National Aeronautics and
Space Administration

EXPLORE
MOON to MARS

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

New Frontiers in Space Use of GNSS: Moon and Beyond

4 September 2019

Space Uses of Global Navigation Satellite Systems (GNSS)

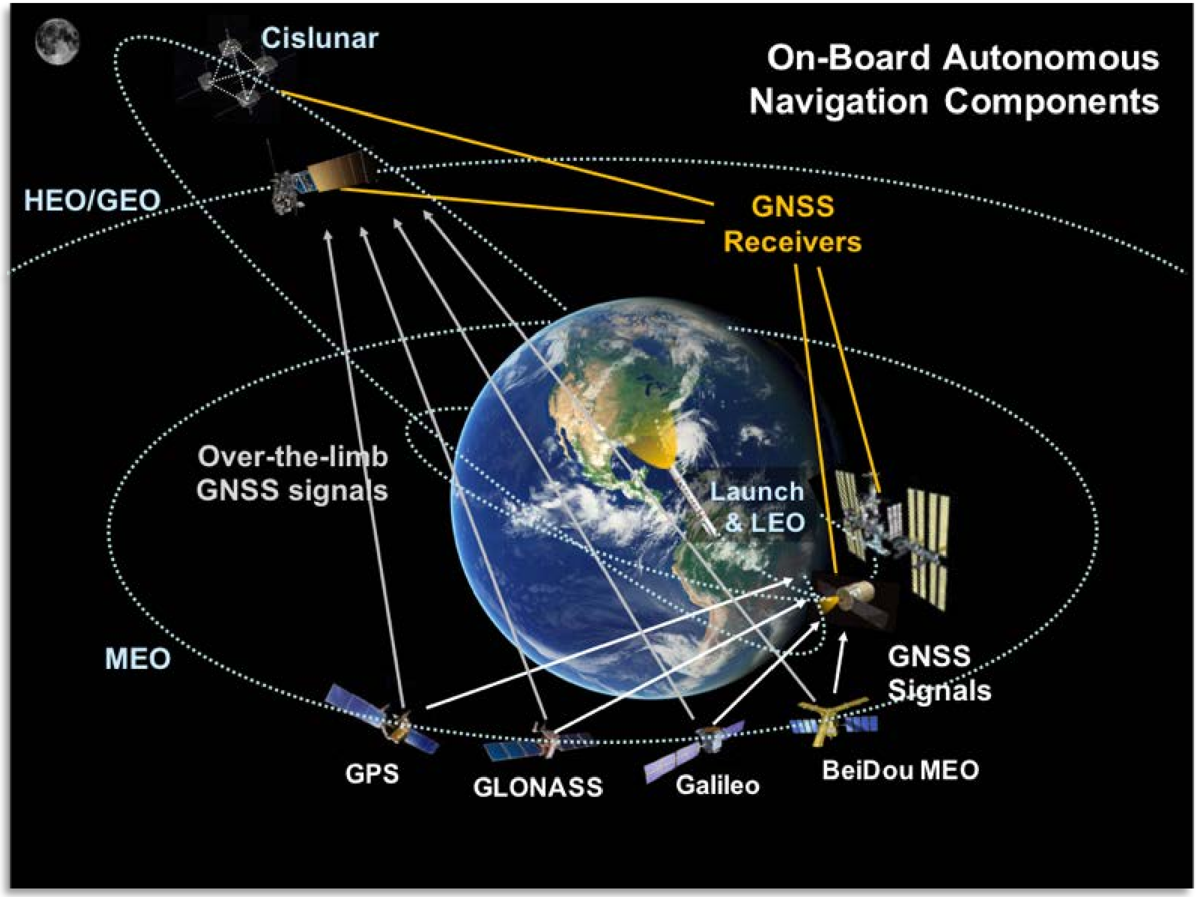
Real-time On-Board Navigation: Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing

Earth Sciences: Used as a remote sensing tool supporting atmospheric and ionospheric sciences, geodesy, geodynamics, monitoring sea levels, ice melt and gravity field measurements

Launch Vehicle Range Ops: Automated launch vehicle flight termination; providing people and property safety net during launch failures and enabling higher cadence launch facility use

Attitude Determination: Enables some missions, such as the International Space Station (ISS) to meet their attitude determination requirements

Time Synchronization: Support precise time-tagging of science observations and synchronization of on-board clocks



First Spaceborne GPS Use

Landsat-4

- **Launched**: July 16, 1982
- **Receiver**: GPSPAC
- **Developed by**: NASA Goddard Space Flight Center, DoD Naval Surface Warfare Center, and the Johns Hopkins Applied Physics Laboratory
- The Landsat program offers the longest continuous global record of the Earth's surface; it continues to deliver visually stunning and scientifically valuable images of our planet.

