National Aeronautics and
Space Administration

Applications and Benefits of

GNSS for Lunar Exploration

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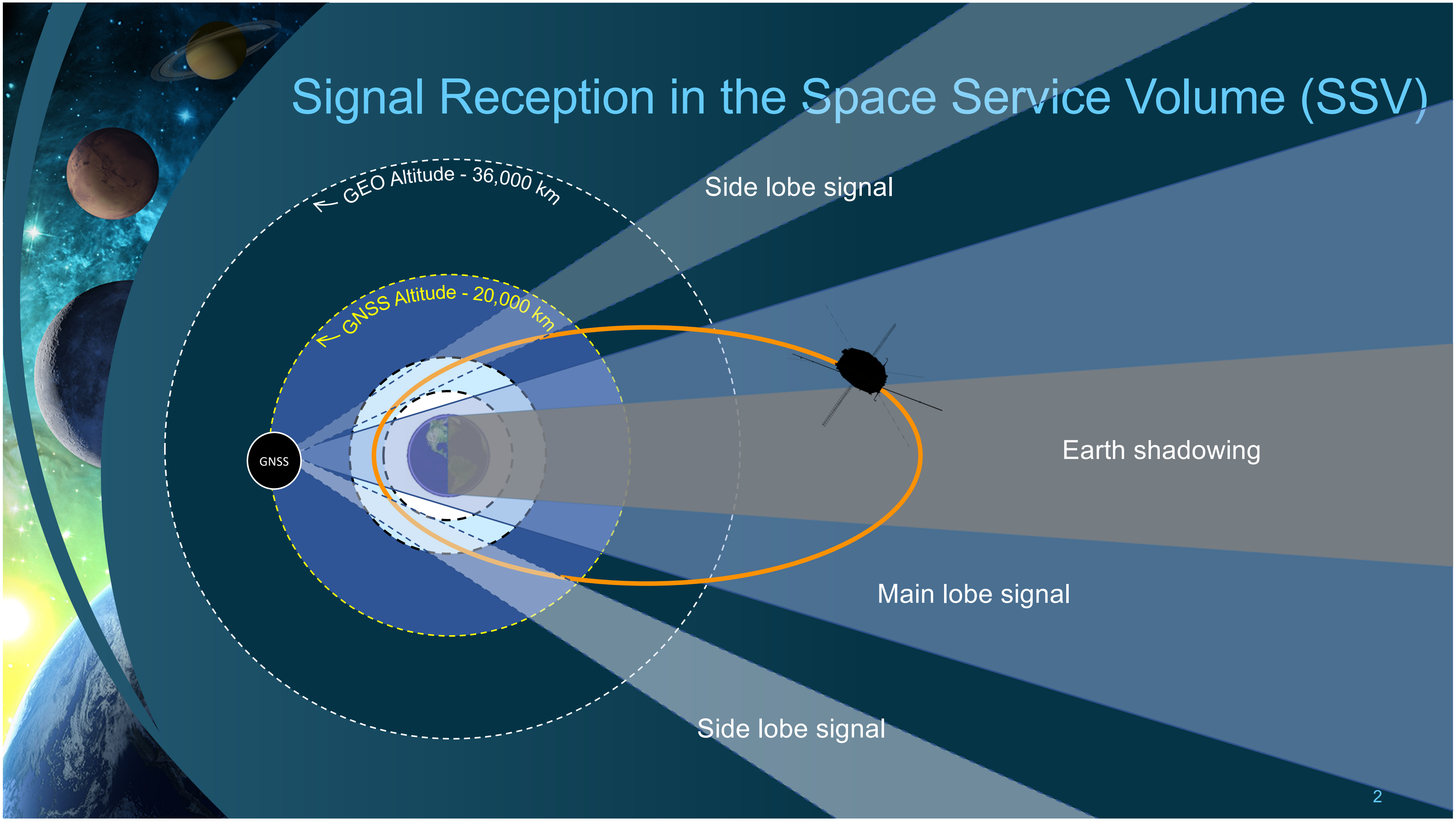
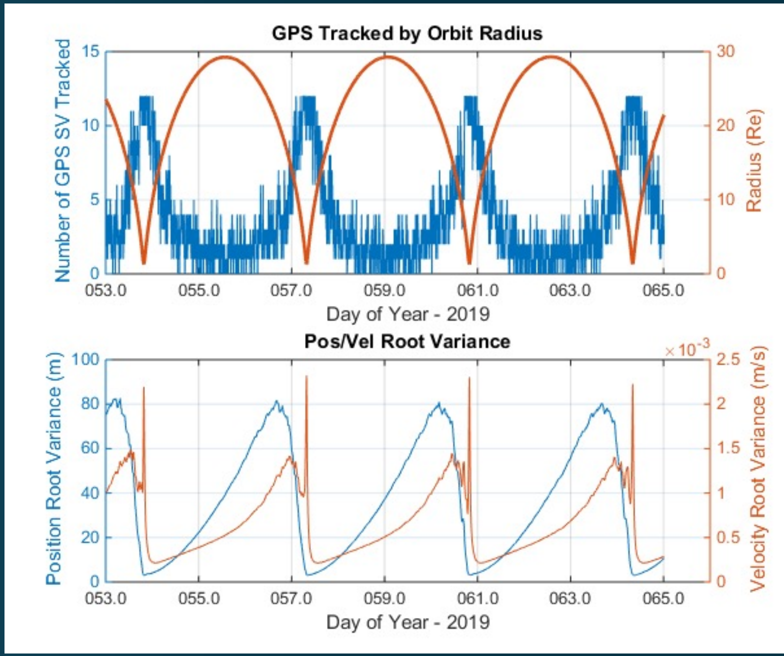
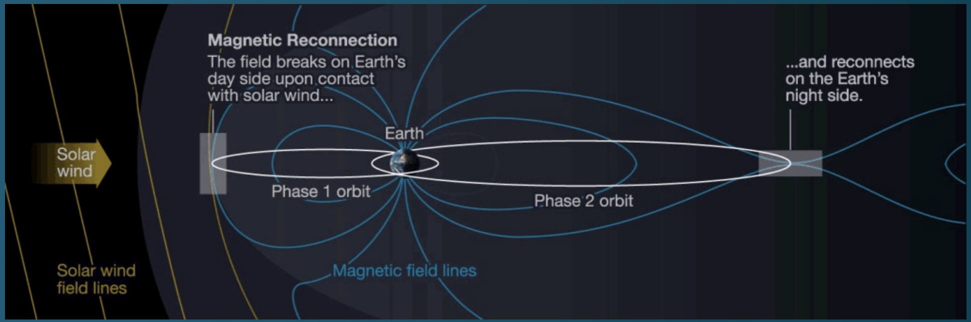


