NASA GNSS Update

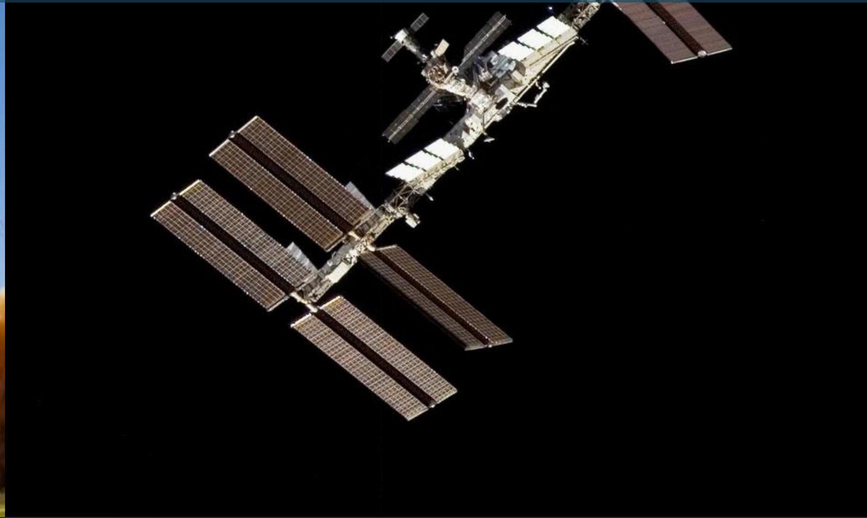
Joel J. K. Parker
NASA Goddard Space Flight Center

ICG-16 WG-B
11 October 2022

Real-Time On-Board Nav

Launch Vehicle Range Ops

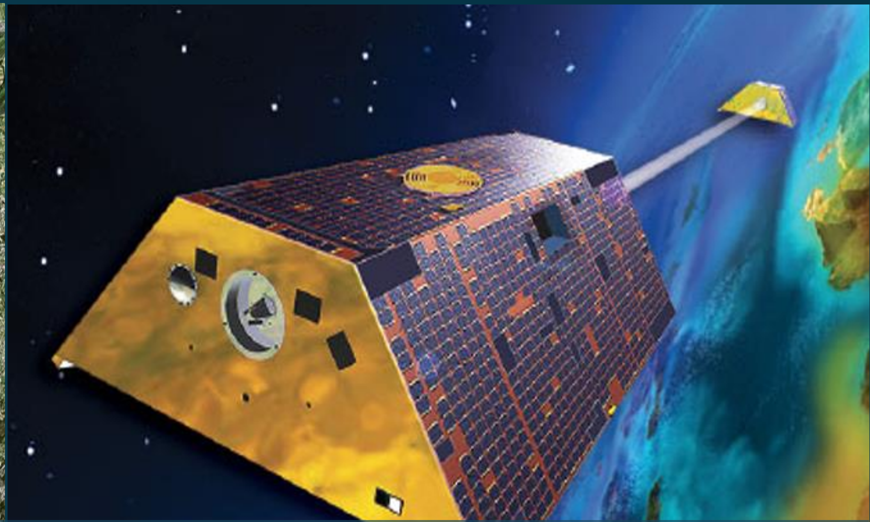
Attitude Determination



Active Space Uses of GNSS at NASA

Time Synchronization

Earth Sciences



Precise Orbit Determination

Mission Updates

In accordance with ICG WG-B recommendation:
"GNSS Space User Database", 2016

International Operations Advisory Group

Forum for identifying common needs across multiple international agencies for coordinating space communications policy, high-level procedures, technical interfaces, and other matters related to interoperability and space communications

It undertakes activities it deems appropriate related to multi-agency space communications

Goal to achieve full interoperability among member agencies

For more information: www.ioag.org

Members

Observers

ICG-IOAG Collaboration: GNSS Space User Database

- IOAG has observer status in the ICG
- ICG recommendations encourage providers, agencies, and research organizations to publish details of GNSS space users and to contribute to IOAG database
- Database last updated on 50 May 2022 for IOAG-25
- Key changes since previous update (13 Nov 2020):
    - Includes **139** total missions from **9** agencies + affiliates
- We continue encouraging service providers, space agencies and research institutions to contribute to the GNSS space user database via their IOAG liaison or ICG WG-B

IOAG Missions & Programs Relying on GNSS

Agency*	Country	2021	2022
ASI	Italy	4	4
CNES	France	10	13
CSA	Canada	**7**	**7**
DLR	Germany	7	7
ESA	Europe	**30**	**30**
JAXA	Japan	**13**	**13**
KARI	Republic of Korea	8	8
NASA	USA	**46**	**52**
UKSA	UK	**-**	**5**

*Includes affiliated organizations

https://www.ioag.org/Public%20Documents/Aggregate%20IOAG%20Missions%20Using%20GNSS%202022-05-20%20(IOAG-25).xlsx

Selected US Mission Database Updates

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
114	NASA	OSAM-1	GPS	L1 C/A	Orbit determination, spacecraft timing, GNSS measurements part of multi-sensor nav filter for AR&D with Landsat 7	Ep	2025	RUAG
121	NASA	Geospace Dynamics Constellation (GDC) (6 satellites)	TBD	TBD	Orbit, time, radio occultation (dedicated instrument)	Ep	2027	
122	NASA/ASI/ESA	UP Aerospace SL-15	GPS Galileo	GPS L1 C/A, L5 Galileo E1, E5a	Orbit, time	O	Nov. 2022	Suborbital flight test with two GNSS receivers provided by ASI and ESA. Each receiver will use the systems and signals indicated.
123	NASA	NOAA-20 (JPSS-1)	GPS	L1 C/A	Orbit, time	Es	18 Nov. 2017	
124	NASA	TIMED	GPS	L1 C/A	Orbit, time	Ei	7 Dec. 2001	
125	NASA	Ionospheric Connection Explorer (ICON)	GPS	L1 C/A	Orbit, time	Ei	11 Oct. 2019	

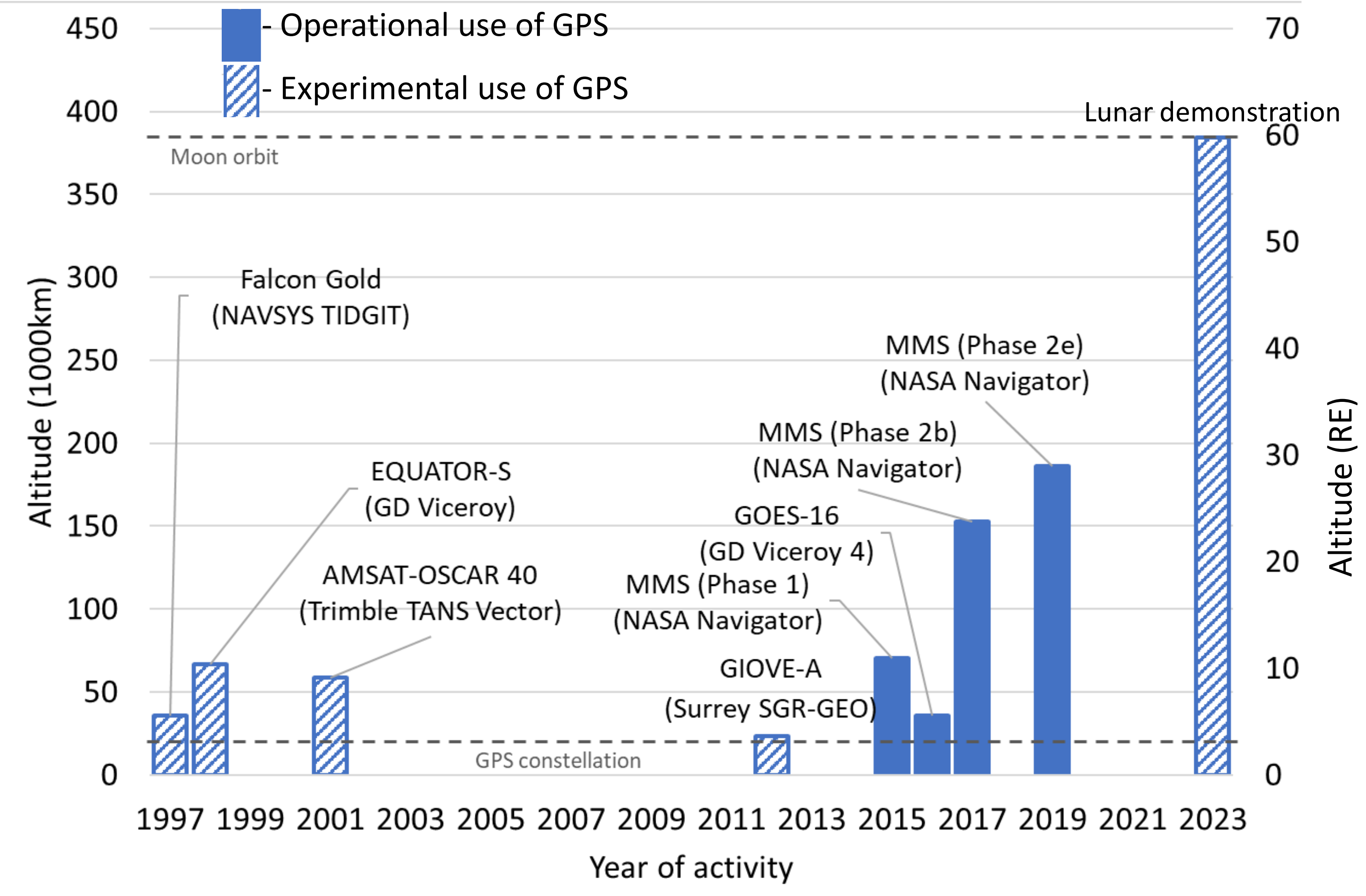
Red = updated in this release
See link on previous slide for full database