1993-2011 Space Shuttle Experiments and Operational Use

1970's	1980's	1990's	2000's	2010's

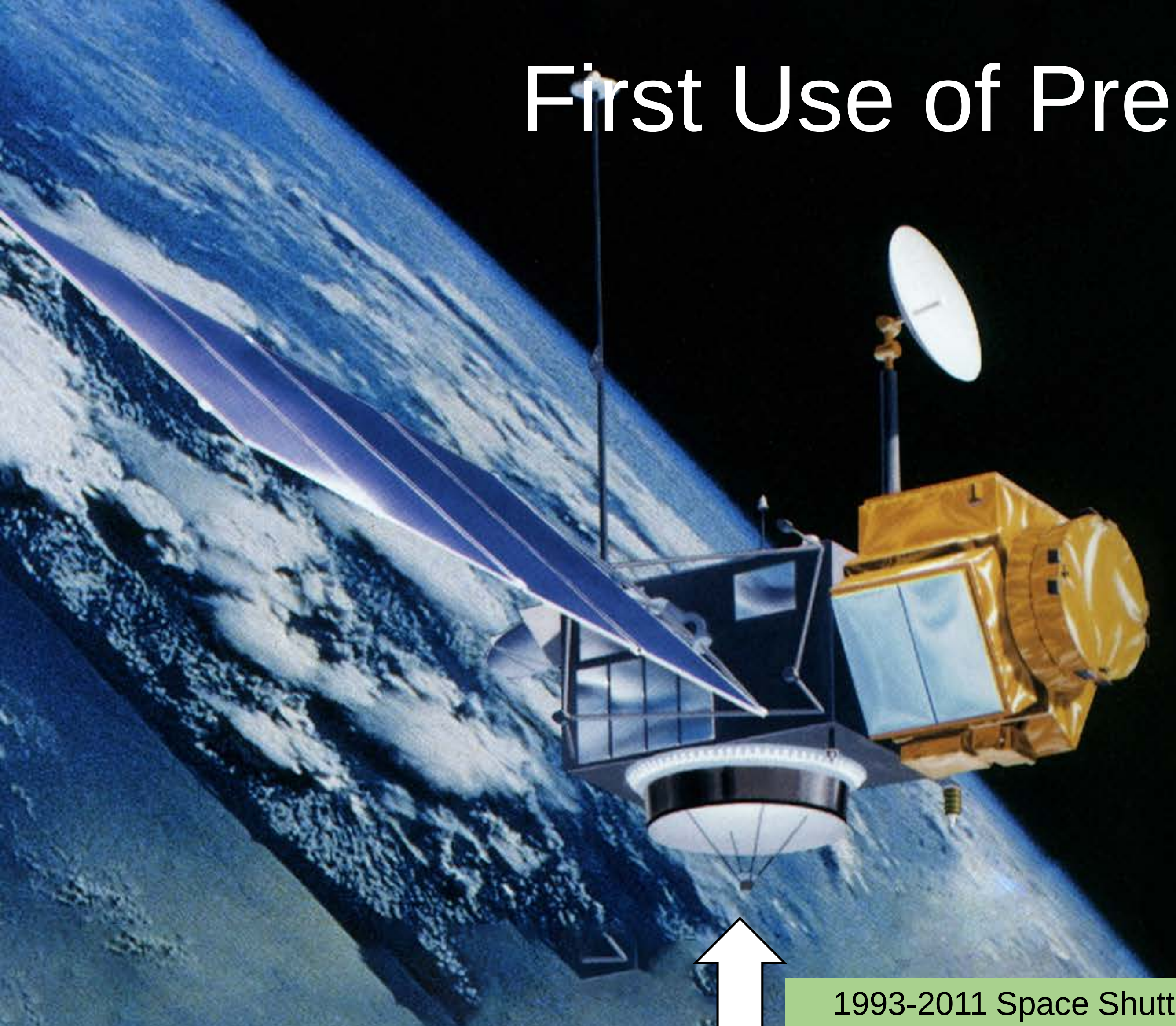
1978, GPS SV 1

1993, GPS IOC

1995, GPS FOC

2000, GPS SA Turned Off

First Use of Precise Orbit Determination



TOPEX/Poseidon

- **Launched**: August 10, 1992
- **Receiver**: Motorola GPSDR
- **Developed by**: NASA Jet Propulsion Laboratory
- Measured ocean surface topography to an accuracy of 4.2 cm, enabled scientists to forecast the 1997-1998 El Niño and improved understanding of ocean circulation and climate

