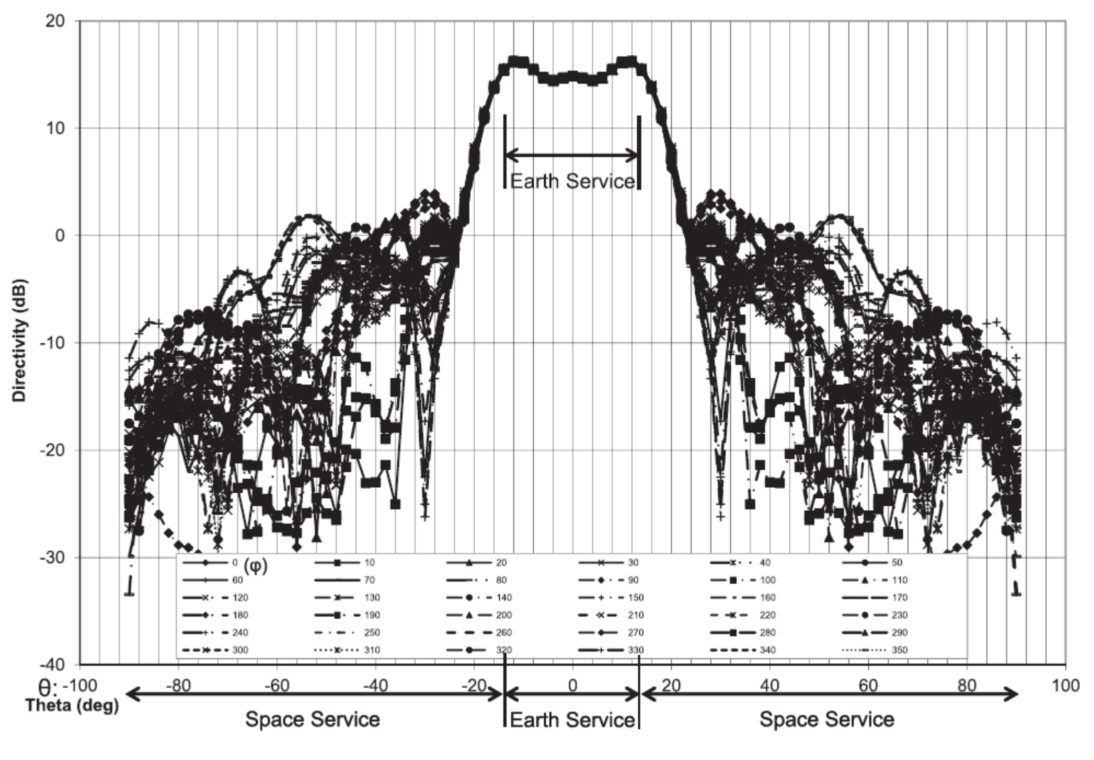


Fig. 26–Average improved antenna pattern – L1

Average L1 antenna pattern, GPS Block IIR-M

Source: Marquis, W.A., and Reigh, D.L. (2015) The GPS Block IIR and IIR-M Broadcast L-band Antenna Panel: Its Pattern and Performance. J Inst Navig, 62:329–347. doi: 10.1002/navi.123.

Characterizing the Space User Base

- Rapid expanding commercial space market (LEO, MEO, GEO & Cislunar) and expanded space use cases necessitate an understanding of current and future spaceborne PNT needs.
- Previous US studies (e.g. "The Economic Value of GPS", 2019) did not look at space user segment.
- Europe has recently published a Space User Needs Report (see right).
- Domestic and international activities underway require a comprehensive understanding of needs to maximize value.
- **Recommendation**: A comprehensive study should be performed to characterize PNT space user segment and needs for US government, commercial, and university customers.

