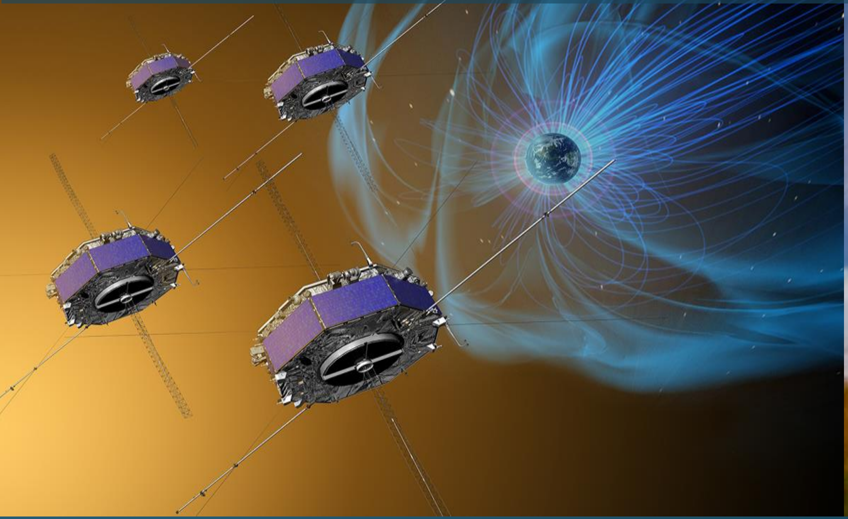
NASA GNSS Update

Joel J. K. Parker
NASA Goddard Space Flight Center

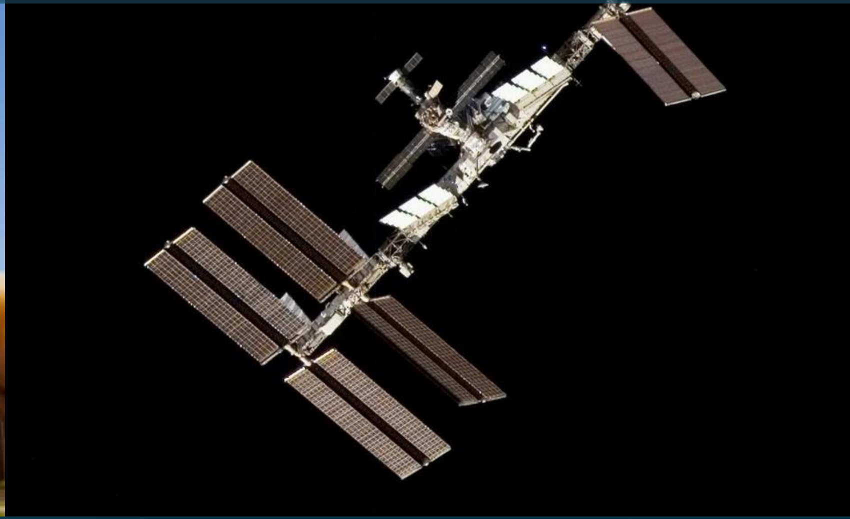
ICG-17 WG-B
17 October 2023

Real-Time On-Board PNT



Launch Vehicle Range Ops

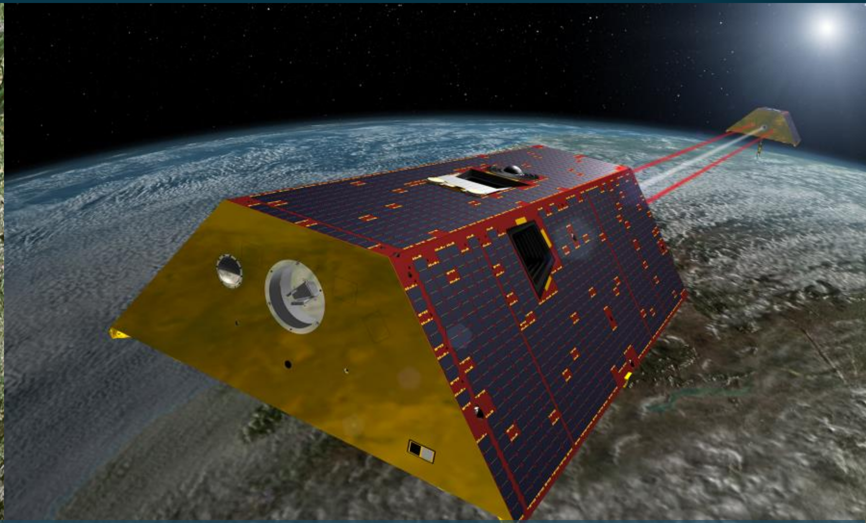
Attitude Determination



Active Space Uses of GNSS at NASA

Time Synchronization

Earth Sciences



Precise Orbit Determination

Mission Updates

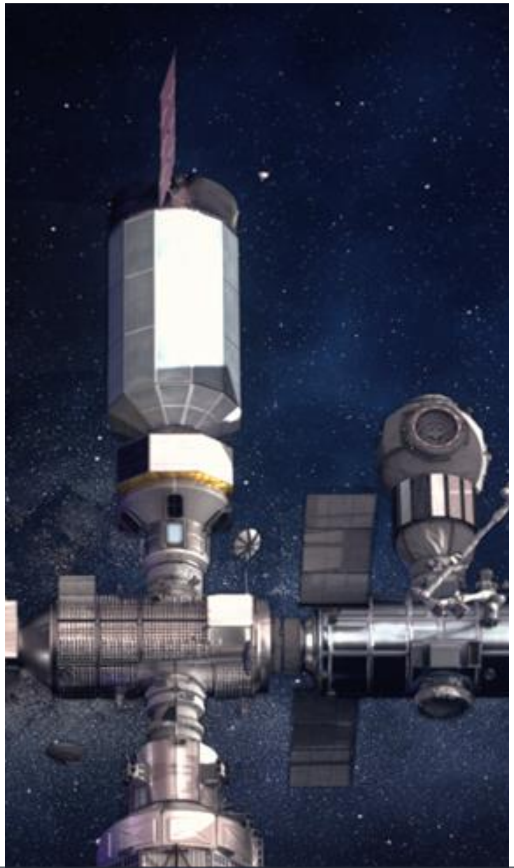
In accordance with ICG WG-B recommendation:
“GNSS Space User Database”, 2016

Lunar PNT: Evolution from Demonstrations to Flight Operations

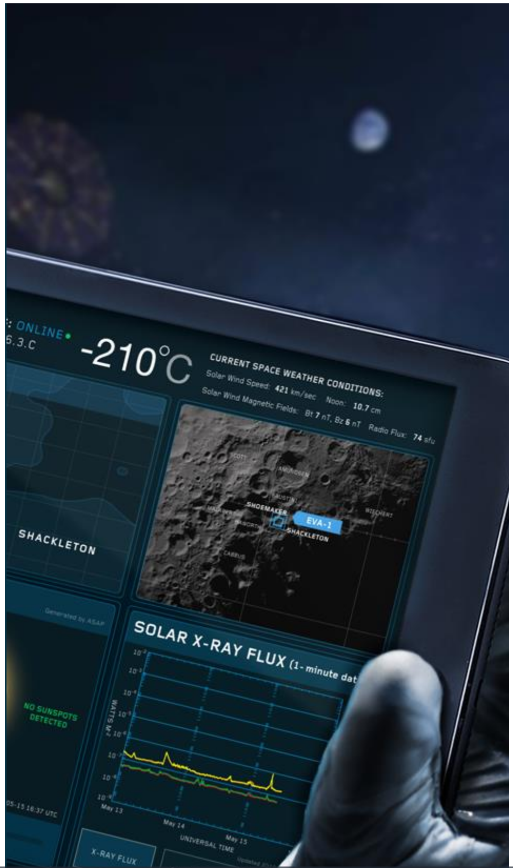
Artemis-1
(LEO receiver)
2022

LuGRE
(NASA)
2024

Lunar Pathfinder
(ESA)
2026



Gateway Payloads
(International)



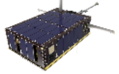
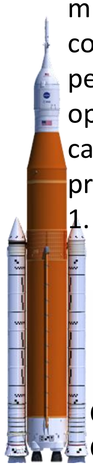
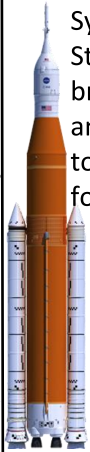
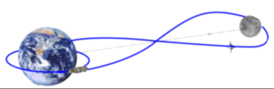
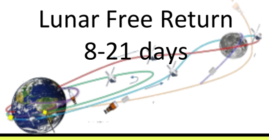
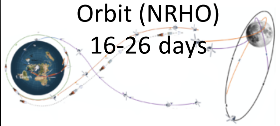
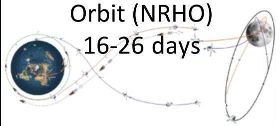
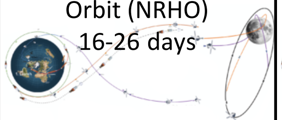
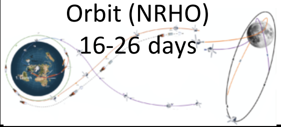
Lunar PNT Services
(International)