1993-2011 Space Shuttle Experiments and Operational Use

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1993, GPS IOC

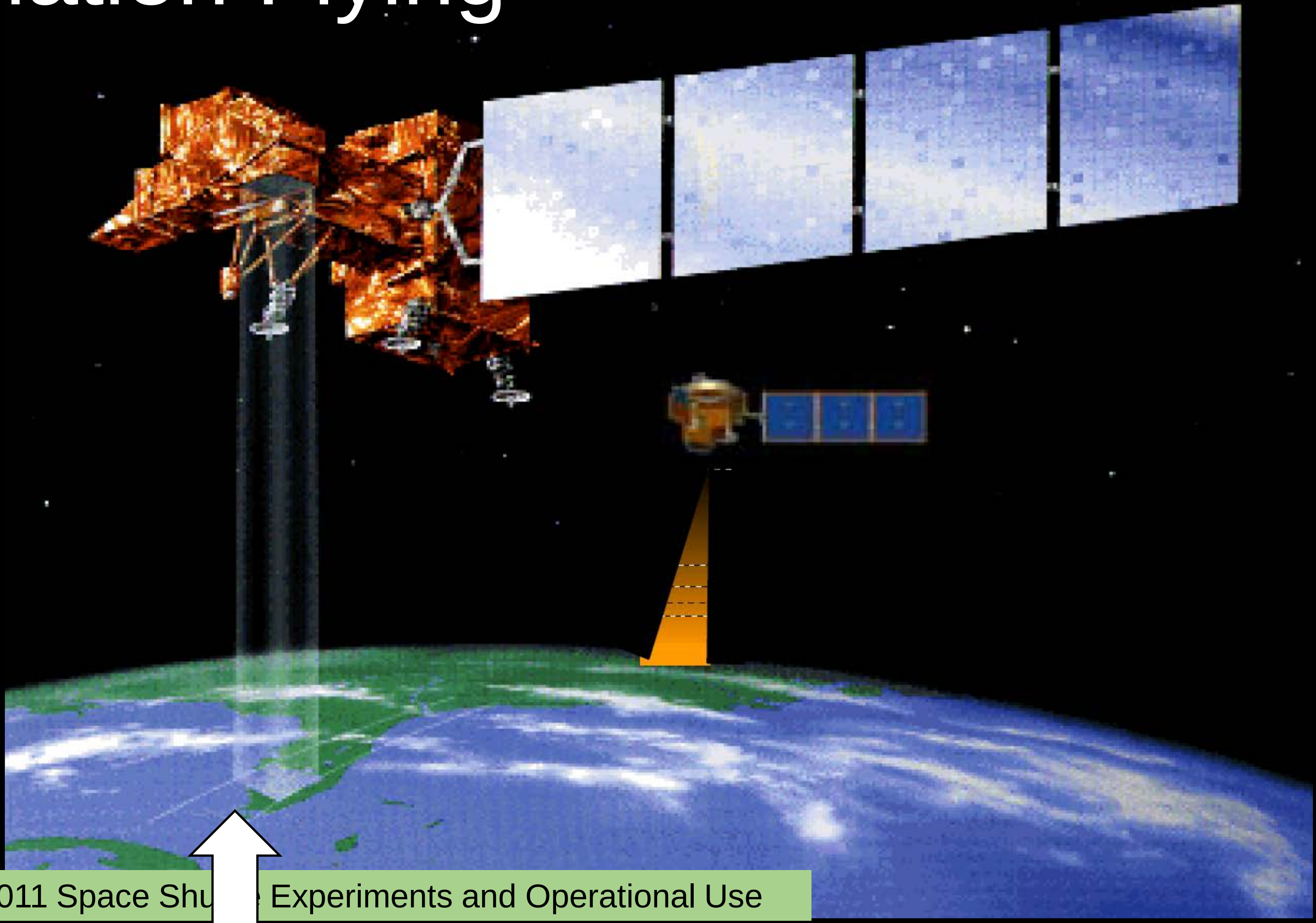
1995, GPS FOC

2000, GPS SA Turned Off

First GPS-Based Formation Flying

Earth Observer-1 & Landsat-7

- **Launched**: April 15, 1999
- **Receiver**: SSL/Laben Tensor
- **Developed by**: NASA Goddard Space Flight Center
- EO-1 used GPS to autonomously navigate and control its formation with Landsat-7 within 1 minute (450 km) in mean motion and within ±3 km of Landsat-7's ground track.



1993-2011 Space Shu e Experiments and Operational Use

1970's	1980's	1990's	2000's	2010's

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2000, GPS SA Turned Off

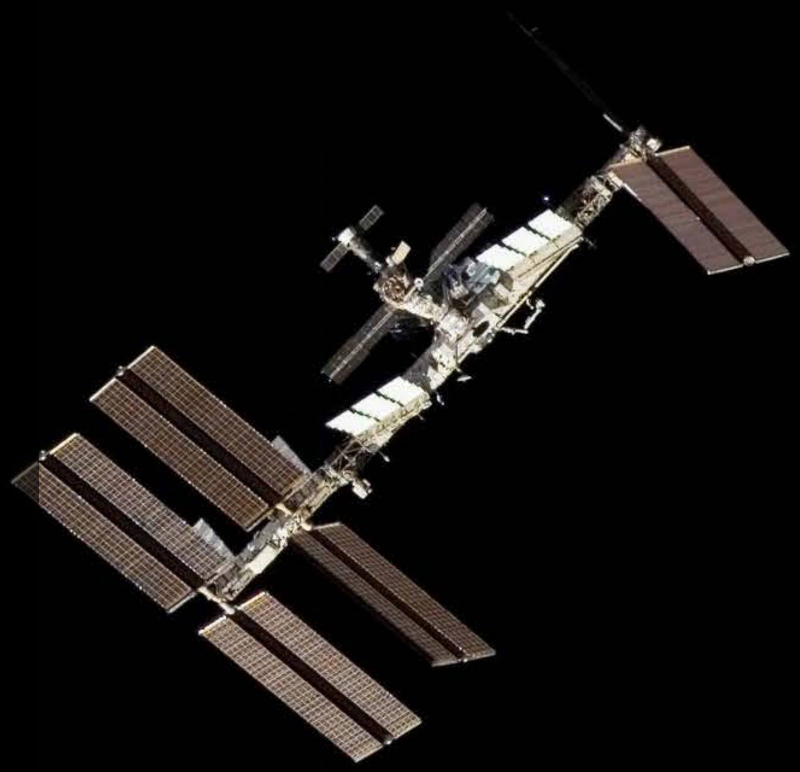
Use of GNSS for navigation in space is now routine

The latest data from the Interagency Operations Advisory Group shows **102** current or upcoming civil missions utilizing GNSS, representing **7** international space agencies.