Signal Reception in the Space Service Volume (SSV)
GEO Altitude - 36,000 km
GNSS Altitude - 20,000 km
GNSS
Side lobe signal
Earth shadowing
Main lobe signal
Side lobe signal
2

Beyond the SSV: MMS

- Four spacecraft form a tetrahedron near apogee for magnetospheric science measurements (space weather)
- 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

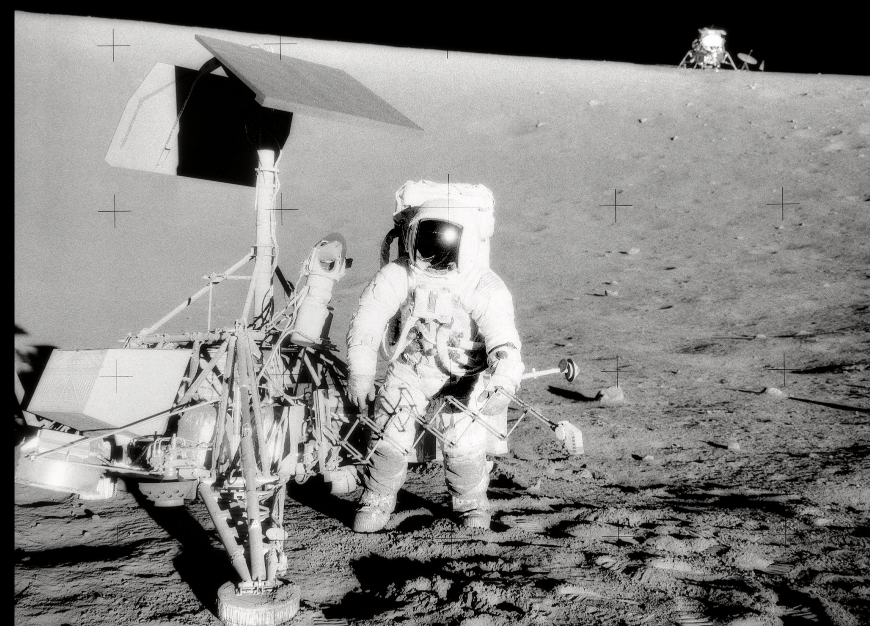




- Nearing the tracking threshold of Navigator receiver/antenna system
- Higher gained antenna and/or more sensitive GNSS receivers can extend signal availability >30 R_E
- MMS data enables design of missions that can reliably use GNSS systems out to lunar distances

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 [1]

The Role of GNSS

Critical technology gaps identified by the GER:

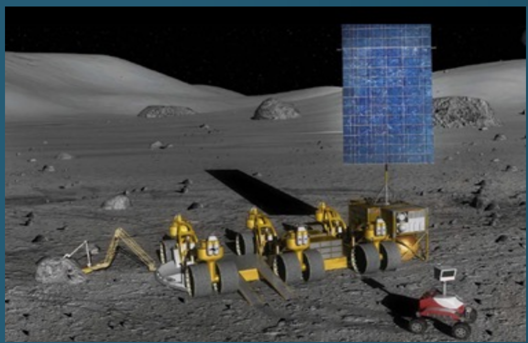
- AR&D Proximity Operations, Target Relative Navigation
- Beyond-LEO crew autonomy

GNSS on lunar missions would:

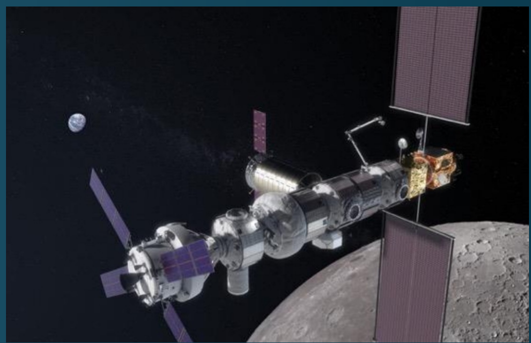
- enable autonomous navigation
- reduce tracking and operations costs
- provide a backup/redundant navigation for human safety
- provide timing source for hosted payloads
- reduce risk for commercial development

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

Lunar Exploration: Roles for GNSS

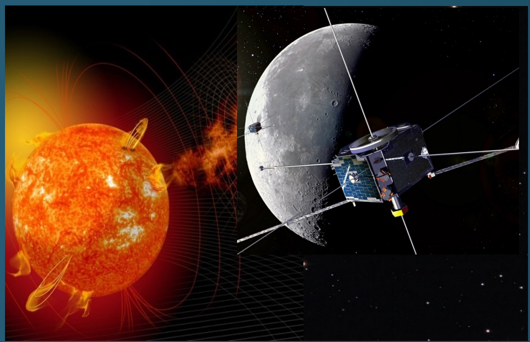


Lunar Surface Operations, Robotic Prospecting,& Human Exploration



Human-tended Lunar Vicinity Vehicles (Gateway)