Lunar Activities

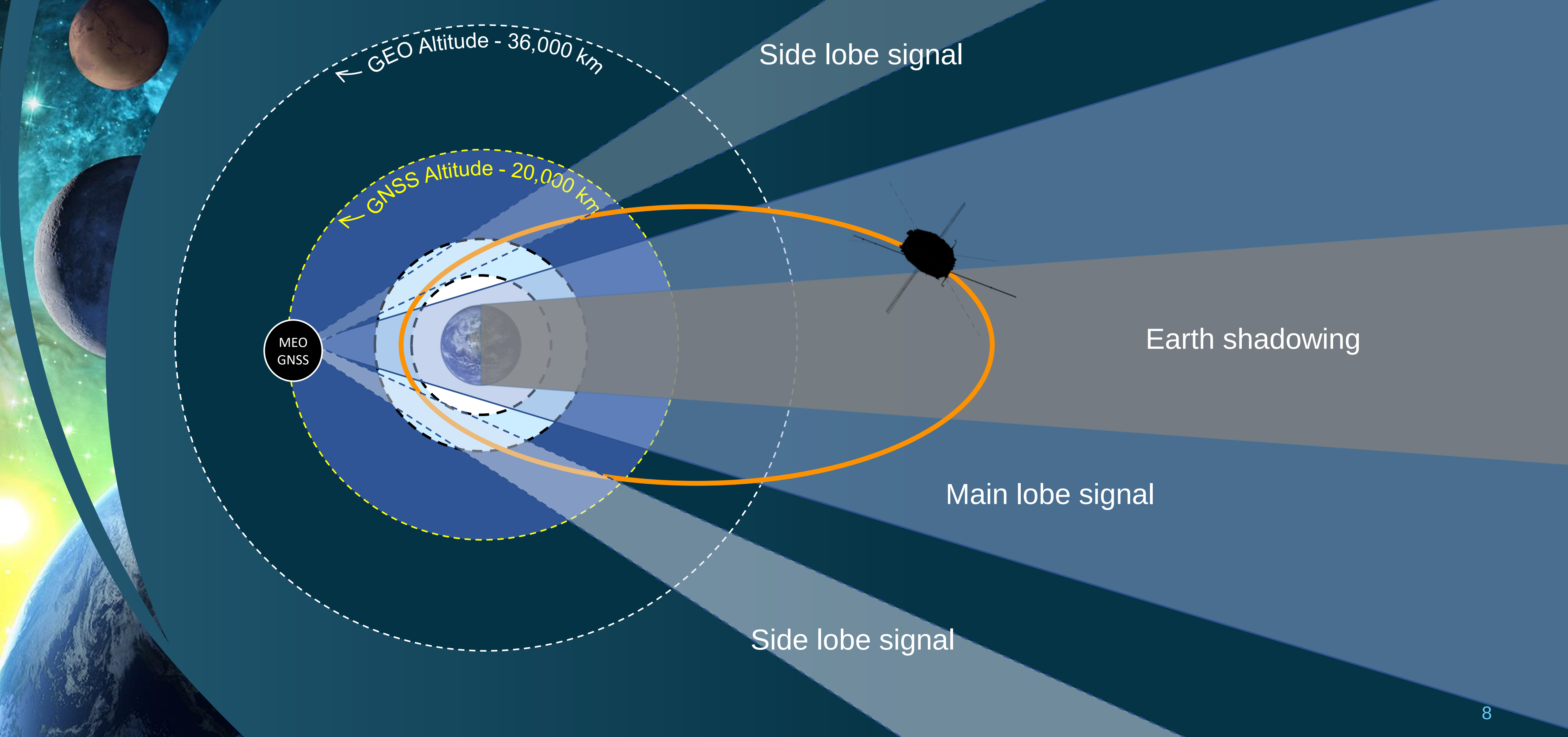
Development of High Altitude GNSS

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

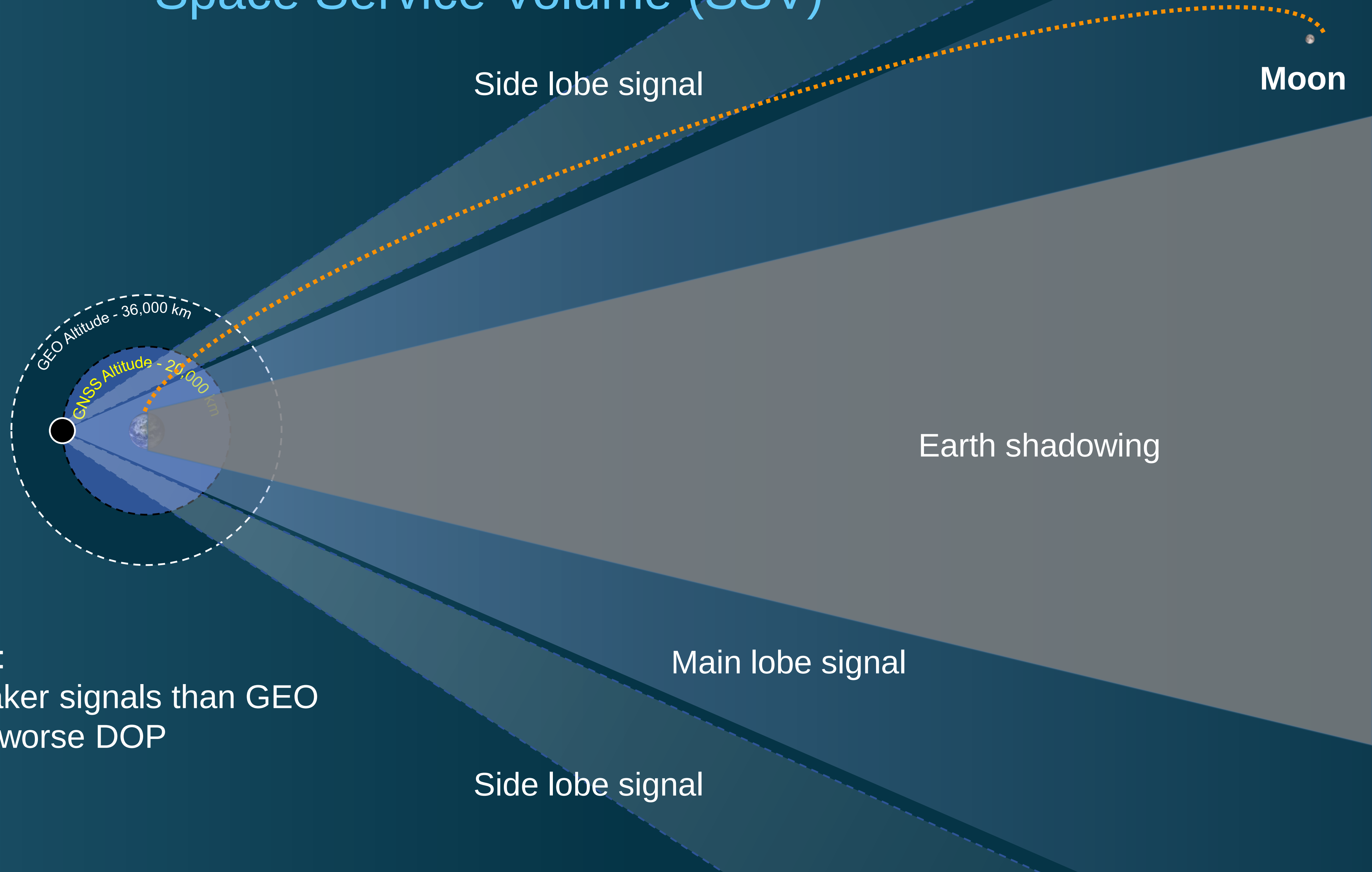
- **1990s**: Early flight experiments—Equator-S, Falcon Gold
- **2000**: Reliable GPS at GEO w/ bent pipe architecture
- **2001**: AMSAT OSCAR-40 mapped GPS main and sidelobe signals
- **2015**: MMS employed GPS operationally at 76,000 km
- **2016–Present**: GOES-16/17/18 employs GPS operationally at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



Signal Reception in the GNSS Space Service Volume (SSV)



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



Challenges:

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

Lunar Role of GNSS

Critical technology gaps identified in the Global Exploration Roadmap:

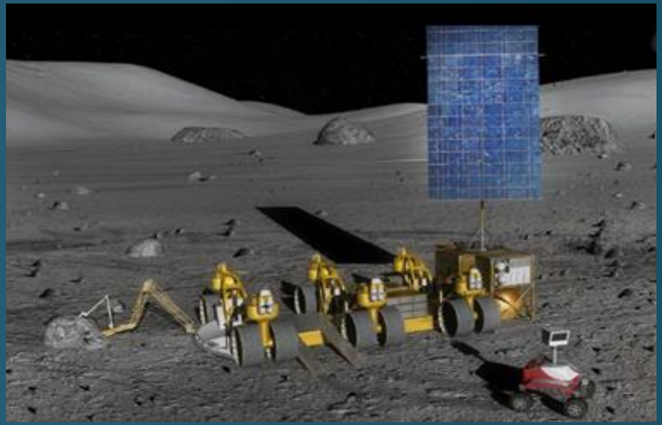
- Autonomous Rendezvous & Docking, Proximity Operations, Target Relative Navigation
- Beyond-LEO crew autonomy

GNSS on lunar missions would:

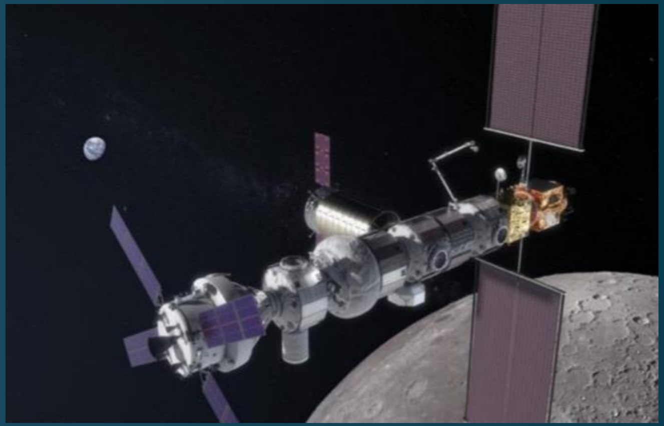
- enable autonomous navigation
- reduce tracking and operations costs
- provide a backup/redundant navigation for human safety
- provide timing source for hosted payloads
- reduce risk for commercial development

Recent advances in high-altitude GNSS can benefit and enable future lunar missions

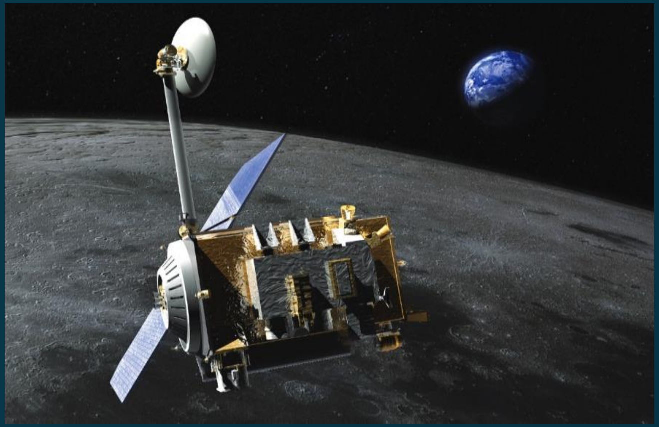
Lunar Exploration: Roles for GNSS



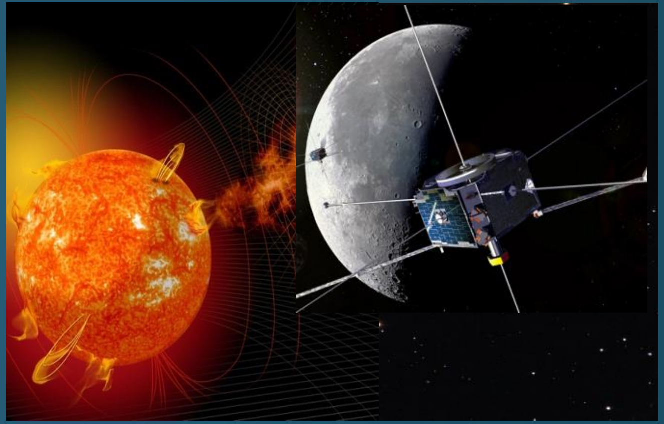
Lunar Surface Operations, Robotic Prospecting,& Human Exploration



