National Aeronautics and
Space Administration

NASA GNSS
Space Use Update

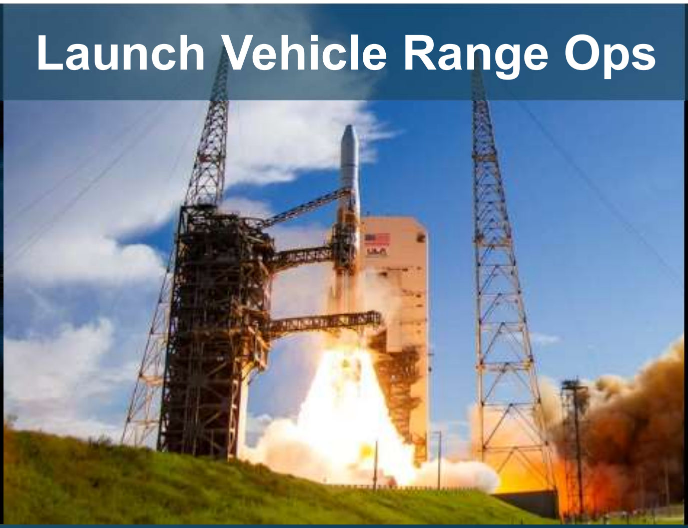
Mr. Joel J. K. Parker, PNT Policy Lead
NASA Goddard Space Flight Center

Mr. J. J. Miller, Deputy Director
Office of Policy and Strategic Communications
NASA Space Communications and Navigation

ICG-15 Working Group B
September 27, 2021

Active Space Uses of GNSS at NASA

Real-Time On-Board Nav

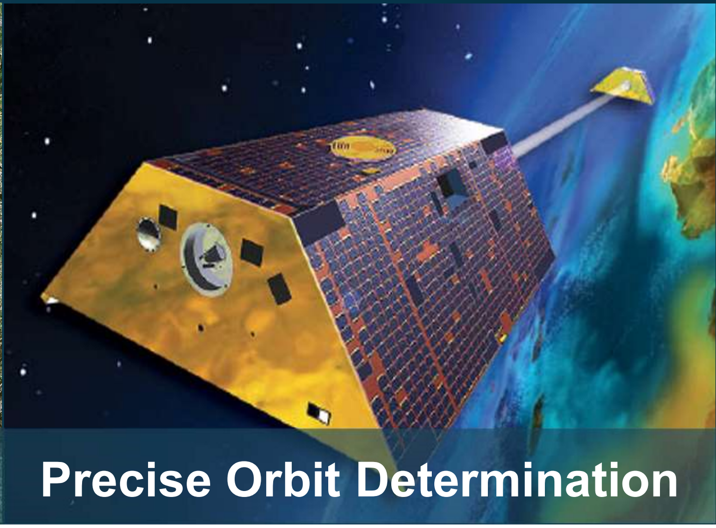


Launch Vehicle Range Ops

Attitude Determination

Time Synchronization

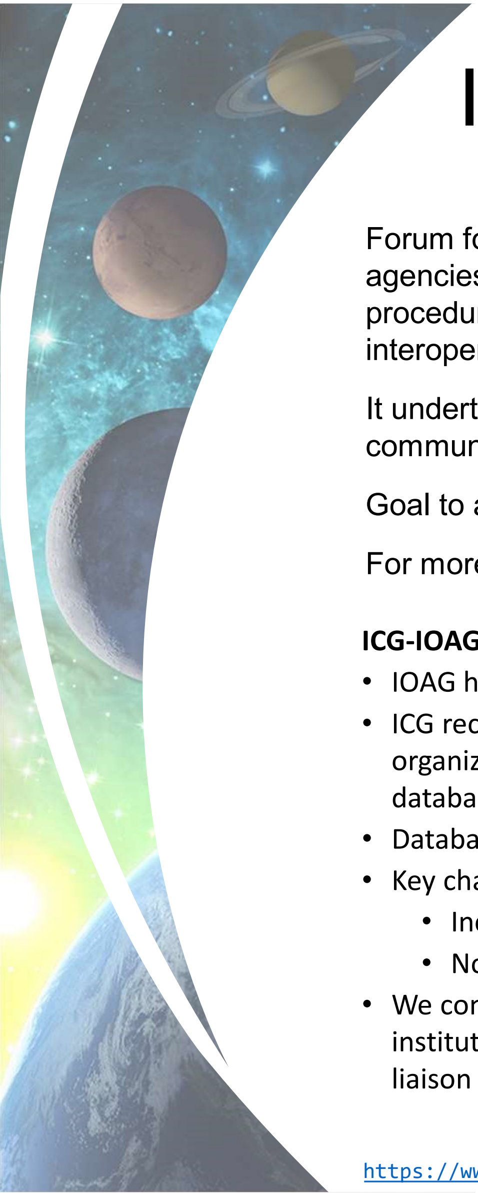
Earth Sciences



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 13 Nov 2020 for IOAG-24a
- Key changes since previous update (8 Oct 2019):
  - Includes 125 total missions from 8 agencies + affiliates
  - Now includes historical data from decommissioned/descoped missions
- 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	2019	2021
ASI	Italy	4	4
CNES	France	10	10
CSA	Canada	5	**7**
DLR	Germany	7	7
ESA	Europe	18	**30**
JAXA	Japan	12	**13**
KARI	Republic of Korea	8	8
NASA	USA	44	**46**

*Includes affiliated organizations

https://www.ioag.org/Public_Documents/Aggregate_IOAG_Missions_Using_GNSS_2020-11-13_(IOAG-24a).xlsx?d=wb2386aa737a443e5abea027305e01dbd

Selected US Mission Database Updates

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
83	NASA	Orion	GPS	L1 C/A	Orbit / navigation	LEO	2014 - Earth Orbit, 2021 Cislunar	Honeywell Aerospace 'Mercury' SPS GPS receiver with GSFC 'Navigator" software.
86	CNES/ NASA	Jason-3	GPS, GLONASS FDMA	L1 C/A, L1/L2 semicodeless, L2C	Precise Orbit Determination, Oceanography	LEO	1/17/2016	IGOR+ (BlackJack) receiver
88	NASA	GOES-16	GPS	L1 C/A	Orbit	GEO	11/19/2016	General Dynamics Viceroy-4
92	NASA/ ESA	Sentinel-6, 2 SATELLITES	GPS, GLONASS FDMA, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Occultation, Precise Orbit Determination	LEO	2020 and 2025	TriG receiver with MIL-STD-1553 interface
99	NASA/ ISRO	NISAR	GPS, GLONASS, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Precise Orbit Determination, timing	LEO	Sep. 2020	TriG Lite receiver
100	NASA/ CNES	SWOT	GPS, GLONASS FDMA, Galileo	L1 C/A, L2C, L5, Galileo, GLONASS FDMA	Precise Orbit Determination - Real Time	LEO	Apr. 2022	TriG receiver with MIL-STD-1553 interface

Red = updated in this release

Selected US Mission Database Updates

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
107	NASA	GOES-17	GPS	L1 C/A	Orbit	GEO	3/1/2018	General Dynamics Viceroy-4
108	NASA	GOES-T	GPS	L1 C/A	Orbit	GEO	Dec. 2021	General Dynamics Viceroy-4
115	NASA	Bobcat-1	GPS, GAL, GLO,BDS, QZSS, NavIC	GPS L1 C/A, L1C, L2C, L2P, L5 GLONASS L1, L2, L3, L5 BeiDou B1I, B1C, B2a, B2I, B3I Galileo E1, E5 AltBOC, E5a, E5b, E6 SBAS L1, L5 QZSS L1 C/A, L1C, L2C, L5, LEX NavIC (IRNSS) L5	Orbit, time	Ei (ISS)	2020	NovAtel OEM719 GNSS receiver
116	NASA	SunRISE	GPS, possibly others	L5 or L2C	Absolute and relative positioning of 6 6U cubesats, precise time transfer	GEO graveyard	2024?	
117*	NASA/ ASI	LuGRE	GPS, Galileo	GPS L1 C/A, L5 Galileo E1, E5a	Orbit, time	O	2023	NASA/ASI collaborative payload on Firefly Blue Ghost Mission 1 to demonstrate GNSS-based PNT during Earth-Moon transit, in lunar orbit, and on the lunar surface. Incorporates Qascom lunar receiver.

Red = updated in this release

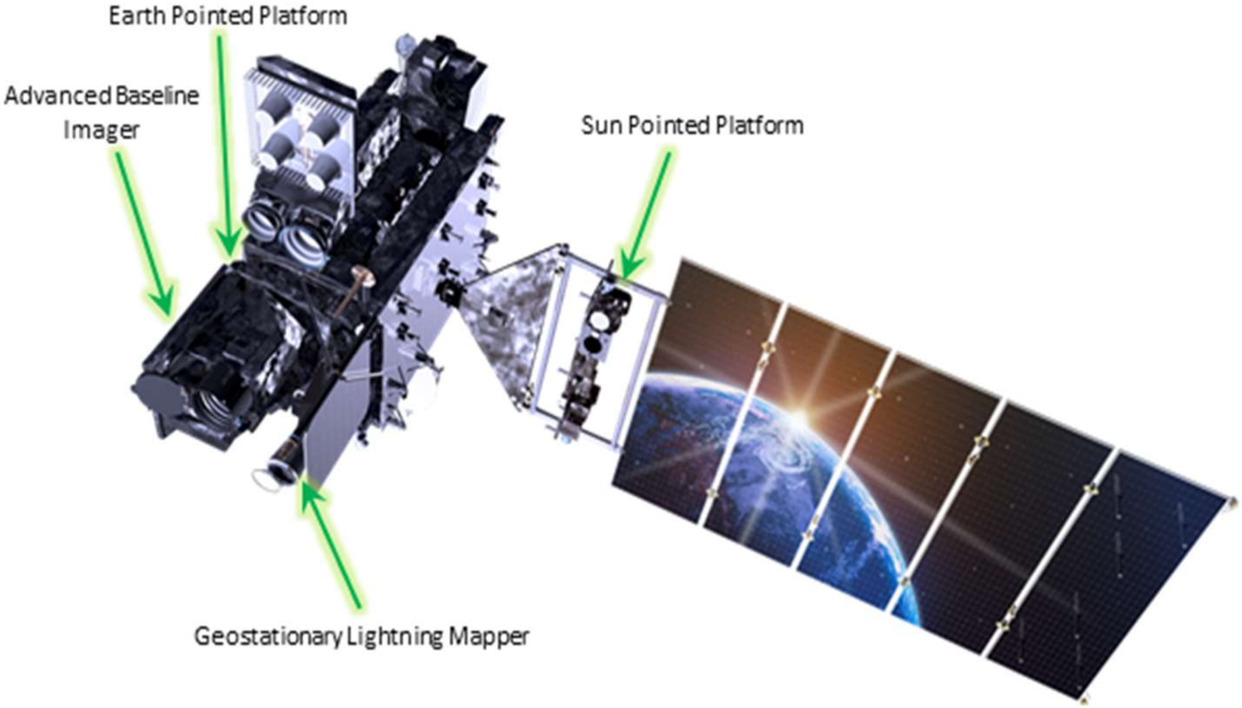
*Added in upcoming database update

GOES-R

Source:
“GPS Constellation Modernization Impact on Sidelobe Capable GPSR in GEO”,
ENC 2021, paper #223
Graeme Ramsey
Jim Chapel
Mark Crews
Douglas Freesland
Alexander Krimchansky

Background: GOES-R Satellites

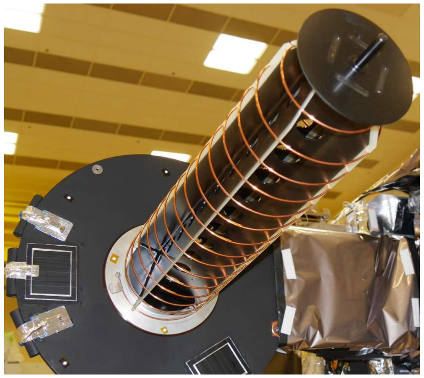
- **Geostationary Operational Environmental Satellite, R series**
  - **Earth-observing and Sun-observing instruments**
  - **The GOES-R spacecraft provide dramatic improvements in geostationary (GEO) weather observation capabilities over the previous generation**
- **Two GOES-R satellites currently on-orbit, GOES-16 (East) and GOES-17 (West)**



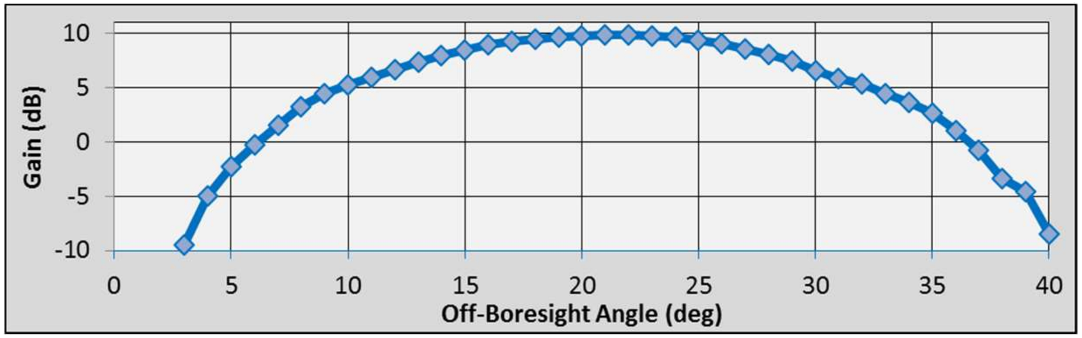
Background: GOES-R GPSR System

- GD Viceroy GPSR and LNA
  - 12-channel L1 C/A Receiver
  - Internal EKF Nav solution output
- LM designed GPS L1 Rx antenna
  - Peak gain at ~20 deg off-boresight
- Signal capabilities
  - Sidelobe capable
  - Signals on the order of 10^{-18} W
- Benefits of GPSR
  - Vehicle position, velocity and time (PVT) knowledge is improved
  - Demand upon ground support is reduced
  - Real-time PVT available to the Flight Software increases automaton