EUSPA Space User Needs Report*

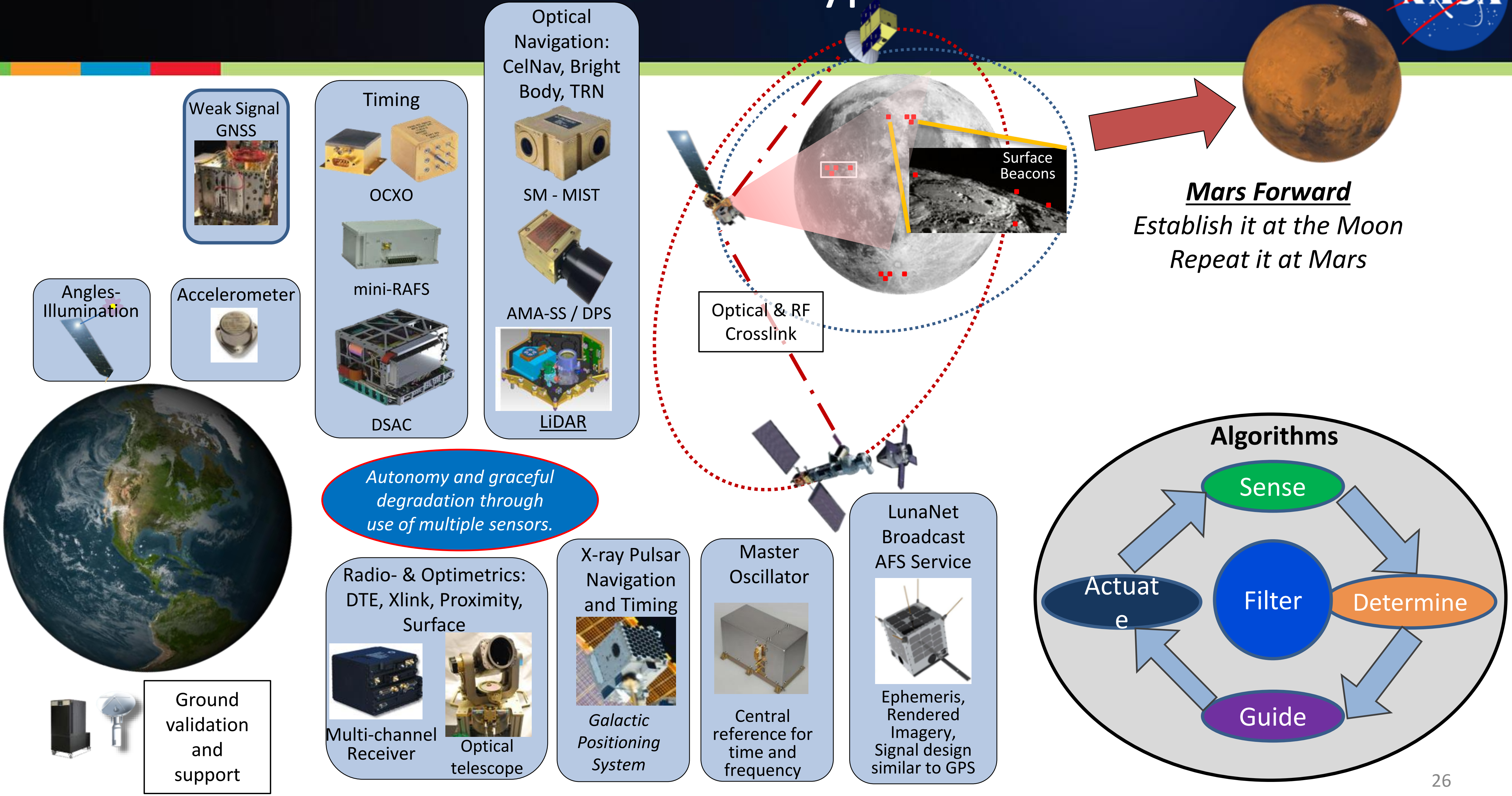
*https://www.gsc-europa.eu/sites/default/files/sites/all/files/Report_on_User_Needs_and_Requirements_Space.pdf

Conclusions

- The Moon is the next frontier in space use of GNSS. NASA is pursuing multiple open, collaborative activities. **The first demonstrations are around the corner.**
- NASA is working within the ICG to enhance the benefit of space use of GNSS through **multi-GNSS interoperability**, to improve PNT performance and resilience.
- The burgeoning space commercial market requires a **comprehensive PNT space use study** to ensure the USA is strategically positioned to support the myriad of missions and capabilities.
- **NASA is proud to work with GPS and the international GNSS providers** to ensure GNSS services are accessible, interoperable, robust, and precise for all users, for the benefit of humanity.