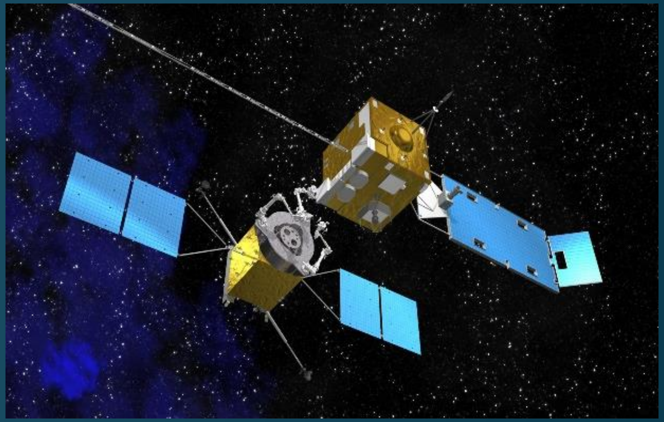
Human-tended Lunar Vicinity Vehicles (Gateway)



Robotic Lunar Orbiters, Resource & Science Sentinels



Earth, Astrophysics, & Solar Science Observations



Satellite Servicing

Lunar Exploration Infrastructure

Phased Expansion of Lunar PNT Services

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

Relative use of signal sources

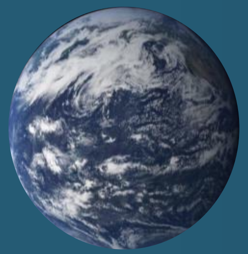
Terrestrial GNSS

Lunar PNT Services (e.g. LunaNet)

Time

Today

Transit use of GNSS and Lunar PNT Services



Lunar PNT Services (e.g. LunaNet)

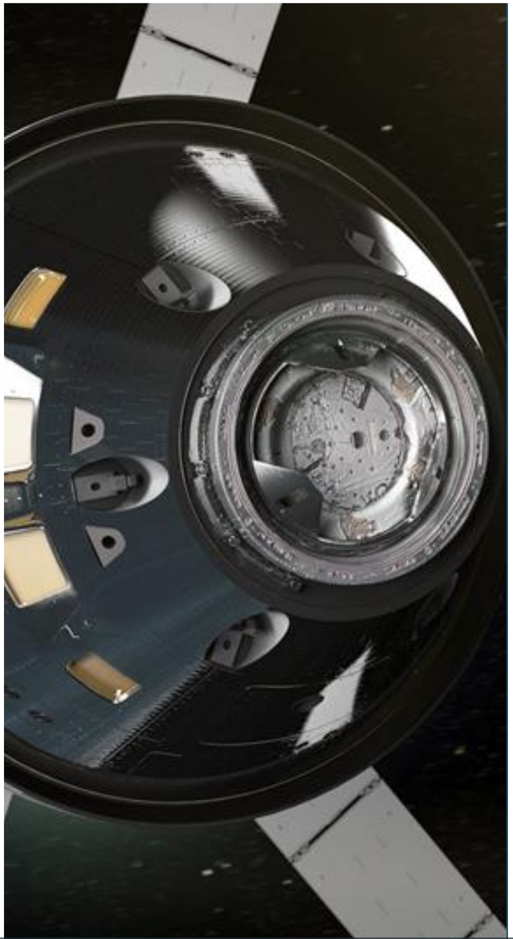
GNSS Use

Lunar PNT Use

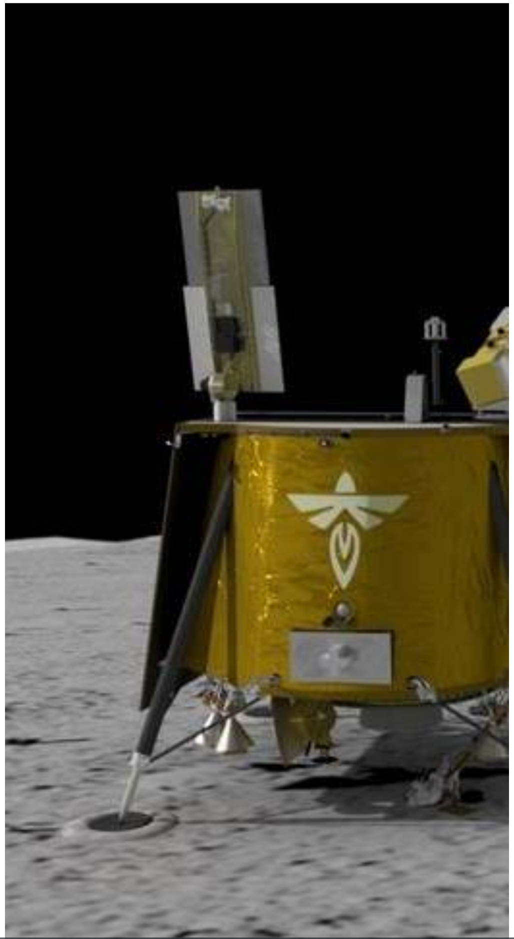
Transit Distance

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.