Terrestrial GNSS

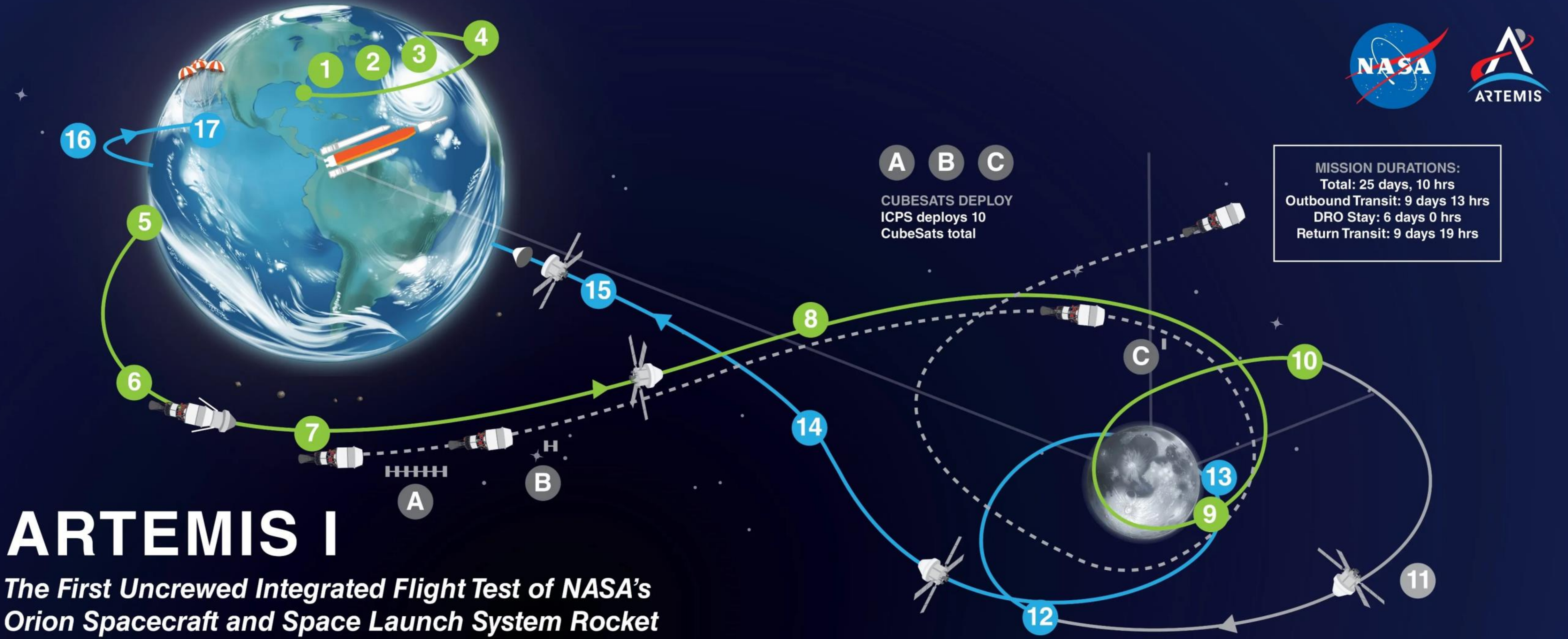
Lunar PNT Services (e.g. LunaNet)

Artemis

GPS use aboard Space Launch System

Artemis-1	Artemis-2	Artemis-3	Artemis-4	Artemis-5	Artemis-6
Nov 2022	Nov 2024	Dec 2025	2028	2029	2030
Block 1: ICPS	Block 1: ICPS	Block 1: ICPS	Block 1B: EUS	Block 1B: EUS	Block 1B: EUS
Cargo	4 Crew	4 Crew	4 Crew	4 Crew	4 Crew
 Cis-Lunar Space Mission to confirm vehicle performance and operational capability.  Uncrewed Orion Capsule  13 CubeSat Payloads	 First crewed mission, to confirm vehicle performance and operational capability, same profile as Artemis 1.  Orion Capsule + Crew	 Orion Docks to Human Landing System (HLS Starship) and brings first woman and next man back to lunar surface for 6.5 days.  Orion Capsule + Crew	 Orion Docks to Gateway, and then HLS/ Starship brings second Crew of two back to lunar surface for 6.5 days.  Orion Capsule + Crew	 Orion Docks to Gateway and HLS/MK2 Lander brings Crew of two to lunar surface for sustainable missions.  Orion Capsule + Crew	 Orion Docks to Gateway and HLS/SLT Lander brings Crew of four to lunar surface for sustainable missions.  Orion Capsule + Crew
Cis-Lunar Trajectory 11-21 days 	Multi-TLI Lunar Free Return 8-21 days 	Near-Rectilinear Halo Orbit (NRHO) 16-26 days 	Near-Rectilinear Halo Orbit (NRHO) 16-26 days 	Near-Rectilinear Halo Orbit (NRHO) 16-26 days 	Near-Rectilinear Halo Orbit (NRHO) 16-26 days 
Orbit: Honeywell SIGI with SPS Trimble Force 524D (L1 C/A Code Only) for Orbit Determination, Trans-Lunar Injection Burn and End-of-Mission disposal burn.	**Ascent**: M-Code L1/L2 in Shadow Mode for Range Safety Metric Tracking during Ascent. **Orbit**: SIGI w/SPS Force 524D	**Ascent**: M-Code L1/L2 in Shadow Mode for Ascent Tracking and Autonomous FTS. **Orbit**: Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	**Ascent**: M-Code L1/L2 as Primary for Ascent Track and Autonomous FTS. **Orbit**: Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	**Ascent**: M-Code L1/L2 as Primary for Ascent Track and Autonomous FTS. **Orbit**: Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	**Ascent**: M-Code L1/L2 as Primary for Ascent Track and Autonomous FTS. **Orbit**: Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.

Latest Mission Dates from public sources as of October 2023.



ARTEMIS I

The First Uncrewed Integrated Flight Test of NASA's Orion Spacecraft and Space Launch System Rocket

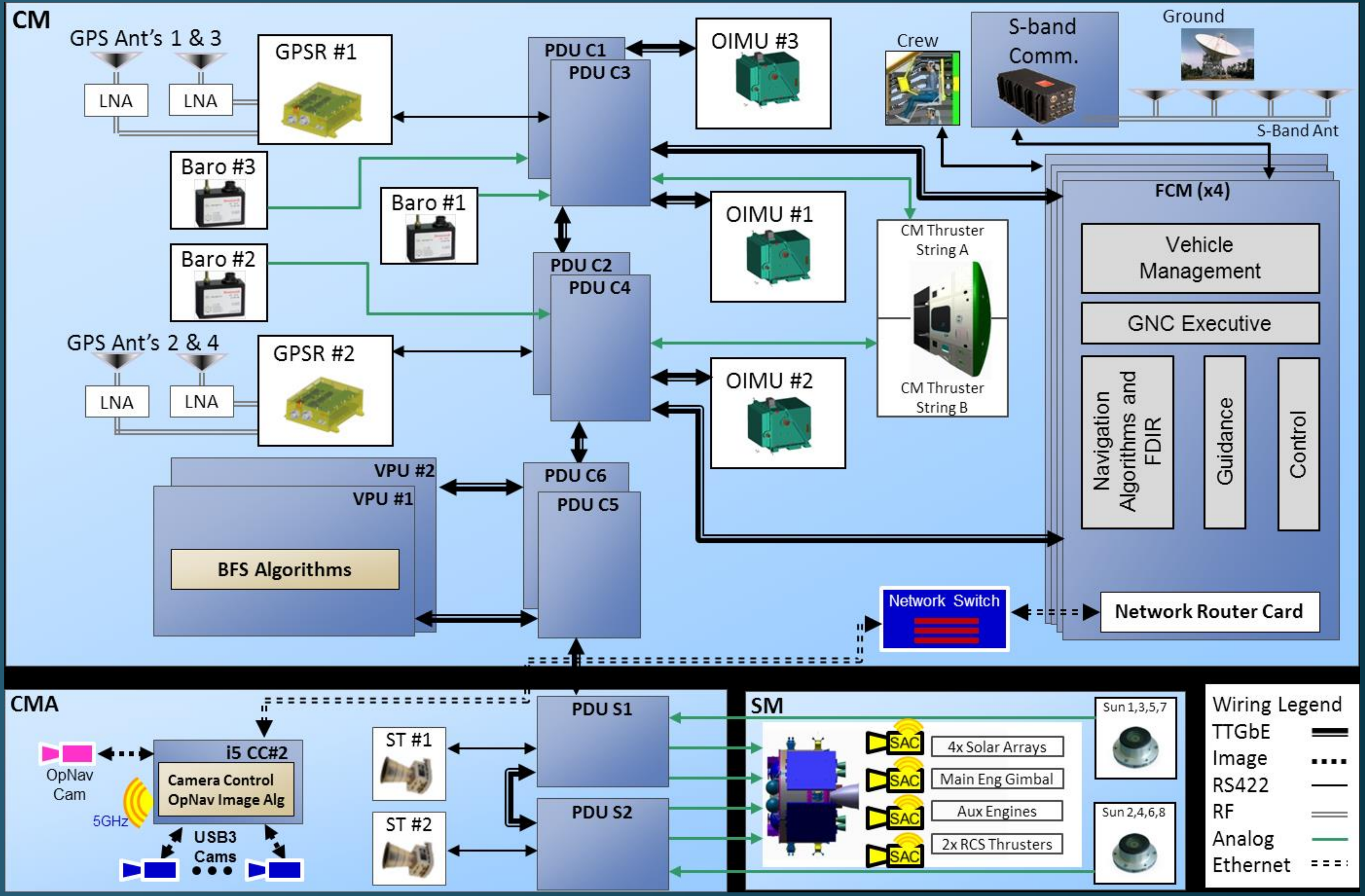
1. **LAUNCH (11/16/22)**
   SLS and Orion lift off from pad 39B at Kennedy Space Center.
2. **JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**
3. **CORE STAGE MAIN ENGINE CUT OFF**
   With separation.
4. **PERIGEE RAISE MANEUVER**
5. **EARTH ORBIT**
   Systems check with solar panel adjustments.
6. **TRANS LUNAR INJECTION (TLI) BURN**
   Maneuver lasts for approximately 20 minutes.
7. **INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION AND DISPOSAL**
   ICPS commits Orion to moon at TLI.
8. **OUTBOUND TRAJECTORY CORRECTION BURNS**
   As necessary adjust trajectory for lunar flyby to Distant Retrograde Orbit (DRO).
9. **OUTBOUND POWERED FLYBY**
   105.5 miles from the Moon; targets DRO insertion.
10. **LUNAR ORBIT INSERTION**
    Enter Distant Retrograde Orbit.
11. **DISTANT RETROGRADE ORBIT**
    Perform a half revolution (6 day duration) in the orbit 43,730 miles from the surface of the Moon.
12. **DRO DEPARTURE**
    Leave DRO and start return to Earth.
13. **RETURN POWERED FLYBY**
    RPF burn prep and return coast to Earth initiated. Closest approach in middle of burn, 81 miles.
14. **RETURN TRANSIT**
    Return Trajectory Correction burns as necessary to aim for Earth's atmosphere.
15. **CREW MODULE SEPARATION FROM SERVICE MODULE**
16. **ENTRY INTERFACE**
    Enter Earth's atmosphere.
17. **SPLASHDOWN (12/11/22)**
    Pacific Ocean landing within view of the U.S. Navy recovery ship.

