National Aeronautics and Space Administration

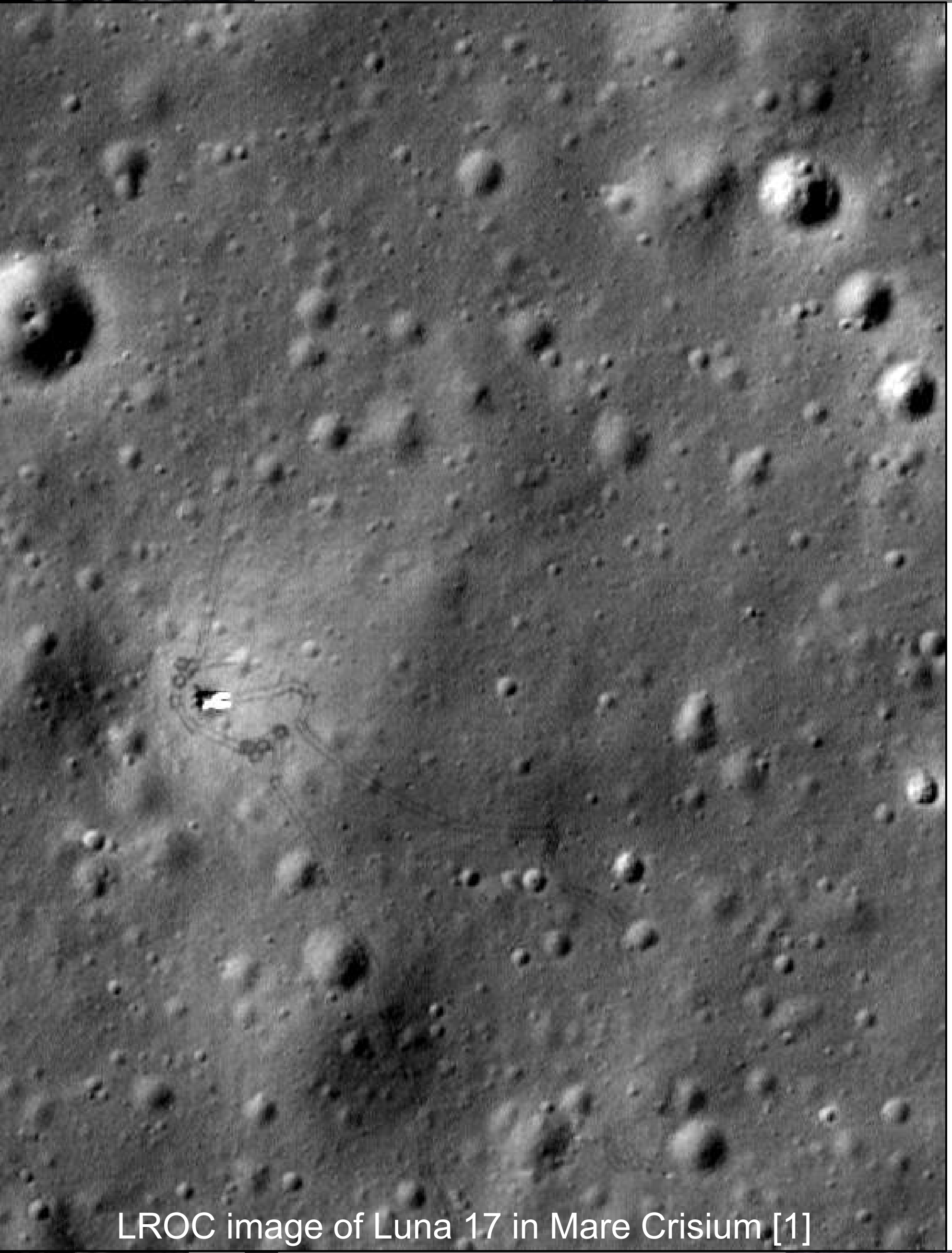
LuGRE
LUNAR GNSS RECEIVER EXPERIMENT

GNSS to the Moon

Ben Ashman

61st Meeting of the CGSIC

September 21, 2021


LROC image of Luna 17 in Mare Crisium [1]

Agenda

01 A New Era of Lunar Exploration

Scientific research, technology development and national prestige

02 The Rise of High Altitude GNSS

Operational use halfway to the Moon

03 U.S. Plans and GNSS

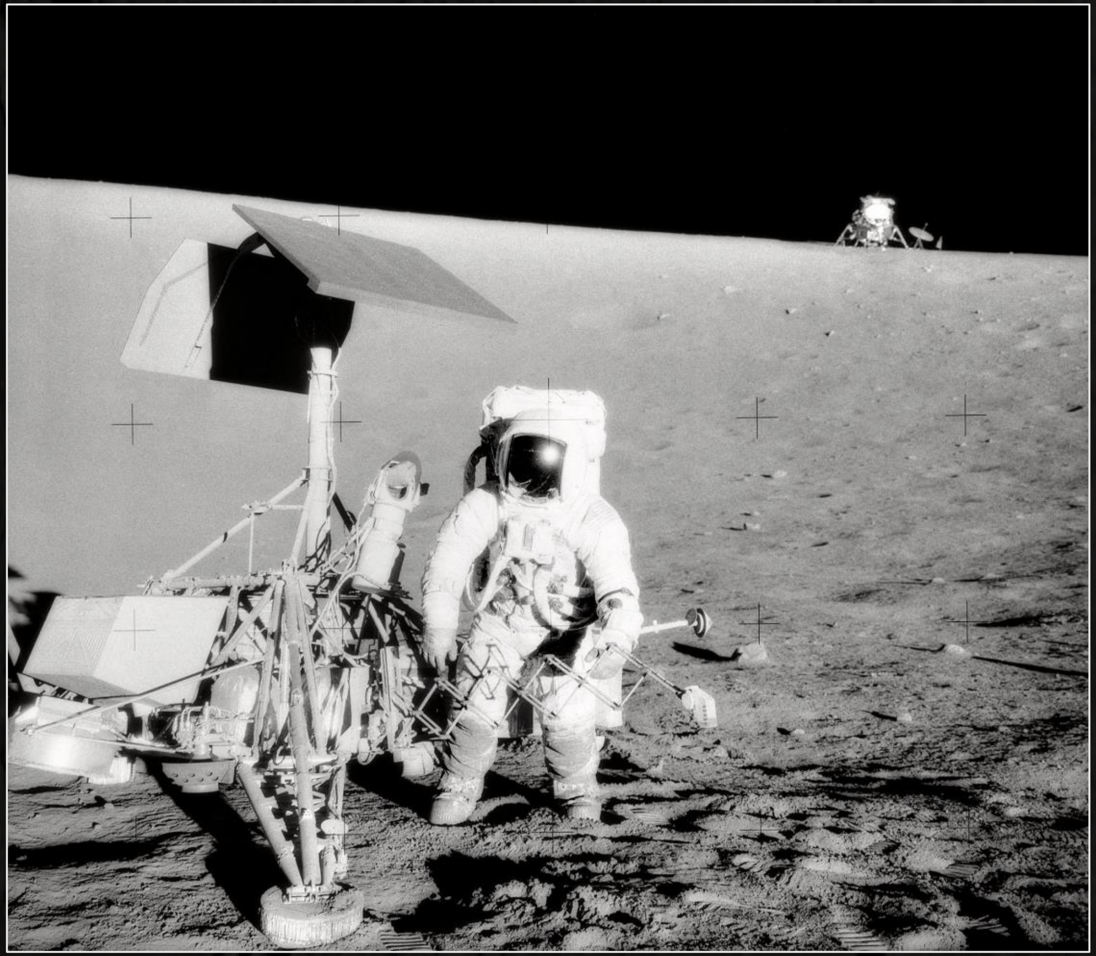
Artemis, Gateway, and CLPS

04 The Lunar GNSS Receiver Experiment

Demonstration of GNSS-based navigation at the Moon

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
- International Space Exploration Coordination Group (ISECG) currently comprised of 26 organizations
  - 2018 Global Exploration Roadmap (GER) identified 14 planned Moon missions
  - Released Lunar Supplement Aug 2020
  - 100-m performance target for precision landing