Evolution from Demonstrations to Flight Operations

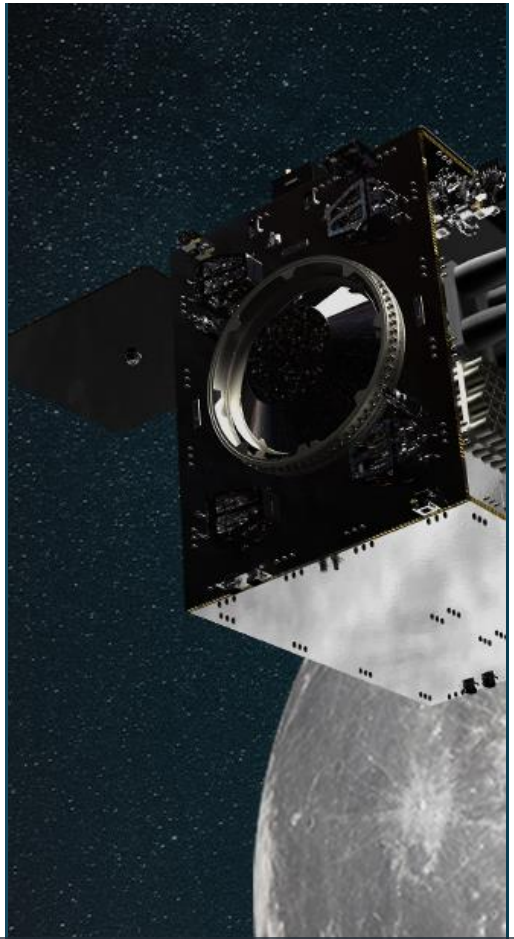


Artemis-1
(LEO receiver)
2022

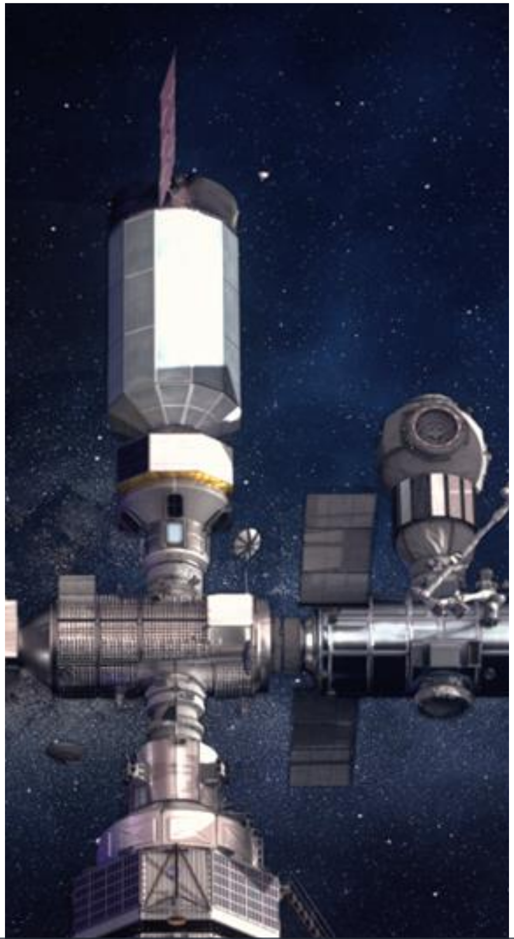


LuGRE

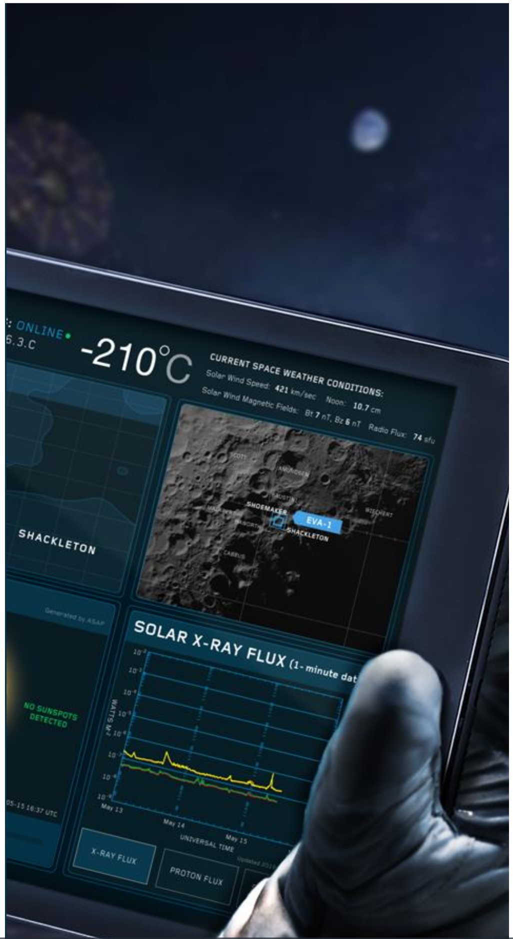
2024



Lunar Pathfinder
(ESA)
2025

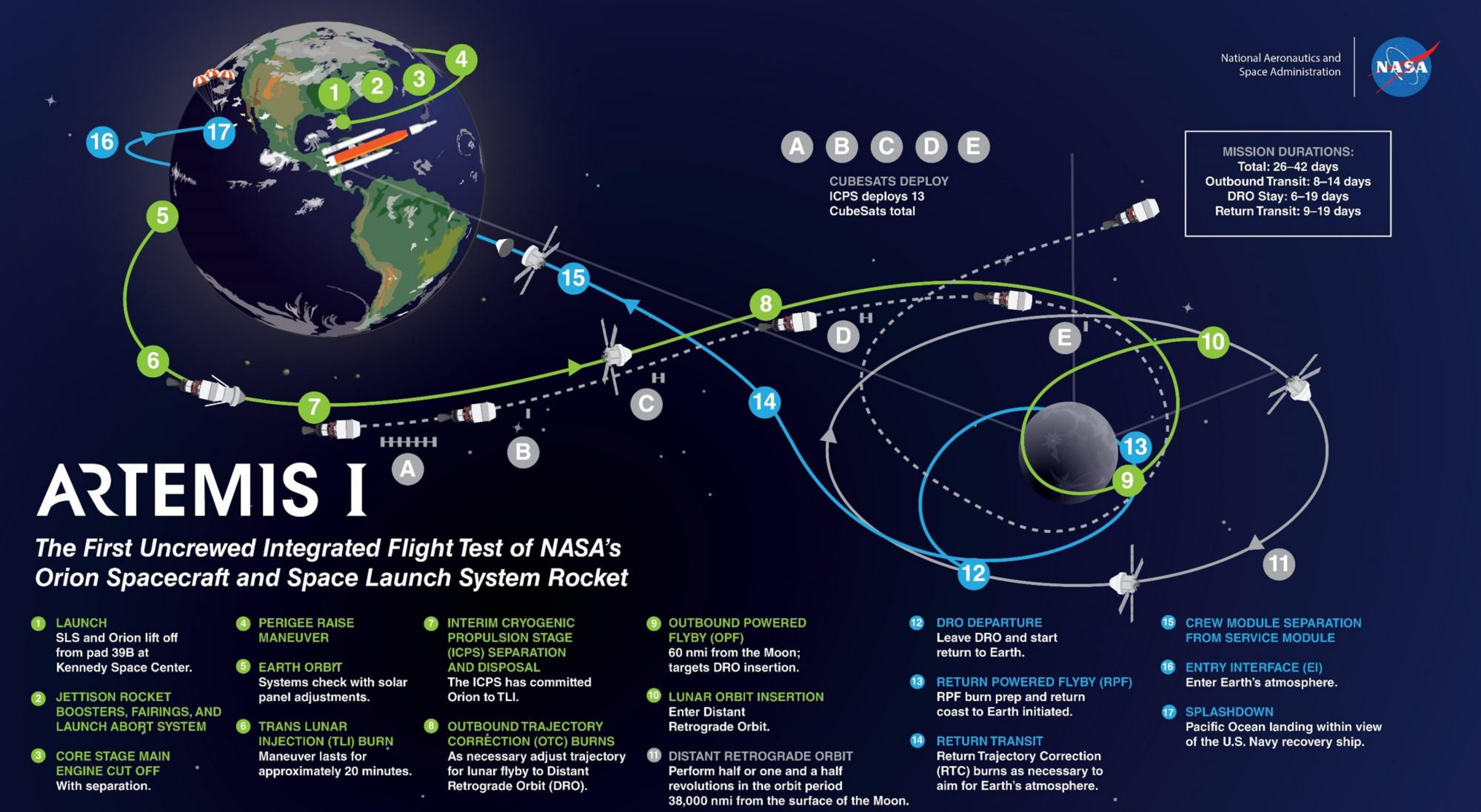


Gateway Payloads



LunaNet

Artemis-1


National Aeronautics and Space Administration
NASA
ARTEMIS I
The First Uncrewed Integrated Flight Test of NASA's Orion Spacecraft and Space Launch System Rocket
A B C D E
CUBESATS DEPLOY
ICPS deploys 13 CubeSats total
MISSION DURATIONS:
Total: 26–42 days
Outbound Transit: 8–14 days
DRO Stay: 6–19 days
Return Transit: 9–19 days
1 LAUNCH
SLS and Orion lift off from pad 39B at Kennedy Space Center.
2 JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM
3 CORE STAGE MAIN ENGINE CUT OFF
With separation.
4 PERIGEE RAISE MANEUVER
5 EARTH ORBIT
Systems check with solar panel adjustments.
6 TRANS LUNAR INJECTION (TLI) BURN
Maneuver lasts for approximately 20 minutes.
7 INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION AND DISPOSAL
The ICPS has committed Orion to TLI.
8 OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS
As necessary adjust trajectory for lunar flyby to Distant Retrograde Orbit (DRO).
9 OUTBOUND POWERED FLYBY (OPF)
60 nmi from the Moon; targets DRO insertion.
10 LUNAR ORBIT INSERTION
Enter Distant Retrograde Orbit.
11 DISTANT RETROGRADE ORBIT
Perform half or one and a half revolutions in the orbit period 38,000 nmi from the surface of the Moon.
12 DRO DEPARTURE
Leave DRO and start return to Earth.
13 RETURN POWERED FLYBY (RPF)
RPF burn prep and return coast to Earth initiated.
14 RETURN TRANSIT
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere.
15 CREW MODULE SEPARATION FROM SERVICE MODULE
16 ENTRY INTERFACE (EI)
Enter Earth's atmosphere.
17 SPLASHDOWN
Pacific Ocean landing within view of the U.S. Navy recovery ship.

Source [3]

LuGRE

LuGRE 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.

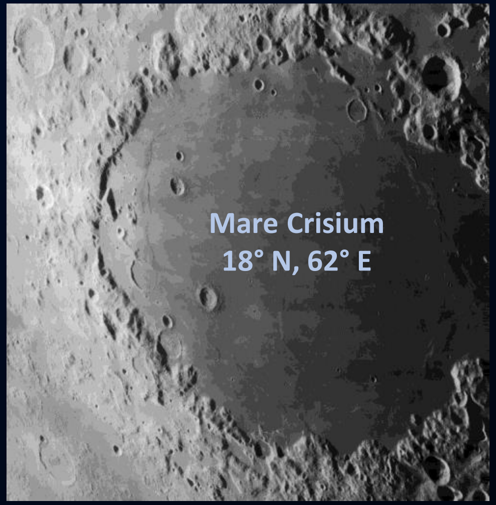
Measurements

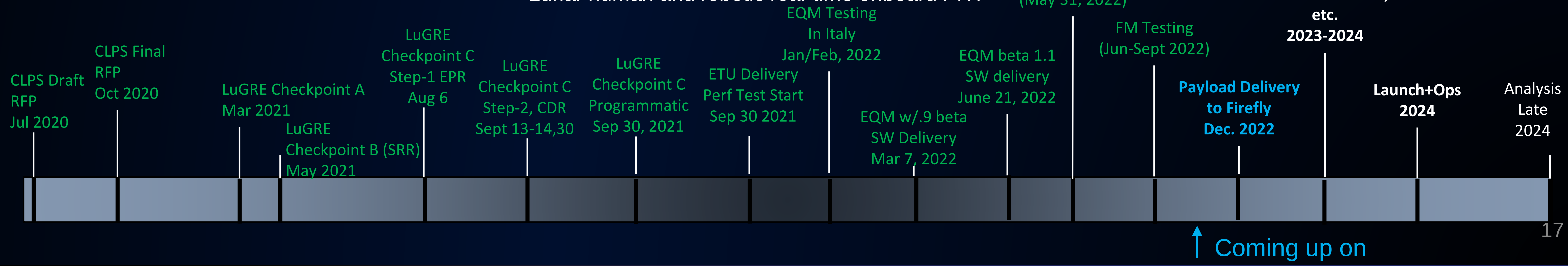
- GPS+Galileo, L1/L5 (E1/E5)
- Onboard products: multi-GNSS point solutions, filter solutions
- Observables: pseudorange, carrier phase, raw baseband samples

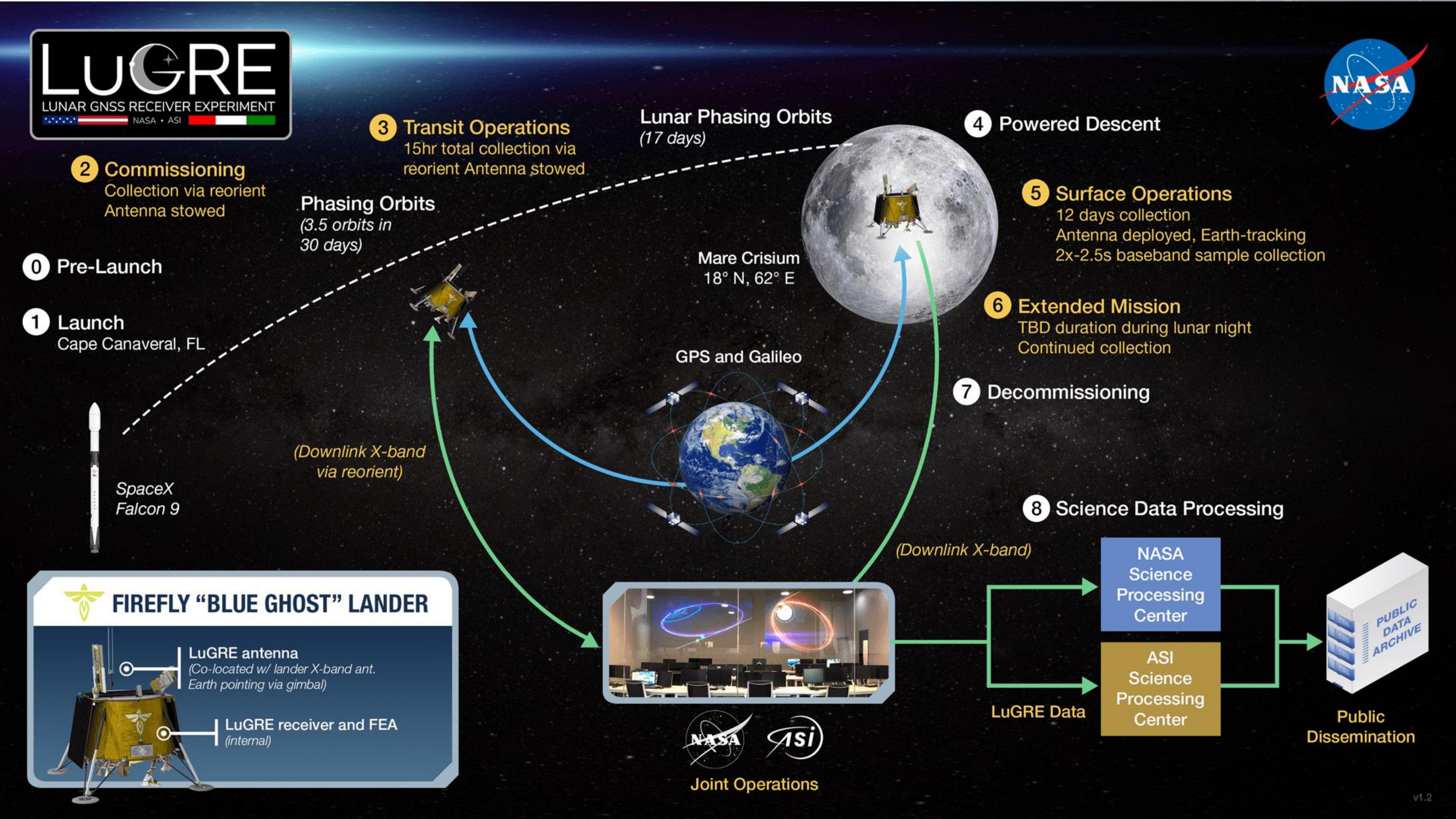
Utilization

- 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






LuGRE
LUNAR GNSS RECEIVER EXPERIMENT
NASA • ASI
NASA
0 Pre-Launch
1 Launch
Cape Canaveral, FL
2 Commissioning
Collection via reorient
Antenna stowed
Phasing Orbits
(3.5 orbits in
30 days)
3 Transit Operations
15hr total collection via
reorient Antenna stowed
Lunar Phasing Orbits
(17 days)
4 Powered Descent
5 Surface Operations
12 days collection
Antenna deployed, Earth-tracking
2x-2.5s baseband sample collection
Mare Crisium
18° N, 62° E
6 Extended Mission
TBD duration during lunar night
Continued collection
GPS and Galileo
7 Decommissioning
(Downlink X-band
via reorient)
SpaceX
Falcon 9
8 Science Data Processing
(Downlink X-band)
NASA Science Processing Center
ASI Science Processing Center
LuGRE Data
PUBLIC DATA ARCHIVE
Public Dissemination
FIREFLY "BLUE GHOST" LANDER
LuGRE antenna
(Co-located w/ lander X-band ant.
Earth pointing via gimbal)
LuGRE receiver and FEA
(internal)
NASA
ASI
Joint Operations
v1.2