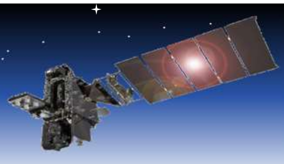
Rx Antenna



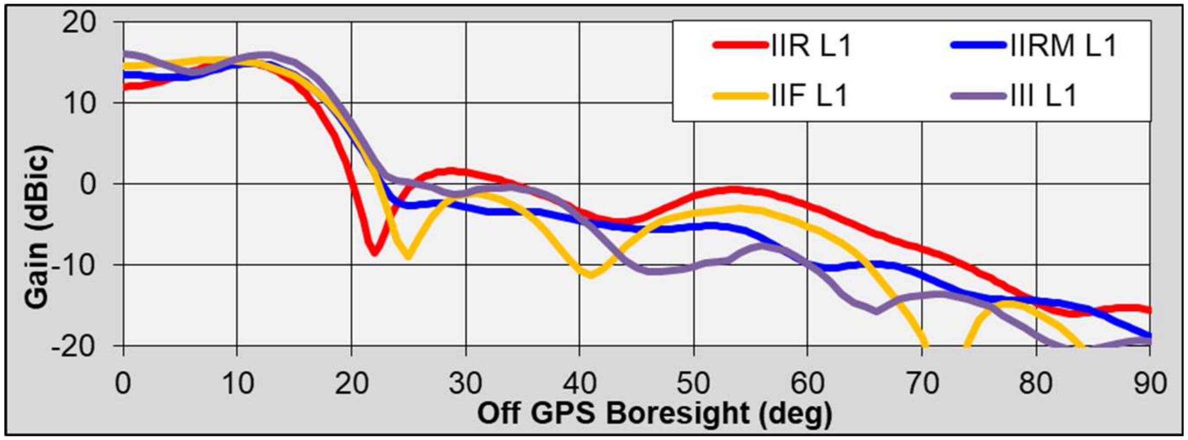
GOES-R GPS Rx Antenna Average Pattern



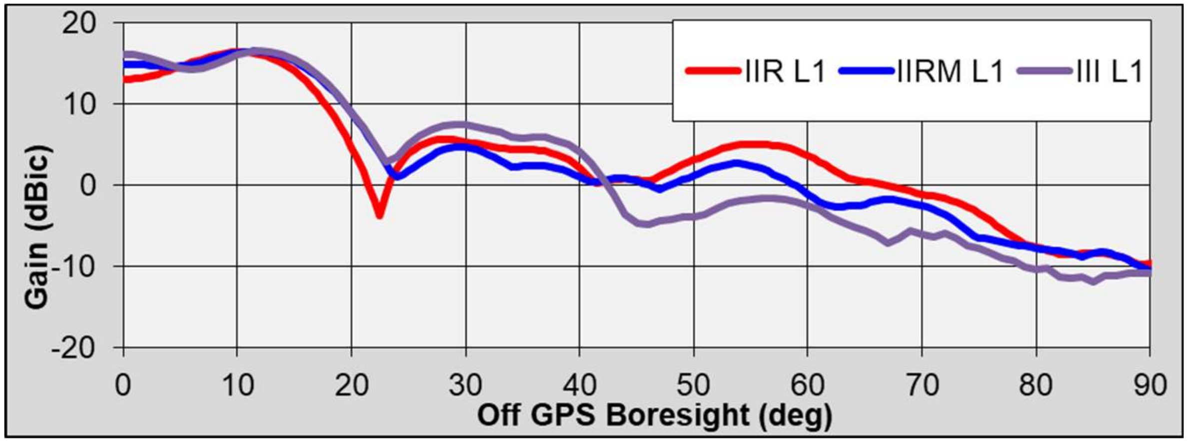
GPS Block-Type Tx Antenna Patterns

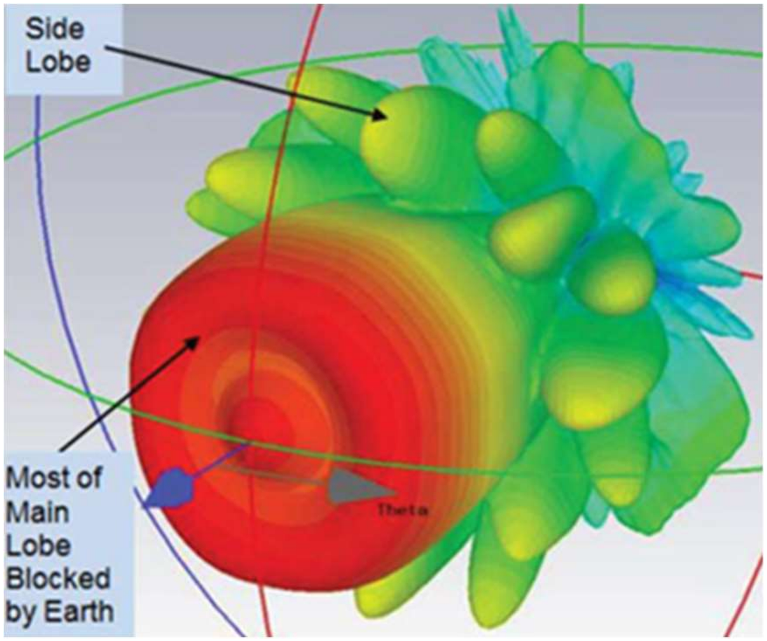


Average



Maximum





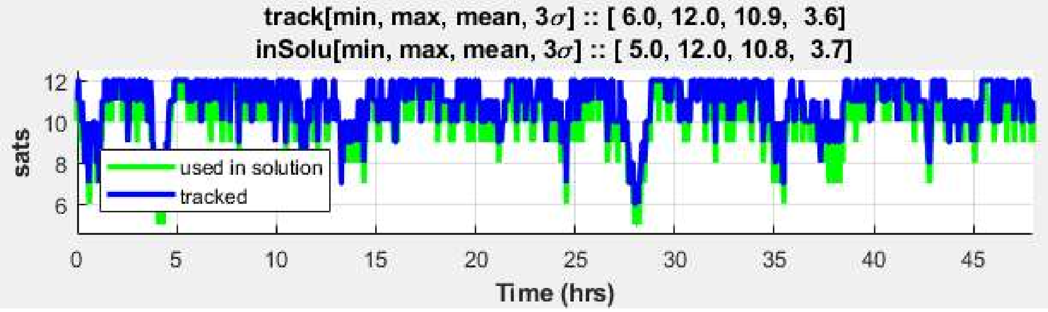
Side Lobe

Most of Main Lobe Blocked by Earth

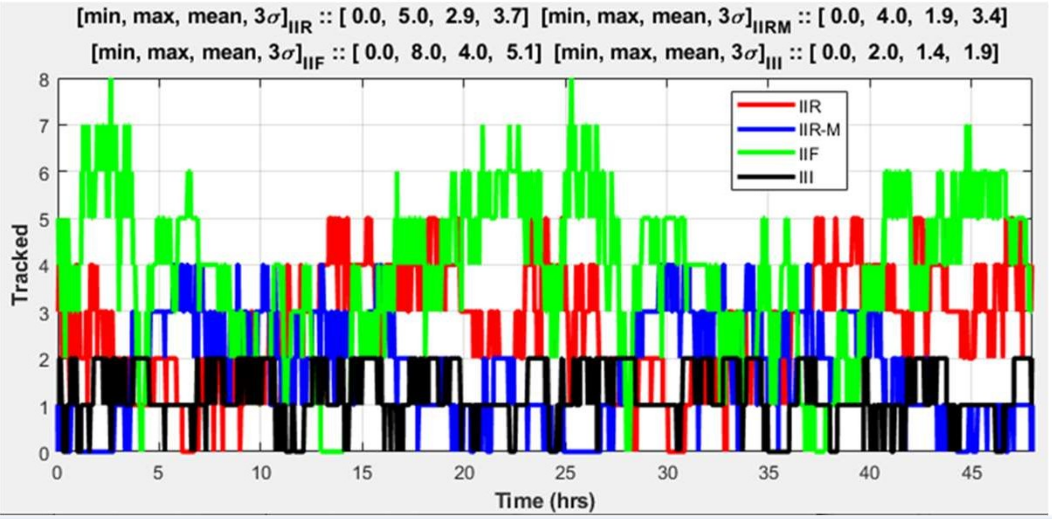
Block-Type Tracking

Data: March 15th - 17th 2021

GOES-16

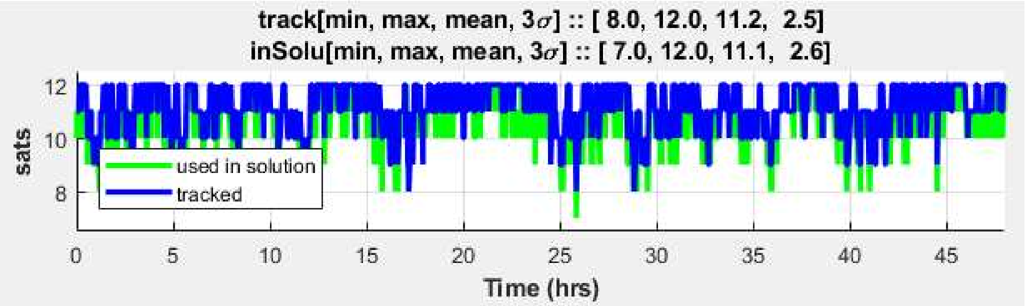


track[min, max, mean, 3σ] :: [6.0, 12.0, 10.9, 3.6]
inSolu[min, max, mean, 3σ] :: [5.0, 12.0, 10.8, 3.7]

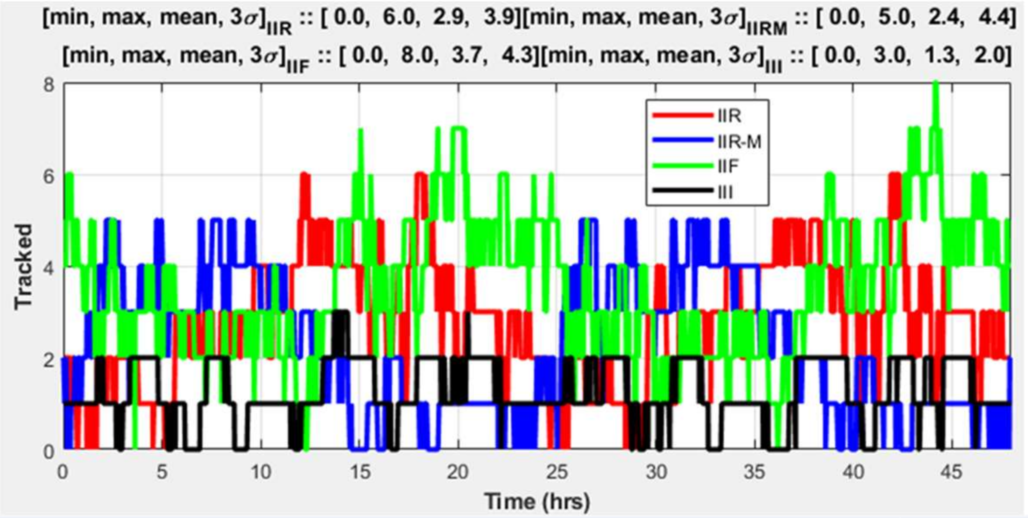


[min, max, mean, 3σ]$_{IIR}$ :: [0.0, 5.0, 2.9, 3.7] [min, max, mean, 3σ]$_{IIRM}$ :: [0.0, 4.0, 1.9, 3.4]
[min, max, mean, 3σ]$_{IIF}$ :: [0.0, 8.0, 4.0, 5.1] [min, max, mean, 3σ]$_{III}$ :: [0.0, 2.0, 1.4, 1.9]

GOES-17



track[min, max, mean, 3σ] :: [8.0, 12.0, 11.2, 2.5]
inSolu[min, max, mean, 3σ] :: [7.0, 12.0, 11.1, 2.6]

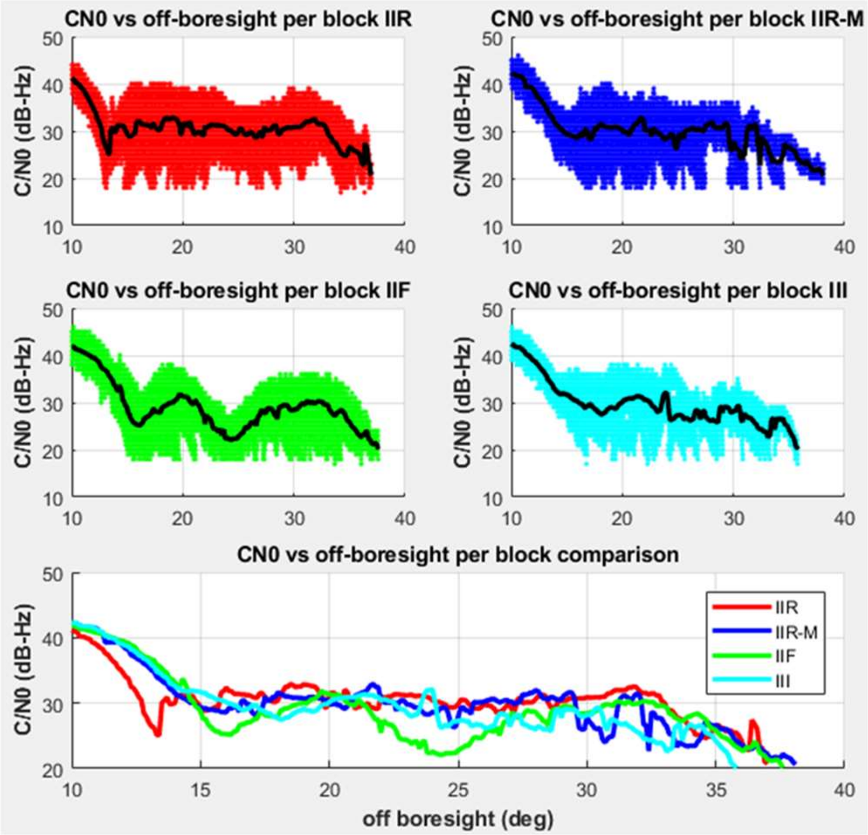


[min, max, mean, 3σ]$_{IIR}$ :: [0.0, 6.0, 2.9, 3.9][min, max, mean, 3σ]$_{IIRM}$ :: [0.0, 5.0, 2.4, 4.4]
[min, max, mean, 3σ]$_{IIF}$ :: [0.0, 8.0, 3.7, 4.3][min, max, mean, 3σ]$_{III}$ :: [0.0, 3.0, 1.3, 2.0]

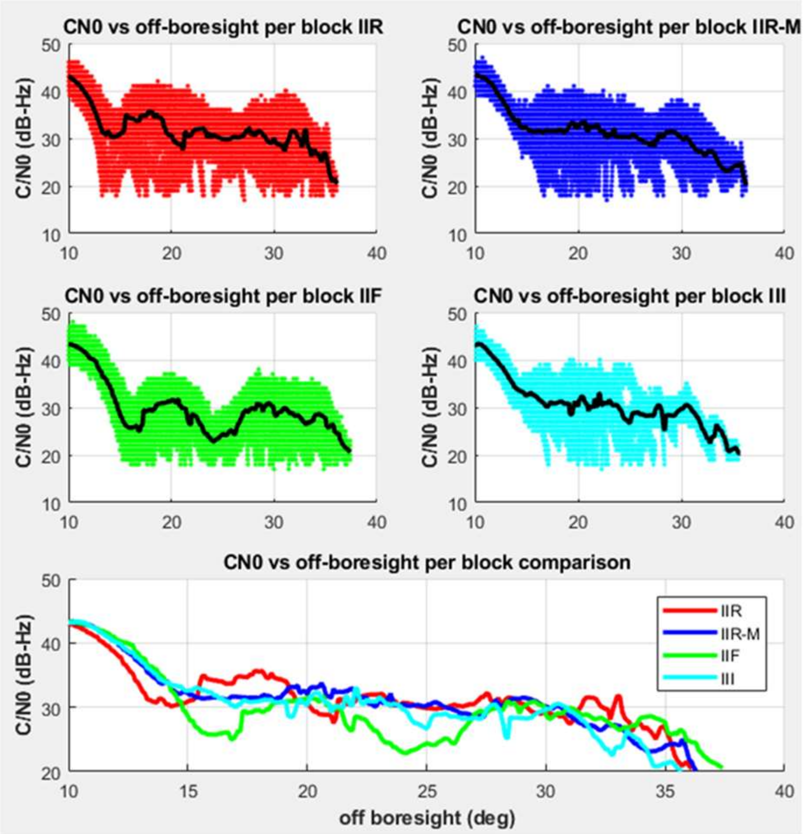
GPS Block-Type C/N0, Off-Boresight

Data: March 15th - 17th 2021

GOES-16



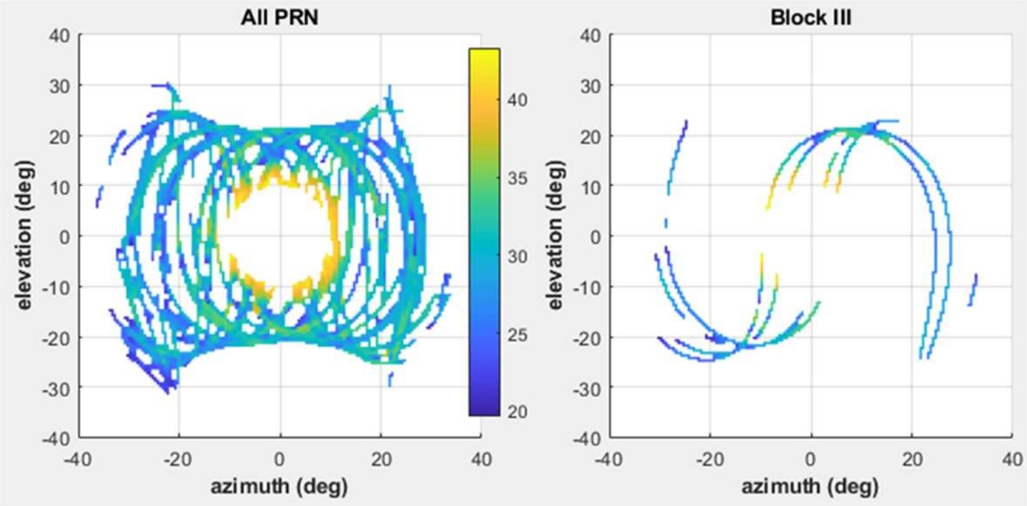
GOES-17



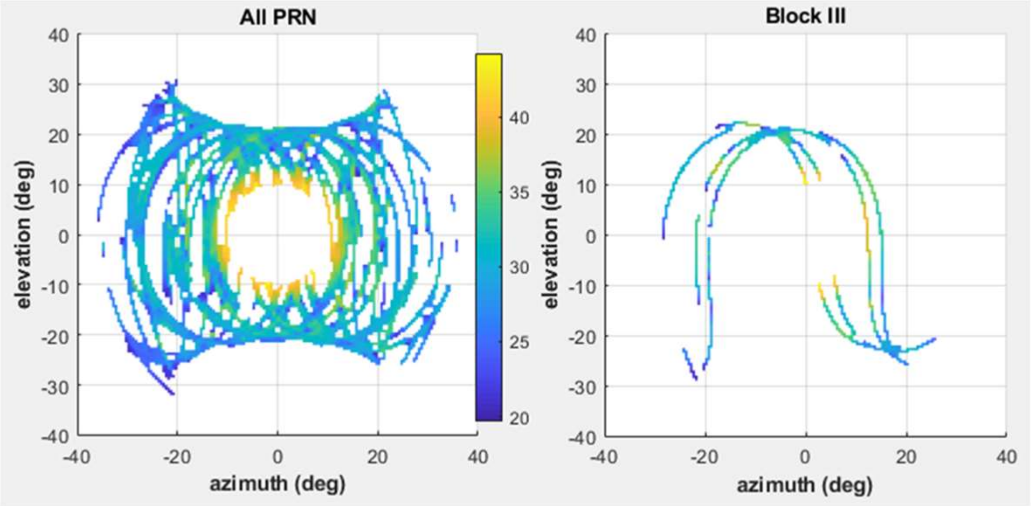
GPS III vs. Constellation C/N0, Azimuth/Elevation