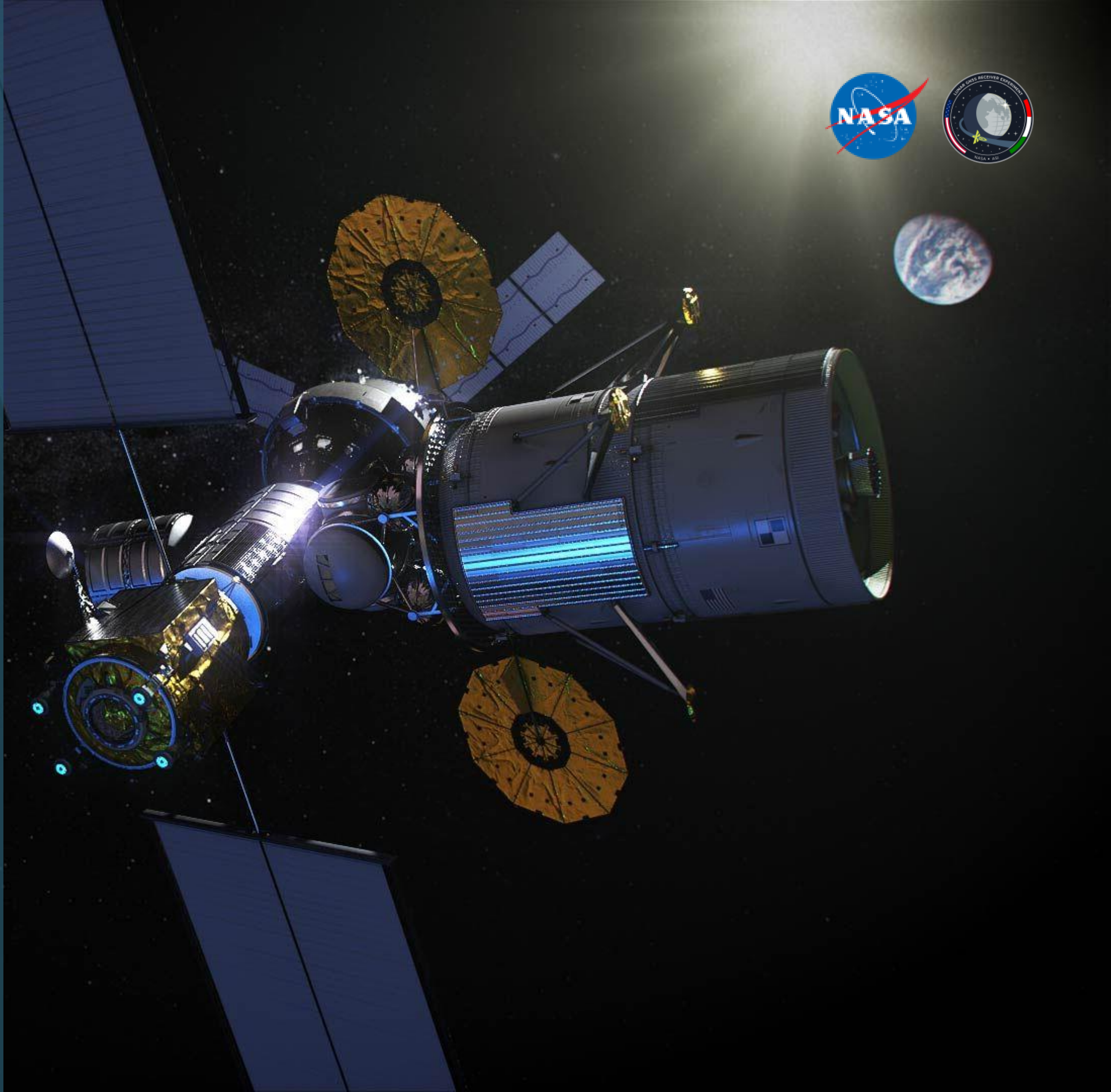


Pete Conrad examines Surveyor III spacecraft during Apollo 12 [2]

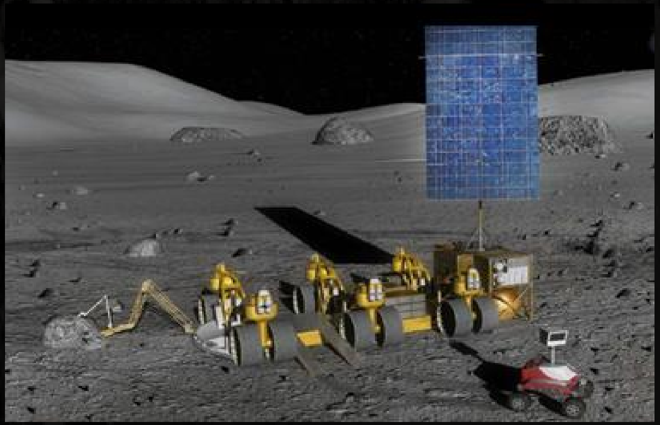
The Role of GNSS

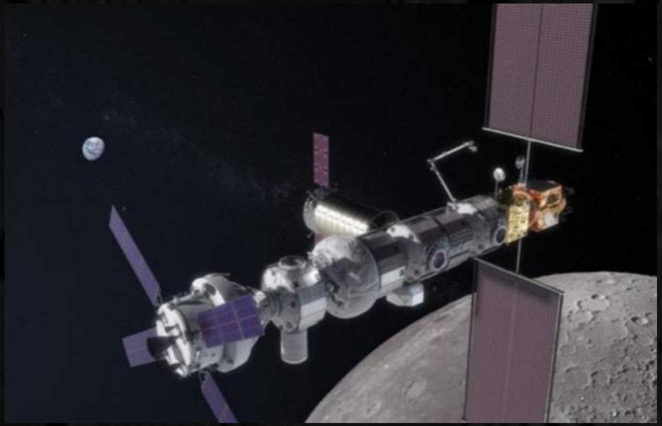
GNSS on lunar missions would:

- 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

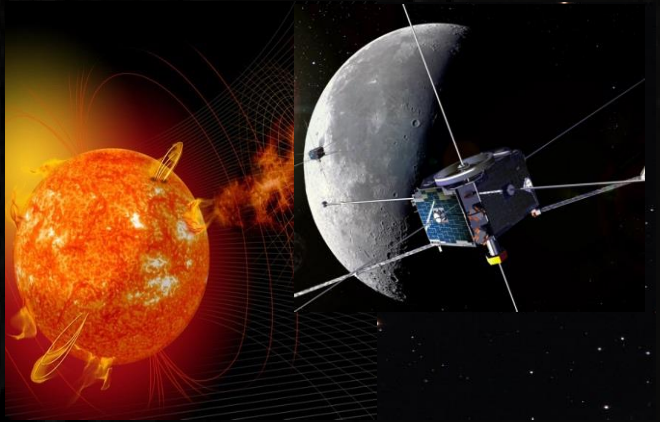


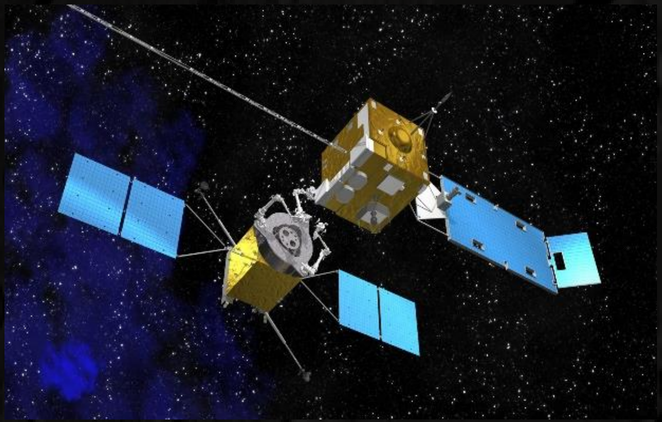
Lunar Exploration Roles for GNSS


Lunar Surface Operations, Robotic Prospecting,& Human Exploration


Human-tended Lunar Vicinity Vehicles (Gateway)