Robotic Lunar Orbiters, Resource & Science Sentinels



Earth, Astrophysics, & Solar Science Observations

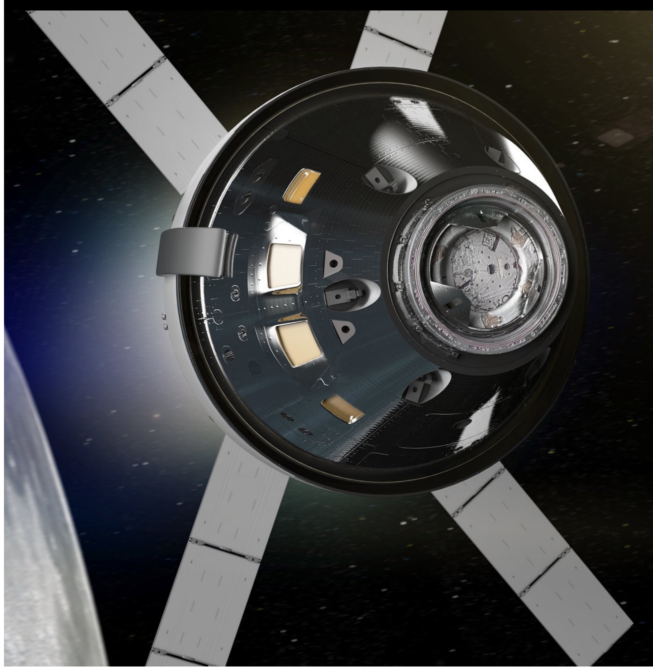
Satellite Servicing

Lunar Exploration Infrastructure

NASA Lunar Exploration Plans

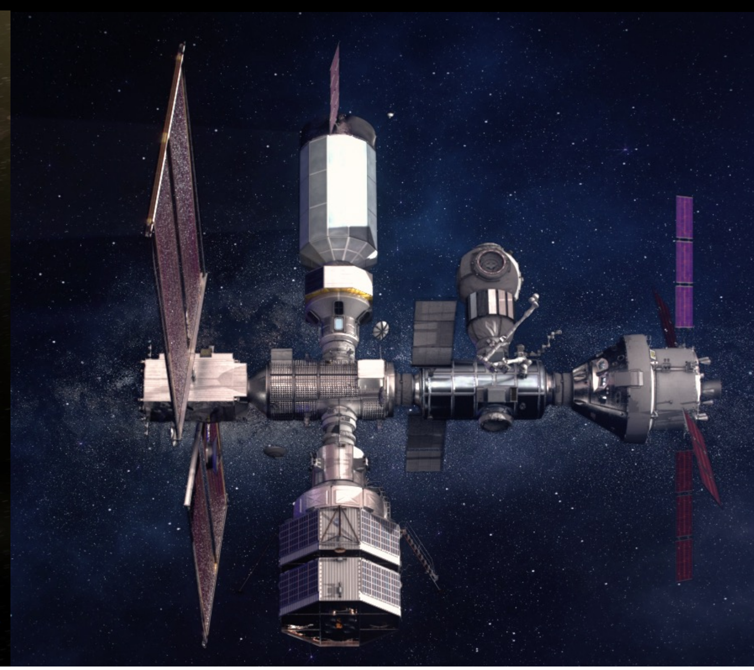