Data: March 15th - 17th 2021

GOES-16



GOES-17



GPS III tracks add good diversity of geometry at reasonable power levels

The modernized constellation should continue to provide useable sidelobe signals to the GOES-R GPSR system resulting in nominal performance

Artemis

Source:
Dr. Benjamin Ashman,
“Applications and Benefits of GNSS for Lunar Exploration”,
SpaceOps 2021

NASA Lunar Exploration Activities

Artemis

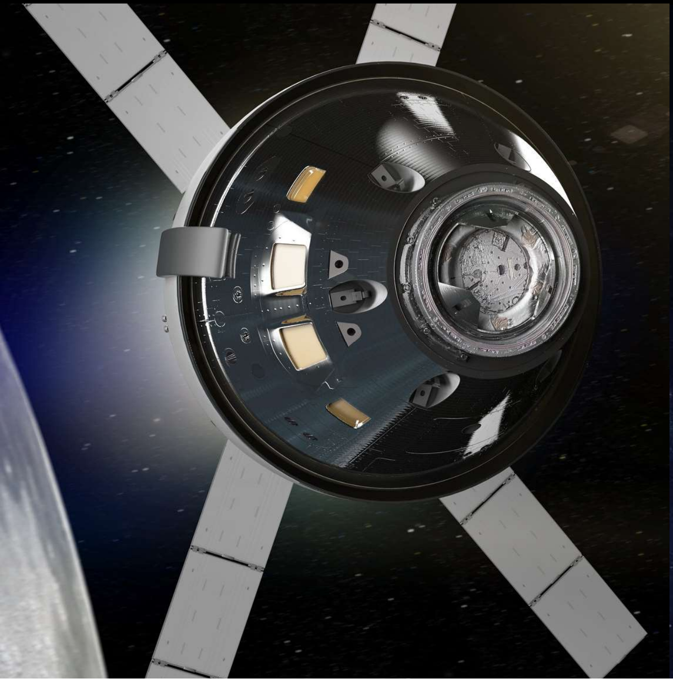
- Series of SLS launches carrying the Orion crew capsule that will return humans to the surface of the Moon

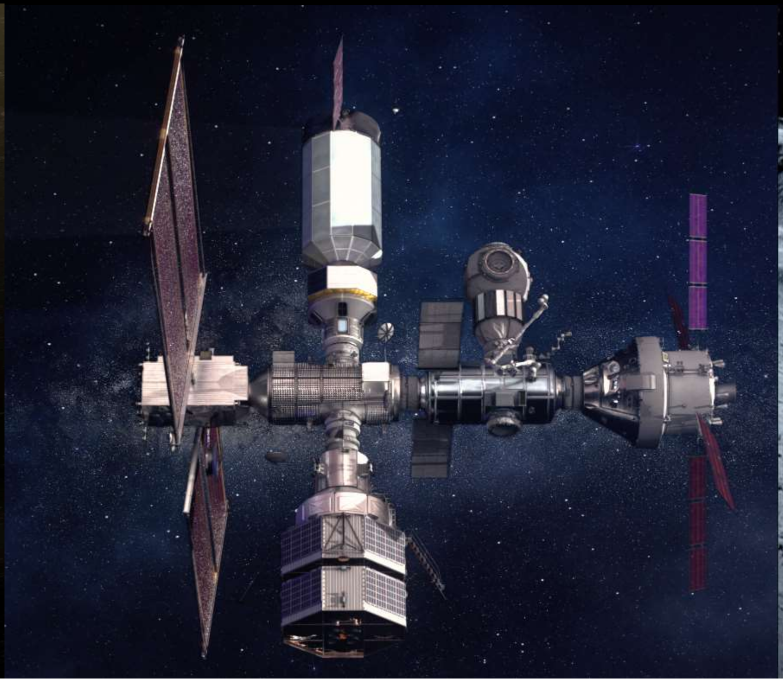
Gateway

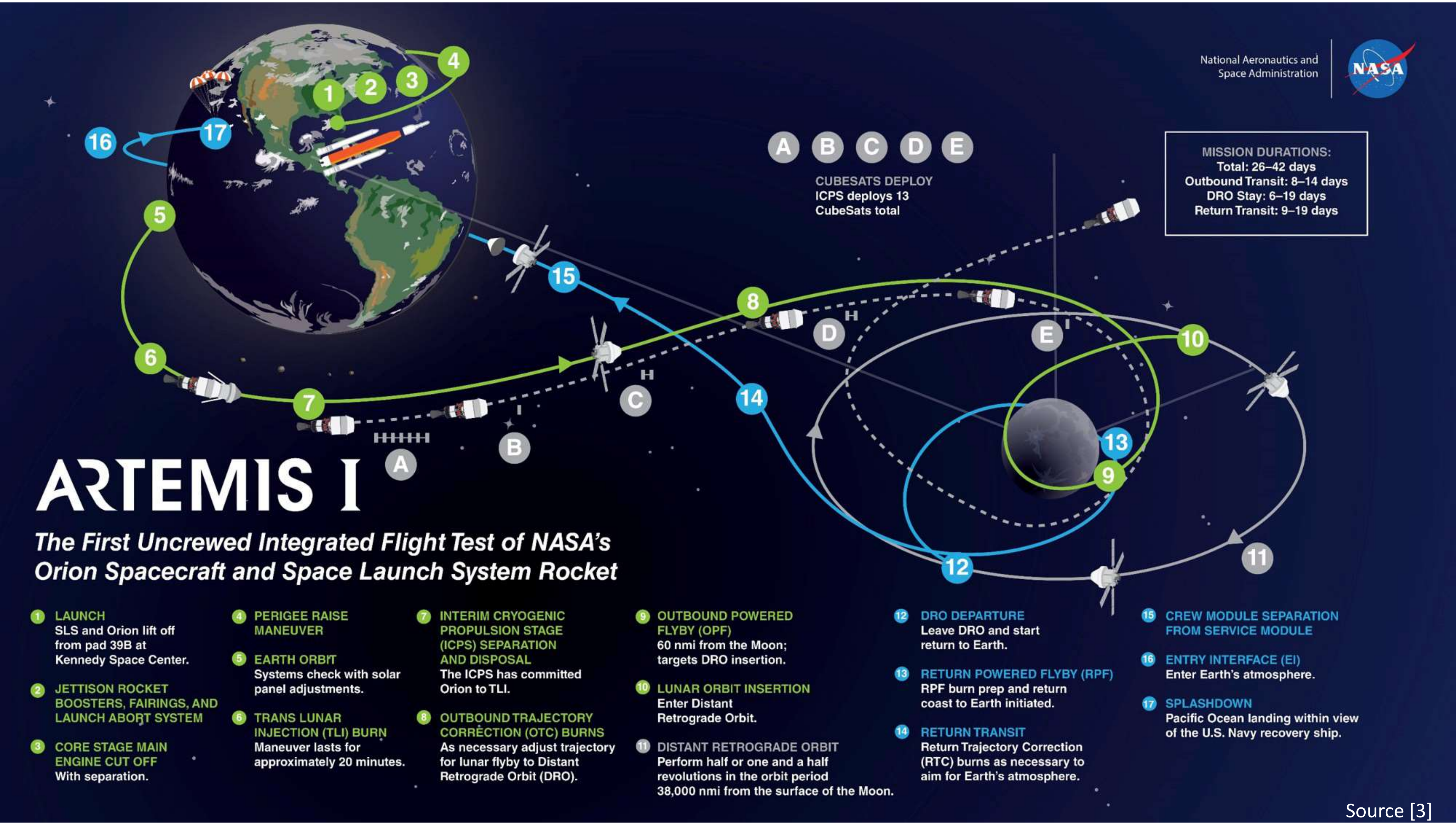
- Orbiter in cislunar space that will serve as a platform for science and technology payloads as well as a crew staging point for lunar surface or deep space missions

Commercial Lander Payload Services (CLPS)

- Robotic precursor landers designed for tech. demonstration and science that will pave the way for crewed missions







National Aeronautics and
Space Administration

NASA

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

ARTEMIS I

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

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.

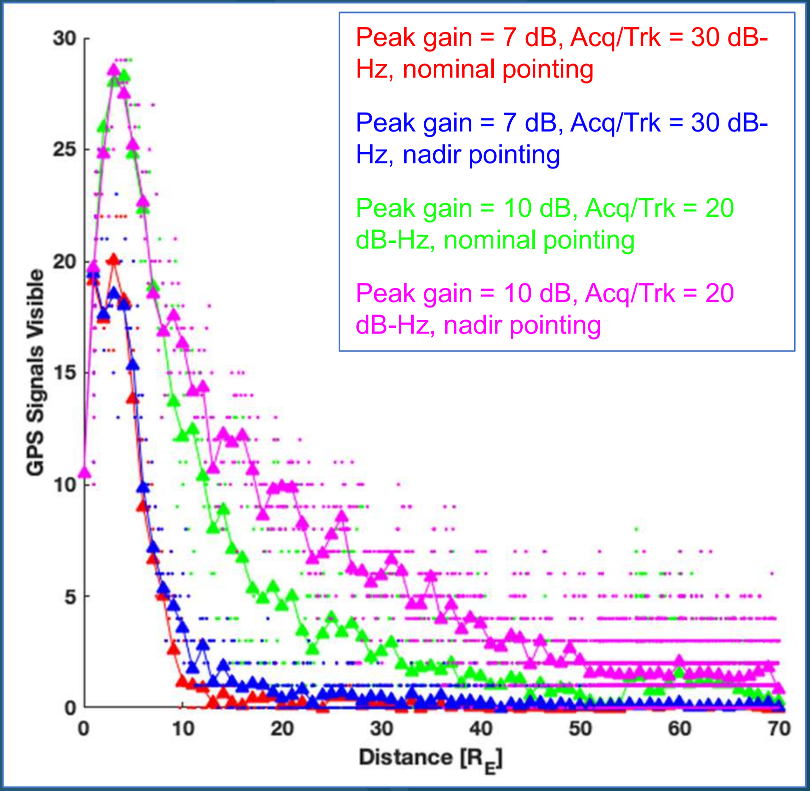
Source [3]

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



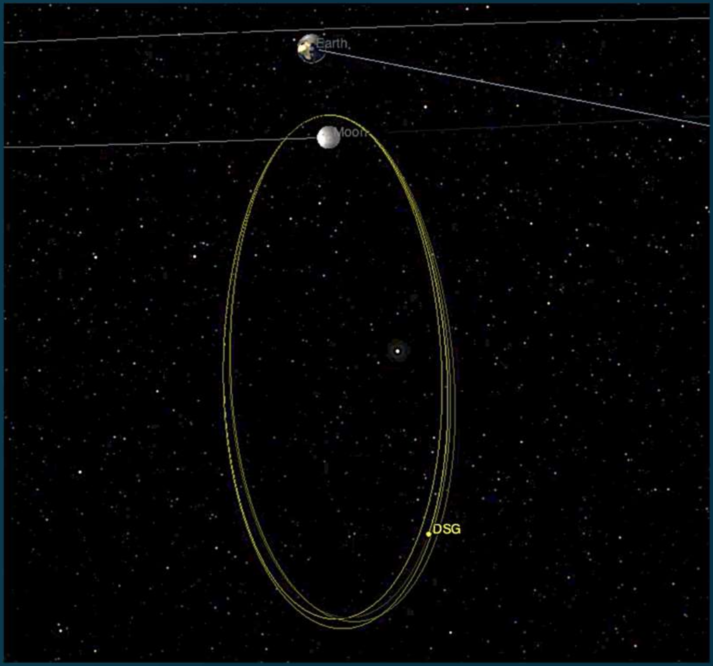
Baseline case in red models planned configuration for Artemis I. Alternate configurations illustrate potential availability with changes to hardware and/or pointing.

Lunar Gateway

- Joint NASA/ESA study on performance of GNSS on Gateway, 2020. NASA GPS-only results summarized here.
- Considered performance on Gateway of 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
  - GPS constellation modeled with per-vehicle GPS ACE 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)

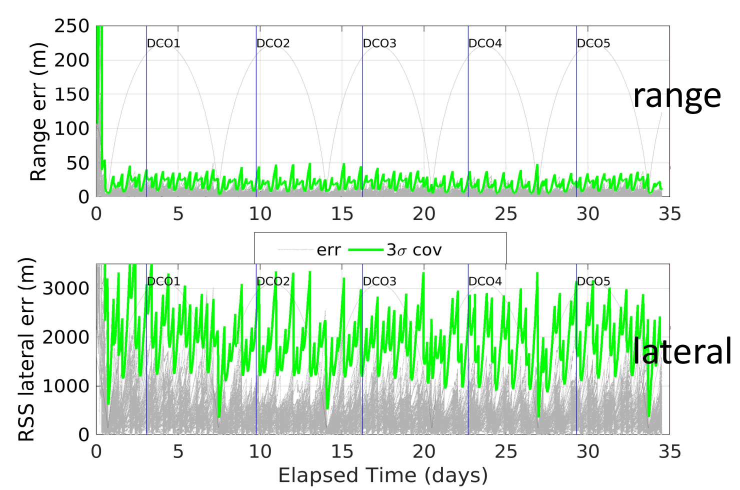
Lunar Gateway

- Position and velocity goals: 10 km and 10 cm/s, respectively
- 70 Monte Carlo cases
- Evaluated max OD error at the Data Cutoff (DCO) and at the final two perilunes and apolunes
- Observations:
  - Under our assumptions, analysis shows GPS can provide greatly improved performance vs. DSN, on-board, in real-time, without reliance on ground-based assets.

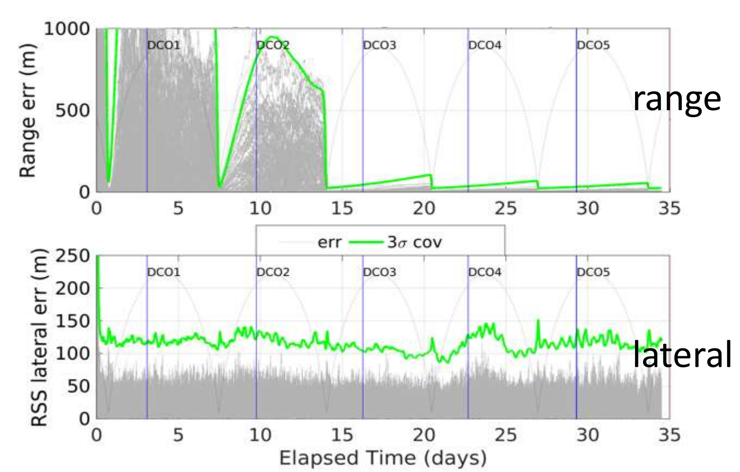
Crewed: Max steady-state errors

	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

DSN only



GPS only



Lunar GNSS Receiver Experiment (LuGRE)

Source:
Mr. Joel J. K. Parker, LuGRE PI
joel.j.k.parker@nasa.gov

LuGRE Mission Overview

NASA
CLPS
Commercial Lunar Payload Services

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

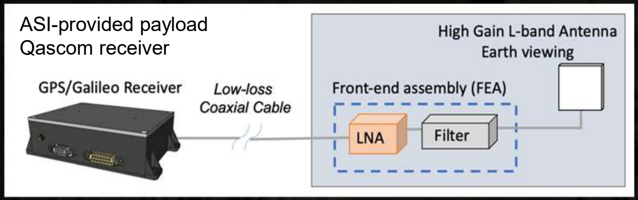
1. Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
2. Demonstrate navigation and time estimation using GNSS data collected at the Moon.
3. Utilize collected data to support development of GNSS receivers specific to lunar use.