Nov 16, 2022

Dec 5, 2022

Dec 11, 2022

Navigation Architecture



- Two GPS L1 C/A receivers
- Honeywell with NASA fast acquisition technology
- Other sensors:
  - 3 IMUs
  - 2 star trackers
  - 1 optical navigation camera
- Four navigation filters:
  - Atmospheric EKF
  - Attitude EKF
  - Earth Orbit EKF
  - Cislunar EKF

Details: Holt, et al, "An Overview of the Artemis I Navigation Performance", https://ntrs.nasa.gov/citations/20230000714

GPS Results

Details: Holt, et al, “An Overview of the Artemis I Navigation Performance”, https://ntrs.nasa.gov/citations/20230000714

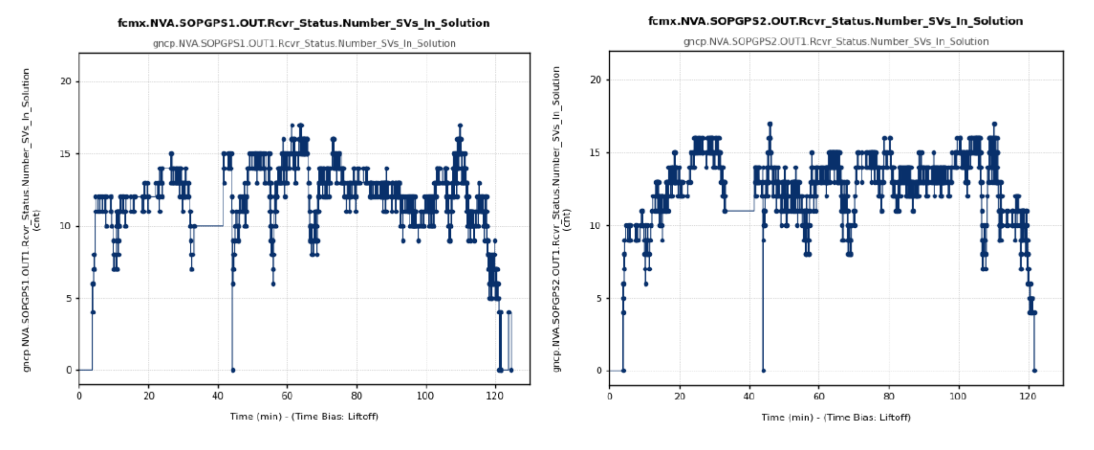


Figure 4. GPS satellite visibility on ascent

Ascent

- Tracking begins after Launch Abort System jettison
- Orion was “passenger” during ascent; SLS in control
- Data shown for first 120 min (LEO)

Reentry

- Zero time: entry interface; splashdown around +20 min
- Good tracking before and after plasma blackout
- Dropout during exo-atmospheric skip
- Rapid navigation filter convergence and low noise levels