LuGRE Outcomes

Characterize the GNSS signal environment	Characterize navigation performance	Share collected data	Facilitate adoption of capability

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

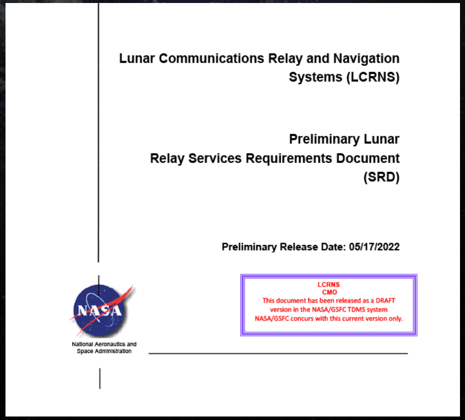
*Specific investigations are coordinated via LuGRE Science Team

LCRNS & LunaNet

Source:
Mr. Andrew Petro, NASA Space Communications and Navigation (SCaN)
Mr. James Schier, NASA Space Communications and Navigation (SCaN)

Lunar Communications Relay and Navigation Systems (LCRNS)

- Enabling a lunar communications and navigation infrastructure that meets NASA’s needs, represents a sustainable, long-term approach to human and robotic exploration, and embodies an extensible solution for future travels to Mars and beyond.
    - Enabling an interoperable approach
    - Directly supports science, technology, and demonstration missions; NASA’s Artemis missions; and the on-going creation of LunaNet
    - See: https://esc.gsfc.nasa.gov/projects/LCRNS?tab=overview
- May 2022: Preliminary LCRNS Lunar Relay Services Requirements Document released: https://esc.gsfc.nasa.gov/static/2fbc056474937c4e3ecfdba1dc595f06/ee60f0dad022948b2e8ce03e6e86a2f0.pdf
    - Scope is communications relay PNT, and search & rescue services
    - Focus is on lunar south pole region (80°–90° south) and lunar far side
    - Timeline is to support Human Landing System (HLS) and CLPS as early as 2024


Lunar Communications Relay and Navigation Systems (LCRNS)

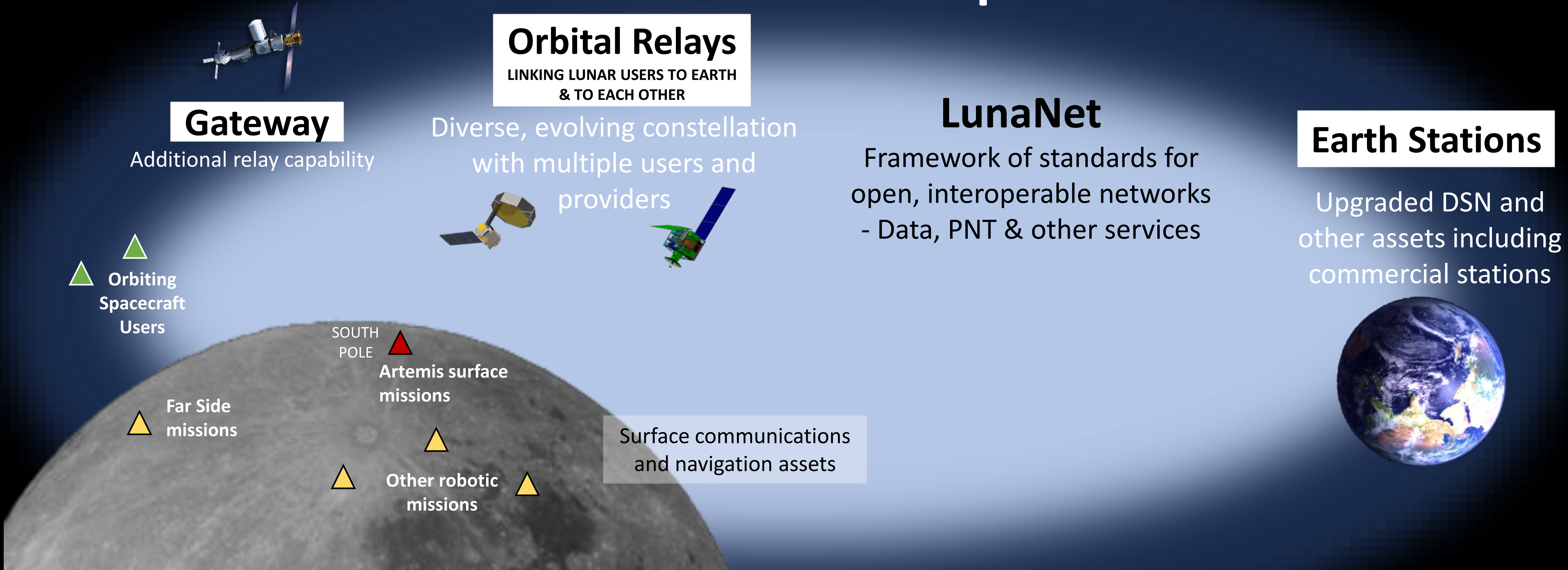
Preliminary Lunar Relay Services Requirements Document (SRD)

Preliminary Release Date: 05/17/2022

LCRNS CMO This document has been released as a DRAFT version in the NASA/GSFC TDMS system NASA/GSFC concurs with this current version only.

National Aeronautics and Space Administration

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

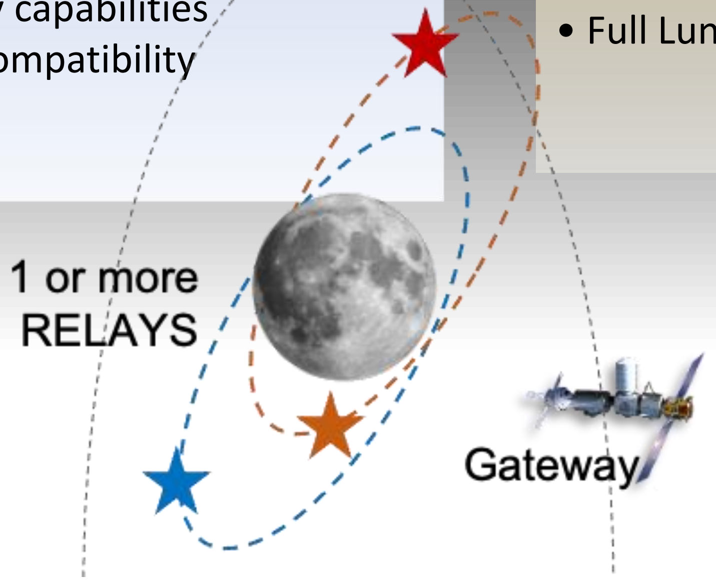
NEEDS
- Global coverage
- Longer, more complex missions, greater mobility

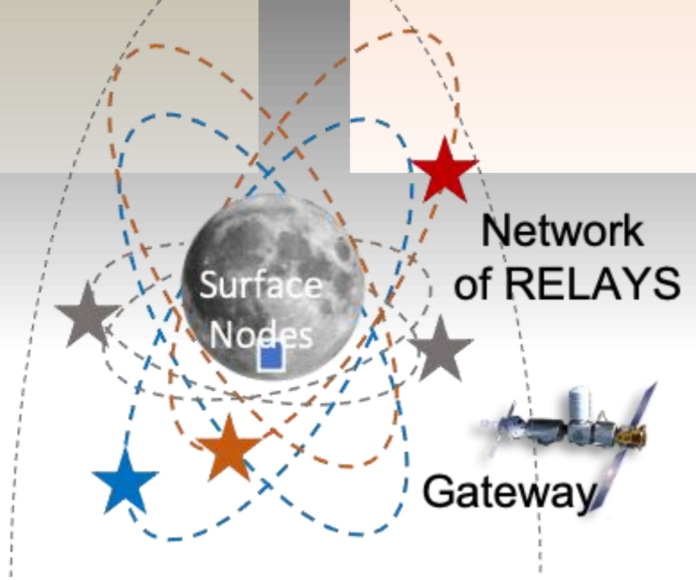
IMPLEMENTATION
- Comprehensive relay network
- Surface comm & nav assets
- Full LunaNet services

Far-Term

NEEDS
- Sustained surface and orbital presence

IMPLEMENTATION
- Evolution of infrastructure
- Infusion of new technology





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

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 proposed Lunanet standards has been drafted and can be found at the link below.
https://go.nasa.gov/3BQrCOk

Lunanet articles of note:
https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=4773&context=smallsat
https://doi.org/10.1109/AERO47225.2020.9172509

Enabling Lunar PNT:
GPS Initiatives

- **GPS III Space Service Volume**
  - Stabilized main lobe signal with spillover to support high-alt. users
- **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**
  - 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
  - Late 2020: IIR/IIR-M antenna gain pattern data (re-release), GPS III SVN 74-77 phase center, group delay, and inter-signal bias data
  - **2021: GPS III SVN 74–78 data updates**
  - **2022: GPS III antenna pattern release**