Backup

Lunar PNT DataTypes

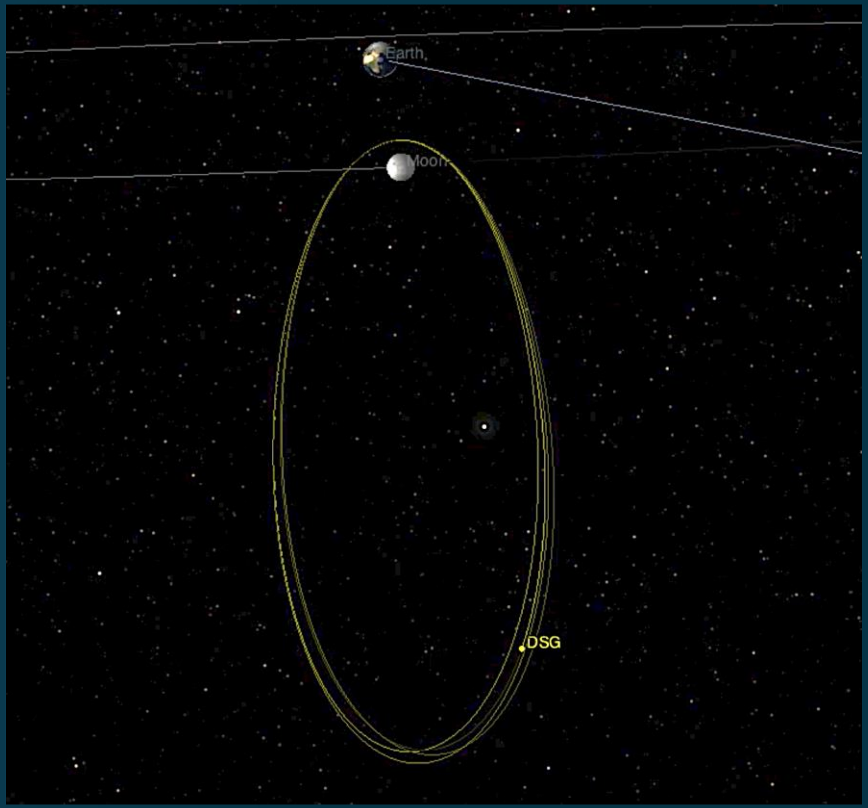


Lunar Gateway

- Joint NASA/ESA performance study. NASA GPS-only results summarized here.
- Assumptions: MMS-like navigation system with Earth-pointed high-gain antenna (~14 dBi) and Goddard Enhanced Onboard Navigation System (GEONS) flight filter software
- Calibrated with flight data from MMS Phase 2B; Employs GPS ACE-derived antenna patterns, IGS yaw model, solar noise model
- L2 southern Near Rectilinear Halo Orbit (NRHO), 6.5 day period
- Cases for both crewed and uncrewed perturb. models:
  - GPS only with Rubidium Atomic Frequency Standard (RAFS)
  - DSN only without atomic clock
  - GPS + DSN

Ground tracking assumptions

- Three contacts per orbit (uncrewed) or continuous (crewed)
- Data Cutoff (DCO) 24 hrs before orbit maintenance maneuvers