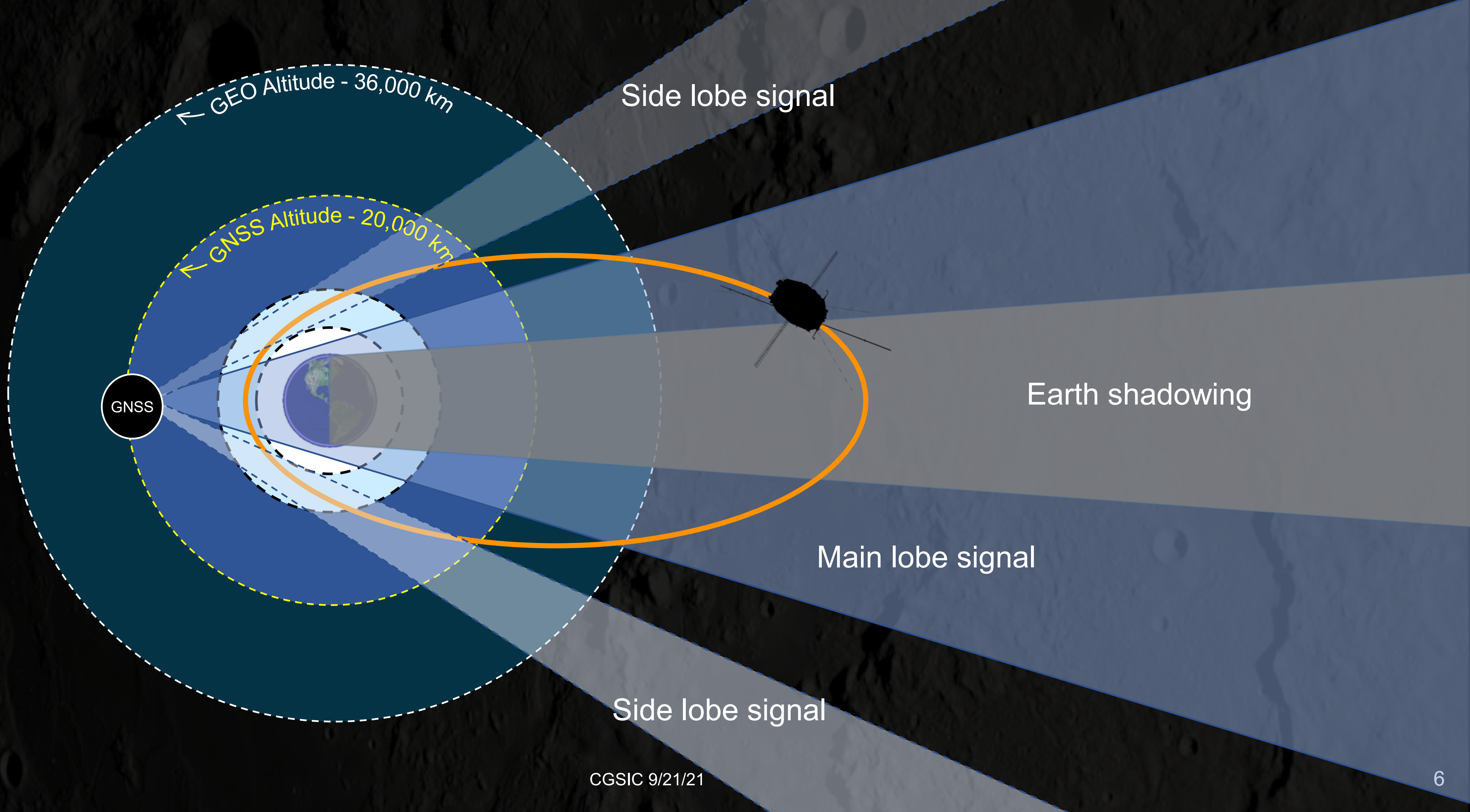

Robotic Lunar Orbiters, Resource & Science Sentinels


Earth, Astrophysics, & Solar Science Observations


Satellite Servicing

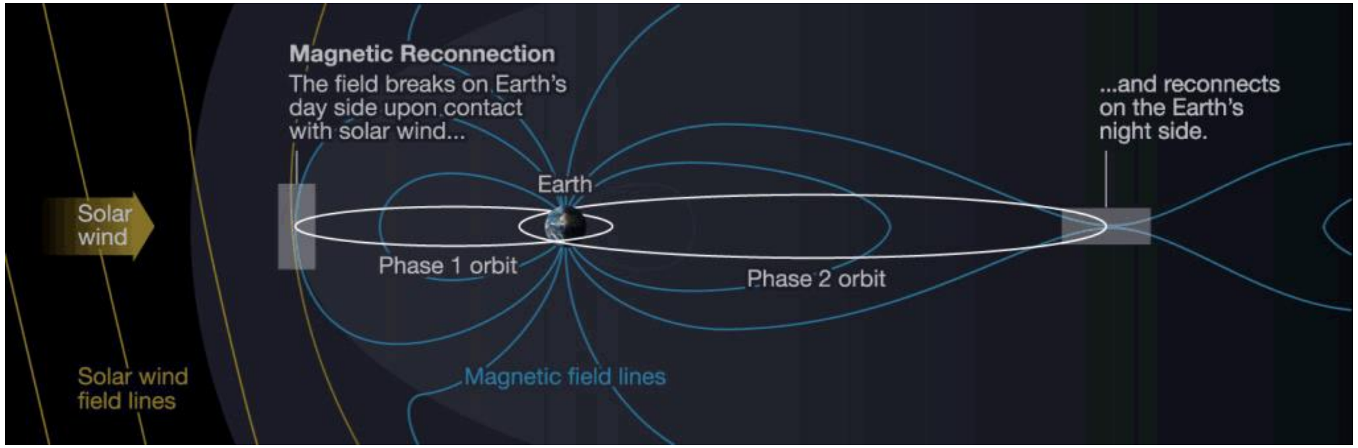

Lunar Exploration Infrastructure

Signal Reception in the Space Service Volume (SSV)



Beyond the SSV: MMS

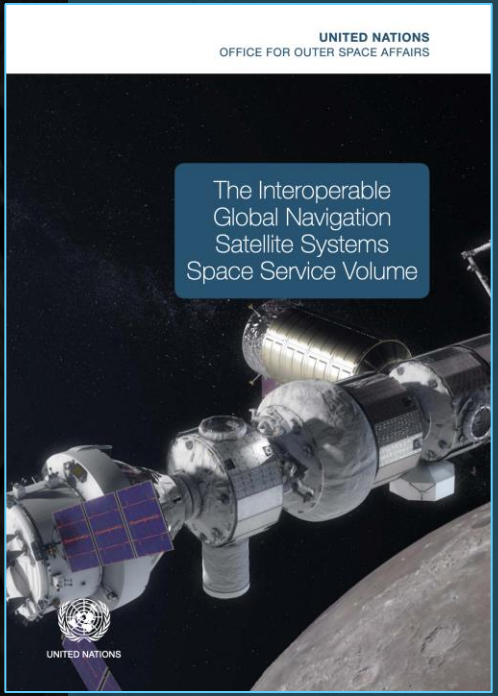
- Four spacecraft form a tetrahedron near apogee for magnetospheric science measurements
- Highest-ever use of GPS
  - Apogee raising beyond 29 RE **(50% lunar distance)** completed in February 2019
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping

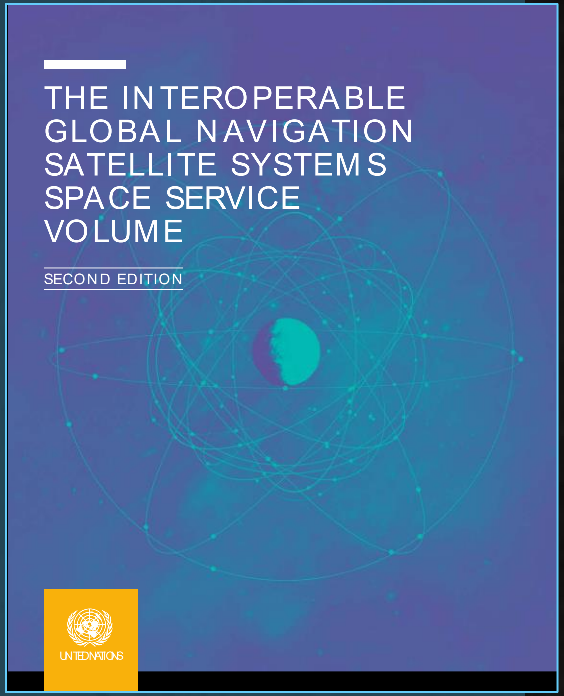


- Continued outstanding GPS performance
  - Root variance: Radial < 70m, lateral <20m
  - Average of 3 signals tracked at apogee
- Nearing the tracking threshold of Navigator receiver/antenna system
- Higher gained antenna and/or more sensitive GNSS receivers can extend signal availability >30 R_E
- **MMS data enables design of missions that can reliably use GNSS systems out to lunar distances**

Enabling Lunar GNSS

- **NASA-USAF Memorandum of Understanding**
  - signed in 2017 to ensure SSV signal continuity for future space users
  - Jennifer Donaldson (NASA GSFC) representing NASA and U.S. civil space in the GPS IIIF procurement cycle
- **UN International Committee on GNSS**
  - Space User Subgroup formed in 2018 within Working Group B (Enhancement of GNSS) co-chaired by the U.S., EU, and China
  - Fully revised 2nd Edition of the Space Service Volume booklet to be published at ICG-15 this month in Vienna
  - Work plan: U.S. leading “Expansion of SSV and GNSS SSV service upgrades” priority





GPS data released to public

- Late 2020: IIR/IIR-M antenna gain pattern data and GPS III SVN 74-77 phase center and inter-signal bias data on navcen.uscg.gov
  - Request from ICG Int’l GNSS Monitoring and Assessment (IGMA) group for PCO/PCV data, action worked by DOT
- USSF Space and Missile Systems Center (SMC) assessing public release of all available GPS data (Blocks IIR through III SV1–10)

U.S. Lunar Activities

- **Artemis Accords**
  - Establish norms of behavior for collaborators in U.S.-led Artemis program
  - Signed by 12 countries since introduction in May 2020
- **Artemis plan**
  - Released Sept 2020 outlining "sustainable course to the Moon"
- **Space Policy Directive 7 (SPD-7)**
  - Signed by the U.S. President Jan 2021
  - "PNT services will also play an important role in space traffic management and future applications in the Cislunar Service Volume, which extends from GEO out to and including the Moon's orbit."

Image source [3]

TECHNOLOGY

NASA is developing and implementing key communication and navigation technologies to support robust exploration at and near the Moon. These technologies include the use of GPS signals by spacecraft and lunar surface systems for navigation, optical communications technology to allow multi-gigabit data connections back to the Earth, and expanding the Internet architecture into space through Disruption Tolerant Networking (DTN) standards and software.

NASA Lunar Exploration Plans

Artemis

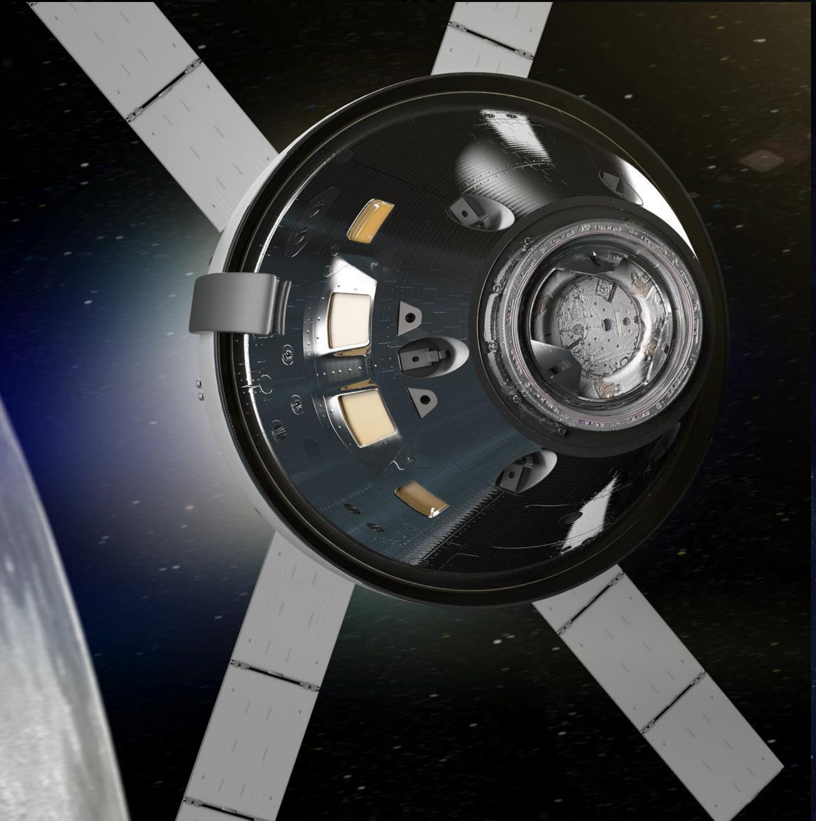
- Series of SLS launches carrying the Orion crew capsule that will return humans to the surface of the Moon

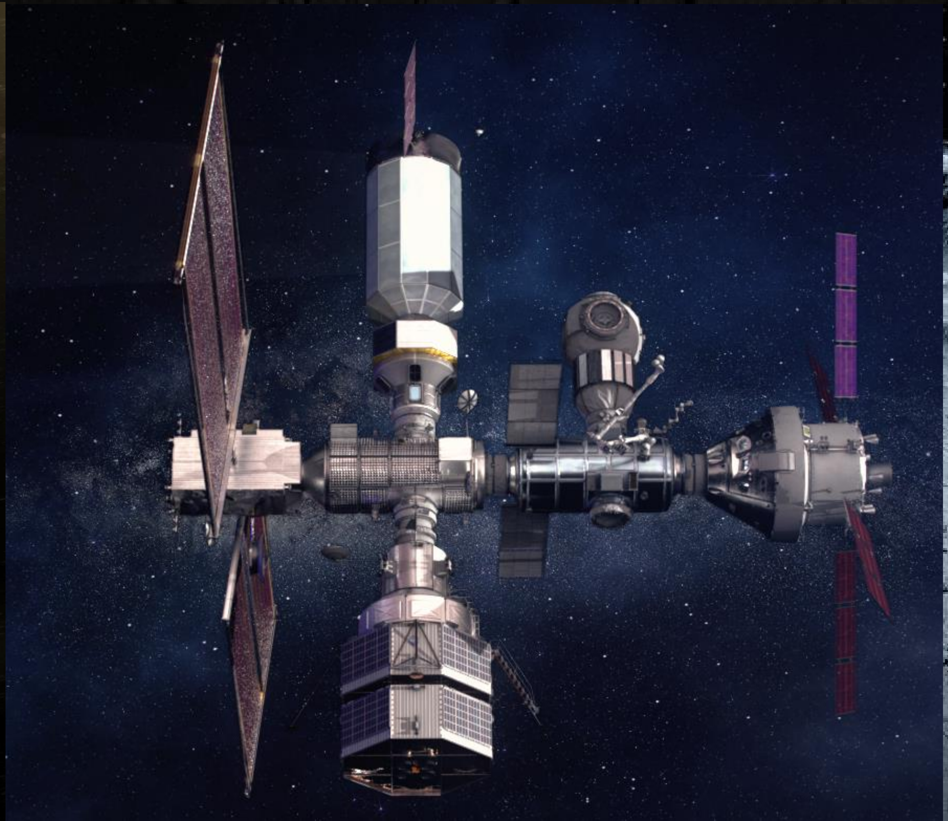
Gateway

- 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





Commercial Lunar Payload Services (CLPS)