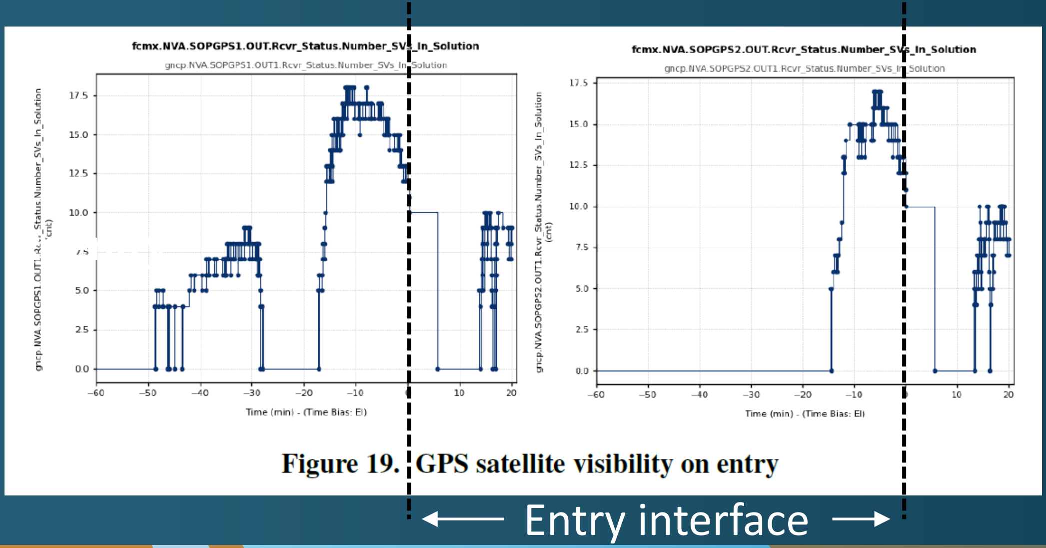


Figure 19. GPS satellite visibility on entry

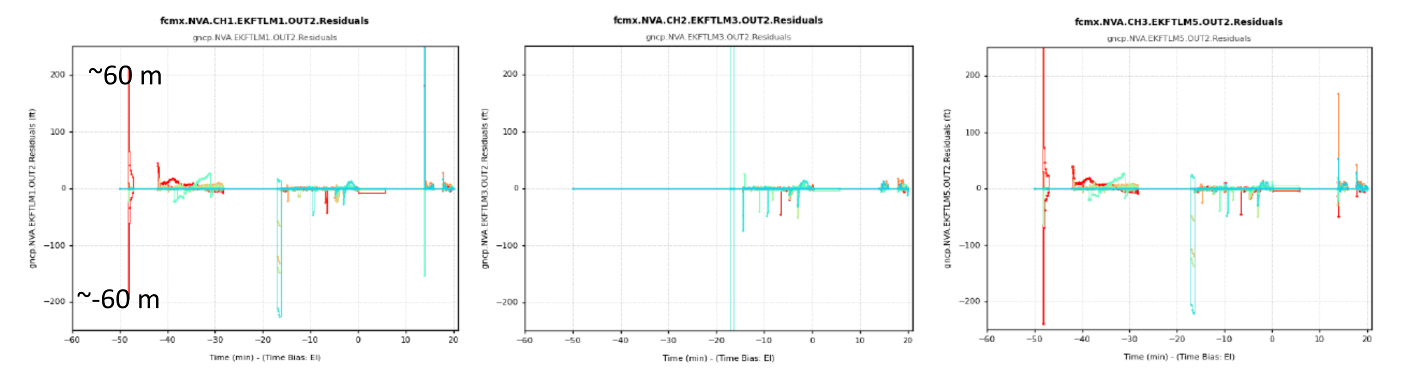


Figure 20. GPS residuals on entry

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

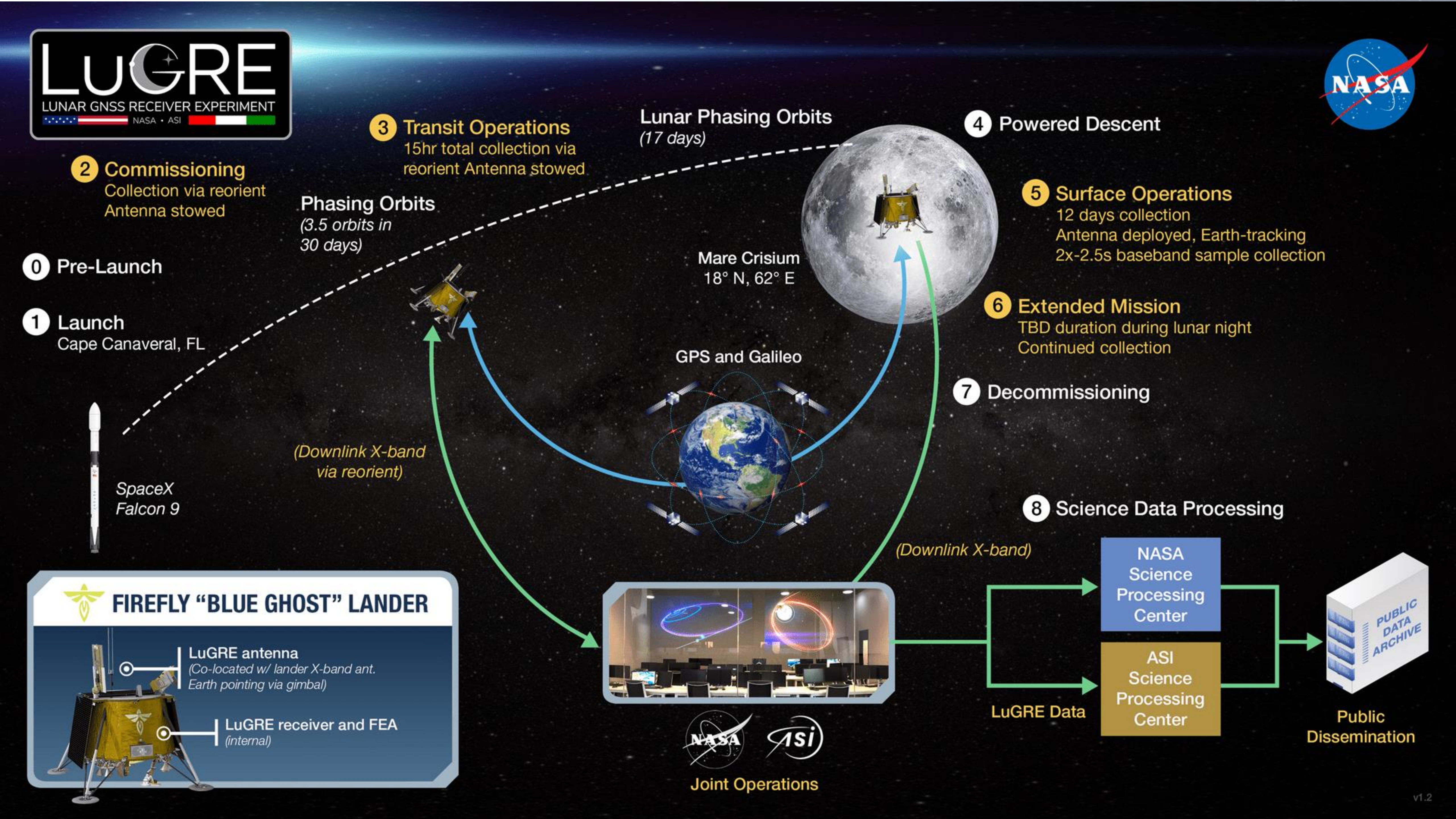
Utilization

- 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

- CLPS Draft RFP Jul 2020
- CLPS Final RFP Oct 2020
- LuGRE Checkpoint A Mar 2021
- LuGRE Checkpoint B (SRR) May 2021
- LuGRE Checkpoint C Step-1 EPR Aug 6
- LuGRE Checkpoint C Step-2, CDR Sept 13-14,30
- LuGRE Checkpoint C Programmatic Sep 30, 2021
- ETU Delivery Perf Test Start Sep 30 2021
- EQM Testing In Italy Jan/Feb, 2022
- EQM w/.9 beta SW Delivery Mar 7, 2022
- EQM beta 1.1 SW delivery June 21, 2022
- Checkpoint- D FM TRR (May 31, 2022)
- EQM & FM Testing (July-Oct 2022)
- **Payload Delivery to Firefly NLT Feb 23, 2023**
- **Lander IRR, TRR, Ops Dry-runs, Launch rehearsal, etc. 2023–2024**
- **Launch+Ops 2024**
- Science Data Processing 2024-2025

We are here


LuGRE
LUNAR GNSS RECEIVER EXPERIMENT
NASA • ASI
NASA
0 Pre-Launch
1 Launch
Cape Canaveral, FL
SpaceX
Falcon 9
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
6 Extended Mission
TBD duration during lunar night
Continued collection
7 Decommissioning
Mare Crisium
18° N, 62° E
GPS and Galileo
(Downlink X-band
via reorient)
(Downlink X-band)
8 Science Data Processing
NASA
Science
Processing
Center
ASI
Science
Processing
Center
LuGRE Data
PUBLIC
DATA
ARCHIVE
Public
Dissemination
Joint Operations
FIREFLY "BLUE GHOST" LANDER
LuGRE antenna
(Co-located w/ lander X-band ant.
Earth pointing via gimbal)
LuGRE receiver and FEA
(internal)
v1.2

LuGRE Payload

Payload characteristics

1.High-altitude GNSS receiver

- Qascom receiver, GPS+Galileo L1/E1 + L5/E5
- Cold redundant configuration
- Mass: 1.3 kg
- Power: 13 W

2.Low-noise amplifier (LNA)

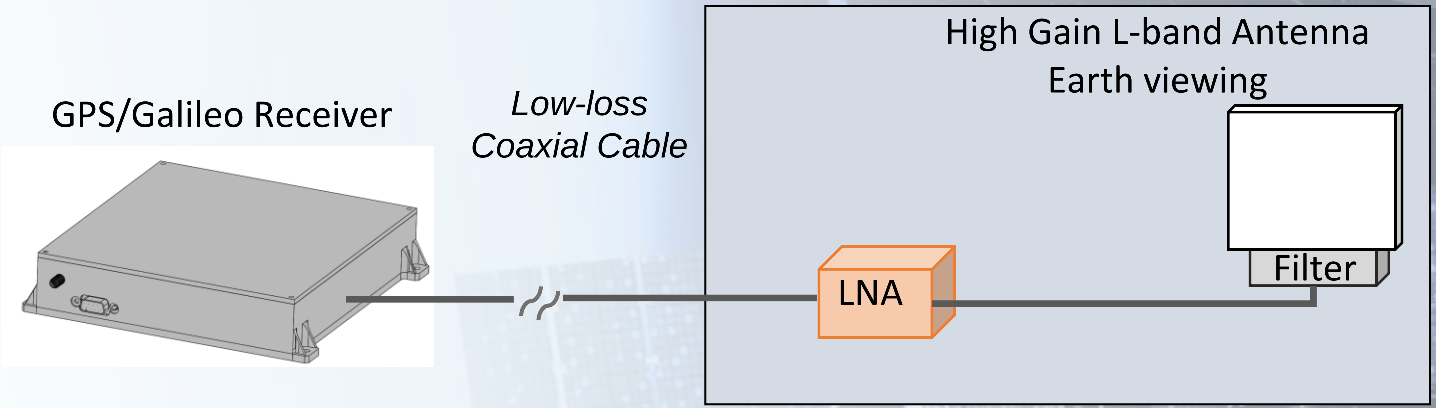
- Mass: 0.85 kg
- Power: 0.7 W

3.High gain L-band antenna + Filter

- Requires Earth pointing for GNSS reception
- 16 dBi peak gain, >10deg FOV
- Mass: 2.1 kg
- Power: 0 W (passive)

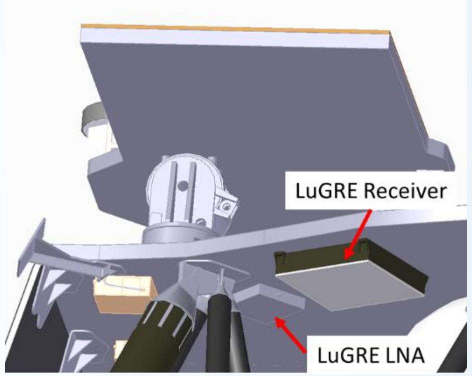
Total resource allocations

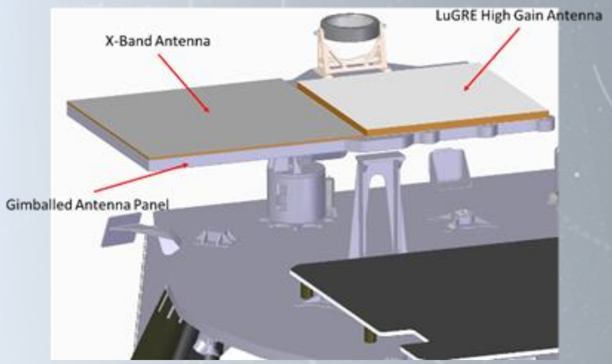
- Mass: 4.64 kg
- Power: 14 W



Operations Concept

- Transit: checkout, 15hr operations, GNSS measurement downlink
- Surface: continuous operations, GNSS measurement downlink
- Baseband sample collection, <2.5s duration, 2x during surface ops