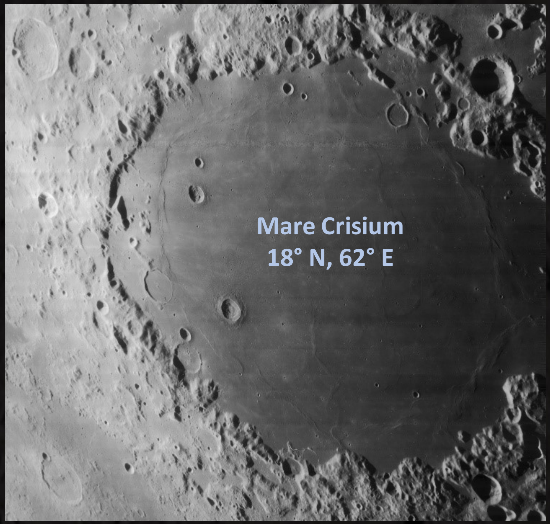
Measurements

- 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





CLPS Lander Award Feb 2021

LuGRE SRR Apr 2021

LuGRE CDR Sept 2021

ETU Delivery Oct 2021

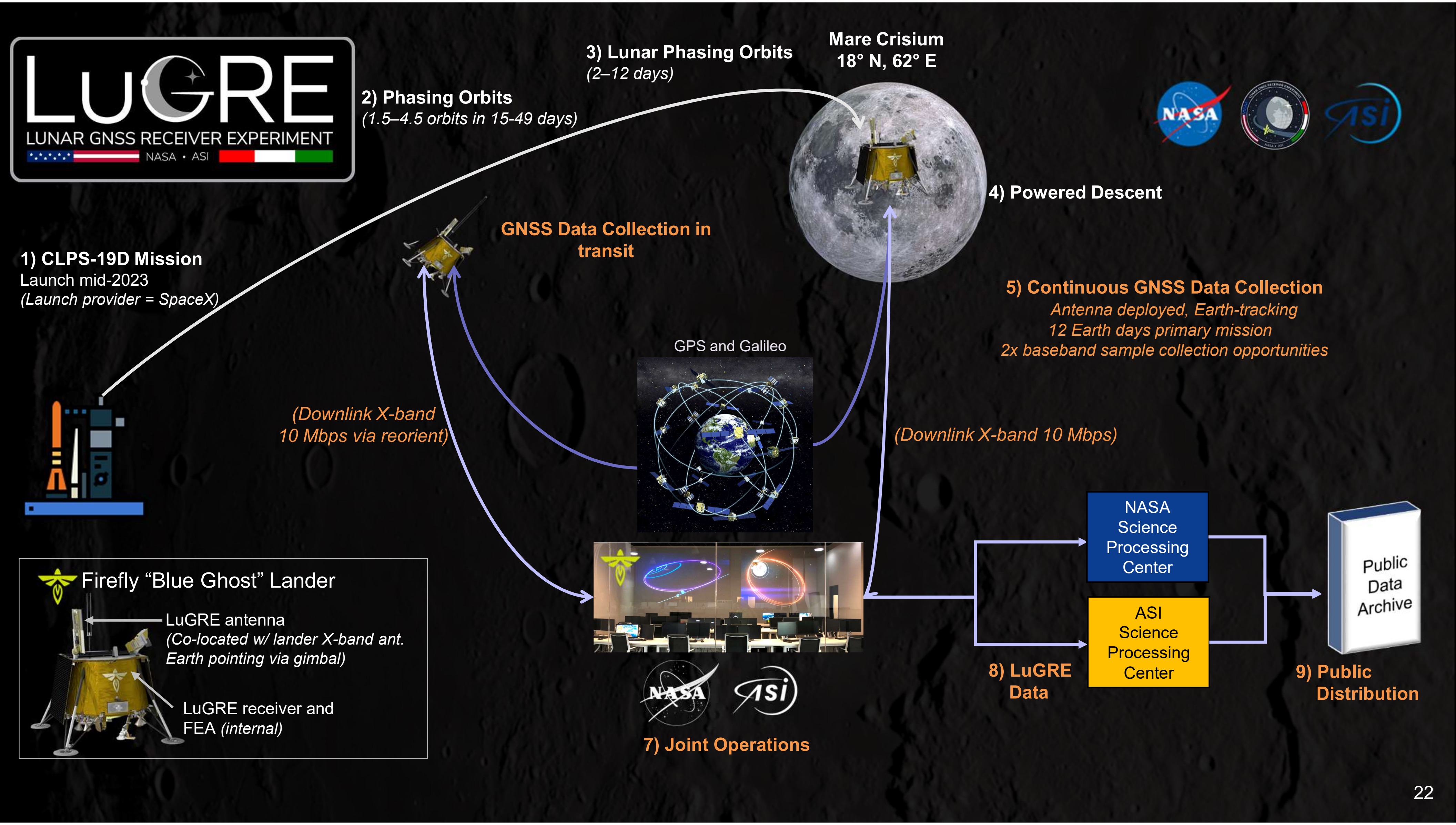
FM Delivery early 2022

Payload Delivery NLT Nov 1, 2022

Launch+Ops Jul–Sep 2023

Analysis late 2023

↑ We are here



LuGRE
LUNAR GNSS RECEIVER EXPERIMENT
NASA • ASI

1) CLPS-19D Mission
Launch mid-2023
(Launch provider = SpaceX)

2) Phasing Orbits
(1.5–4.5 orbits in 15-49 days)

3) Lunar Phasing Orbits
(2–12 days)

Mare Crisium
18° N, 62° E

4) Powered Descent

GNSS Data Collection in transit

5) Continuous GNSS Data Collection
Antenna deployed, Earth-tracking
12 Earth days primary mission
2x baseband sample collection opportunities

GPS and Galileo

(Downlink X-band 10 Mbps via reorient)

(Downlink X-band 10 Mbps)

Firefly "Blue Ghost" Lander
LuGRE antenna
(Co-located w/ lander X-band ant. Earth pointing via gimbal)
LuGRE receiver and FEA *(internal)*

7) Joint Operations

8) LuGRE Data

NASA Science Processing Center

ASI Science Processing Center

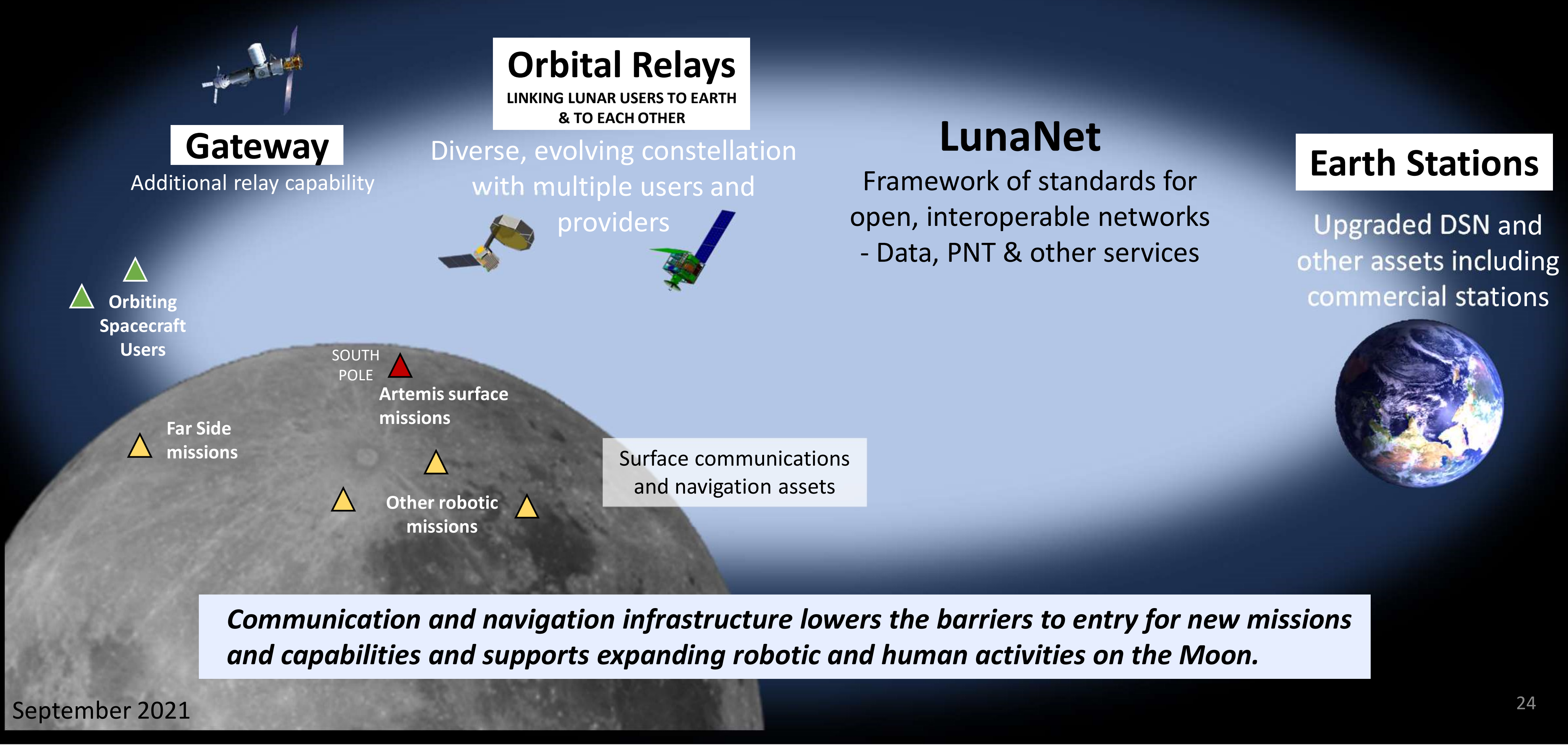
Public Data Archive

9) Public Distribution

LunaNet

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

Early Lunar Communications 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

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.

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

September 2021

Technology Updates

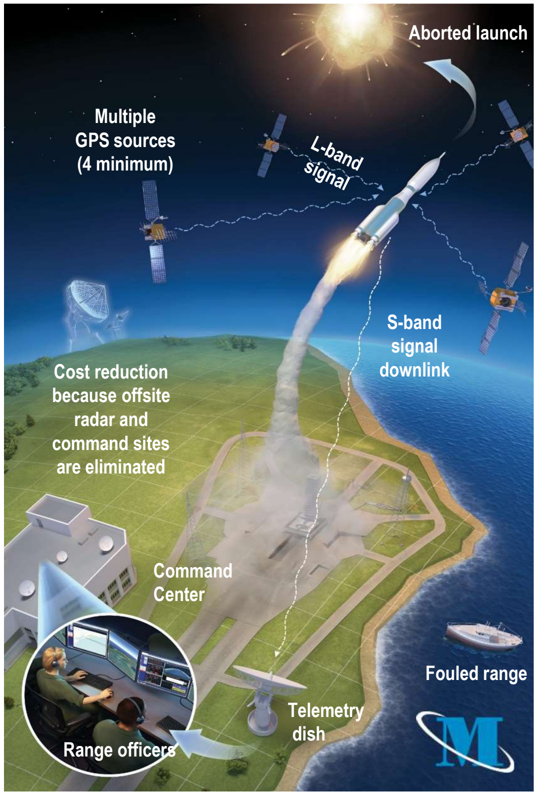
Autonomous Flight Termination System (AFTS)

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

Autonomous Flight Termination

NASA, in partnership with DARPA, built an Autonomous Flight Termination Unit

- Box on the vehicle (AFTU)
  - Uses Tracking data from GPS and INS/IMU sensors
  - Rule set built in pre-flight period
  - If a rule is violated the flight is terminated
- Radar and Command stations recede into past
- Telemetry down-link drops from safety critical to situational awareness, post-flight analysis , & mishap investigation
- Advantages
  - Cost reduction due to decreased need for ground-based assets
  - Global coverage (vehicle does not have to be launched from a range)
  - Increased launch responsiveness
  - Boundary limits increase
  - Can support multiple vehicles simultaneously (such as flyback boosters)



NASA performed Qualification and Certification of the AFTU HW & SW

•The NASA/DARPA AFTU has been flying operationally since Dec 2019

•Prior to operational use, NASA performed many shadow flights of the AFTU including:
  -UP Aerospace SL-14 (last shadow flight before operational use)
    •NASA AFTU with integrated GPS receivers
    •Note: As a secondary experiment, a stand-alone ASI/Qascom GARHEO multi-GNSS (GPS + Galileo) signal recorder was flown in record-only mode to evaluate the receiver's performance in a highly dynamic launch environment – it was not integrated with the AFTU and no data was transmitted in real-time. The mission was a success, and the receiver performed nominally.

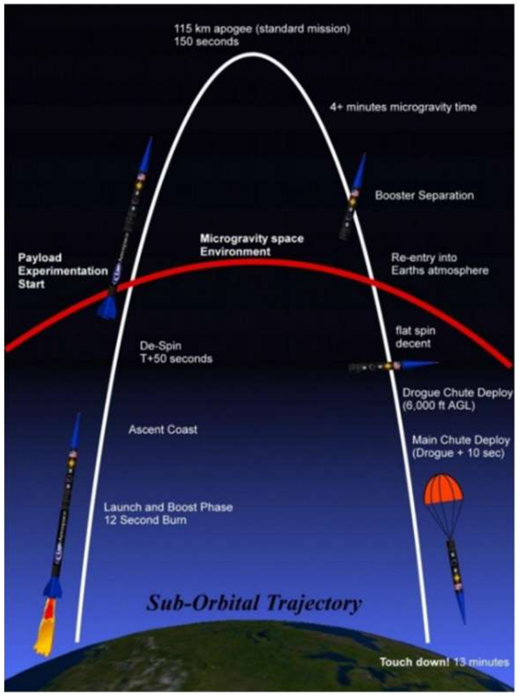
SL-15 Launch with AFTS and GNSS

- 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

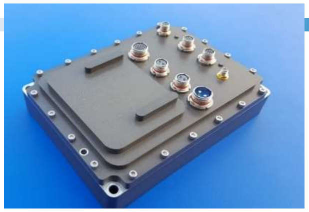
SL-15 Mission provided by NASA's Flight Opportunities Program:
-Scheduled for launch in March 2022 from Spaceport America, NM
-Utilizing L1/E1/L2/E5a

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



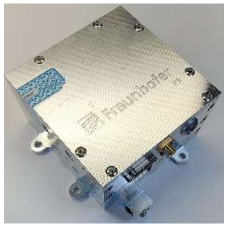
SL-15 Multi-GNSS Payload Hardware



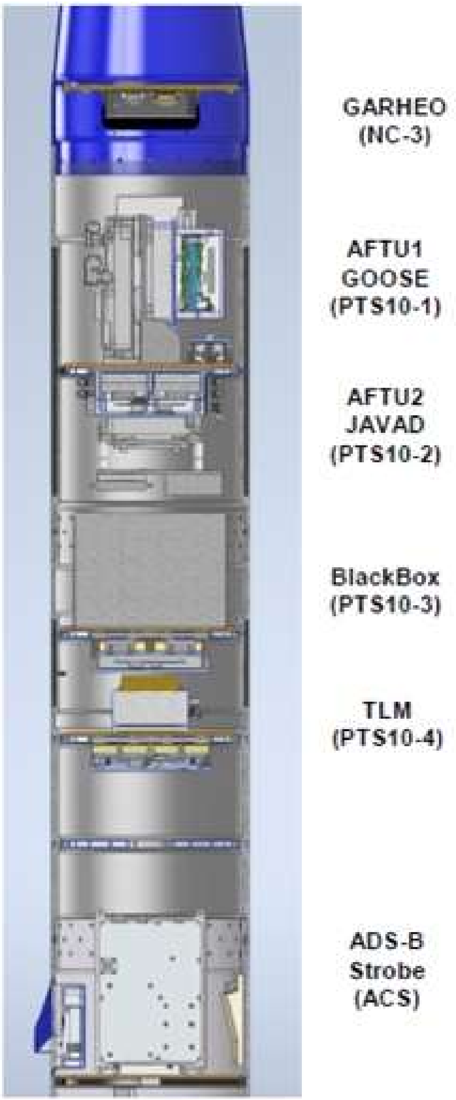
AFTU:
Weight: 1.3kg
Size: 5cm X 14cm X 19cm
Power: 7W, 5.5A, 28V DC