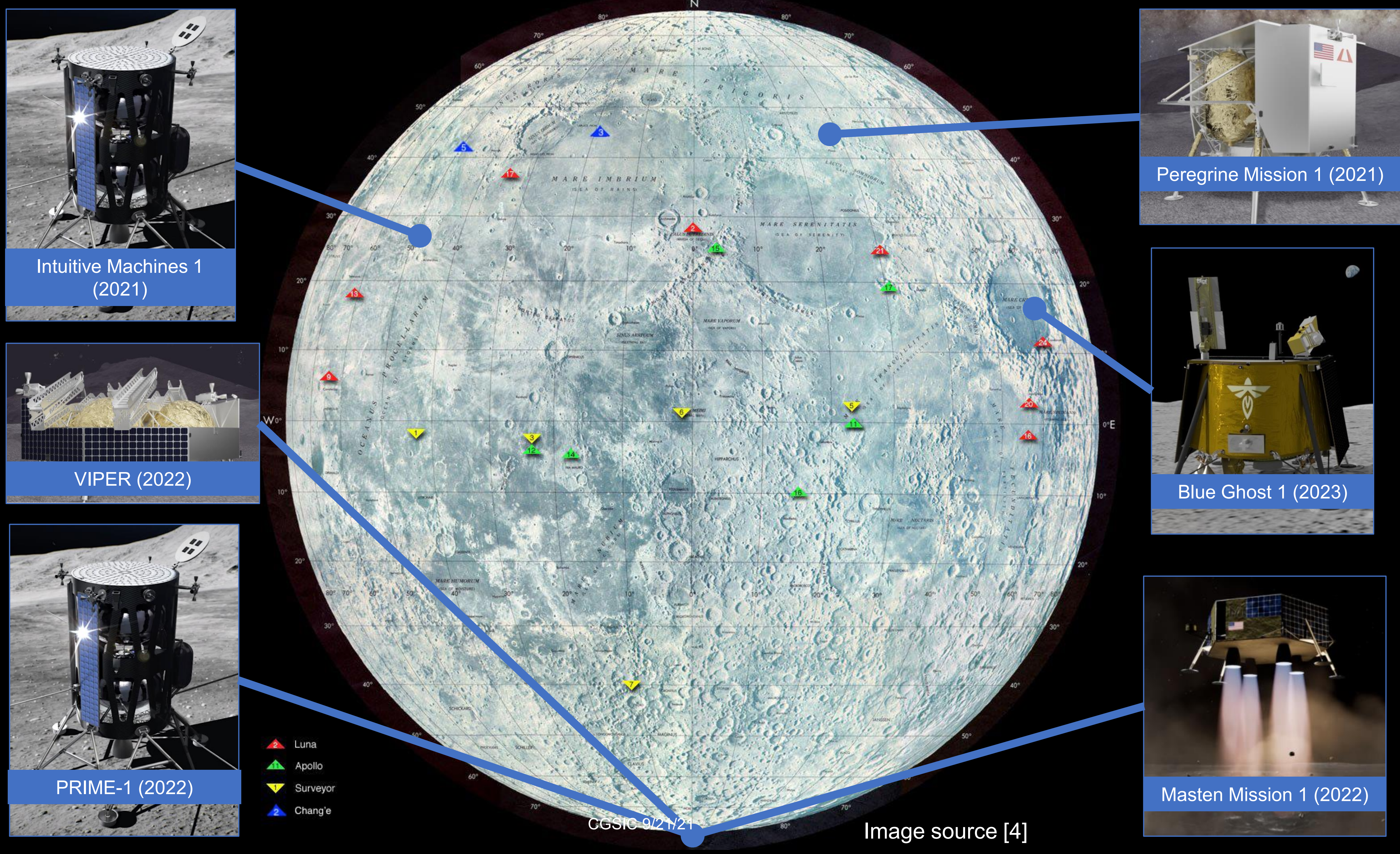
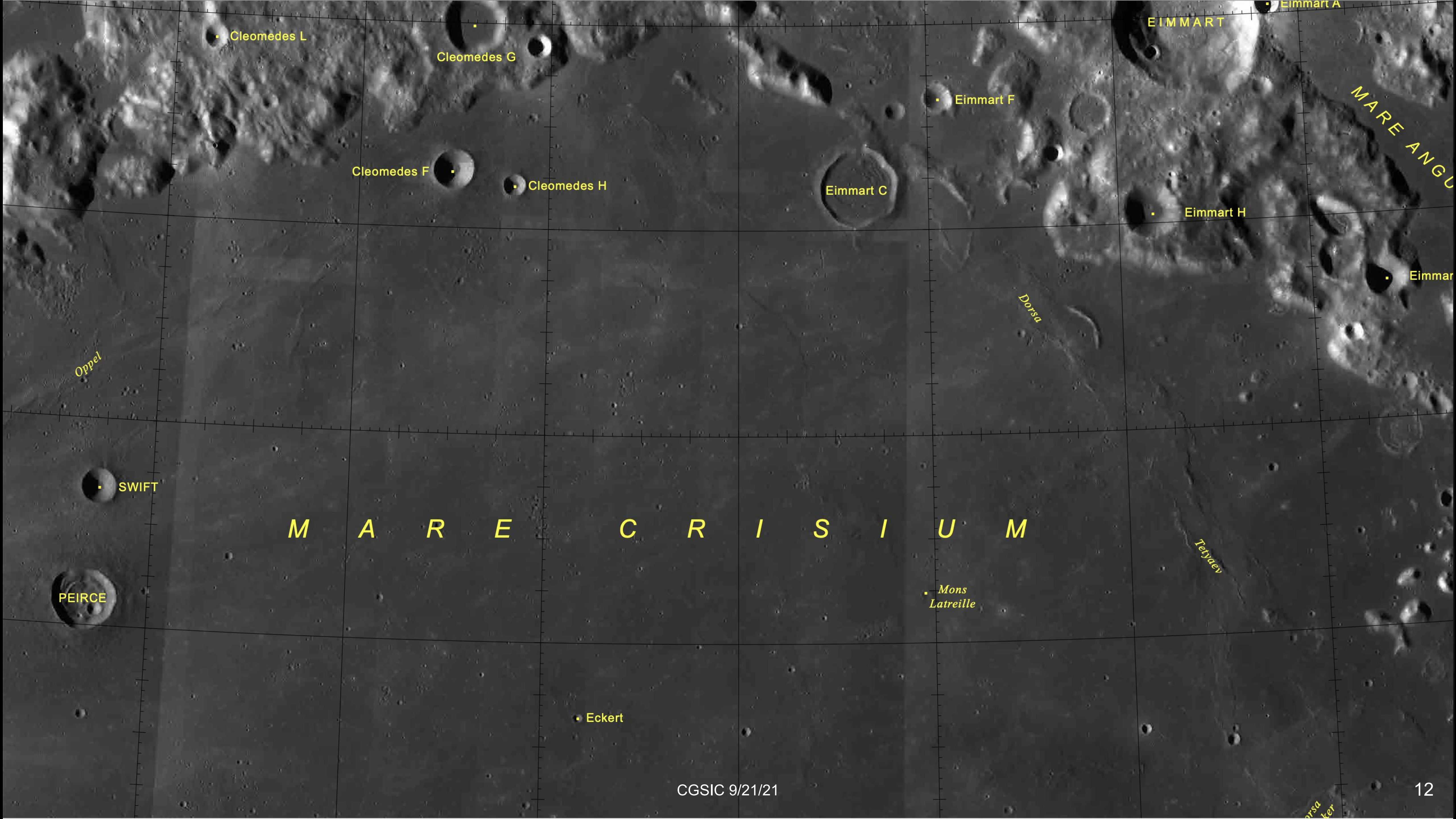
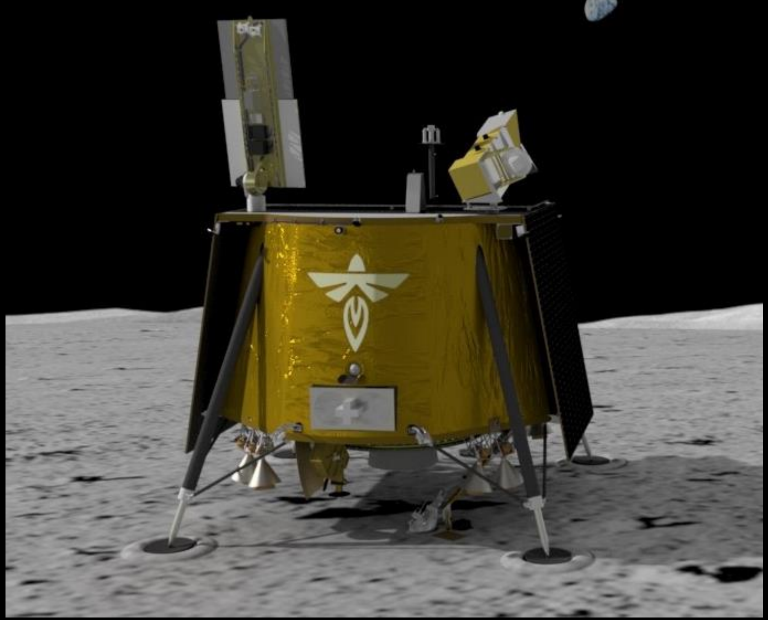