This data does **not** include:

- Commercial users (e.g. communication satellites)
- Many other government space agencies
- Non-civil users
- Educational applications, etc.

Therefore, it is likely that **hundreds** of satellites have used GNSS in space since the initial experiments in the 1980s, and that number is only increasing.



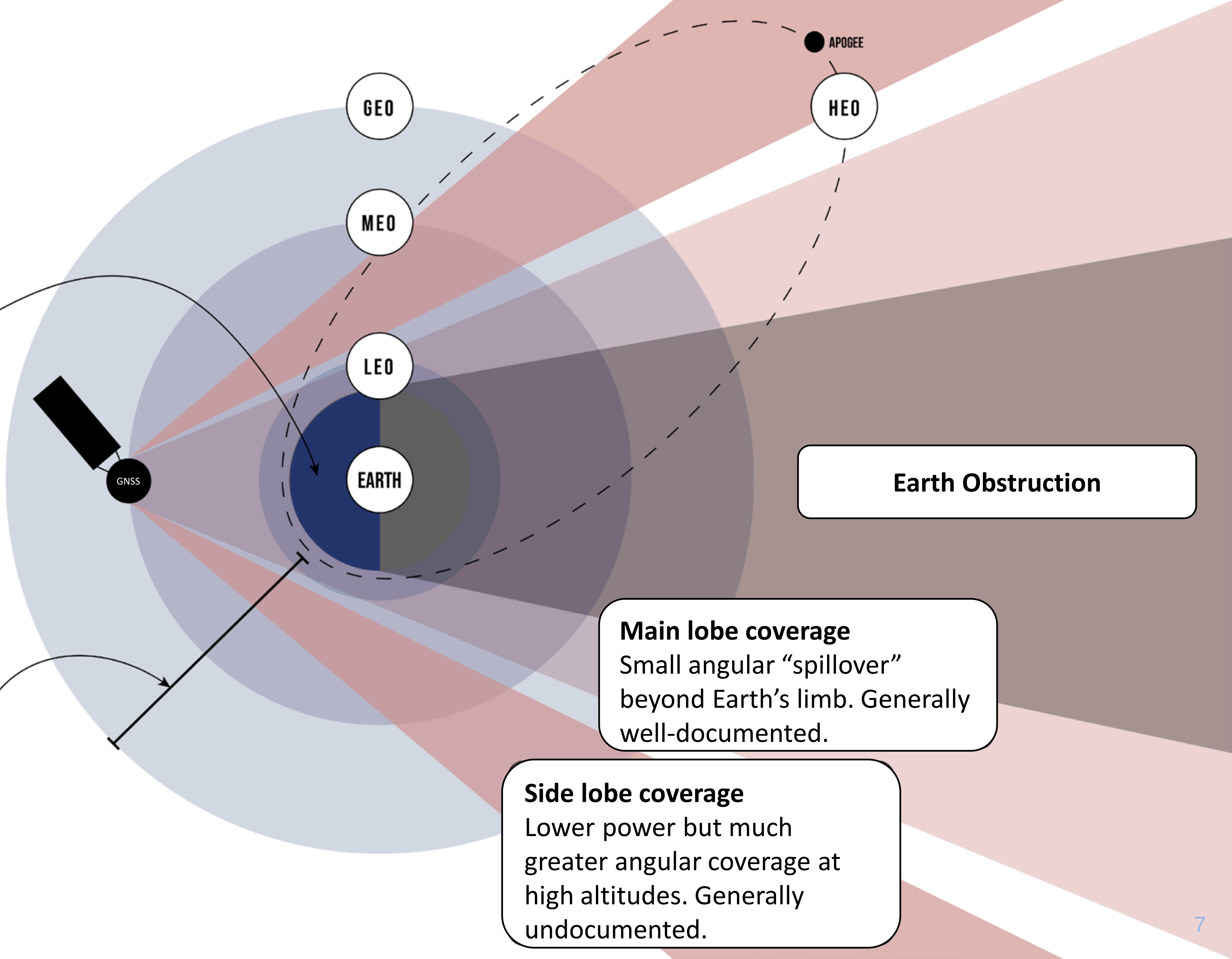
Of these, a small fraction are considered high-altitude users, orbiting at altitudes above approximately 3,000 km.

Image: International Space Station (NASA)

SPACE SERVICE VOLUME

Terrestrial Service Volume
0–3,000 km altitude

LEO = low-Earth orbit region
MEO = medium-Earth orbit region
GEO = geosynchronous orbit
HEO = highly elliptical orbit