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

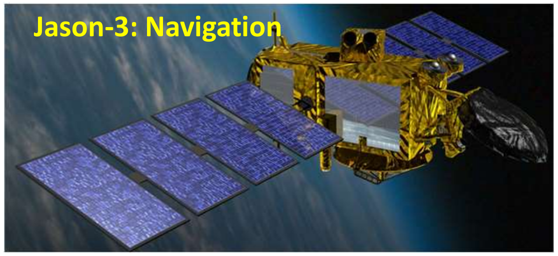
Source:
TriG/Cion: Dr. Yoaz Bar-Sever, Jet Propulsion Laboratory, California Institute of Technology
NavCube: Mr. Munther Hassouneh, NASA Goddard Space Flight Center

Continuing a Long Legacy of Remote Sensing and Navigation Space Receivers

12 Trig-class receivers successfully operating in space


Cosmic-2: Navigation + RO

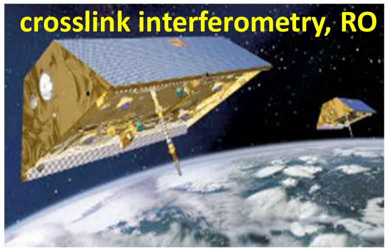

Sentinel-6: Navigation + RO


Jason-3: Navigation

Deep Space Atomic


(DSAC):
Navigation and ultra-precise timing
(https://www.nature.com/articles/s41586-021-03571-7.pdf)

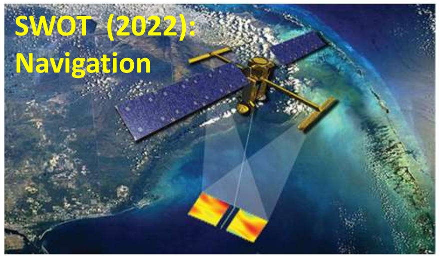
GRACE FO: Navigation,


crosslink interferometry, RO


Cicero

Upcoming missions relying on the Trig


NISAR (2022):
Navigation

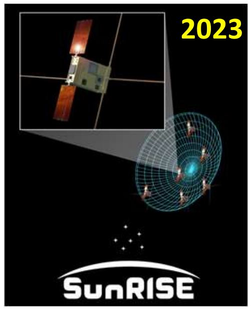

SWOT (2022):
Navigation

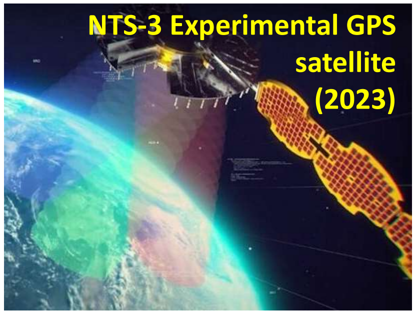
Cion - A new Low-Cost, High Performance Class of GNSS Science Receivers

- TriG technology heritage but with low-cost, low-power components
- High-performance, high-reliability RTGx navigation software
- Radio occultation version flying on GeoOptics' Cicero cubesats since 2017

Will provide navigation and timing in geosynchronous orbits for SunRISE and NTS-3

- Weak signal capability
- Multi GNSS, multi-frequency
- Survey GNSS SSV signals

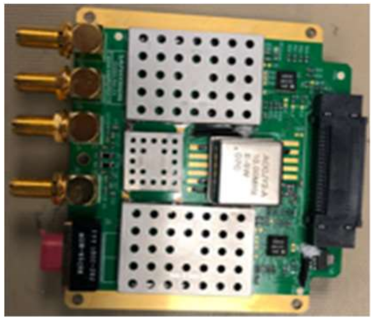

2023


NTS-3 Experimental GPS satellite
(2023)

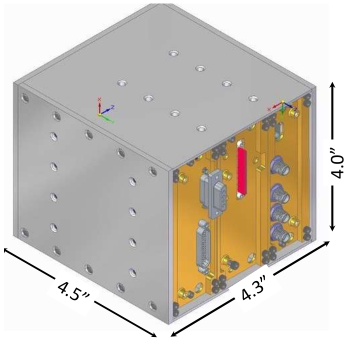
NavCube 3.0 mini GNSS Receiver

NavCube 3.0 mini (NC3m)

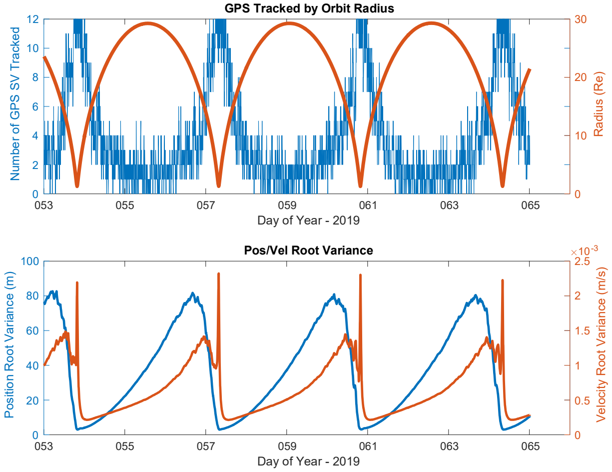
- Low SWaP-C GNSS receiver appropriate for all orbit regimes including cislunar space and lunar orbit
- Rad-hard RF front-end card
- Wide-band, dual-frequency RF card provides GPS L1 C/A and either L2C or L5
  - Galileo E1 and E5a also possible for additional SWaP-C
- Supports onboard or an external reference clock
- Builds on proven GSFC MMS Navigator flight heritage
  - Fast acquisition/weak signal acquisition capabilities
  - Currently operating at 29.3 Re (halfway to the moon)
- On-orbit upgradable software and firmware adaptable to new mission types and operations concepts
- Integrated Goddard Enhanced Onboard Navigation System (GEONS) navigation filter provides multi-sensor fusion and prediction onboard



NC3m GNSS RF card(~3.5”x3.5”)



NC3m standalone GNSS receiver



MMS Navigator on-orbit performance at 29.3 Re

Status

- NC3m is currently in development
- Standalone version of NC3m will be TRL6 in February 2022 (estimated)

Enabling the SSV

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

- **GPS data released to public**
  - 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
  - USSF Space and Missile Systems Center (SMC) assessing public release of all available GPS data (Blocks IIR through III SV1–10)

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

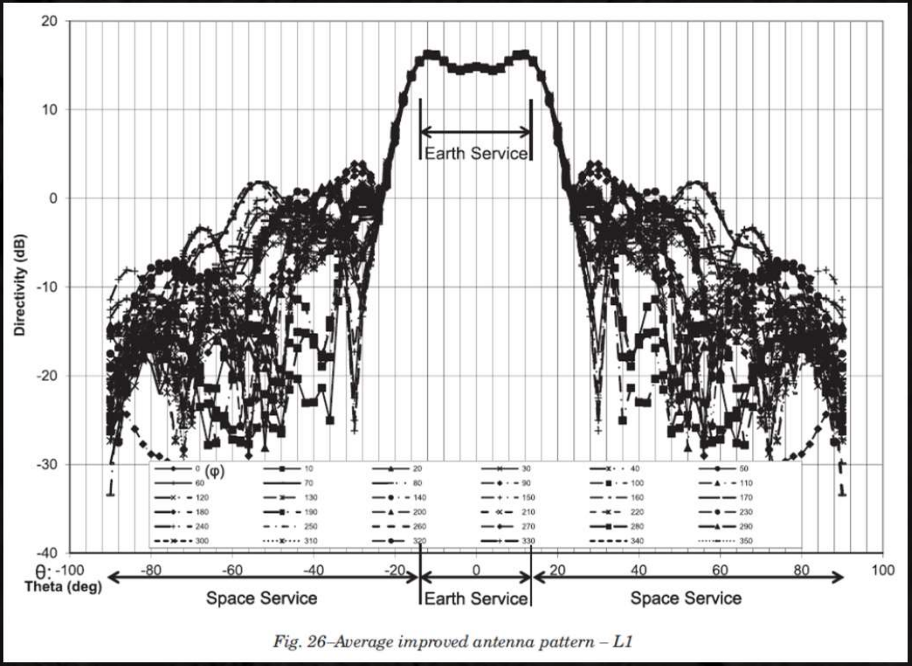
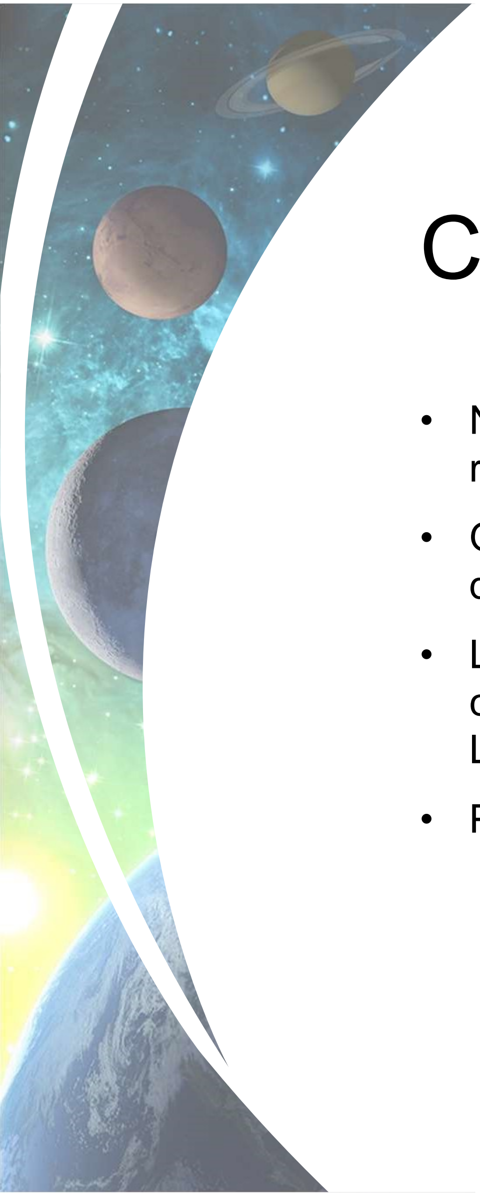


Fig. 26–Average improved antenna pattern – L1

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.



Conclusions

- NASA reports GNSS use on at least **40** 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.

Backup

IOAG Database of GNSS Missions

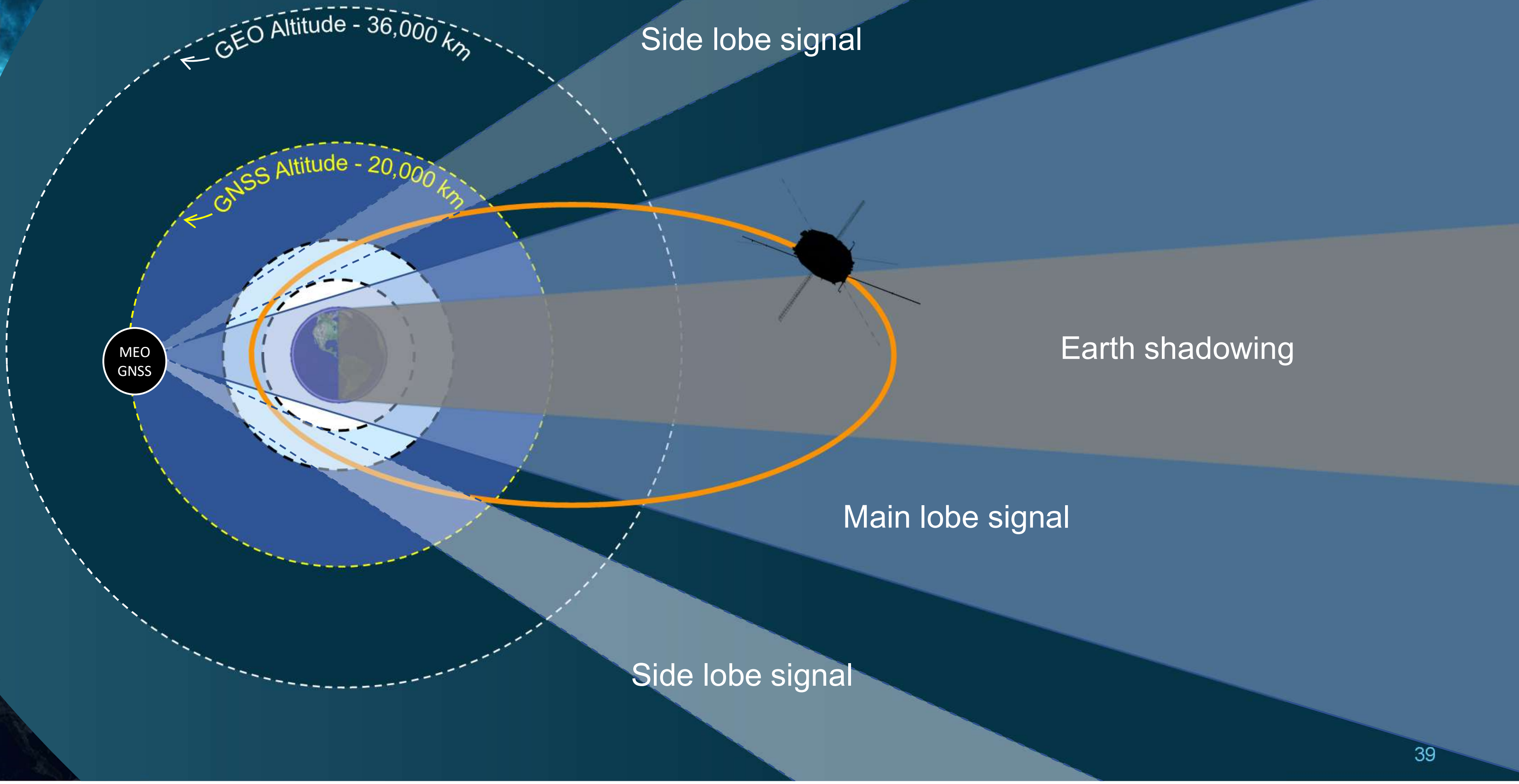
- The full “Aggregate IOAG Missions Using GNSS” is available at:

  https://www.ioag.org/Public%20Documents/Aggregate%20IOAG%20Missions%20Using%20GNSS%202020-11-13%20(IOAG-24a).xlsx?d=wb2386aa737a443e5abea027305e01dbd

- Also embedded here:

Aggregate IOAG
sions Using GNSS

Signal Reception in the Space Service Volume (SSV)