Ground tracking sim. parameters

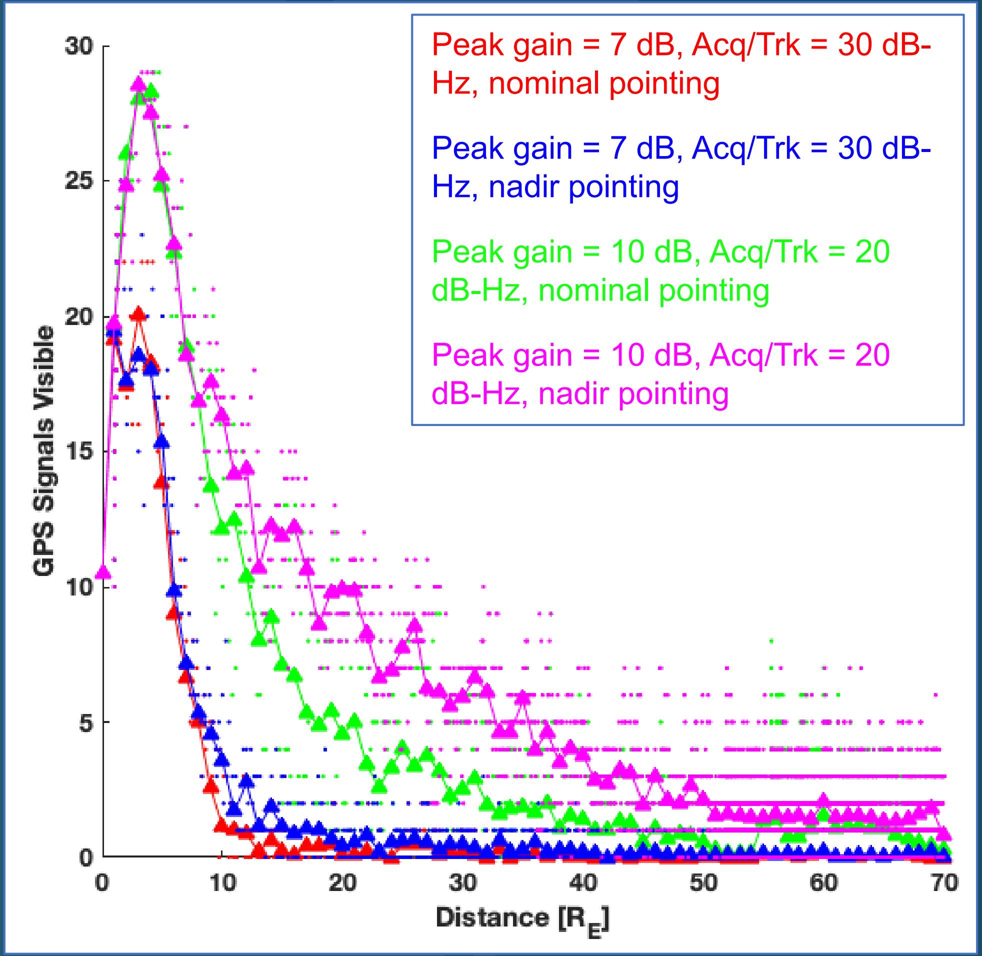
Noise/Bias Type	Value
Measurement Rate	10 s
Range Noise	1.0 m (1-sigma)
Range Bias	2.5 m (1-sigma)
Doppler Noise	0.33 mm/s (1-sigma)

Artemis I

Orbit Determination Toolbox (ODTBX) simulation of GPS signal availability over Artemis I trajectory

- Signal available/visible if received C/N0 exceeds receiver acquisition/tracking threshold
- GPS constellation modeled using per-vehicle Antenna Characterization Experiment side lobe patterns and per-block public main lobe data, calibrated with MMS and GOES-16 flight data
- Four antennas around Orion capsule nose, receiver and antenna properties calibrated with EFT-1 flight data

Signal availability is only part of the story, but it's clear **antenna placement and pointing are critical for feasibility** of GNSS at the Moon



Baseline case in red models planned configuration for Artemis I. Alternate configurations illustrate potential availability with changes to hardware and/or pointing.

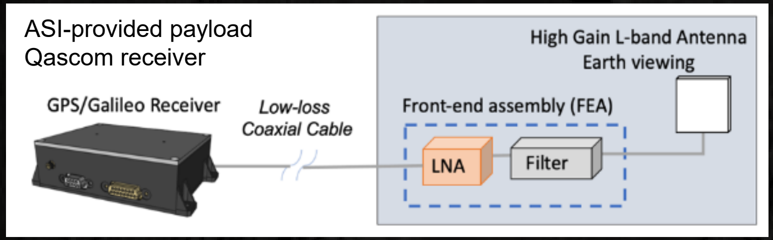
LuGRE Mission Overview

Mission
- NASA HEOMD payload for CLPS “19D” flight
- Joint NASA/Italian Space Agency mission
- “Do No Harm” class
- Firefly Blue Ghost commercial lander
- Transit + surface observation campaign
- Expected surface duration: one lunar day (~12 Earth days)