Image source [4]


Cleomedes L
Cleomedes G
Eimmart A
EIMMART
MARE ANGU
Eimmart F
Cleomedes F
Cleomedes H
Eimmart C
Eimmart H
Eimmar
Dorsa
Oppel
SWIFT
M A R E C R I S I U M
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]

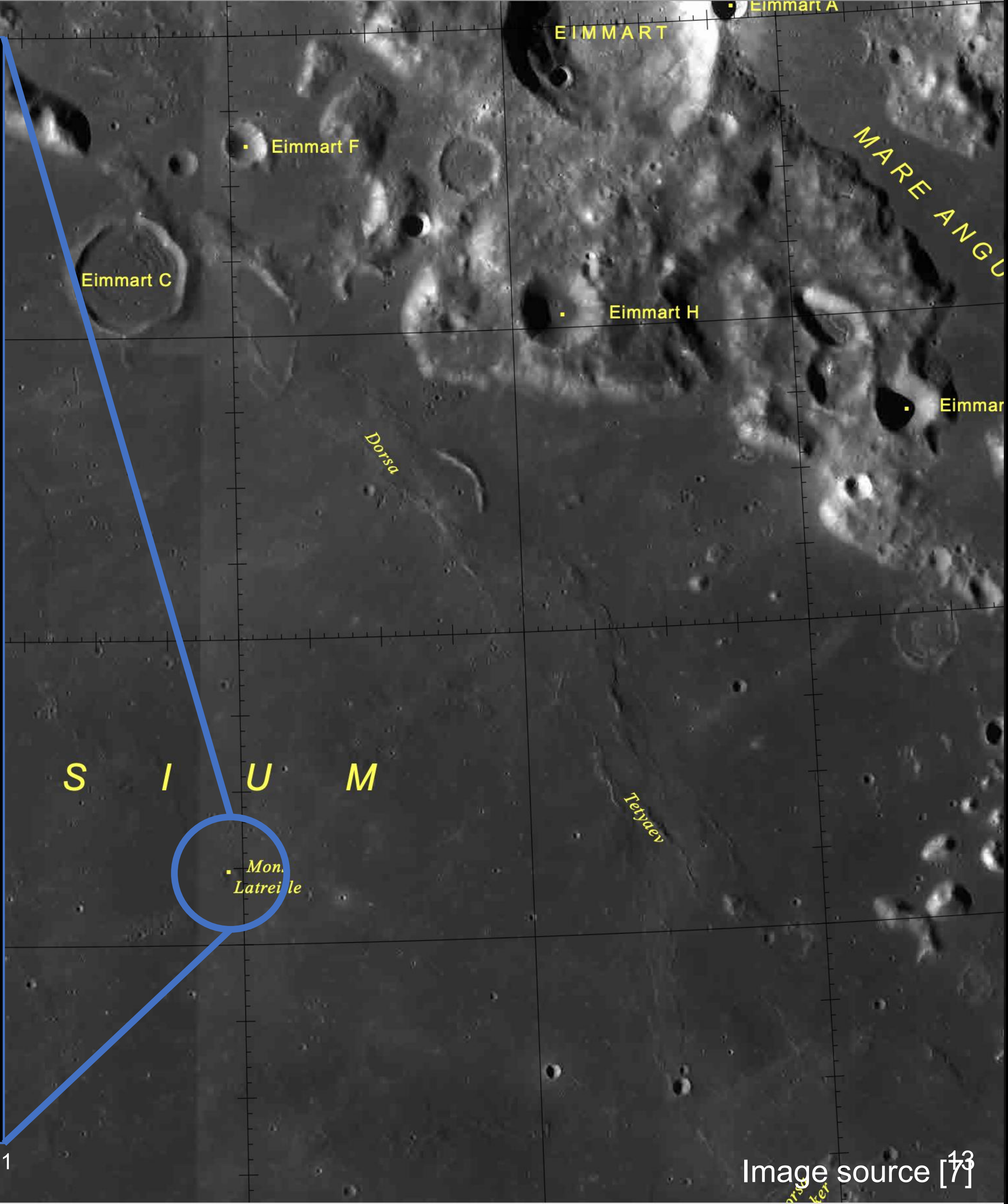
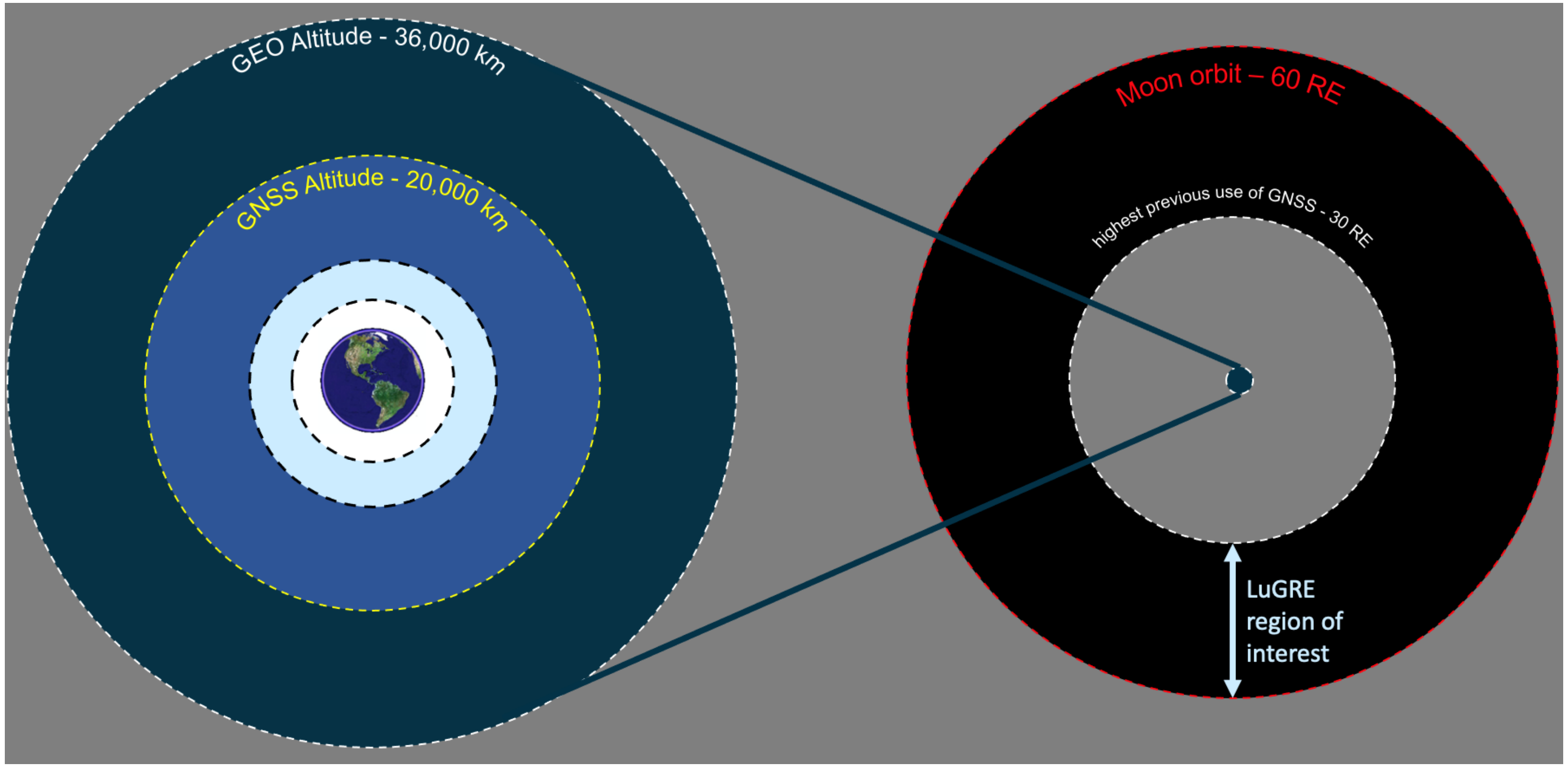