Artemis

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



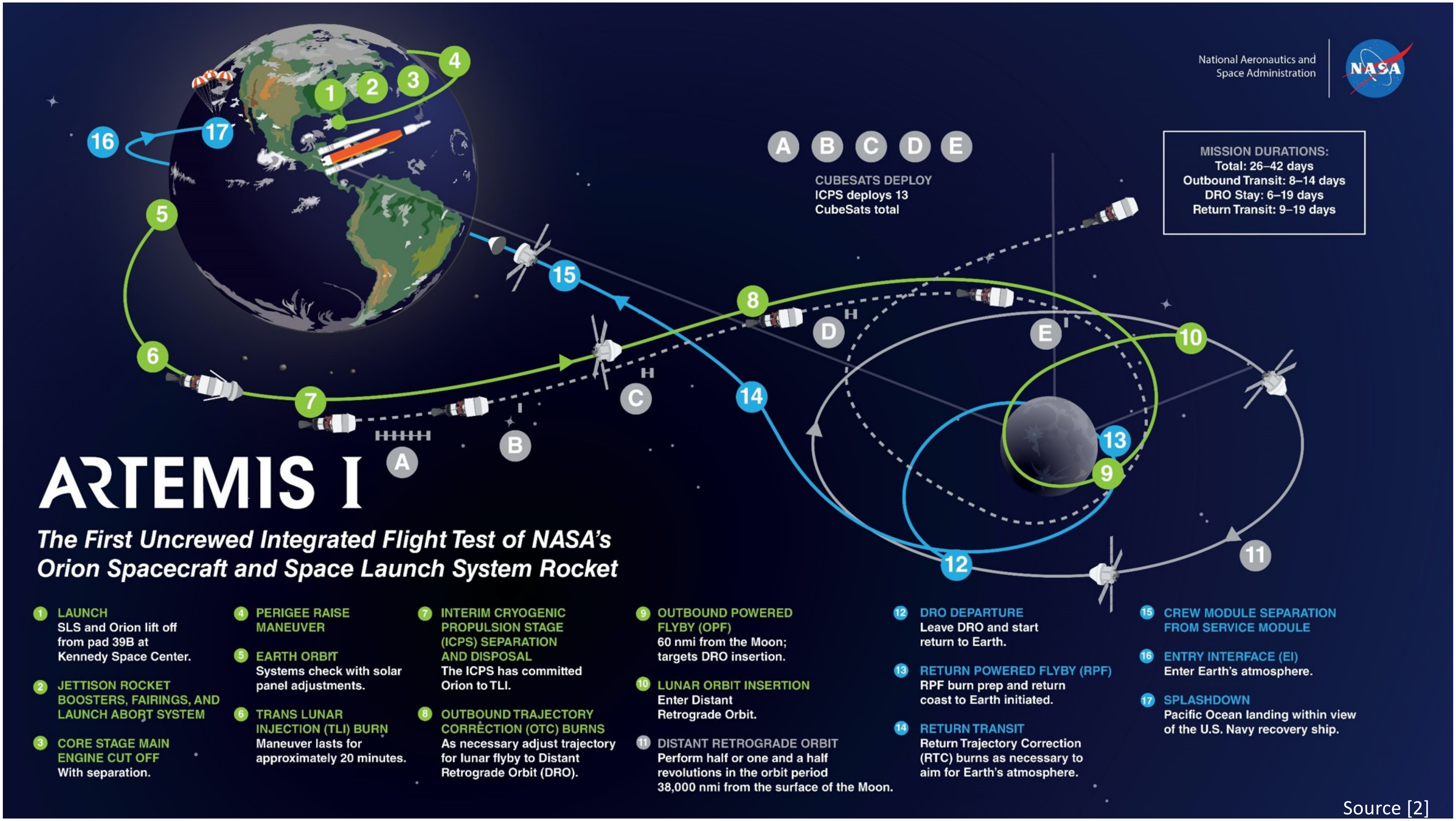
Gateway

- 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


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.

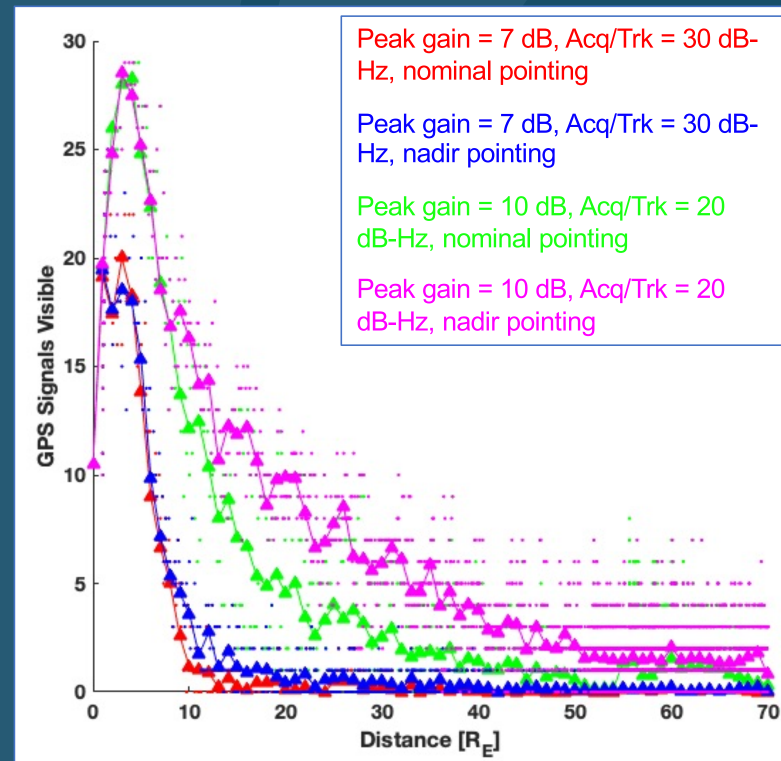
Source [2]