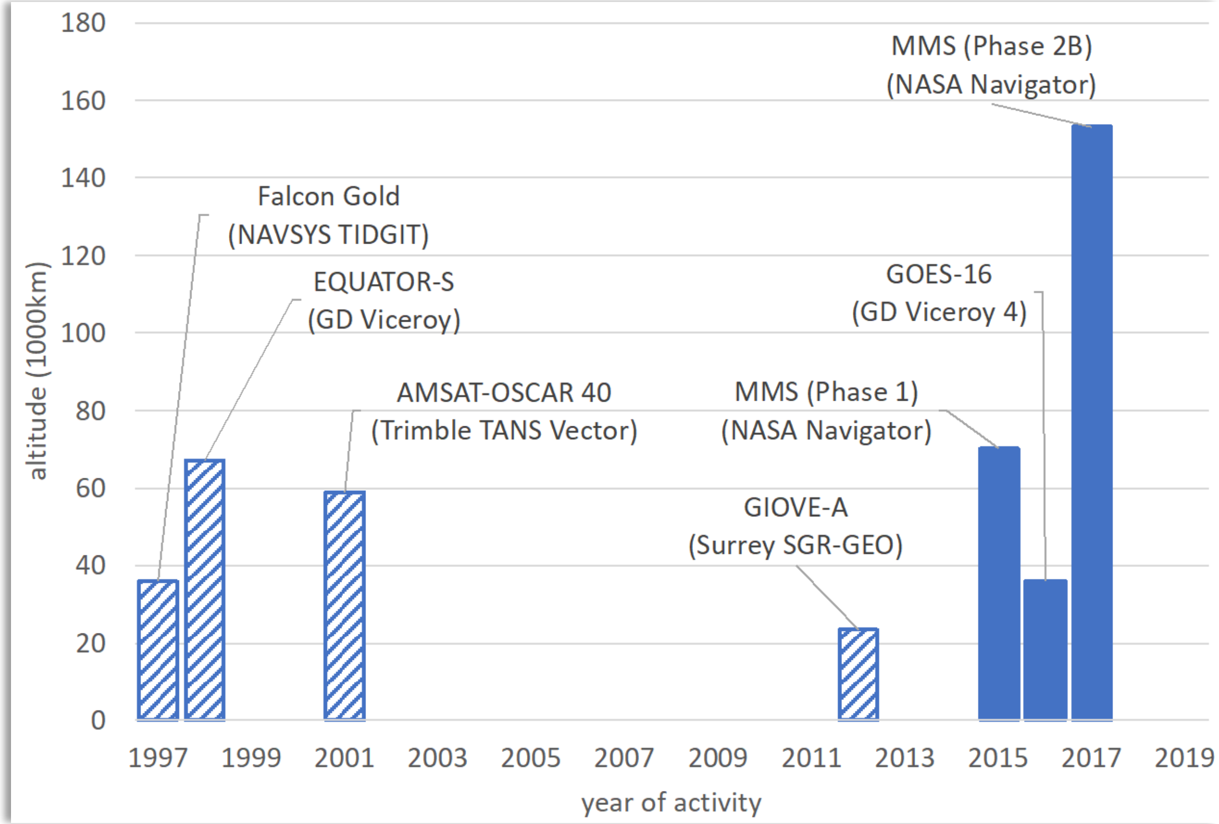
Space Service Volume
3,000–36,000 km (GEO) altitude