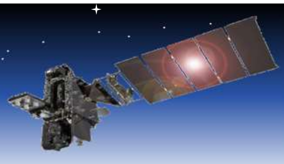


GPS Constellation Modernization Impact on Sidelobe Capable GPSR in GEO

Graeme Ramsey
Jim Chapel
Mark Crews
Douglas Freesland
Alexander Krimchansky

ESA GNC 2021: Paper #223

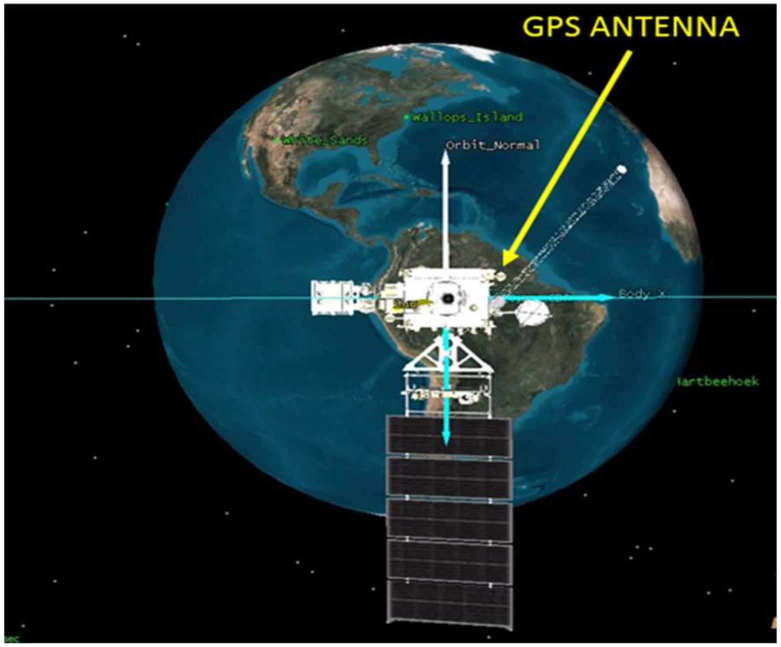
Purpose

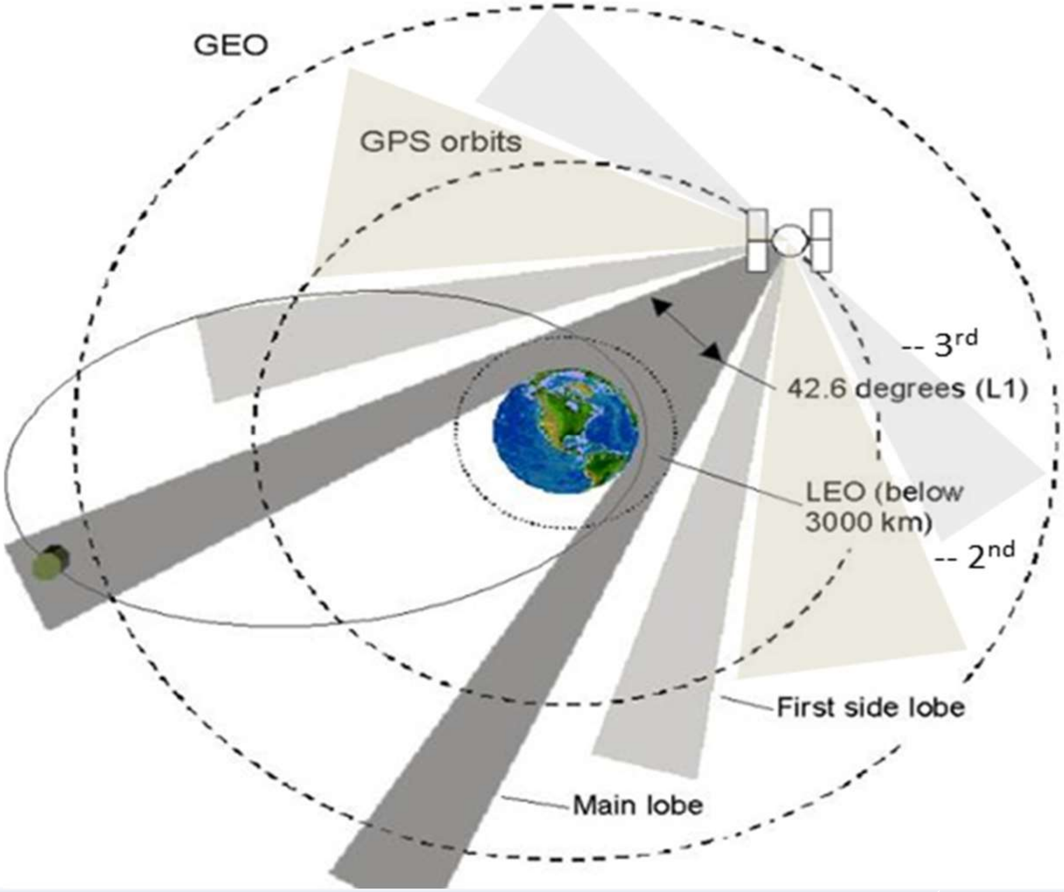


- GPS Constellation Modernization Impact on Sidelobe Capable GPSR at GEO

- Heritage and modern GPS transmit pattern comparison
- Relevant signal requirements as it pertains to GEO GPSR facilitation
- GOES-R GPSR acquisition and tracking characterization regarding the first four operational GPS III vehicles

Background: Orbit, Attitude and Signal Regimes





Background: GPS Modernization

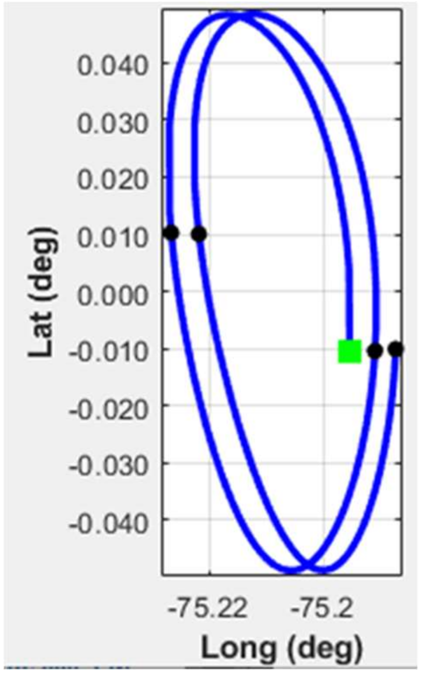
GPS III SV	01	02	03	04
SVN	74	75	76	77
PRN	04	18	23	14
Orbit Slot	F4	D6	E5	B6
Launch Date	12/23/2018	8/22/2019	6/30/2020	11/5/2020
Operational Date	12/23/2019	3/27/2020	10/1/2020	12/2/2020

- **GPS History**
  - **First SV launched in 1978, fully operational in 1993, civilian use w/o impediments in 2000, first GPS III launched in 2018**
- **Current GPS Constellation Status**
  - **31 operational satellites**
  - **8 IIR, 7 IIR-M, 12 IIF and 4 III block-types**
- **GPS III**
  - **The GPS III program includes 10 space vehicles (SVs)**
  - **Six GPS III SVs awaiting launch, available for launch, or in production**
  - **Performance improvements: 8x better anti-jamming, 3x better ground accuracy, 15 year life (+25%), L1C signal**

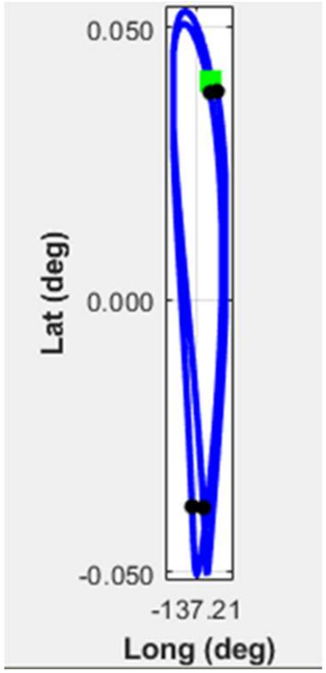
GOES-16 and GOES-17 On-Orbit Data

- Data presented in this section are from both GOES-16 (East Station) and GOES-17 (West Station) over common time spans
- Stations
  - East Station: 75.2 West longitude
  - West Station: 137.2 West longitude
  - Delta in the repeatable geometry between the vehicles
- Time spans
  - March 15th - 17th 2021
  - Two days of data allows for two repeatable relative geometry cycles