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



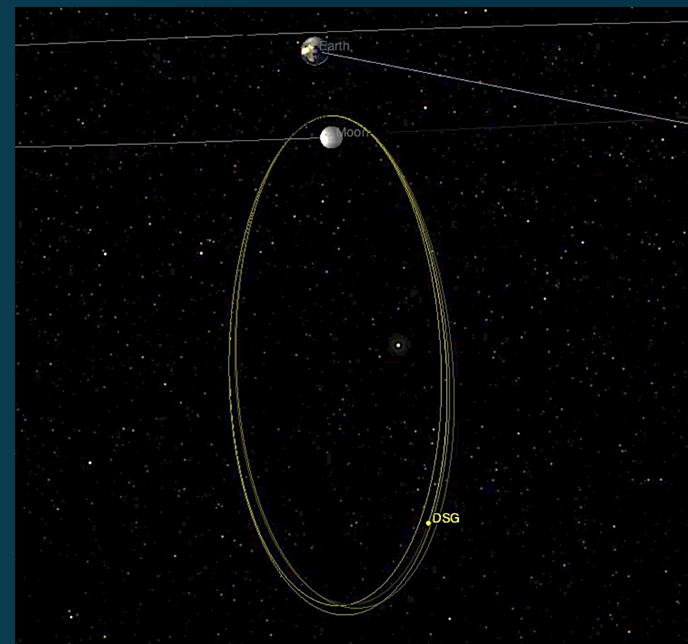
Baseline case in red models planned configuration for Artemis I. Alternate configurations illustrate potential availability with changes to hardware and/or pointing.

Gateway

- 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)

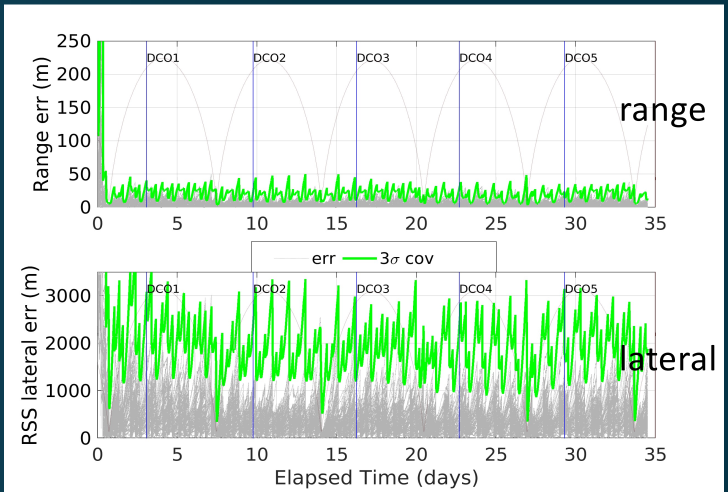
Gateway

- 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.