Image source [7]

Lunar GNSS Receiver Experiment (LuGRE)

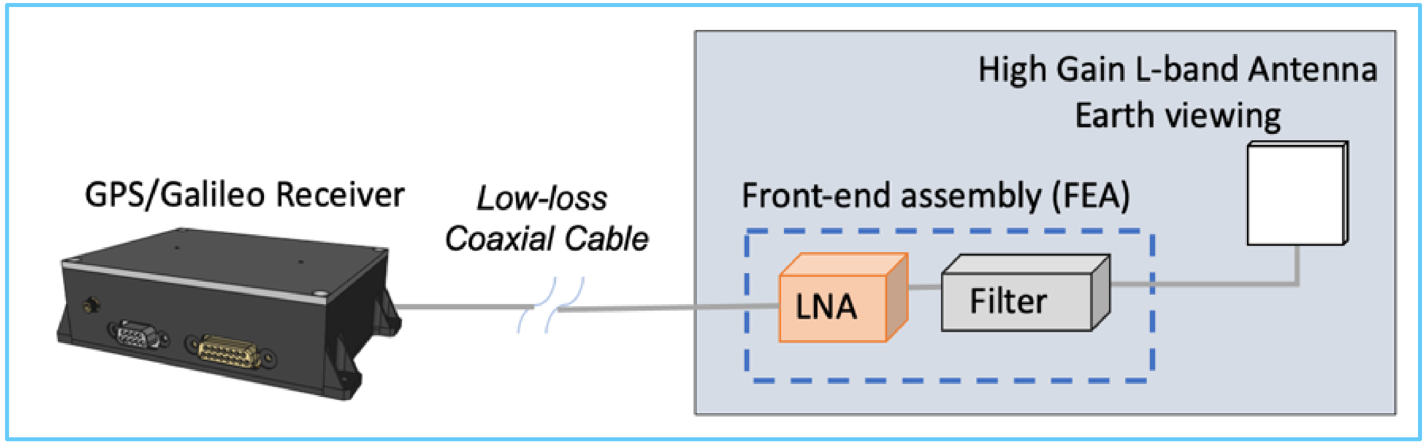
Goal: Extend GNSS-based navigation to the Moon

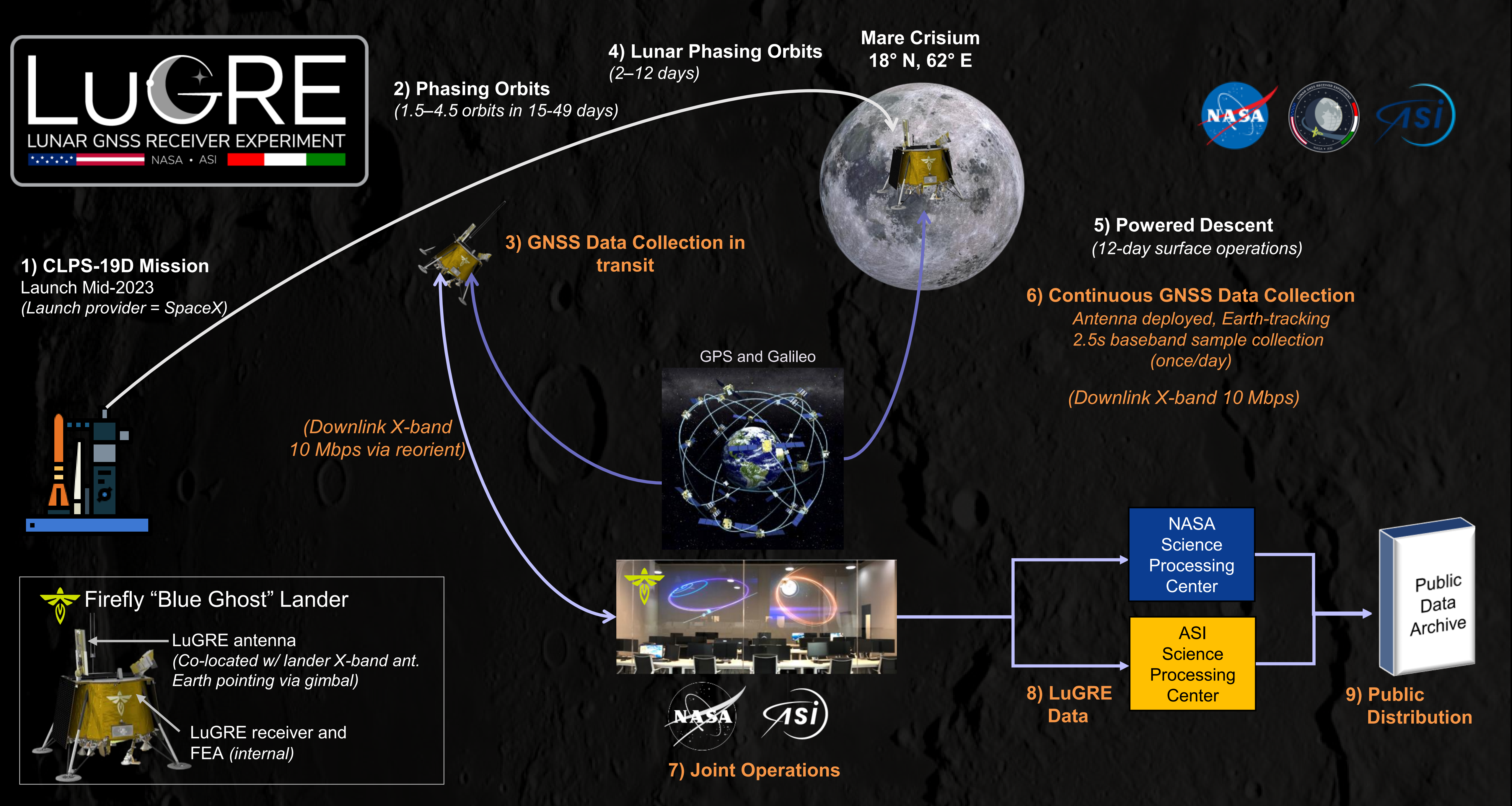
- Objectives
  1. Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
  2. Demonstrate navigation and time estimation using GNSS data collected at the Moon.
  3. Utilize collected data to support development of GNSS receivers specific to lunar use.