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

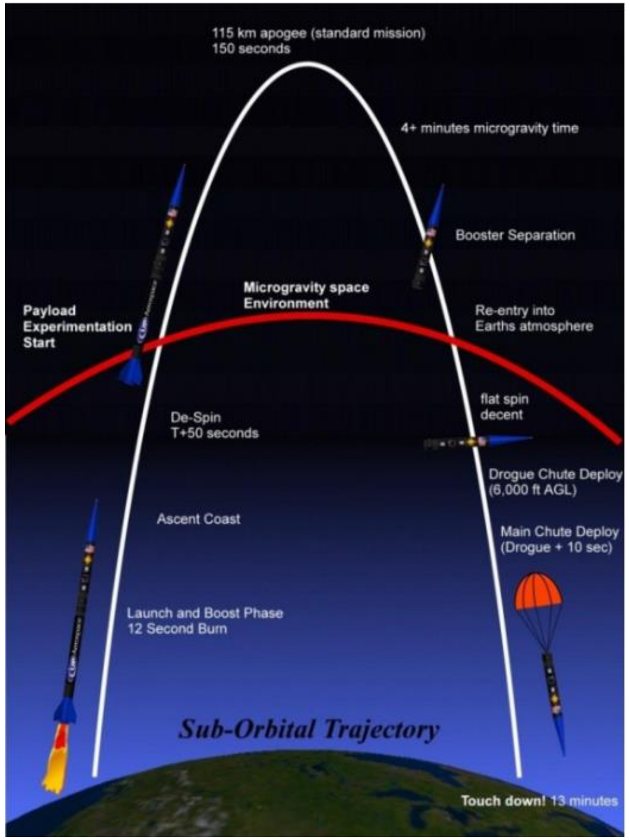
SL-15 Mission provided by NASA's Flight Opportunities Program:

-Scheduled for launch in **Spring 2024** from Spaceport America, NM

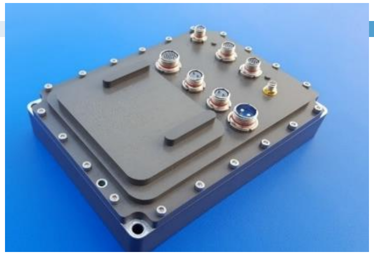
-Utilizing L1/E1/L2/E5a

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



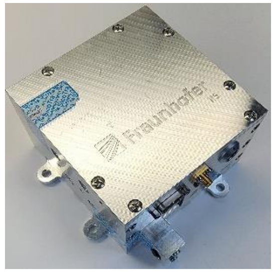
SL-15 Multi-GNSS Payload Hardware



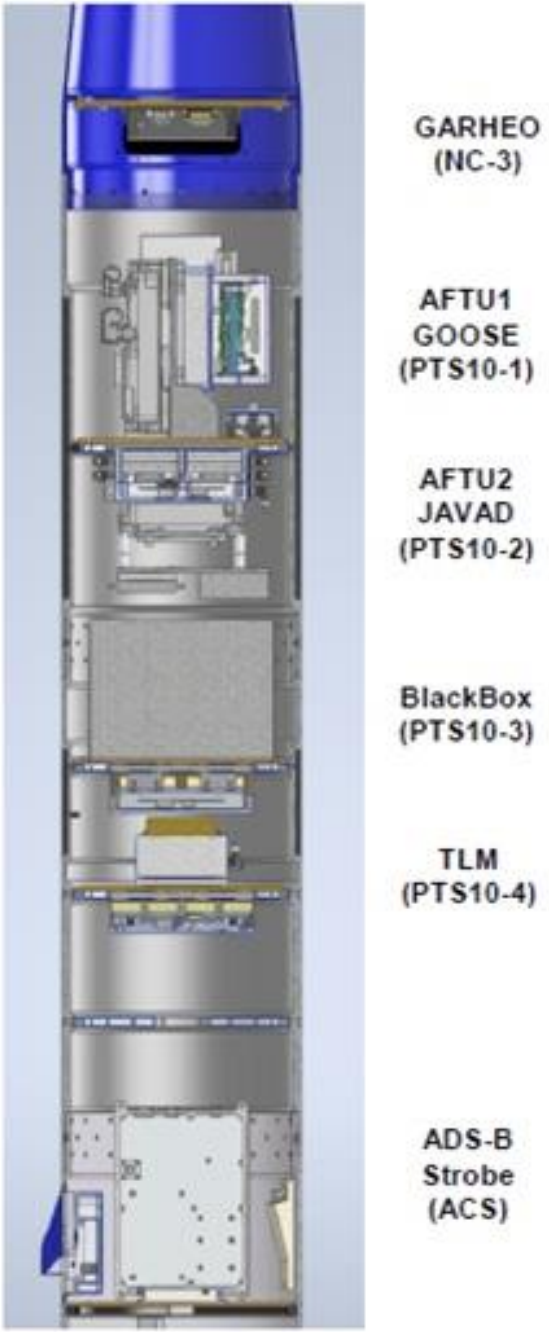
AFTU:
Weight: 1.3kg
Size: 5cm X 14cm X 19cm
Power: 7W, 5.5A, 28V DC

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



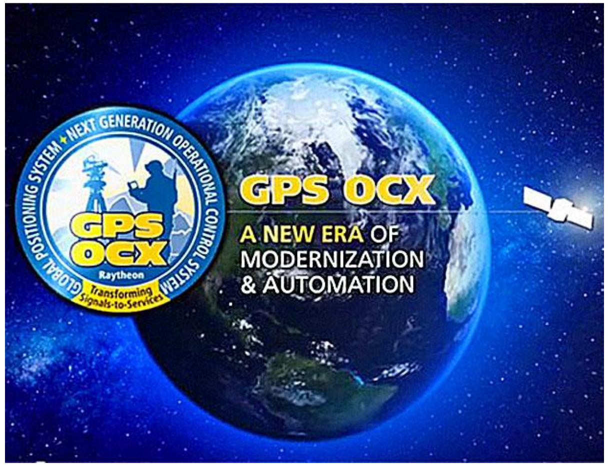
JPL

Source:
Dr. Yoaz Bar-Sever, Jet Propulsion Laboratory, California Institute of Technology

JPL's Technology Drives GPS Evolution

JPL's RTGx software is the orbit determination and prediction software for the next generation GPS operational control segment (OCX), slated for completion in 2024

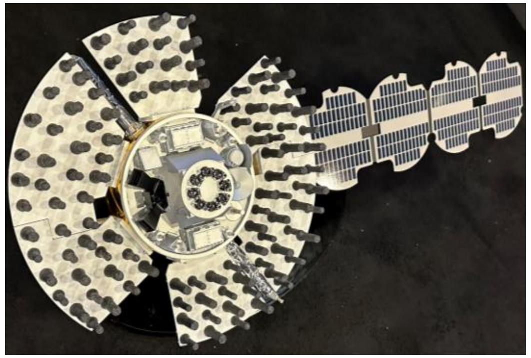
- Will usher in a leap in signal in space performance, and many other operational improvements
- JPL will help OCX ensure sustained cutting edge performance



Assessing the impact of the upcoming Block IIIF spacecraft (launching 2026/2027) on the geodetic community in terms of orbit determination and prediction due to the addition of the Regional Military Protection (RMP) high gain antenna

JPL provides the 'Cion' navigation autonomy payload, as well as ground tracking and orbit determination, for the Air Force Research Laboratory (AFRL) mission Navigation Technology Satellite – 3 (NTS-3), the first experimental GPS Satellite since 1977; vital for enhancing the resiliency of GPS to jamming, spoofing and cyber attacks; expected launch in 2024 to geosynchronous orbit

- The Cion weak-signal GNSS receiver will also survey and characterize multiple GNSS space service volume signals, never observed before, to determine their utility for cis-lunar and HEO navigation



NTS-3 spacecraft, with Cion antenna at center

GPS 3F spacecraft

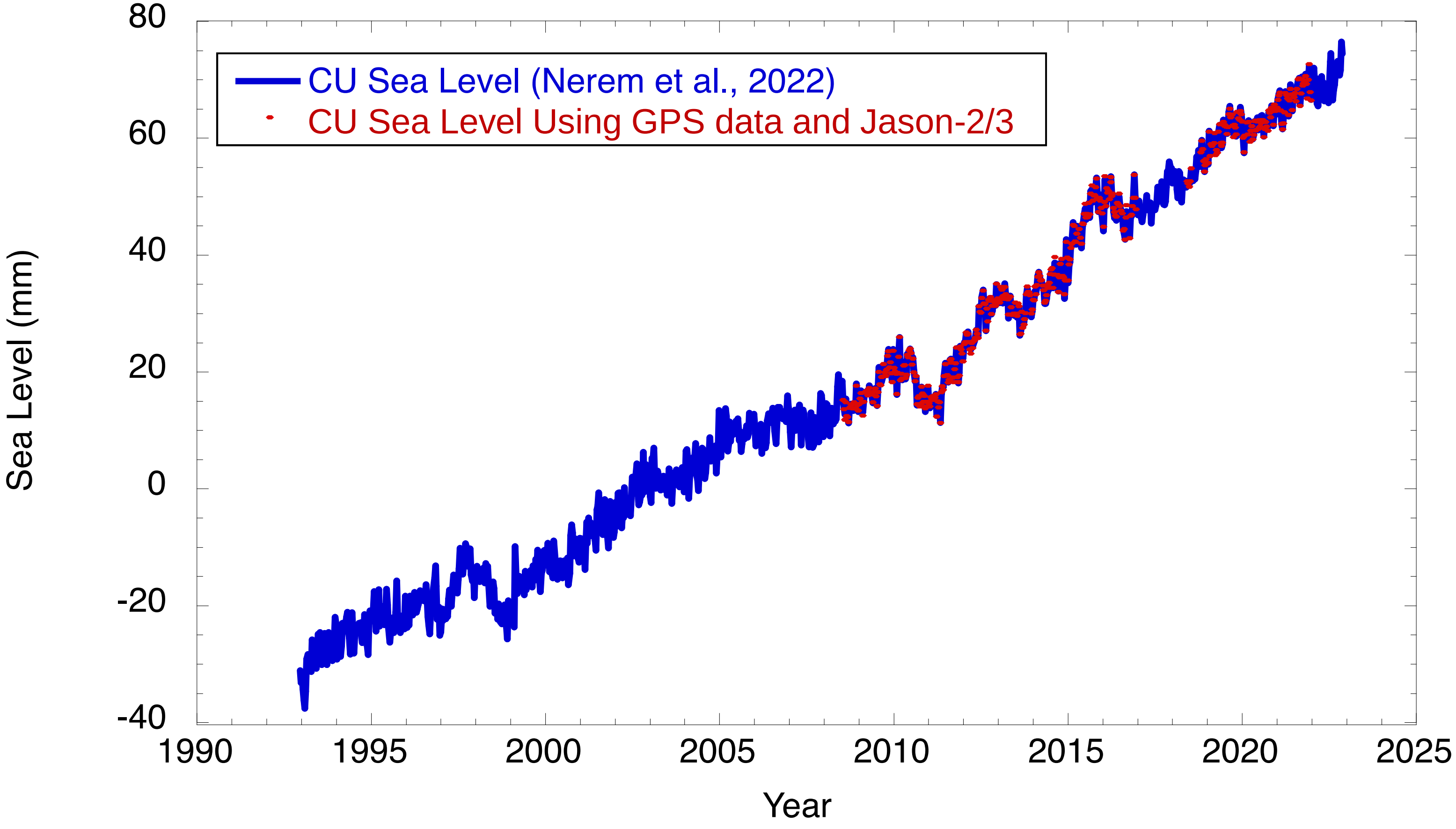
Modernized Terrestrial Reference Frame (TRF) with Space Ties Replacing Ground Ties - a Breakthrough in Efficiency and Timeliness