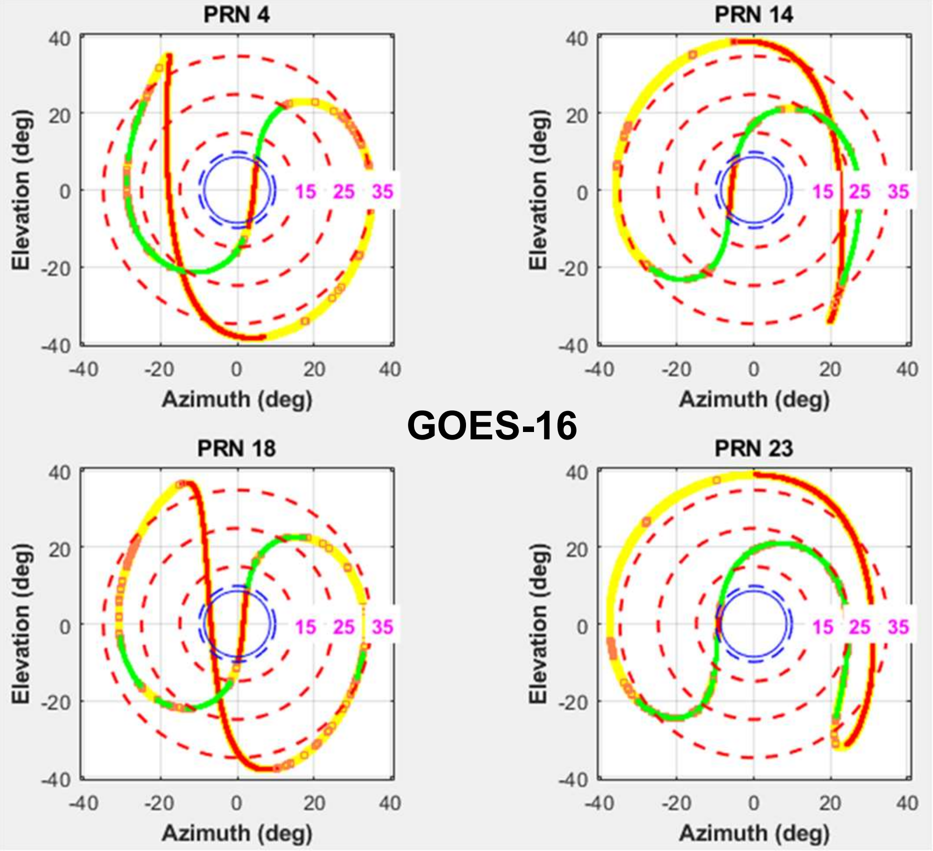
GOES-16

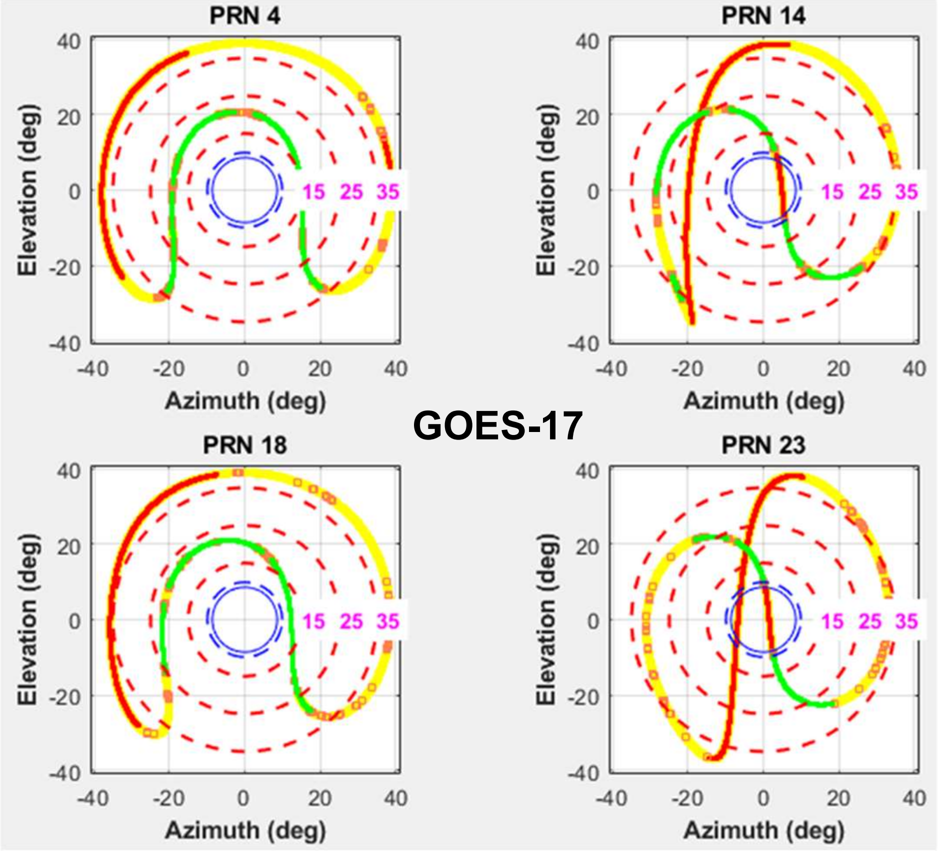


GOES-17

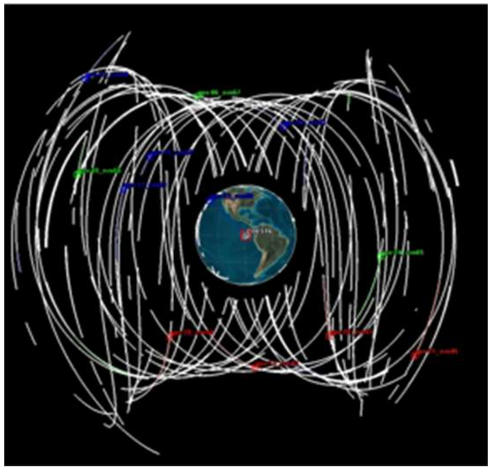


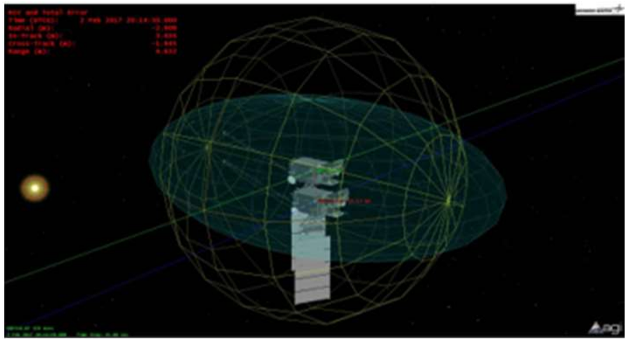
GPSIII Tracking Skyplots

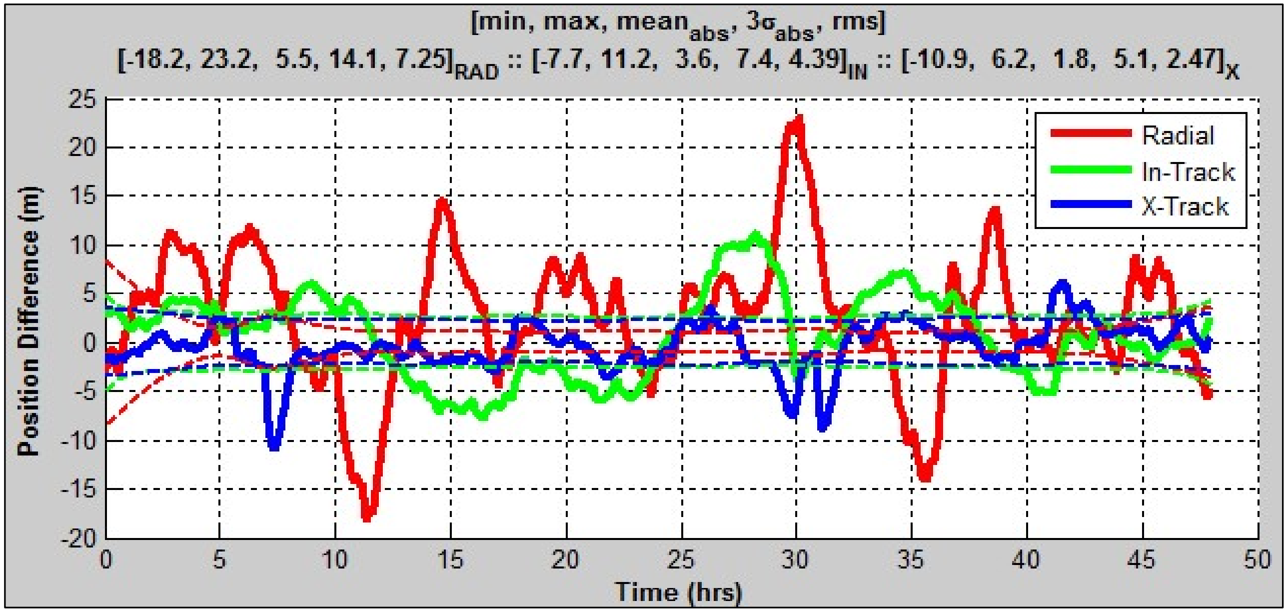




Previously Defined GOES-R GPSR Navigation Performance





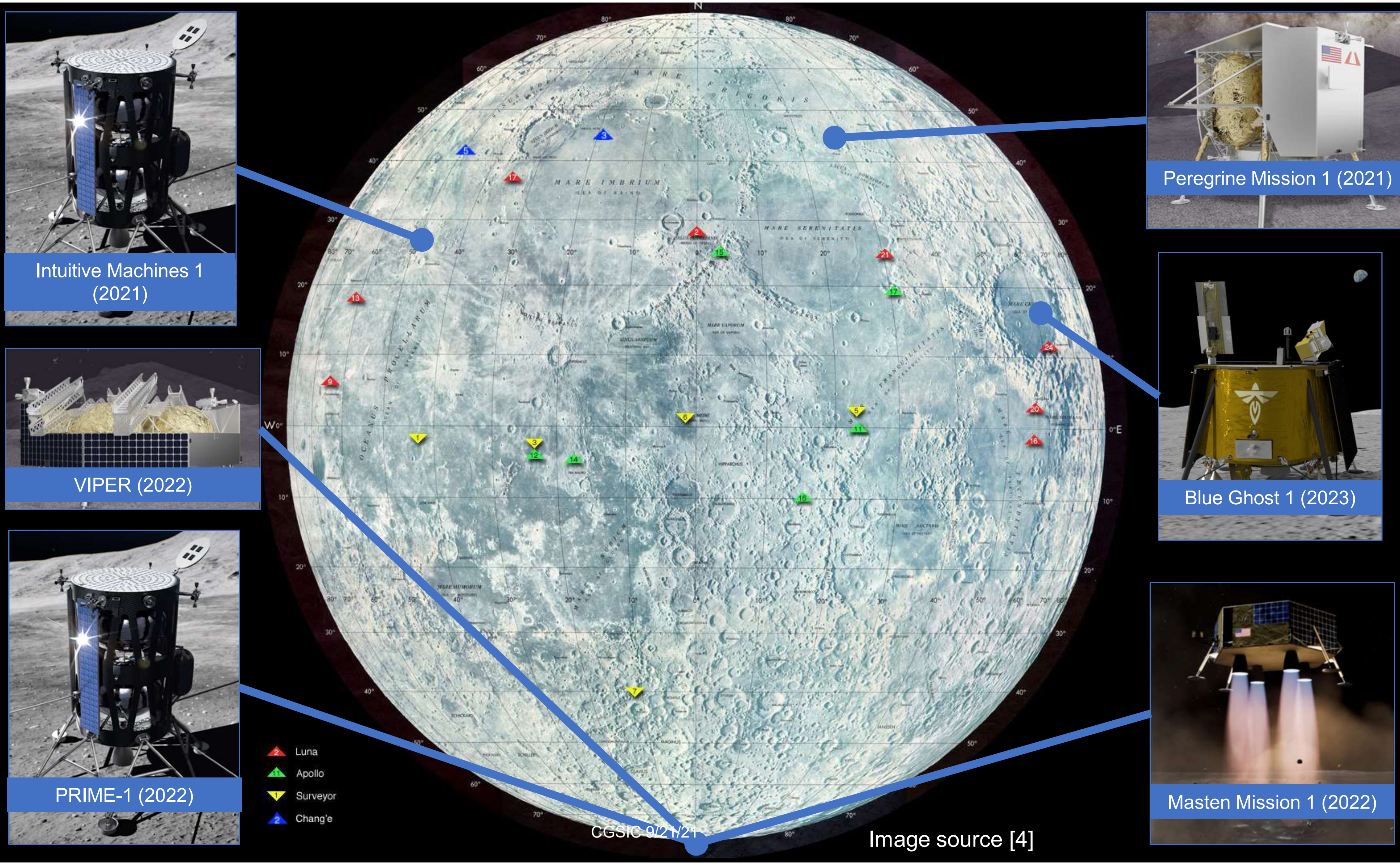


	Radial				In-Track				Cross-Track				SEP		
	max	mean	3σ	RMS	max	mean	3σ	RMS	max	mean	3σ	RMS	R61	R90	R99
Position (m)	23.2	2.6	20	7.3	11.2	0.7	13	4.4	10.9	-0.4	7.3	2.5	8.4	11.3	15.2
Velocity (cm/s)	0.42	0.02	0.4	0.14	0.91	0.001	0.28	0.09	2	-0.02	0.69	0.23	0.28	0.38	0.51

Conclusions

- The overall on-orbit GEO GPSR sidelobe tracking performance continues to be more than sufficient to support the GOES-R mission needs regardless of block-type
- The impact due to the GPS III transmit pattern gain decrease above 40 degrees off GPS boresight is mitigated in part by the design of the GOES-R GPS receive antenna and otherwise by the robustness of the GPSR system
- All future GEO satellites using GPSR need to take into consideration changes in the constellation makeup and the resulting performance implications, particularly with regard to the receive antenna design, and GPSR acquisition and tracking sensitivity thresholds

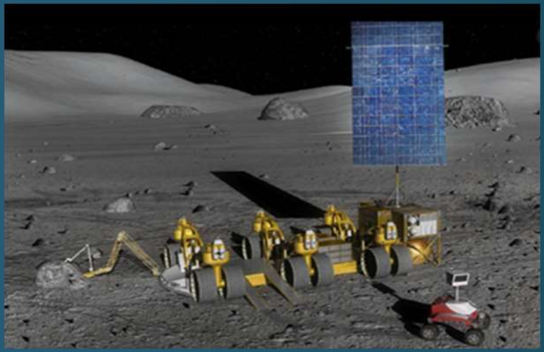
Commercial Lunar Payload Services (CLPS)



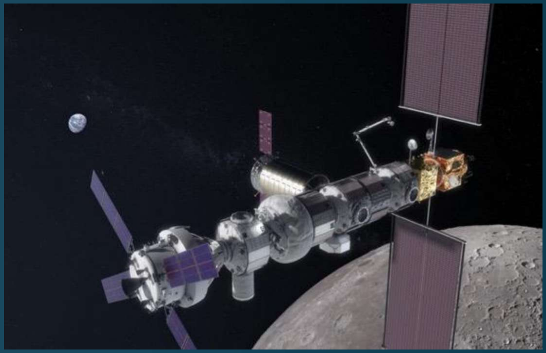
CGSIC 9/21/21

Image source [4]

Lunar Exploration: Roles for GNSS

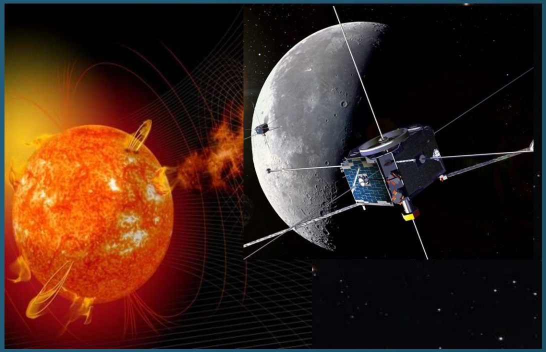


Lunar Surface Operations, Robotic Prospecting,& Human Exploration



Human-tended Lunar Vicinity Vehicles (Gateway)

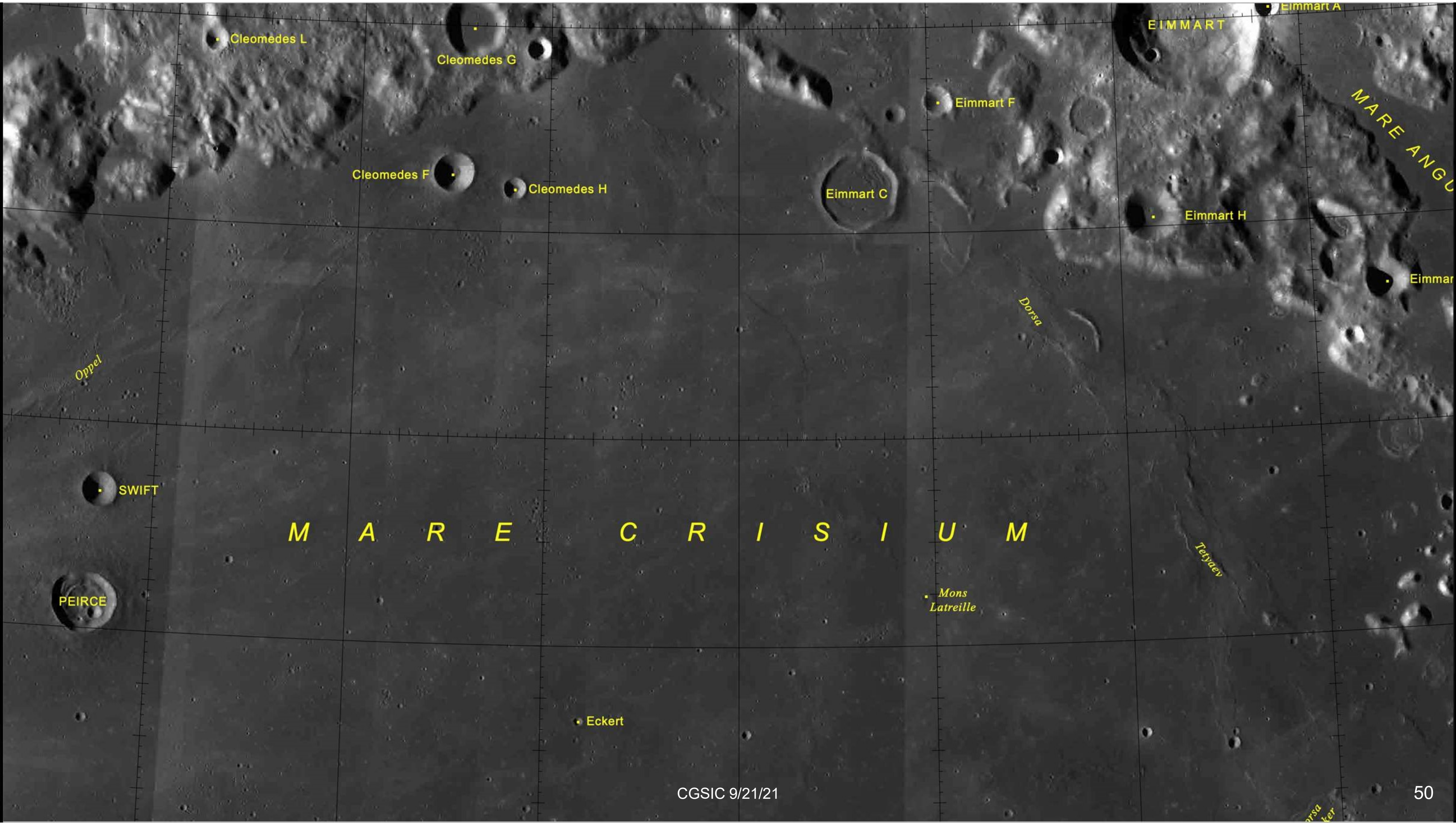
Robotic Lunar Orbiters, Resource & Science Sentinels



Earth, Astrophysics, & Solar Science Observations

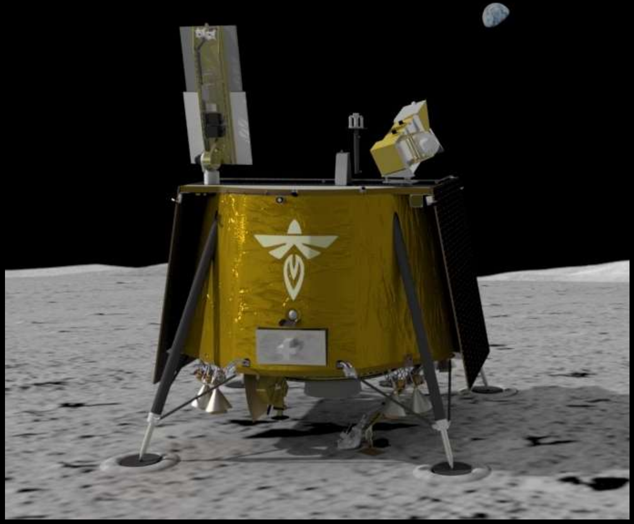
Satellite Servicing

Lunar Exploration Infrastructure


Eimmart A
Cleomedes L
Cleomedes G
EIMMART
Eimmart F
MARE ANGU
Cleomedes F
Cleomedes H
Eimmart C
Eimmart H
Eimmar
Dorsa
Oppel
SWIFT
MARE CRISIUM
Tetyaev
PEIRCE
Mons Latreille
Eckert

Blue Ghost 1

- Firefly Aerospace Systems awarded CLPS 19D flight in Feb. 2021
- Launching July 2023 and landing in Mare Crisium near Mons Latreille
- 10 NASA payloads including the Lunar GNSS Receiver Experiment (LuGRE)
- Transit + surface observation campaign
- Surface duration of one lunar day (~12 Earth days)



Entomologist Pierre André Latreille (1762-1833)

Image sources [5] [6]

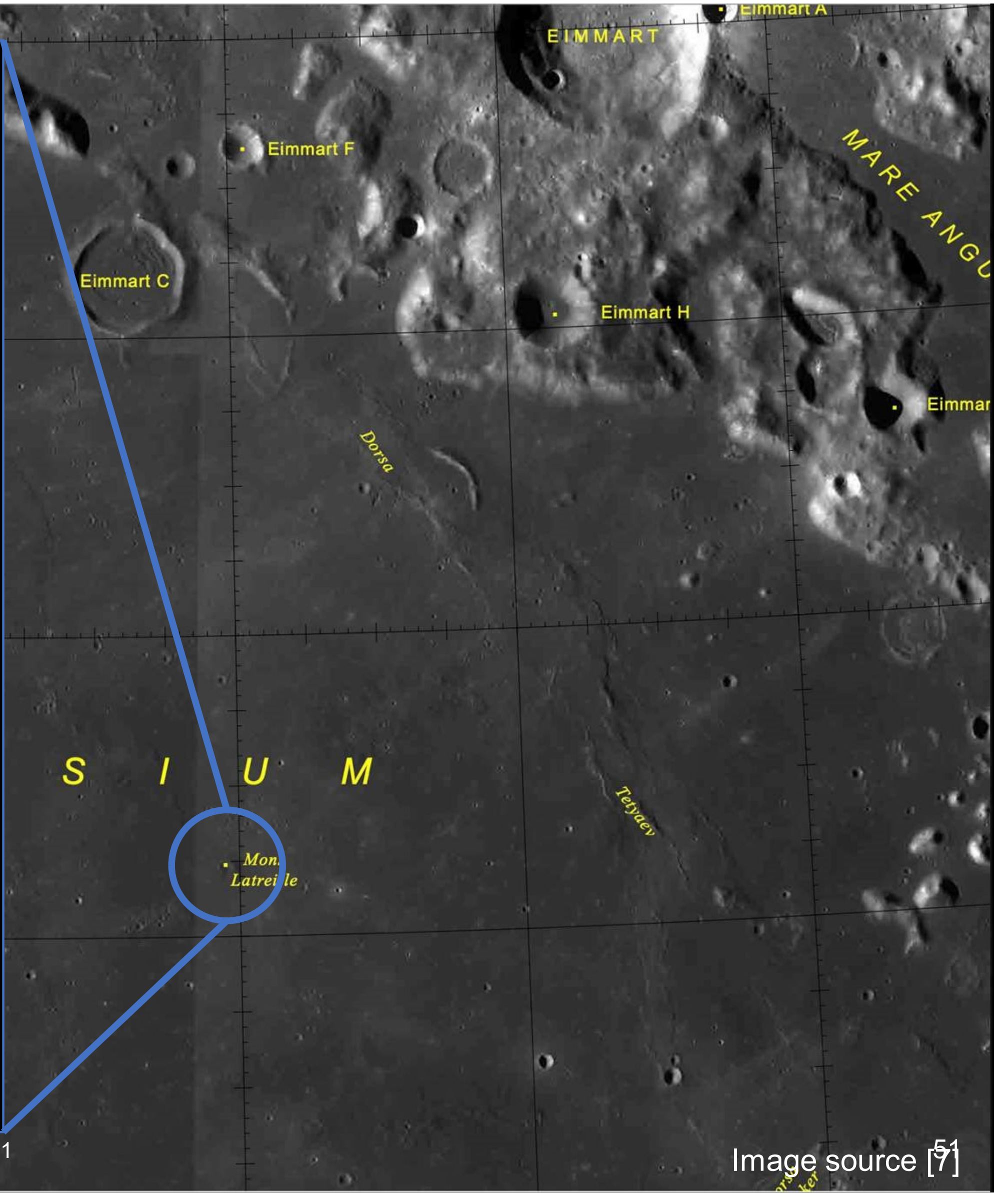
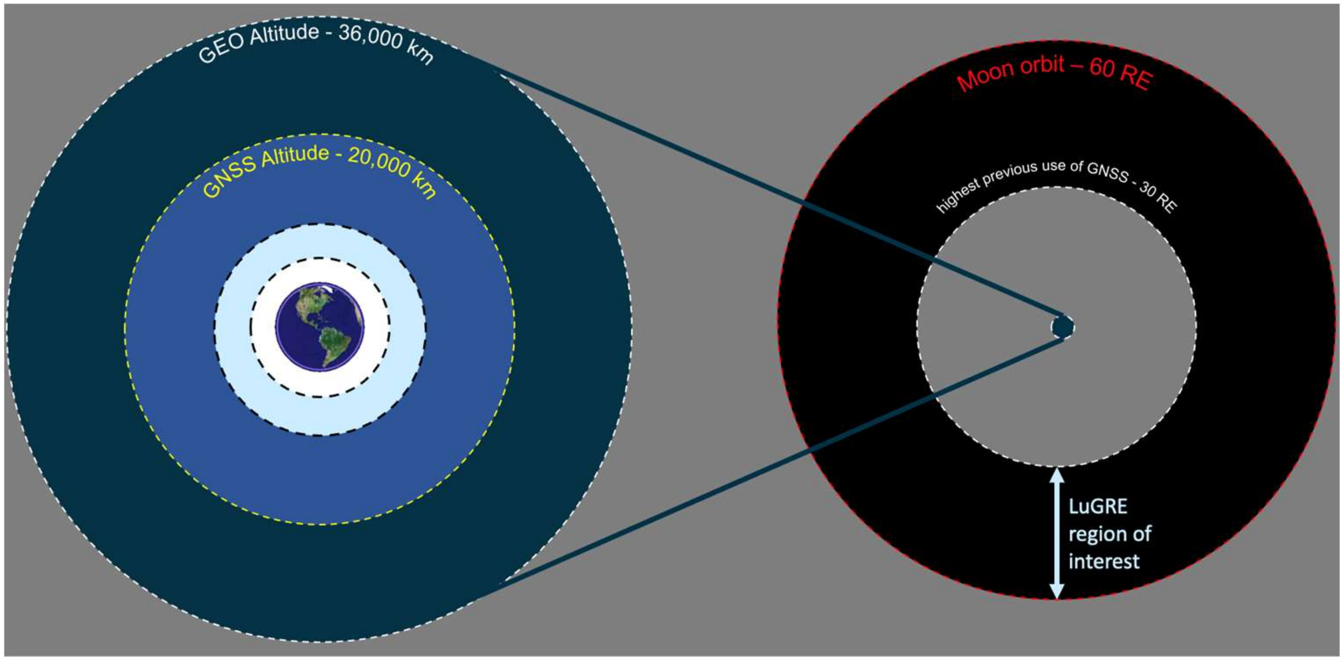