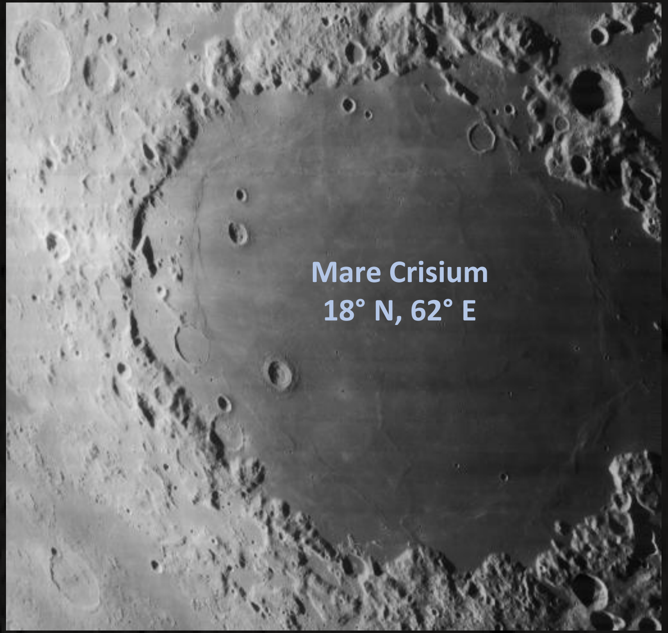
Payload objectives
1. Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
2. Demonstrate navigation and time estimation using GNSS data collected at the Moon.
3. Utilize collected data to support development of GNSS receivers specific to lunar use.

Measurements
- GPS+Galileo, L1/L5 (E1/E5)
- Onboard products: multi-GNSS point solutions, filter solutions
- Observables: pseudorange, carrier phase, raw baseband samples

Utilization
- Data + lessons learned for operational lunar receiver development
- Potential collaborative science: heliophysics, lunar geodesy
- Lunar human and robotic real-time onboard PNT



NASA
CLPS
Commercial Lunar Payload Services



- CLPS Lander Award Feb 2021
- LuGRE SRR Apr 2021
- LuGRE CDR Sept 2021
- ETU Delivery Oct 2021
- FM Delivery early 2022
- **Payload Delivery NLT Nov 1, 2022**
- **Launch+Ops Jul–Sep 2023**
- Analysis late 2023

We are here

LunaNet Services

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

LunaNet

LunaNet is envisioned as a framework of standards, protocols, and interfaces to support a scalable, interoperable communications and navigation network-of-networks with nodes provided by NASA, commercial, and international partners.

Networked Communication Services

- Critical data transmitted in real time.
- Data aggregated and transmitted in store-and-forward mode from orbiting and surface relays
- Data exchanged among lunar users with no need for transfer to and from Earth
- Data sent on demand by user or scheduled to better manage Earth stations loading & spectrum use

PNT Services

- Precise position, velocity & time for autonomous nav & collision avoidance
- Fusion of multiple data types including radiometrics, optimetrics, celestial nav, optical nav, terrain relative nav, & GNSS
- Broadcast service supplies time transfer and metric tracking to synchronize users

Detection & Information Services

- Alerts for events such as space weather, collision avoidance, & surface impact predictions sent to all LunaNet subscribers
- Mission sensors for space weather and other measurements distribute information services to other users via LunaNet information services

Science Services

- Use RF & optical assets (part of) as scientific instruments
- Supports Radio & Radar Sciences, Radio Astronomy / Very Long Baseline Interferometry (VLBI) & other space sciences

See details in backup

Lunar Communications and Navigation Interoperability Standards

In collaboration with other agencies, international partners and private companies, NASA is seeking to define a framework of mutually agreed-upon standards to be applied by lunar users and service providers in a set of cooperating networks.

The framework would apply to communication transmission services for science, exploration and commercial operations, distribution of navigation and timing references, and sharing of information. These standards can be introduced as part of the earliest missions and accommodate expansion as new commercial and government users and service providers join in an open and evolving architecture.

An initial version of these proposed standards has been drafted and can be found at the link below.
https://go.nasa.gov/3BQrCOk