- **Combines techniques (GPS + SLR +VLBI) at the observation level**
- **Dispenses with traditional ground ties for SLR/GPS**
  – Connection between SLR and GPS is exclusively through space ties
  – Connection between VLBI and GPS uses traditional ground ties
- **Capitalizes on strength of GPS LEO observations**
  – Enables accurate calibration of GPS transmitter antenna patterns
  – De-couples frame estimates from GPS draconitic errors (especially Z axis)
  – Vastly improves observability and coverage relative to ground network
- **Single software system (GipsyX) for all techniques**
  – Ensures consistent standards
  – Allows constraint of common model parameters, e.g., troposphere
- **Enables short latencies (<1 month) for product generation at single center**
  – Compare to years between ITRFs, e.g. ITRF14 and ITRF20
- **Reduces burden on infrastructure and processing**
  – Resilient to the inevitable change and degradation of ground infrastructure
- **Co-sponsored by NASA and the National Geospatial Intelligence Agency (NGA)**
- **Incorporates key aspects of the Geodetic Reference Antenna in Space (GRASP) mission concept, proposed to NASA and ESA, and the recent announced GENESIS ESA mission**

Space Components of TRF

Modernized Terrestrial Reference Frame (TRF) with Space Ties Replacing Ground Ties – Interim Results

- **Indistinguishable from ITRF2020 in terms of long-term stability**
- **Confirmed powerful contribution of GPS LEO observations in augmenting ground data**
- ***With GPS data alone (no SLR, DORIS, or VLBI)*, fully competitive with ITRF-based approach to Global Sea Level, and allays concern about latent systematic errors in either technique**

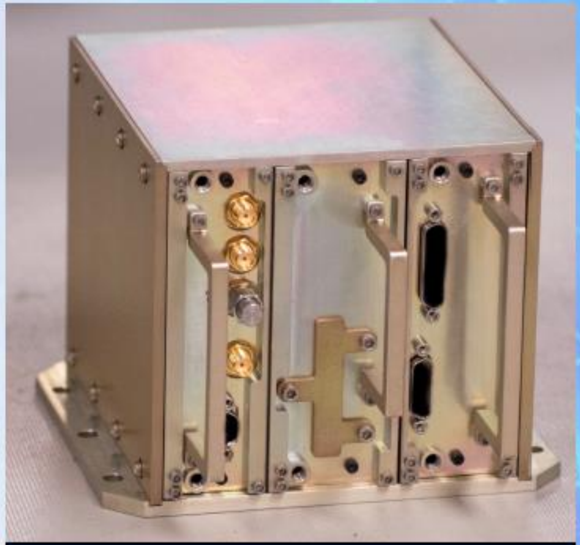


NavCube

Source:
Hassouneh, Munther A., Midkiff, Darren, Winternitz, Luke M.B., Price, Samuel R., Thomas, Luke, Hatke, David, Lee, Tyler, Bamford, William, Mitchell, Jason W., "NavCube3-mini Lunar GNSS Receiver," *Proceedings of the 36th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2023)*, Denver, Colorado, September 2023, pp. 3540-3548.
https://doi.org/10.33012/2023.19343

NavCube3–mini (NC3m) GNSS Receiver – Overview (1)

- Low-SWaP GNSS receiver for all orbit regimes, especially **cislunar/lunar space**
  - High sensitivity receiver with fast acquisition
  - GPS L1C/A and L2C (or L5) currently available
  - Galileo E1 and E5a in development
  - On-orbit upgradable, FPGA-based radiation tolerant
  - Currently at TRL6 (L1C/A and L2C)
- Includes Goddard's onboard navigation filter software: Goddard Enhanced Onboard Navigation System (GEONS)
  - Enables high-altitude operation with sparse visibility and poor geometry
- Builds on the flight proven (TRL9), high altitude, Magnetospheric Multiscale (MMS) Mission Navigator GPS receiver



NC3m GNSS Receiver

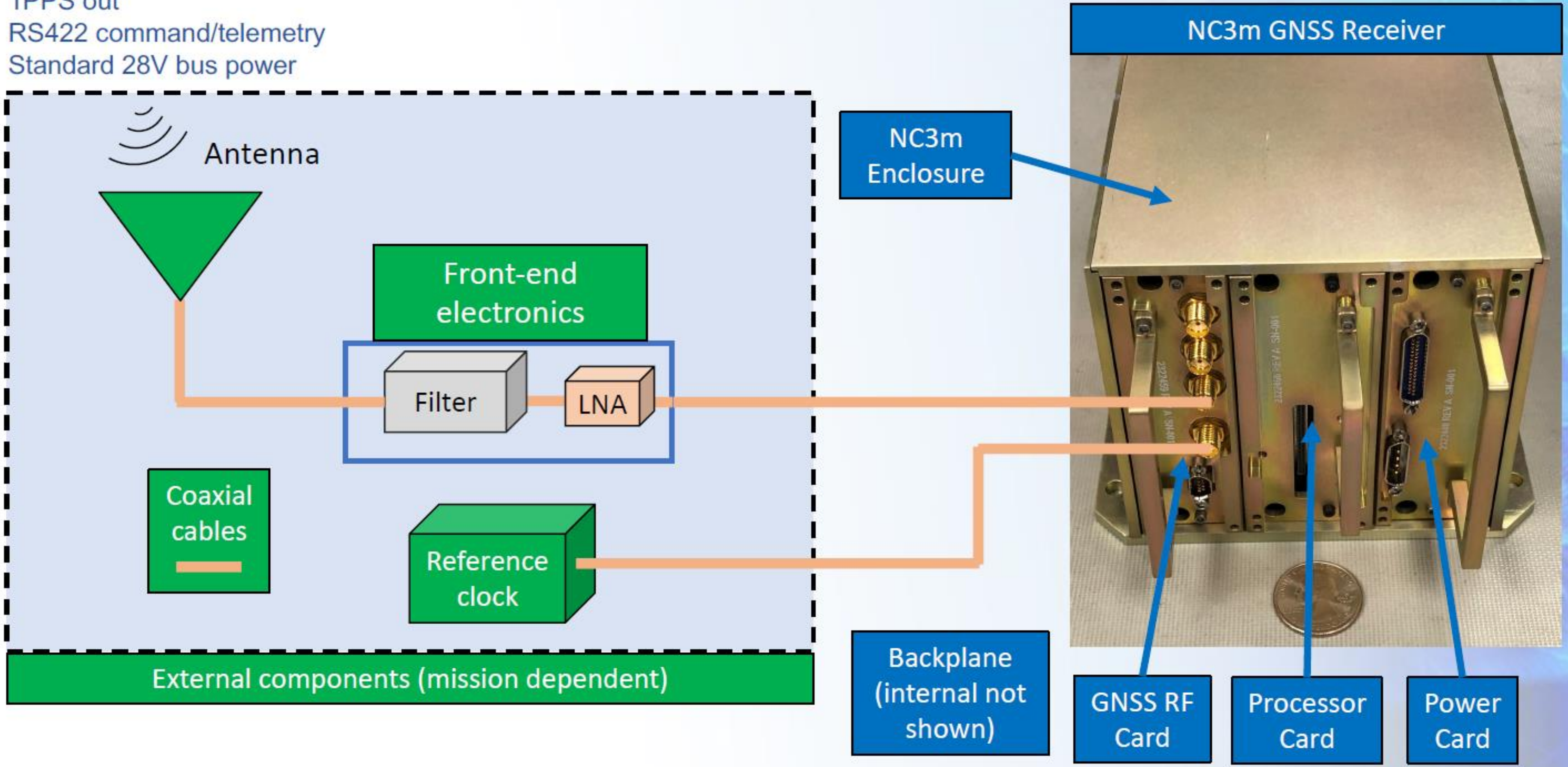
NC3m – Overview (2)