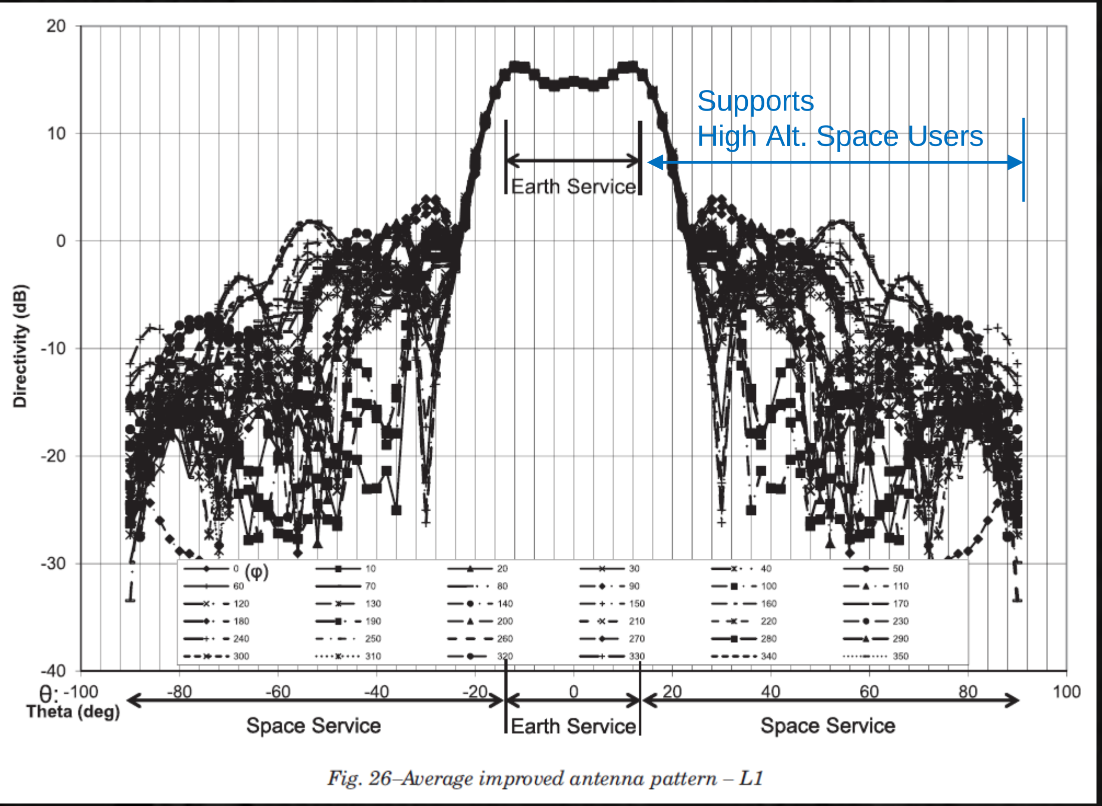
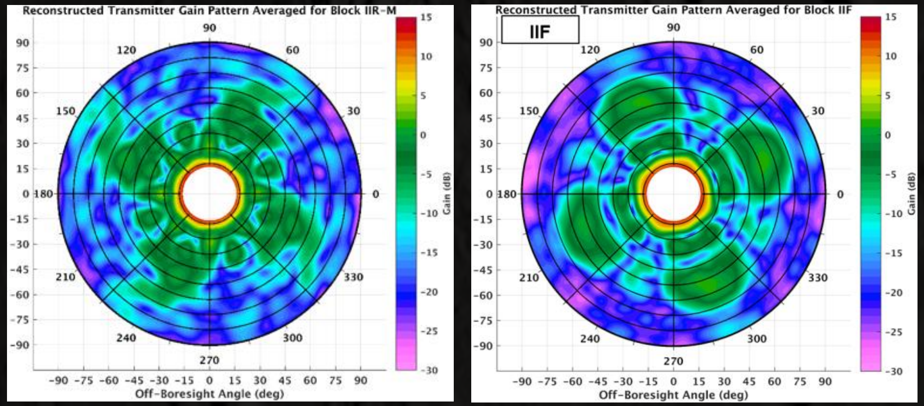


Fig. 26–Average improved antenna pattern – L1

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.



NASA GPS ACE Reconstructed Patterns for Block IIR-M (left) and IIF (right)

Source: https://doi.org/10.1002/navi.361

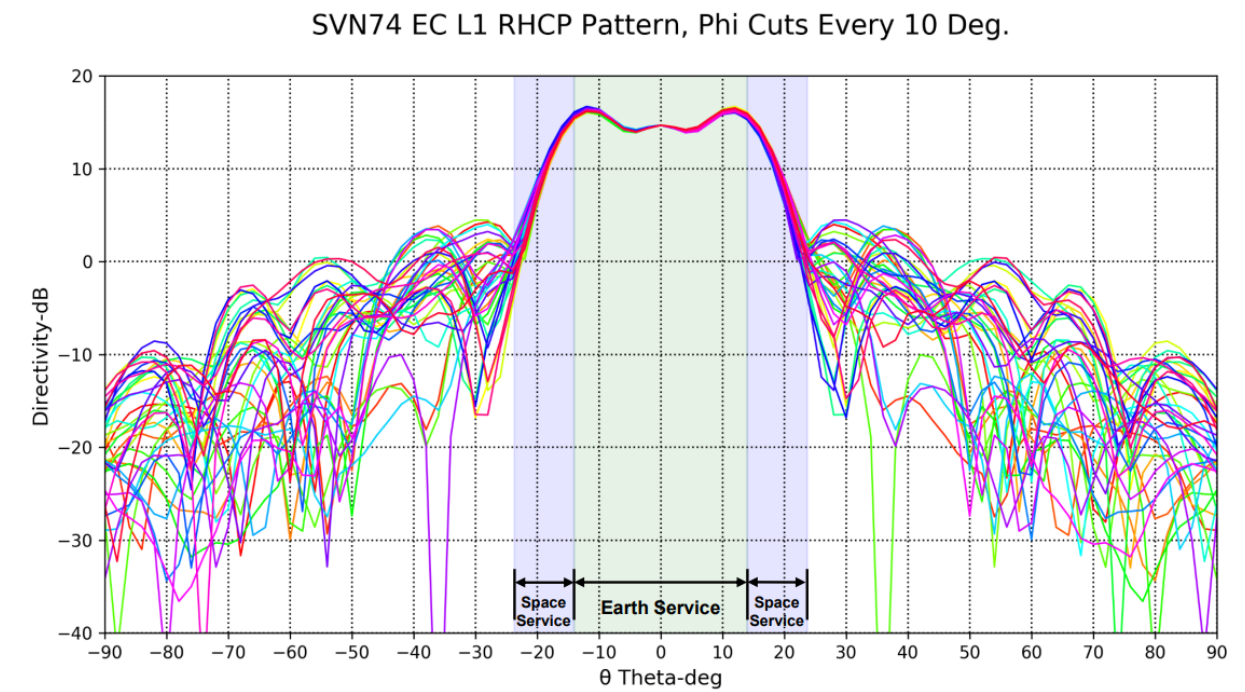
GPS III antenna pattern release

- GPS has released key technical data for GPS III SVN 74–78, including:
  - Antenna gain patterns
  - Antenna phase center
  - Group delay
  - Inter-signal corrections

- This is responsive to recommendations from both WG-B and WG-D.

- This type of data is critical to support high-accuracy applications and use within the Space Service Volume, including new lunar applications of GNSS.

- Gain pattern data includes ground-measured directivity and phase for all open signals: L1, L2, L5 w/ resolution 2° in theta, 10° in phi



All data is available from USCG NAVCEN:
https://www.navcen.uscg.gov/gps-technical-references

Technology Updates

SL-15

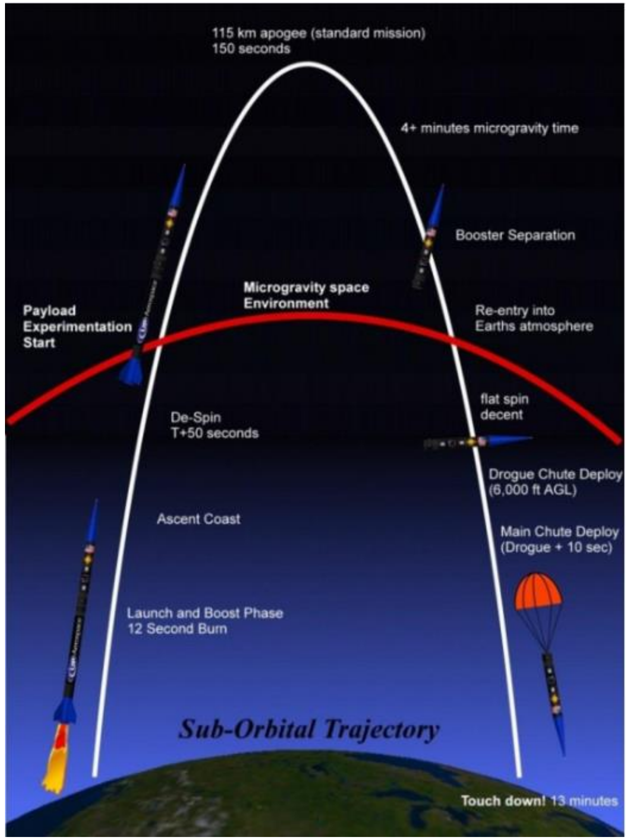
Source:
Ms. Lisa Valencia, Senior Systems Engineer, Overlook Systems Technologies

SL-15 Launch with AFTS and GNSS

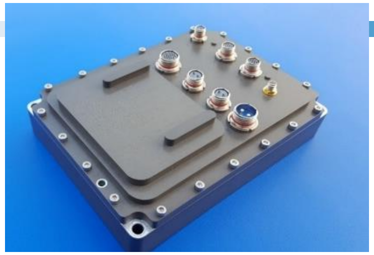
- NASA has two International Agreements with the Italian Space Agency (ASI) and with the European Space Agency (ESA) to fly two GPS-Galileo receivers on a sounding rocket
- Builds on the success of the SL-14 launch
  https://www.youtube.com/watch?v=fE_S88wzWzM
- SL-15 Objective: Assess GPS-Galileo performance in a highly dynamic environment, including potential to augment GPS in range safety system
- Includes two multi-GNSS receivers, one GPS receiver, and two AFTUs on UP Aerospace Space Loft (SL)-15 sounding rocket

SL-15 Mission provided by NASA's Flight Opportunities Program:
-Scheduled for launch in November 30, 2022 from Spaceport America, NM
-Utilizing L1/E1/L2/E5a

Mission profile
- Launch and boost phase (12 s)
- Ascent coasting until 100 km Apogee
- Descent, re-entry, and landing
- Total duration: 13 minutes
- Maximum speed: 1400 m/s
- Maximum acceleration: 13.5 G
- Maximum Spin rate: 7 Hz



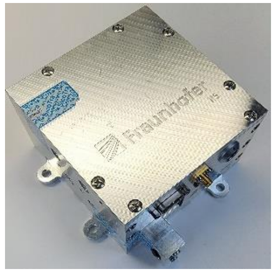
SL-15 Multi-GNSS Payload Hardware



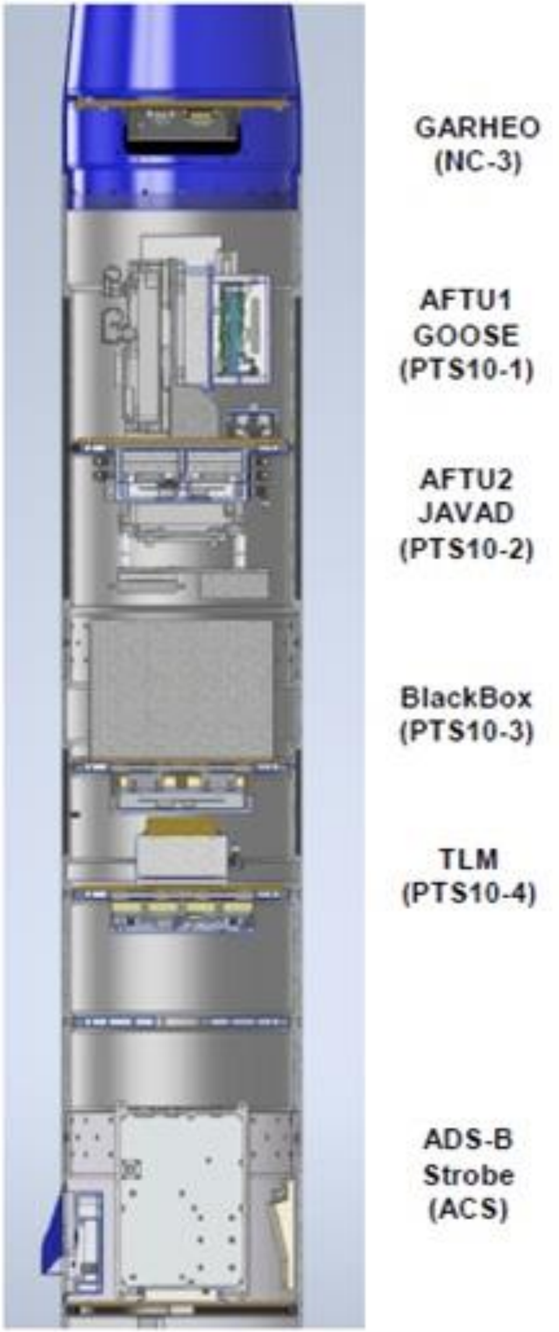
AFTU:
Weight: 1.3kg
Size: 5cm X 14cm X 19cm
Power: 7W, 5.5A, 28V DC