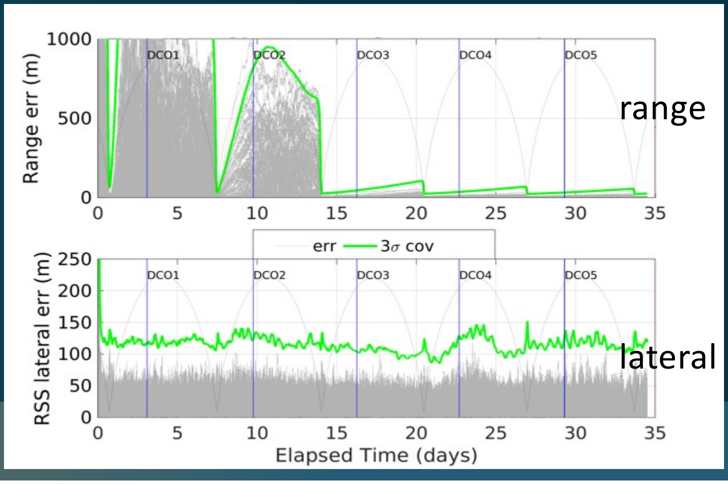
Crewed: Max steady-state errors

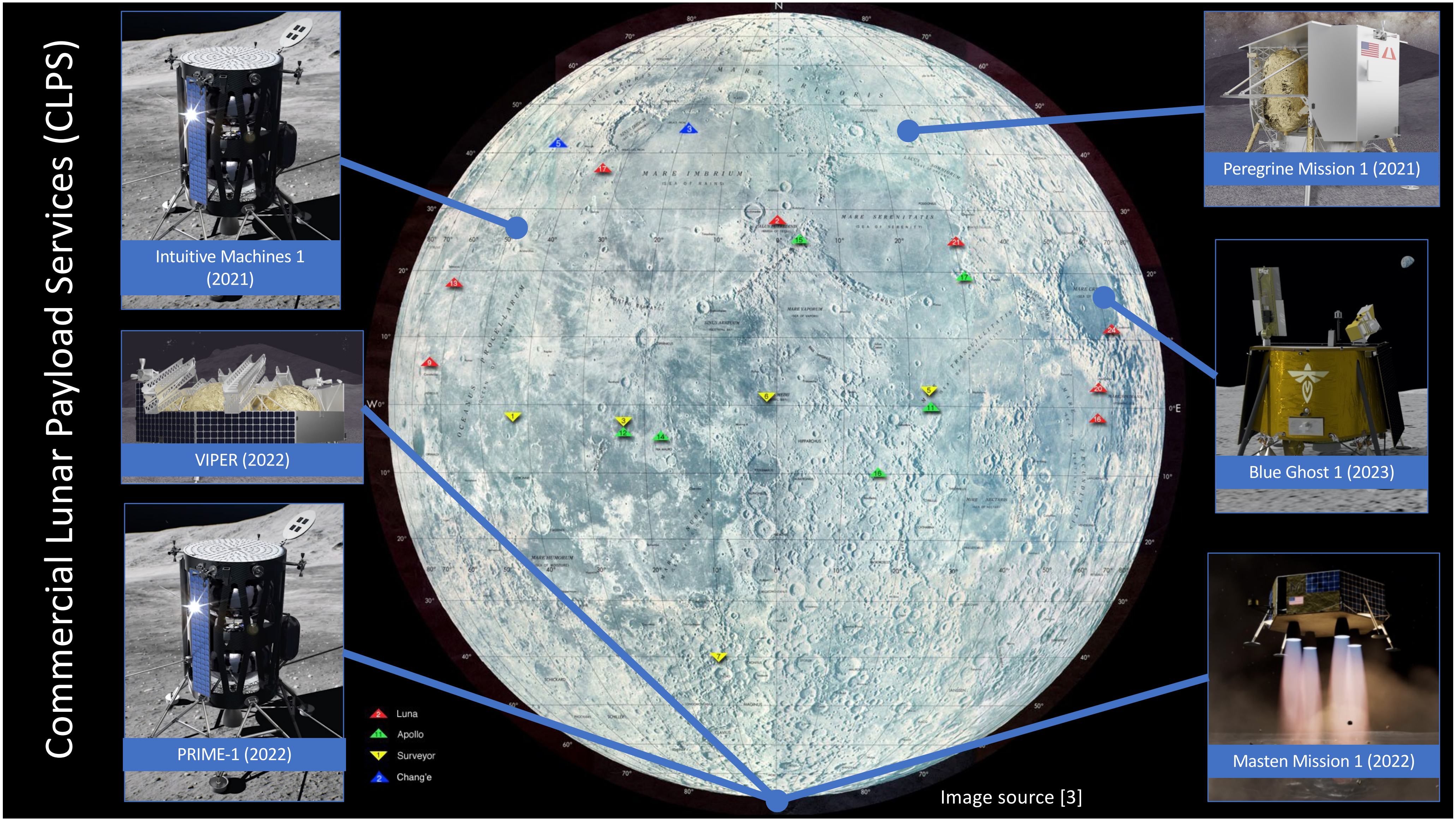
	Case	DCO	Apolune	Perilune	All
Position [m]	DSN	1469.7	1326.4	319.8	2353.6
	GPS	60.4	84.5	73.0	118.7
	DSN+GPS	57.7	81.7	107.0	117.4