NC3m Receiver External Interfaces:

- L-band RF signal
- External reference oscillator (internal option available)
- 1PPS out
- RS422 command/telemetry
- Standard 28V bus power

NC3m Receiver SWaP

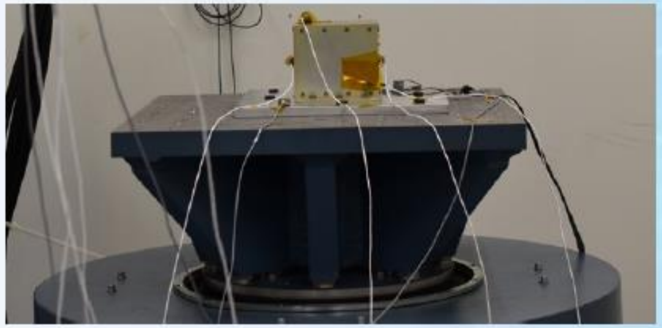
- Size: WxDxH: 5.0”x5.0”x4.0”, Mass: 1.5 kg, Power: 13 W



Technology Readiness Level 6 (TRL6) Testing

- Technology Readiness Levels commonly used by NASA and elsewhere for tracking technology maturation.
  - TRL6 is a critical level which requires *demonstration of a system/subsystem model or prototype in a relevant environment*
- Conducted on a flight-like NC3m Engineering Test Unit (ETU), using an ultra-stable reference oscillator and suitable front-end electronics
- High fidelity hardware-in-the-loop simulations developed as the comprehensive performance tests
  - Covered LEO, GEO, and lunar scenarios
  - Calibrated against MMS flight data
  - Ionosphere, broadcast, maneuver errors omitted because focus was on hardware performance. Impact of these errors is mild, mission dependent.
- Completed TRL6 testing in July 2022
  - Performance testing at NASA Goddard Formation Flying Testbed, a world-class spaceflight GNSS test facility
  - Conducted vibration, thermal vacuum, and EMI testing at Goddard environmental test facilities
- *Excellent performance demonstrated, results well matched to predictions, and passed test criteria*
- Passed TRL6 Assessment Review in Dec 2022

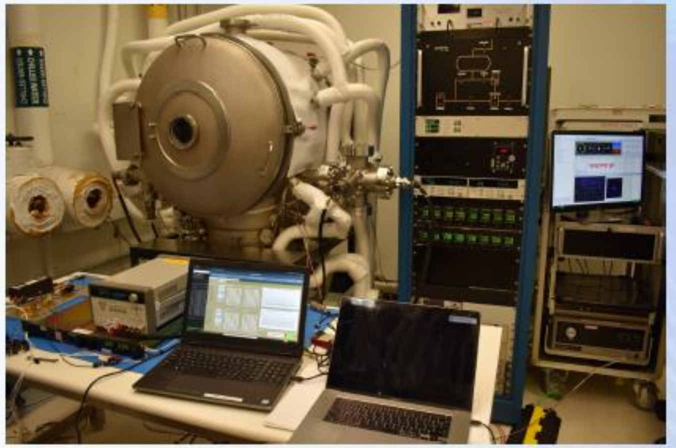
Vibration table with NC3m ETU



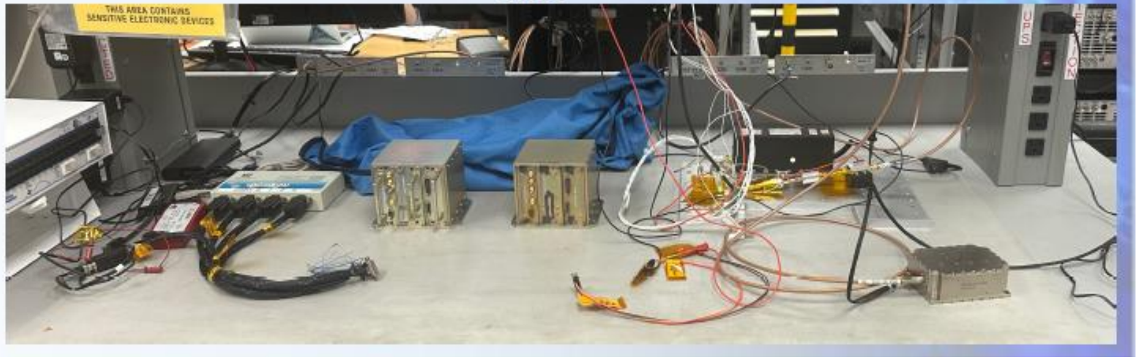
Cesium time standard

GNSS Simulator

Thermal Vacuum Chamber containing NC3m ETU

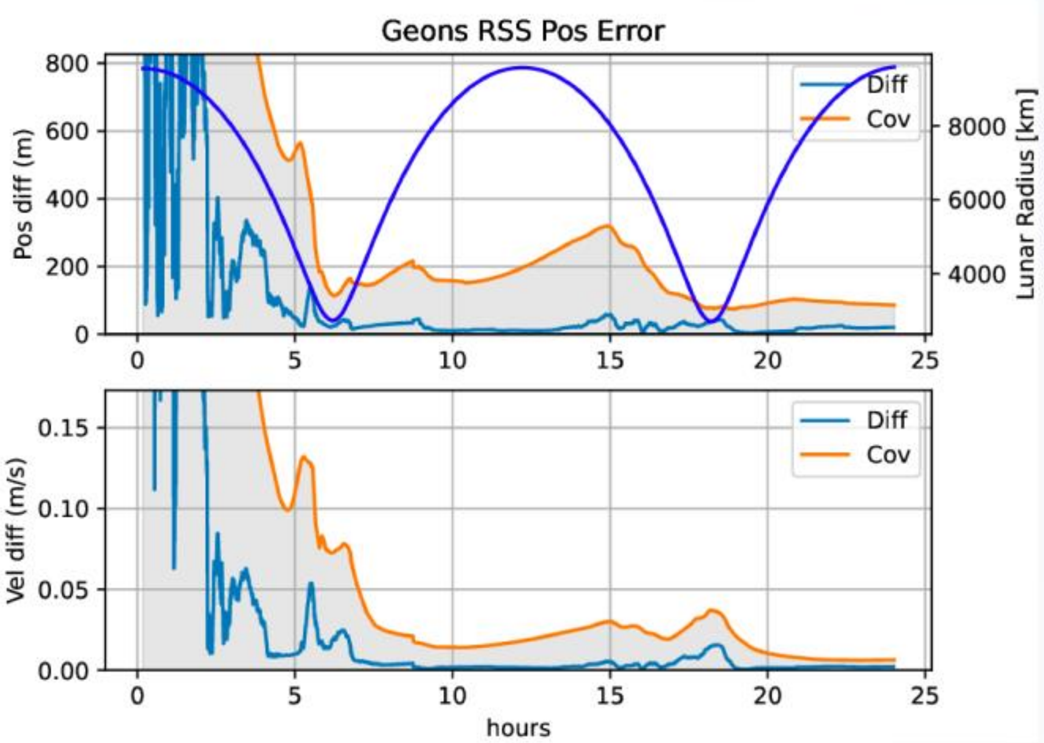


Bench top performance testing with NC3m ETU (right) and a development unit

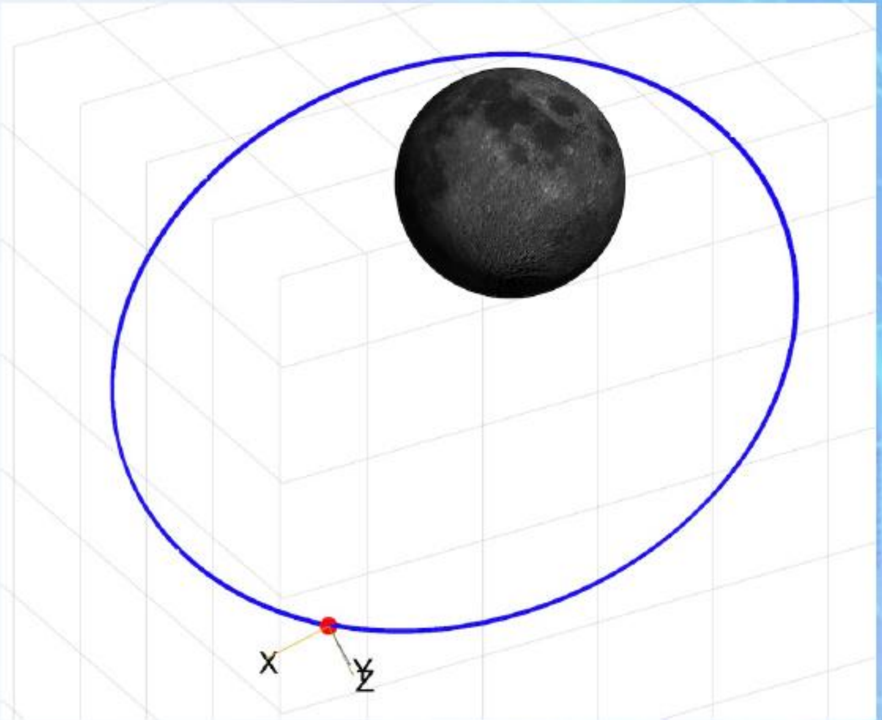


Example TRL6 test results: lunar orbit

- Reference 12-hour Elliptical lunar frozen-type orbit (ELFO) with apolune south pole coverage
- Uses simple Earth-pointed 16dBi-peak high-gain antenna model
- Achieves <100m, <1cm/s RSS error at 24 hours