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
LUNAR GNSS RECEIVER EXPERIMENT
NASA • ASI
2) Phasing Orbits
(1.5–4.5 orbits in 15-49 days)
4) Lunar Phasing Orbits
(2–12 days)
Mare Crisium
18° N, 62° E
1) CLPS-19D Mission
Launch Mid-2023
(Launch provider = SpaceX)
3) GNSS Data Collection in transit
5) Powered Descent
(12-day surface operations)
6) Continuous GNSS Data Collection
Antenna deployed, Earth-tracking
2.5s baseband sample collection
(once/day)
(Downlink X-band 10 Mbps)
GPS and Galileo
(Downlink X-band
10 Mbps via reorient)
Firefly "Blue Ghost" Lander
LuGRE antenna
(Co-located w/ lander X-band ant.
Earth pointing via gimbal)
LuGRE receiver and
FEA (internal)
NASA
ASI
7) Joint Operations
NASA Science Processing Center
ASI Science Processing Center
8) LuGRE Data
Public Data Archive
9) Public Distribution

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

LuGRE Outcomes

*Specific investigations are coordinated via LuGRE Science Team

Characterize the GNSS signal environment	Characterize navigation performance	Share collected data	Facilitate adoption of capability
• **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)	• Time to first position fix (and restarts) • Comparison to other navigation sources (lander, retroreflector) • Navigation solution accuracy over time • Filter versus point solution	• Commercial lunar landers • Lunar payloads • GNSS receiver developers • Mission designers (HEOMD, SMD) • Human Lander System (HLS) teams • International space agencies • GNSS community • Science community	• 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

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

LuGRE Outcomes

*Specific investigations are coordinated via LuGRE Science Team

Characterize the GNSS signal environment	Characterize navigation performance	**Share collected data**	Facilitate adoption of capability
• 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)	• Time to first position fix (and restarts) • Comparison to other navigation sources (lander, retroreflector) • Navigation solution accuracy over time • Filter versus point solution	• Commercial lunar landers • Lunar payloads • **GNSS receiver developers** • Mission designers (HEOMD, SMD) • Human Lander System (HLS) teams • International space agencies • **GNSS community** • Science community	• 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

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

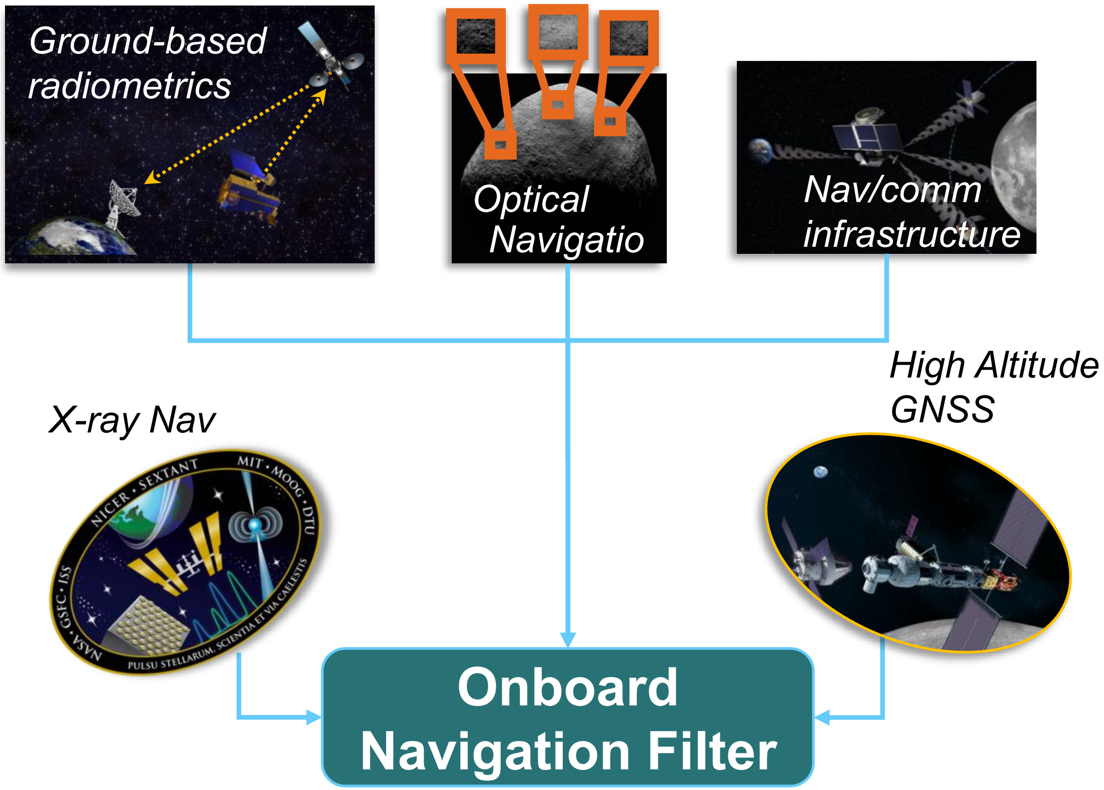
Share collected data

- 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

Conclusions



- Robust high-altitude PNT relies on a diversity of navigation sources, each with strengths and weaknesses
- GNSS offers a proven source of one-way range, Doppler and time transfer unique among available navigation measurements
- For many mission classes, GNSS can provide 100-meter-class absolute navigation, centimeter-class relative navigation, and time-synchronization on the order of 1 microsecond or better

National Aeronautics and
Space Administration

Benjamin W. Ashman, Ph.D.
LuGRE Deputy PI
Navigation and Mission Design Branch
NASA Goddard Space Flight Center
benjamin.w.ashman@nasa.gov

Joel J.K. Parker
LuGRE PI
Navigation and Mission Design Branch
NASA Goddard Space Flight Center
joel.j.k.parker@nasa.gov

James Joseph Miller
Deputy Director
Policy & Strategic Communications –
Space Communications and
Navigation – NASA Headquarters
jj.miller@nasa.gov

References

[1] http://lroc.sese.asu.edu/posts/650

[2] https://www.flickr.com/photos/nasacommons/9460246670/in/album-72157634967531957/

[3] https://spacepolicyonline.com/news/eight-countries-sign-artemis-accords/

[4] https://www.nasa.gov/mission_pages/LRO/multimedia/moonimg_07.html

[5] https://www.nasa.gov/press-release/nasa-selects-firefly-aerospace-for-artemis-commercial-moon-delivery-in-2023[6] https://en.wikipedia.org/wiki/Pierre_Andr%C3%A9_Latreille

[7] https://quickmap.lroc.asu.edu/

See also:

B. Ashman, L. Schlenker, J. Parker, F. Bauer, L. Winternitz, A. Long, K. Craft, M. Hassouneh, Applications and Benefits of GNSS for Lunar Exploration, 16th International Conference on Space Operations, virtual, 3-5 May 2021.

Beyond the SSV: MMS