Javad Receiver:
Weight: 1.3kg
Size: 2cm X 5cm X 8cm
Power: 5.3W, 5.3A, 28V DC

ASI/Qascom GARHEO Receiver:
Weight: 0.7 Kg
Size: 16.8cm x 12.6cm x 3.5 cm
Power: 5W, 1A, 5V



ESA/Fraunhofer GOOSE Receiver:
- Weight: 1.591 kg
- Size: 6.9 cm x 12.0 cm x 14.55 cm
- Power: 15W, 1.67A, 12V



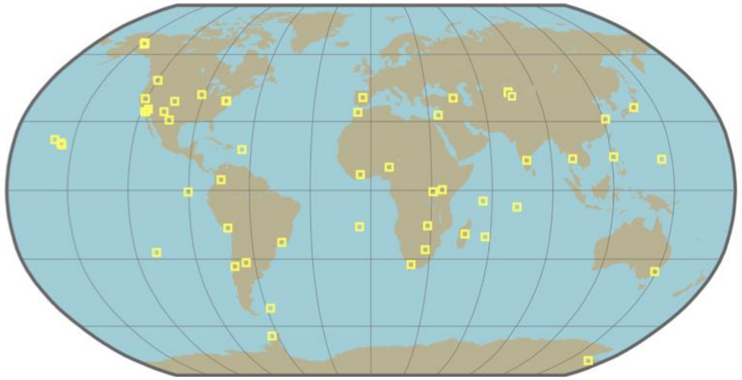
Receiver Development

Source:
TriG/Cion: Dr. Yoaz Bar-Sever, Jet Propulsion Laboratory, California Institute of Technology
NavCube: Mr. Munther Hassouneh, NASA Goddard Space Flight Center

Space Geodesy Infrastructure and Operations

JPL continues to operate the NASA Global GNSS Network (GGN) - the largest centrally-managed network contributor to the IGS

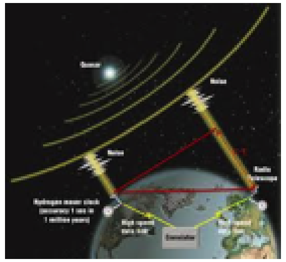
- Initiated in 1991 as the first global civilian GPS network
- Now tracks GPS, GLONASS, BeiDou, Galileo, QZSS, NAVIC
- ~60 sites streaming real-time tracking data
- Public access via CDDIS



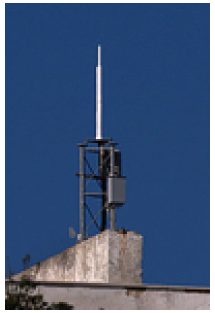
JPL's Terrestrial Reference Frame (JTRF) is derived from a time series of coordinates of tracking station for all four geodetic techniques, and reduces the degradation over time of the TRF

GNSS

SLR

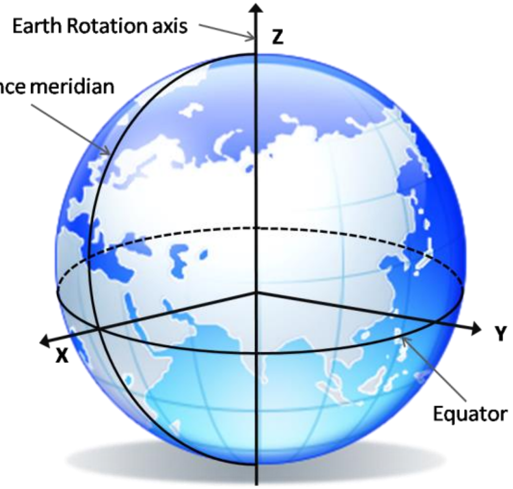


VLBI



DORIS

Terrestrial Reference Frame



International Terrestrial Reference Frame
I T R F

JPL has been certified by the IERS as one of three International Terrestrial Reference System (ITRS) Combination Centers

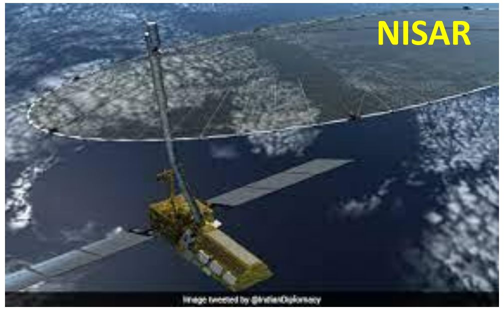
Space Geodesy Infrastructure and Operations (Contd.)

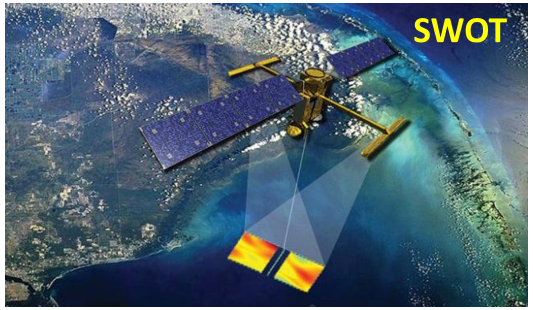
Orbit determination of all GNSS constellations is needed foundation for many NASA's science missions and applications

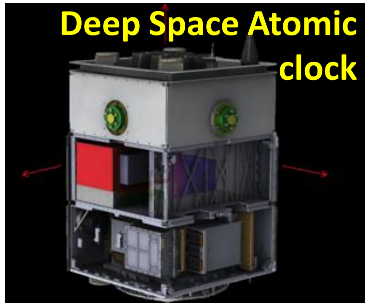
- GPS, GLONASS, BeiDou, Galileo, QZSS (real-time only), NAVIC (real-time only)
- Full spectrum of accuracy vs latency: Weekly ('Final'), Daily ('Rapid'), Hourly ('Ultra'), Seconds (real-time)

A wide variety of science missions depend on the JPL GNSS products on the reference frame they represent

- GRACE-FO, Sentinel-6, DSAC, SWOT, NISAR, COSMIC-2,…

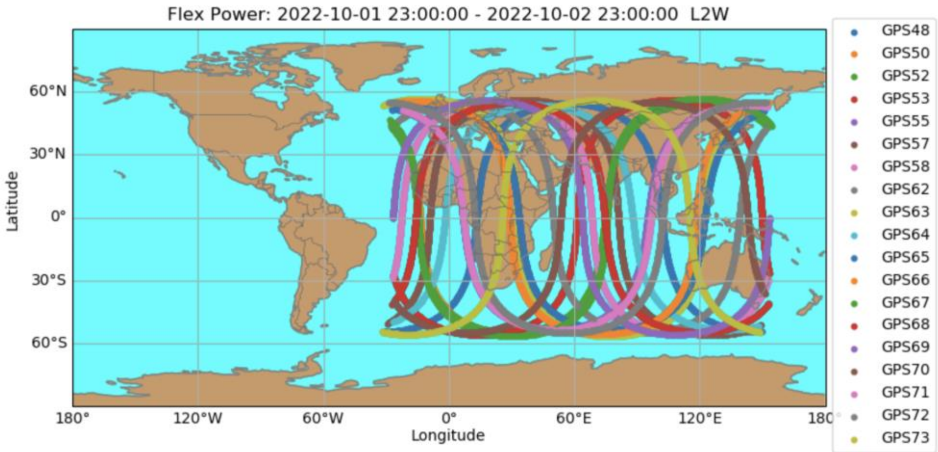






GNSS monitoring and situational assessment for all NASA missions by JPL's Global Differential GPS (GDGPS) System

- For example, real-time GPS Flex Power



NavCube 3.0 mini GNSS Receiver

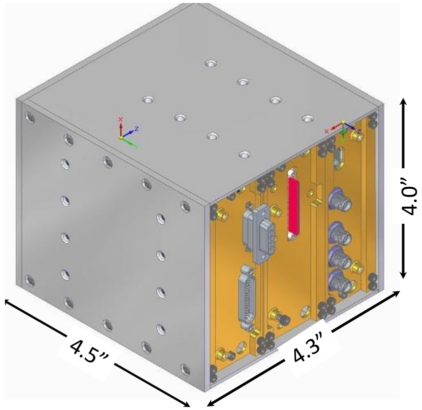
NC3m Description

- A low SWaP multi-GNSS receiver for cislunar/lunar space
  - Combined fast acquisition and weak signal acquisition
  - GPS L1 C/A and L2C currently available
  - GPS L5 and Galileo E1 and E5a in development
  - Flight software follows NPR7150.2C
- Builds on flight proven GSFC MMS Navigator software and firmware
- On-orbit upgradable, FPGA-based radiation tolerant
- Integrated GEONS navigation filter
  - Heritage dating back to 1990's and operational on MMS, GPM, NICER/SEXTANT
  - Provides critical filtering for high altitude applications with sparse visibility and poor geometry

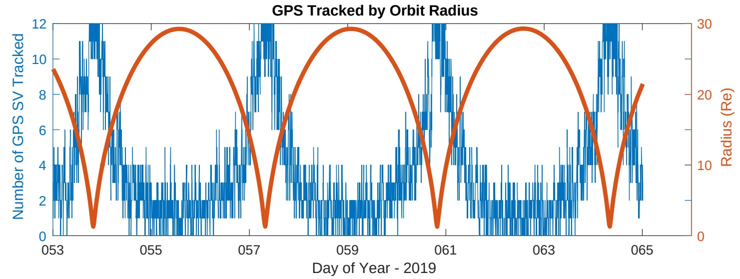
Status

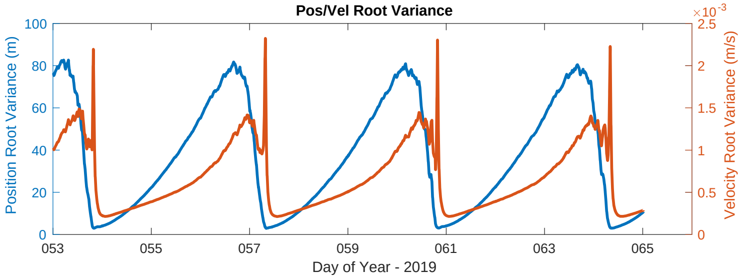
- Standalone version of NC3m completed TRL6 testing in July 2022

NC3m GNSS RF card(~3.5"x3.5")