GEONS RSS errors (blue) and 3x RSS covariance diagonal (orange) with orbit radius (also blue)

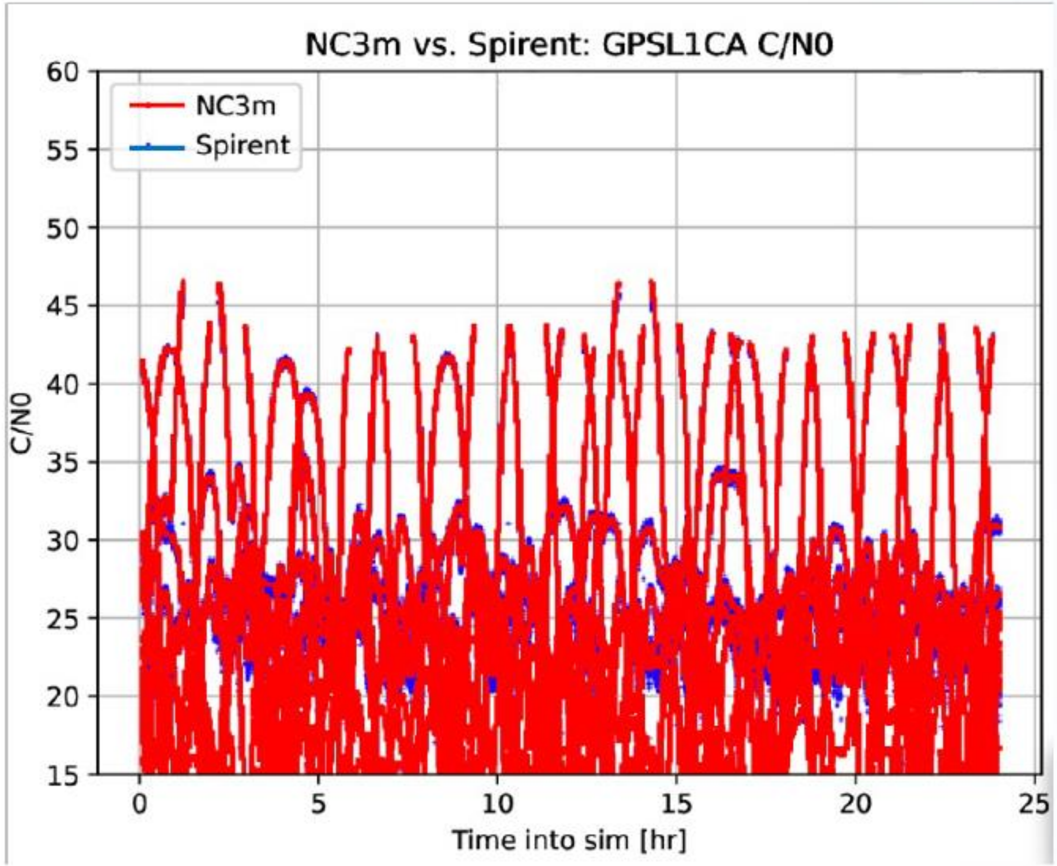


Notional 12-hour frozen orbit with apolune south pole coverage

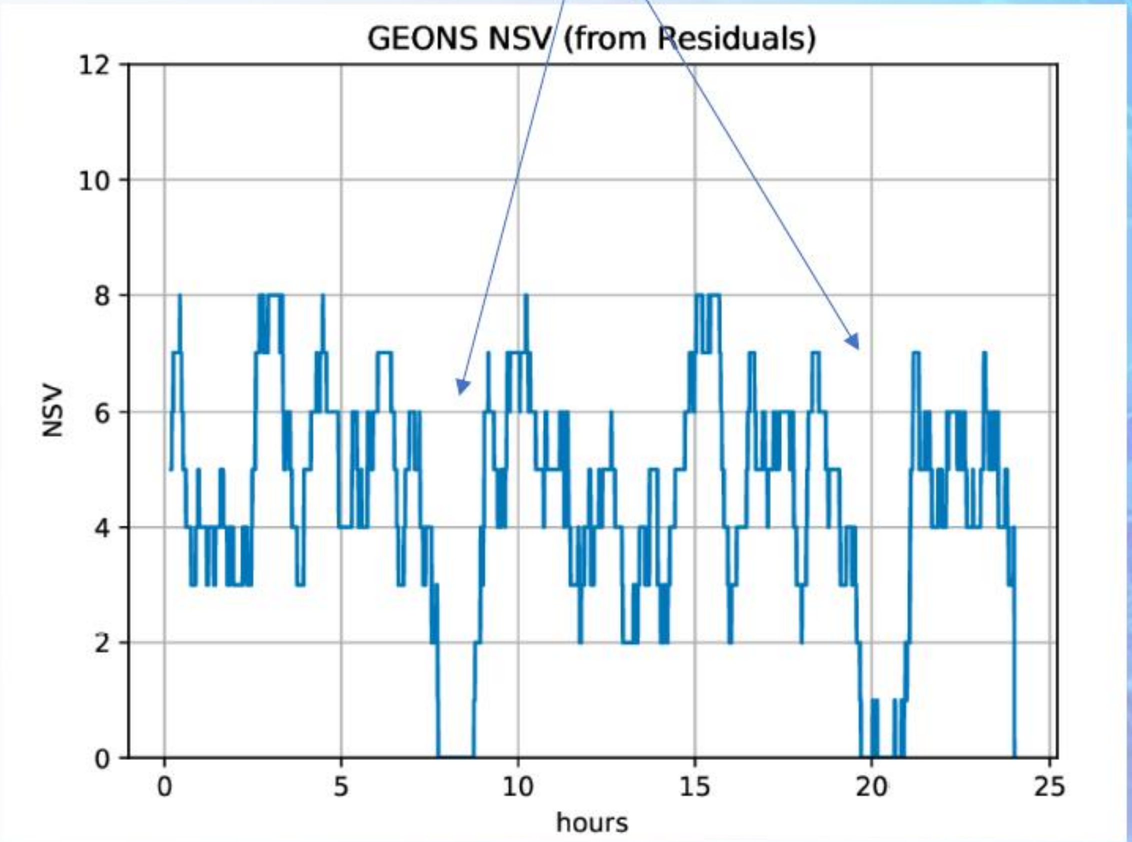
Moon Image from: https://astropedia.astrogeology.usgs.gov/download/Moon/LRO/LROC_WAC/thumbs/Moon_LRO_LROC-WAC_Mosaic_global_1024.jpg

Example TRL6 test results: lunar orbit

Drops to zero signals correspond to lunar occultations (excluded by GEONS filter, but not modelled by simulator)



Simulated vs. tracked signal to noise ratio



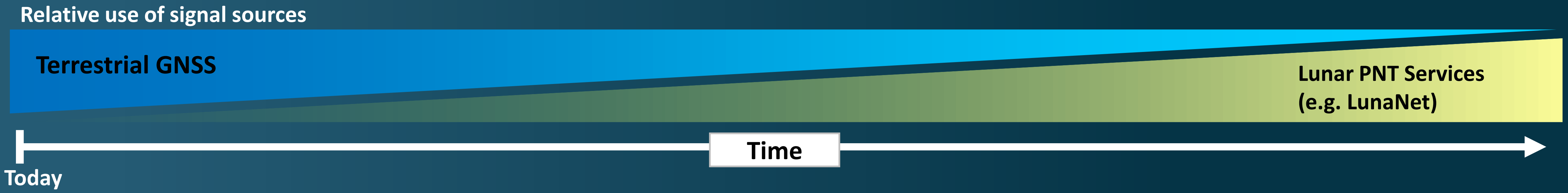
Number of GPS signals processed by GEONS

Conclusions

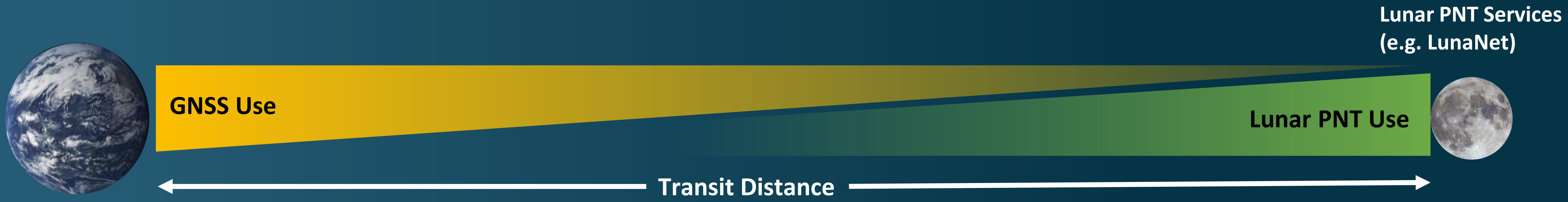
- NASA reports GNSS use on at least **52** current and future missions in every orbit regime, including LEO, GEO, HEO, and soon lunar.
- Ongoing technology development targets high-precision, high-altitude, and high-dynamic use cases.
- Lunar PNT remains the next frontier in space use of GNSS. NASA is 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.

Phased Expansion of Lunar PNT Services

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



Transit use of GNSS and Lunar PNT Services



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.

Backup

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

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