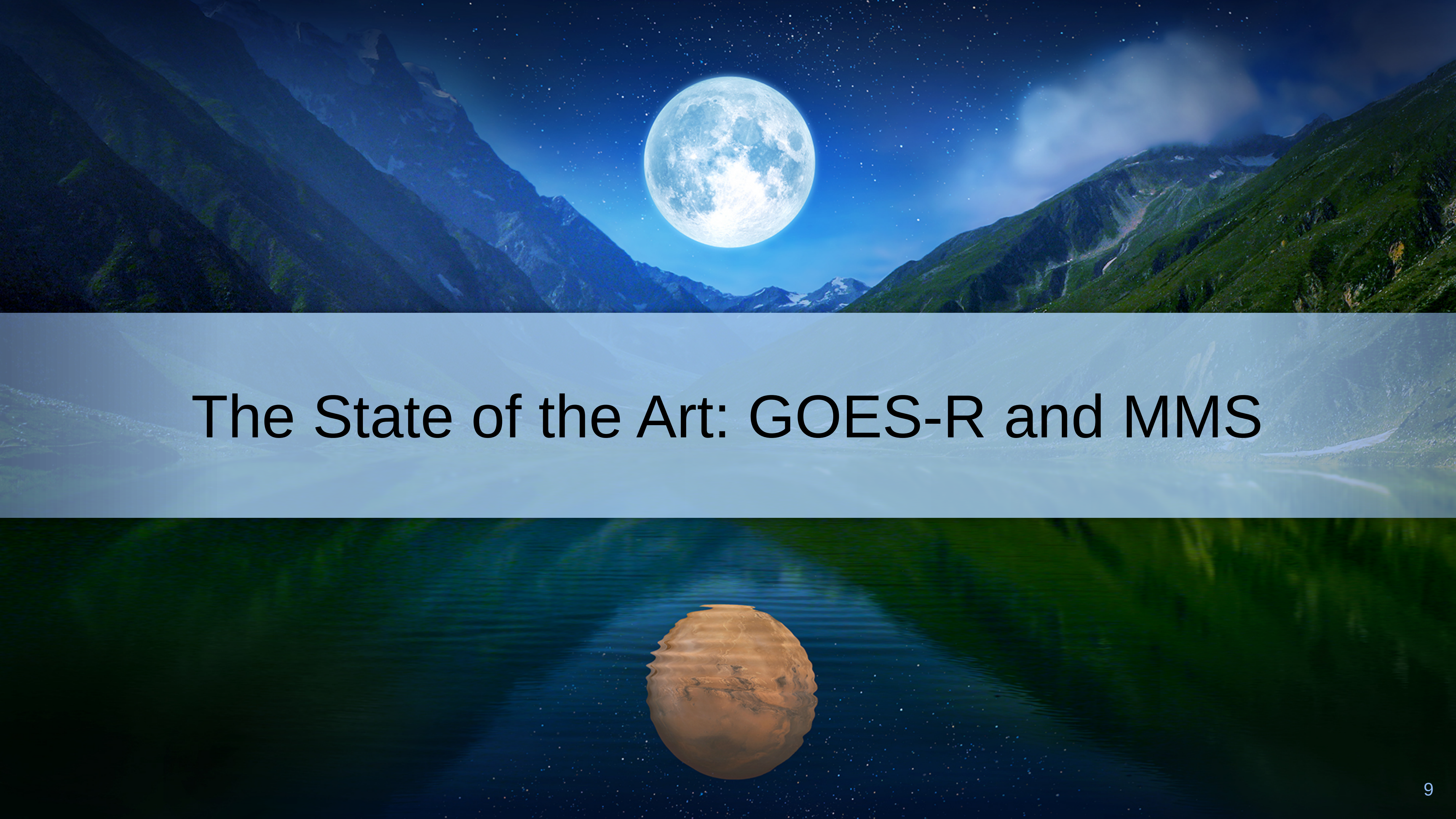
The Development of High-Altitude GNSS

Transition from experimentation to operational use:

- **1990s**: Early flight experiments demonstrated basic feasibility – **Equator-S**, **Falcon Gold**
- **2000**: Reliable GPS orbit determination demonstrated at GEO employing a bent pipe architecture and ground-based receiver (Kronman 2000)
- **2001**: **AMSAT OSCAR-40** mapped GPS main and sidelobe signals (Davis et al. 2001)
- **2015**: **MMS** employed GPS operationally at 76,000 km (recently increased to 150,000 km)
- **2016–2017**: **GOES-16/17** employed GPS operationally at GEO

	Altitude [km]	Altitude [R_E]
GPS	20,200	3
GEO	36,000	5.6
MMS 1	76,000	12
MMS 2	153,000	24
Moon	378,000	60



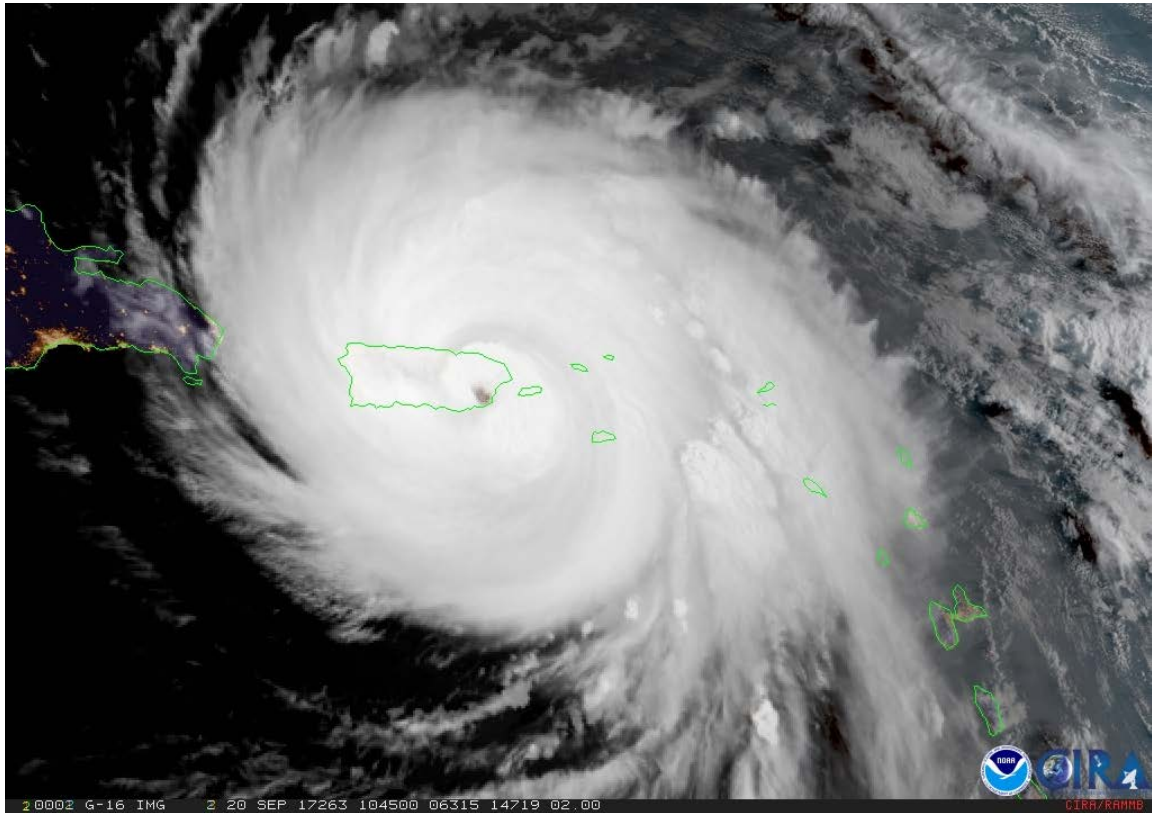


The State of the Art: GOES-R and MMS

Flight Example: GOES-R Series Weather Satellites

- **GOES-R, -S, -T, -U**: 4th generation NOAA operational weather satellites
- **GOES-R/GOES-16 Launch**: 19 Nov 2016
- **GOES-S/GOES-17 Launch**: 1 Mar 2018
- 15 year life, series operational through mid-2030s