Image source [7]

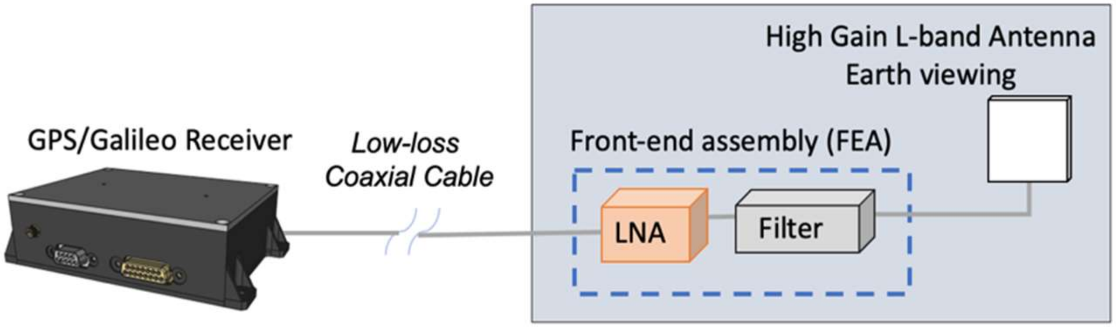
Lunar GNSS Receiver Experiment (LuGRE)

- **Goal: Extend GNSS-based navigation to the Moon**
- 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.



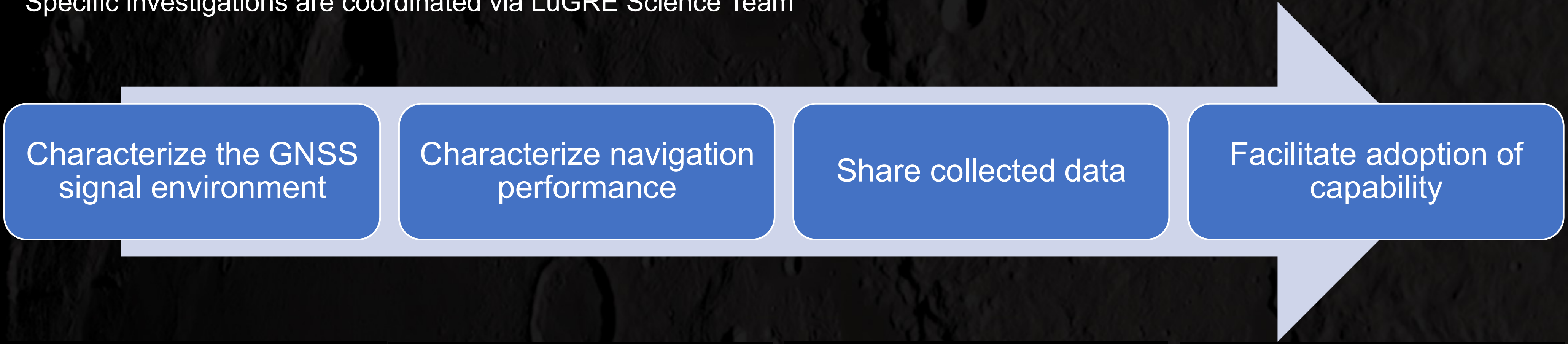
LuGRE Payload

- Global Navigation Satellite System (GNSS) receiver, antenna and front end provided by the Italian Space Agency (ASI)
    - GNSS receiver designed/built for lunar applications by Qascom leveraging heritage from their QN400 space receiver
- Payload can receive and process GPS (L1 and L5) and Galileo (E1 and E5a) signals
- Data: Raw RF samples, GNSS observables (pseudoranges, Doppler, C/N0, carrier phase), and navigation measurements (position, velocity and time from the onboard filter and instantaneous point solutions)



LuGRE Outcomes

*Specific investigations are coordinated via LuGRE Science Team



Characterize the GNSS signal environment

- Received carrier-to-noise spectral density (C/N_0)
- Transmit antenna patterns for Galileo and GPS
- Signal availability (average number of signals, max outage duration, outage frequency)
- Dilution of Precision due to clock and signal geometry
- Multipath (lunar surface, lander)
- Ionospheric perturbations (Earth and Moon)

Characterize navigation performance

- Time to first position fix (and restarts)
- Comparison to other navigation sources (lander, retroreflector)
- Navigation solution accuracy over time
- Filter versus point solution

Share collected data

- Commercial lunar landers
- Lunar payloads
- GNSS receiver developers
- Mission designers (HEOMD, SMD)
- Human Lander System (HLS) teams
- International space agencies
- GNSS community
- Science community

Facilitate adoption of capability

- NASA Tech Memo of research conclusions
- Publications within the wider GNSS and space navigation, operations, and mission planning community
- Provide lessons learned to GNSS hardware and software developers
- Improve modeling tools to predict GNSS-based navigation performance for future lunar missions

Lunar Communications & Navigation Evolution

Now to 2024

NEEDS

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

IMPLEMENTATION

- Existing ground networks
- Initial relay capabilities
- LunaNet compatibility

2024 to 2028

NEEDS

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

IMPLEMENTATION

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

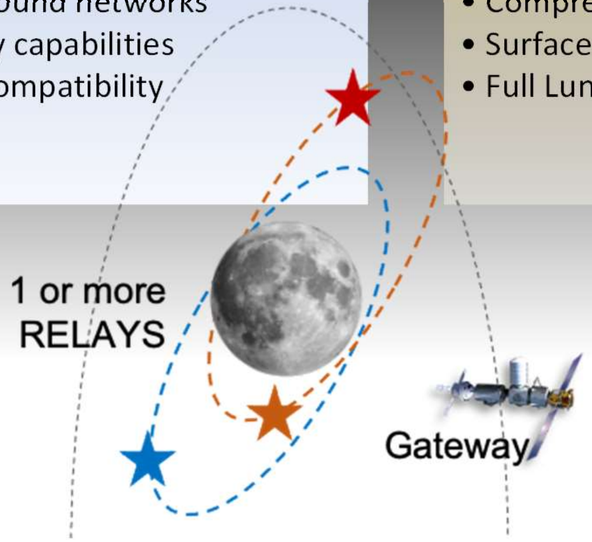
2028 and Beyond

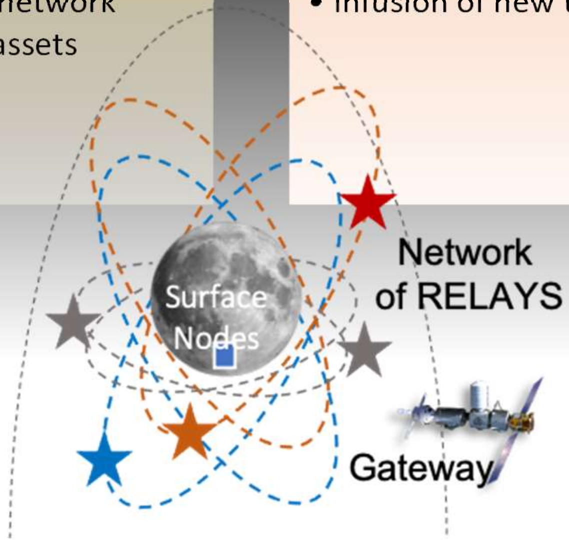
NEEDS

- Sustained surface and orbital presence

IMPLEMENTATION

- Evolution of infrastructure
- Infusion of new technology

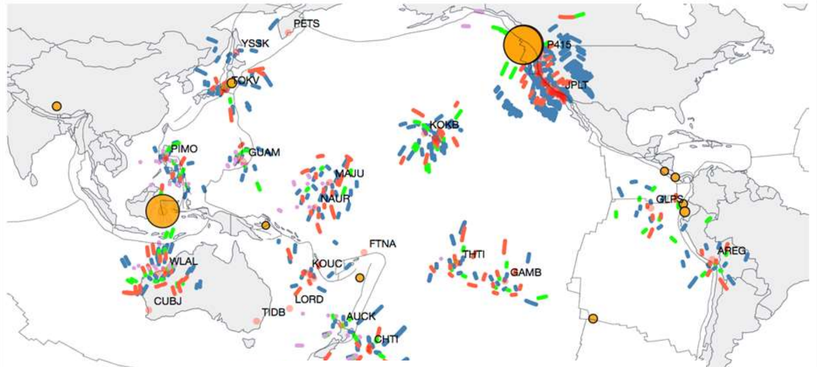




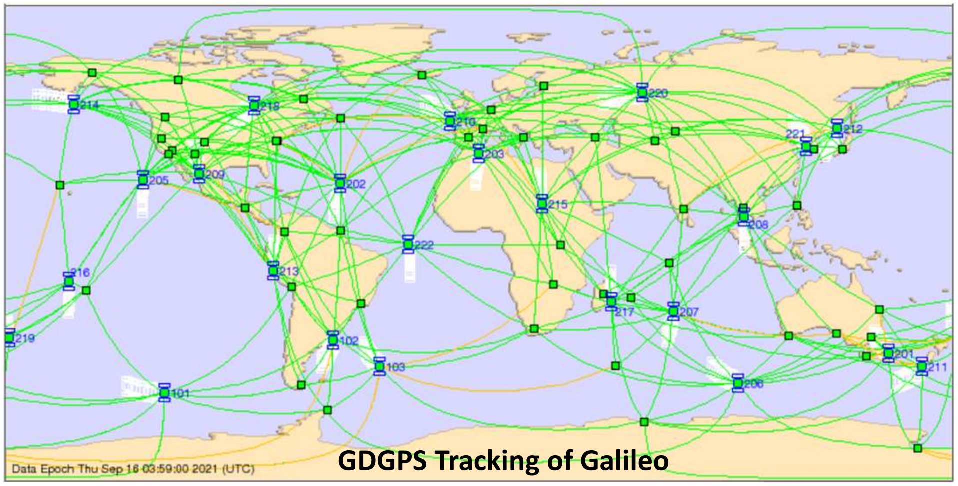
On the Ground: Complete GNSS Monitoring and Integration of all Space geodetic Techniques

Real-time monitoring of GPS, GLONASS, BeiDou, Galileo, QZSS, and NAVIC by the Global Differential GPS (GDGPS) System

Real-time monitoring of earthquakes and tsunamis using ground motion and ionospheric sensing



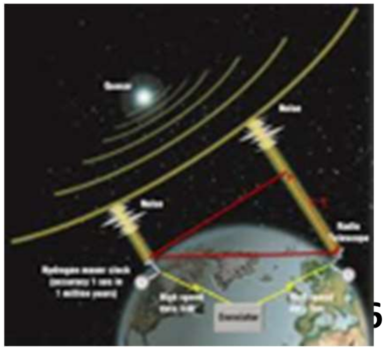
Iono pierce points to GNSS constellations



GDGPS Tracking of Galileo

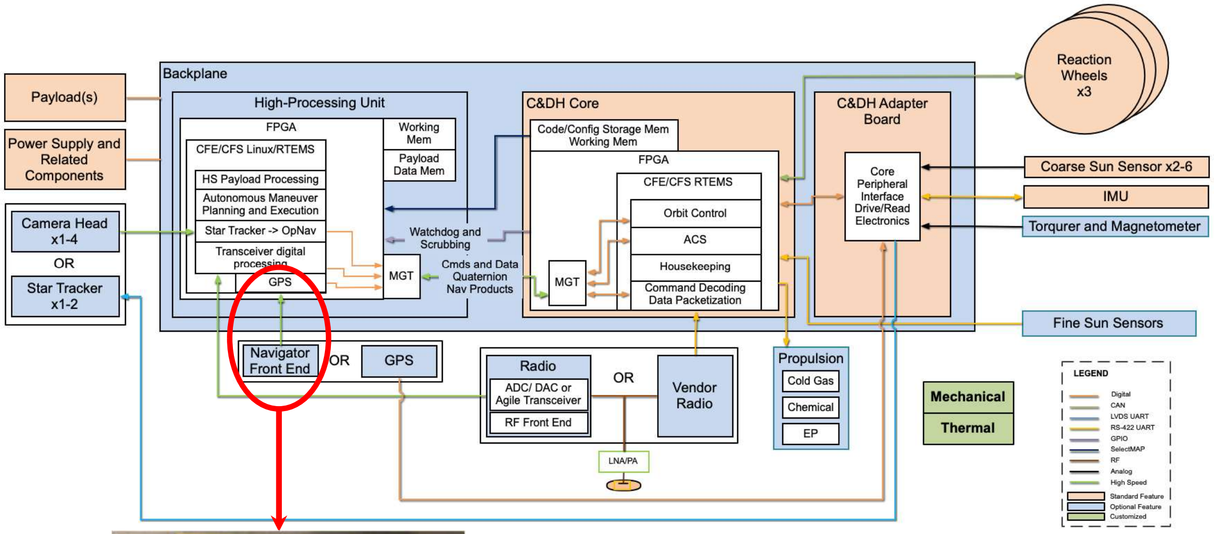
GipsyX/RTGx software added VLBI to its multi-technique capabilities, already including GNSS, DORIS, and SLR

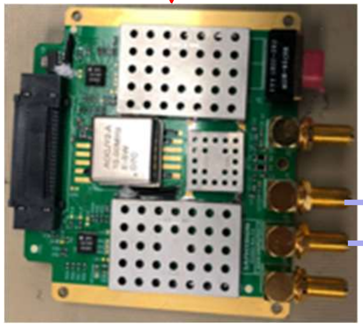
- Preparing JPL’s contribution to the next International Terrestrial Reference Frame (ITRF2020)



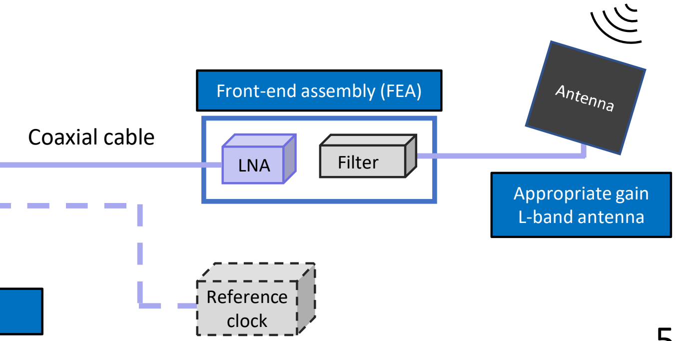
NC3m as an Add-on to MARES

- Rad-hard GNSS RF front-end down conversion card
- GPS software and firmware runs on MARES processor/FPGA
- Front-end assembly
  - Low Noise Amplifier (LNA)
  - Filter
  - RF cables
- GNSS antenna
- Option for enhanced external reference clock





NC3m GNSS RF card (~3.5”x3.5”)



NC3m Details

- Rad-hard RF front-end card
- Wide-band, dual-frequency RF card provides GPS L1 C/A and either L2C or L5
  - Galileo E1 and E5a also possible for additional SWaP-C
- Supports onboard or an external reference clock
- Provides 1 Pulse Per Second (1PPS) output
- GPS software and firmware builds on proven GSFC MMS Navigator flight heritage
- On-orbit upgradable software and firmware adaptable to new mission types and operations concepts
- Integrated GEONS navigation filter provides filtered GPS solution and propagates solution through GPS outages

Status:

- NC3m is currently in development
- NC3m is being integrated on MARES
- Standalone version of NC3m will be TRL6 in February 2022 (estimated)
- An NTR submitted for this technology

NC3m Applications and Benefits

Provide precise position, velocity, and time (PVT) for missions in all orbit regimes

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