NC3m standalone GNSS receiver

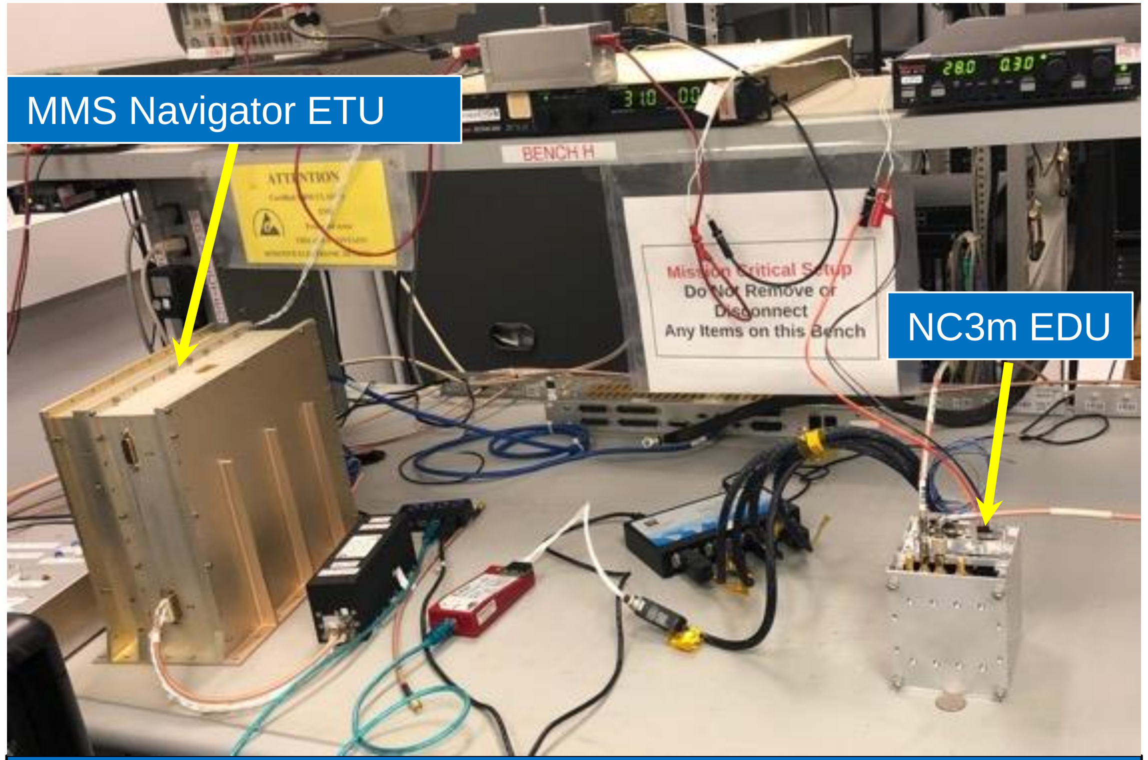




MMS Navigator on-orbit performance at 29.3 Re

NC3m Applications and Benefits

- Provide precise position, velocity, and time (PVT) for missions in all orbit regimes including lunar space
- Provides 1PPS output referenced to GPS time
- Raw GNSS signal measurements can be directly used for science in some cases (e.g., study of TEC=total electron content)
- Support reliable onboard autonomous navigation and time, reducing reliance on ground-based navigation



NC3m Development and Testing Bench

Conclusions

- NASA reports GNSS use on at least **52** current and future missions in every orbit regime, including LEO, GEO, HEO, and soon lunar.
- Ongoing technology development targets high-precision, high-altitude, and high-dynamic use cases.
- Lunar PNT remains the next frontier in space use of GNSS. NASA is pursuing this capability via multiple open, collaborative activities, including Artemis, LuGRE, and LunaNet.
- Policy coordination, including via the ICG, enables robust utilization of GNSS in space.
- New lunar PNT architectures are being devised now. We must work within the ICG and IOAG 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.

Backup

Lunar Exploration

- The Moon is again a top space exploration priority
- Current lunar exploration efforts more diverse and collaborative
  - >80 national space agencies
  - numerous private companies and partnerships
- Over 20 nations have signed the Artemis Accords to coorperate 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
- International space agencies are developing lunar PNT capabilities **NOW**; need to ensure these are interoperable, compatible and available to all
- GNSS will play a meaningful role in Lunar PNT

Gateway

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)

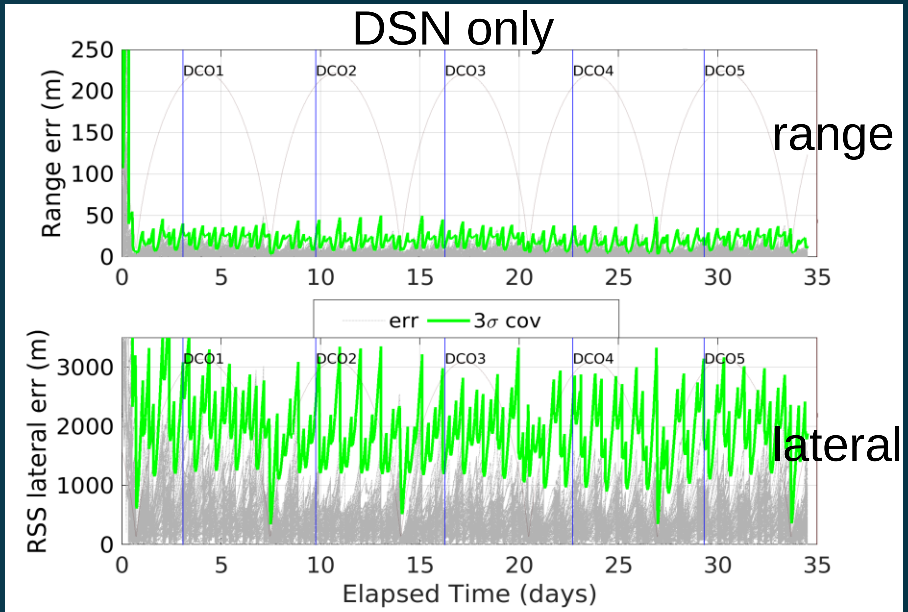
Lunar Gateway Study – Sep 2020

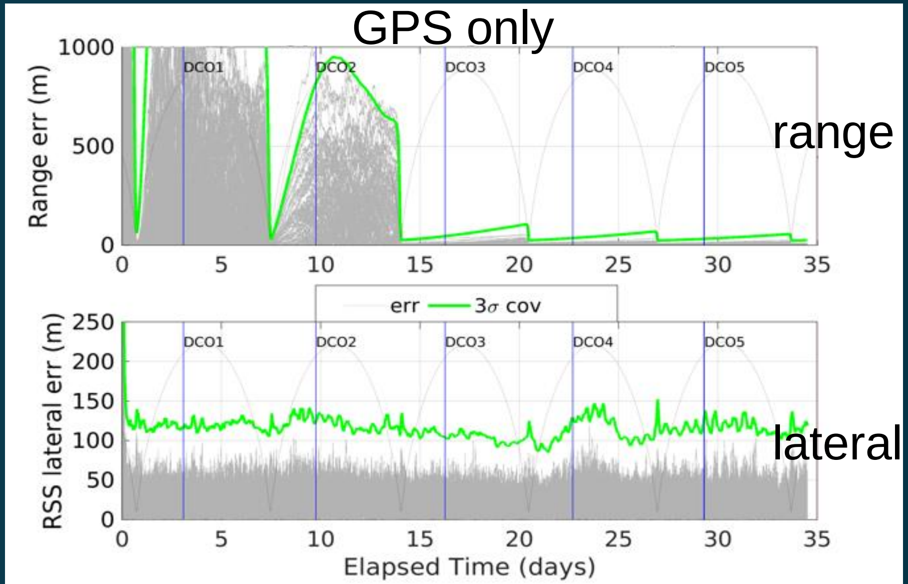
GPS Expected Performance

- 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 Architecture Solution to Meet Capacity Drivers

Deep Space Network (DSN) Lunar Exploration Upgrades (DLEU)*

- Upgrades to two 34-m DSN antennas at each of the three complexes (totaling six upgraded antennas)
  - Simultaneous operations – S+Ka-band or X+Ka-band, simultaneous Ka-band
  - Low latency data processing for > 150Mbps
  - Increased data rates – greater than 100Mbps downlink in Ka-band

Lunar Exploration Ground Segment (LEGS)*

(18-Meter Class Antenna Subnet)

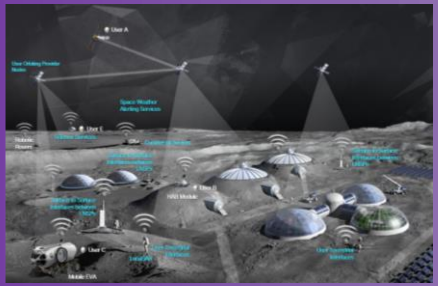
- NASA pursuing build of LEGS sites #1-3
  - Dedicated new set of antennas– 18m or greater equivalent capability– designed to support lunar missions
  - Alleviate the user load on the current 34-meter subnet, to allow for a focus on deep space support
  - Minimum of three sites around the Earth for continuous coverage
- Commercial services for LEGS 4-6 and beyond – add assets as demand grows and to meet redundancy / resiliency needs

Lunar Communications Relay and Navigation Services*

- Initial relay deployment targeted at South Pole and Far-Side, with range and range rate services – nominal commercial service procurement approach
  - Removes DTE line-of-sight comm constraint– reduces user burden
  - Continuous communication during HLS descent is easier supported through a relay link than a DTE link
- Growth in relay satellite nodes / associated services to provide more robust service and coverage
- Alternate options for a government-developed solution

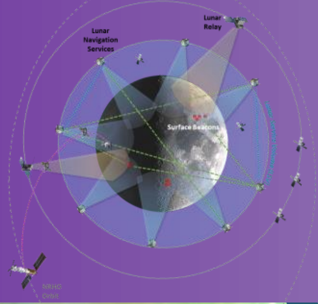
* DLEU, LEGS, LCRNS, surface wireless, LNS and optical are components of a future cooperative lunar network → LunaNet

Lunar Architecture Solution to Meet Capability Drivers



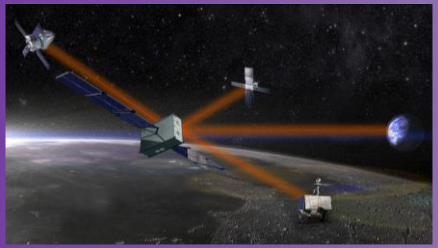
Surface Wireless Communications*

- 3GPP/5G cellular technology for a robust lunar surface C&N infrastructure that is scalable to meet long-term needs
- Essential to address surface and orbital link proliferation
- Enables direct surface/local communication and aggregates data for transition to backhaul
- Technology demonstration on Artemis III
- Fully implemented for Artemis V – connectivity between HLS, LTV, and EVA



Lunar Navigation Services*

- "Like GPS, but at / for the Moon"
- Support near term needs for 10-m surface positioning and 50-m HLS landing knowledge requirements
- Long-term support of complex surface ops, Search and Rescue (SAR) functionality, situational awareness, prediction and avoidance
- LNS deployment of minimum nodes for Artemis V



Lunar Optical Communications*

- Operational optical communications between the Earth and Moon (coherent, multi-gigabit) supports high bandwidth needs, data aggregation and relieves spectrum pressure
- LunaNet compatible, with high-speed Disruption Tolerant Networking (DTN)
- 1 m class operational optical ground station w/ adaptive optics
- Complete prototype (TRL 6) optical relay payload system

* DLEU, LEGS, LCRNS, surface wireless, LNS and optical are components of a future cooperative lunar network → LunaNet