- Features new CONOPS over previous generation:
  - Daily low-thrust station-keeping maneuvers, rather than annual high-thrust events
  - Continuous data collection through maneuvers, <120 min of outage per year
  - Tighter navigation accuracy requirements and faster cadence needed to support highly increased operational tempo
- Employs on-board GPS at GEO to meet stringent navigation requirements
- Utilizes GPS sidelobe signals to increase SSV performance and ensure continuous availability

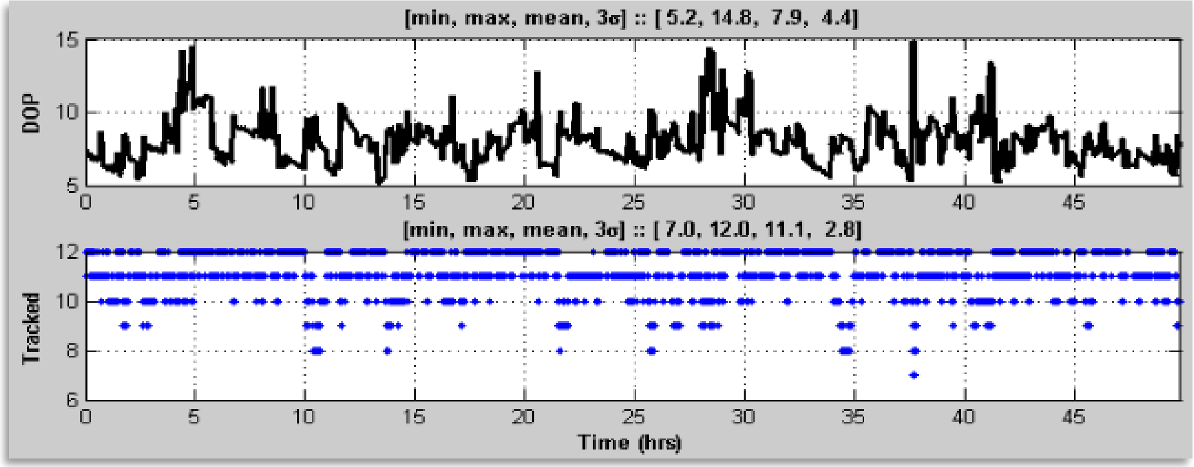


GOES-16 image of Hurricane Maria making landfall over Puerto Rico, 20 Sep 2017

Flight Example: GOES-R Series Weather Satellites

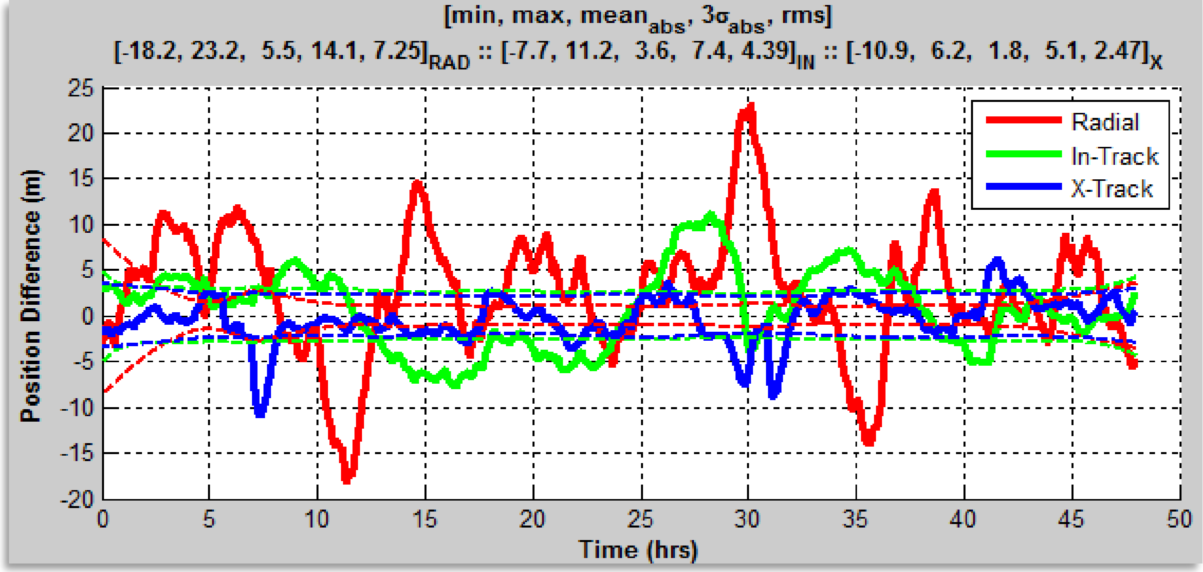
GPS Visibility

- Minimum SVs visible: 7
- DOP: 5–15
- Major improvement over GPS guaranteed performance spec: 4+ SVs visible 1% of time



Navigation Performance

- 3σ position difference from smoothed ground solution:
  - Radial: 14.1 m
  - In-track: 7.4 m
  - Cross-track: 5.1 m
- **Compare to requirement:** (100, 75, 75) m



Source: Winkler, S., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D., Krimchansky, A., and Concha, M., "GPS Receiver On-Orbit Performance for the GOES-R Spacecraft," ESA GNC 2017, 29 May-2 Jun 2017, Salzburg, Austria.