DSN only



GPS only




Commercial Lunar Payload Services (CLPS)
Intuitive Machines 1 (2021)
VIPER (2022)
PRIME-1 (2022)
Peregrine Mission 1 (2021)
Blue Ghost 1 (2023)
Masten Mission 1 (2022)
Luna
Apollo
Surveyor
Chang'e
Image source [3]

Lunar GNSS Receiver Experiment: Mission Overview

Mission

- Joint NASA/Italian Space Agency payload
- NASA HEOMD payload for CLPS “19D” flight
- “Do No Harm” class payload
- Transit + surface observation campaign
- Expected surface duration: one lunar day
  (~12 Earth days)
- Implements NASA’s role under SPD-7

Objectives

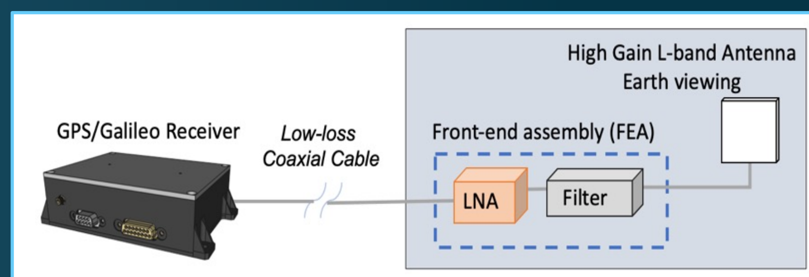
1. Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
2. Demonstrate navigation and time estimation using GNSS data collected at the Moon.
3. Utilize collected data to support development of GNSS receivers specific to lunar use.

Measurements

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

Utilization

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



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 is capable of providing 100-meter-class absolute navigation, centimeter-class relative navigation, and time-synchronization on the order of 1 microsecond or better

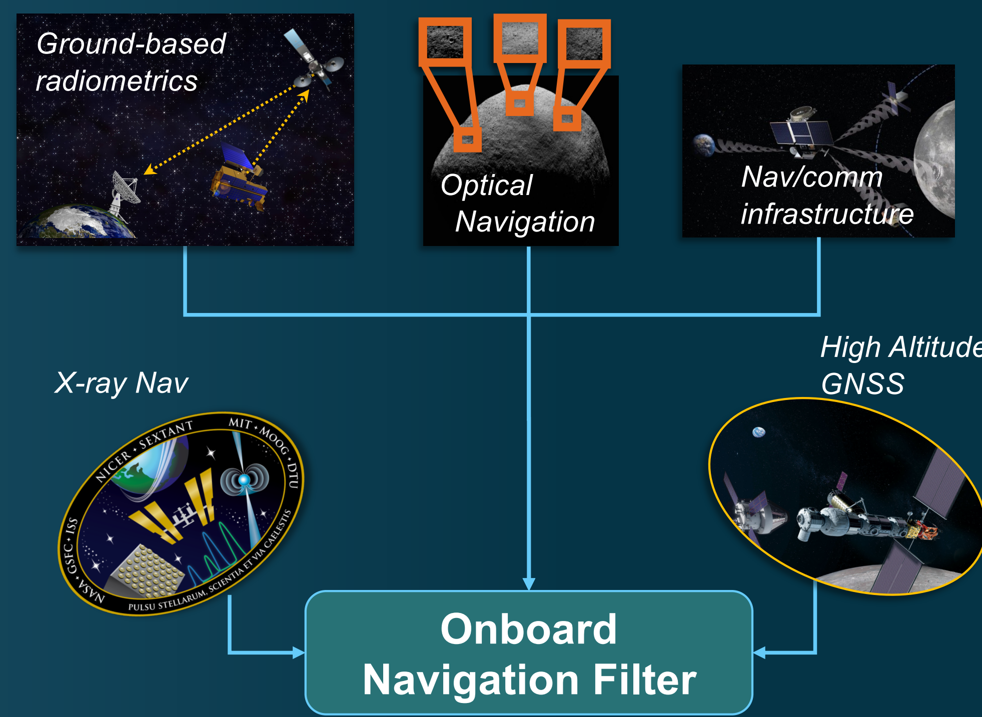


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Image Sources

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

[2] https://www.nasa.gov/sites/default/files/thumbnails/image/artemis_i_map_20210315_1.jpg

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