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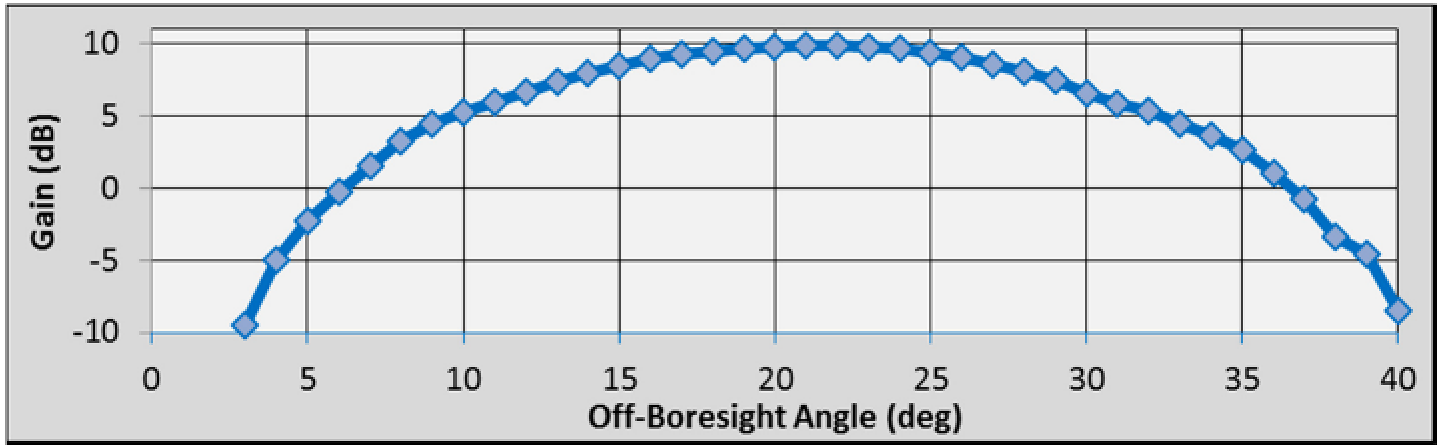
Flight Example: GOES-R Series Weather Satellites

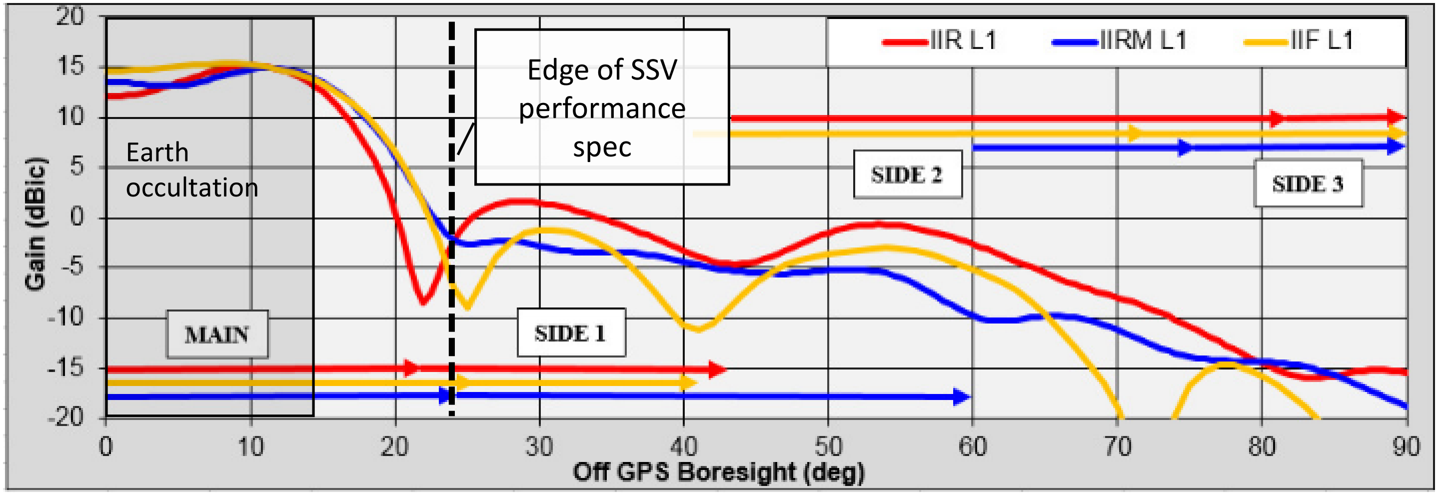
GOES-R features unique GPS signal reception characteristics

- General Dynamics Viceroy GPS receiver
- Custom receive antenna designed for above-the-constellation use
- Max gain @20 deg off-nadir angle
- Tuned to process main lobe spillover + first side lobe

Antenna patterns



RX



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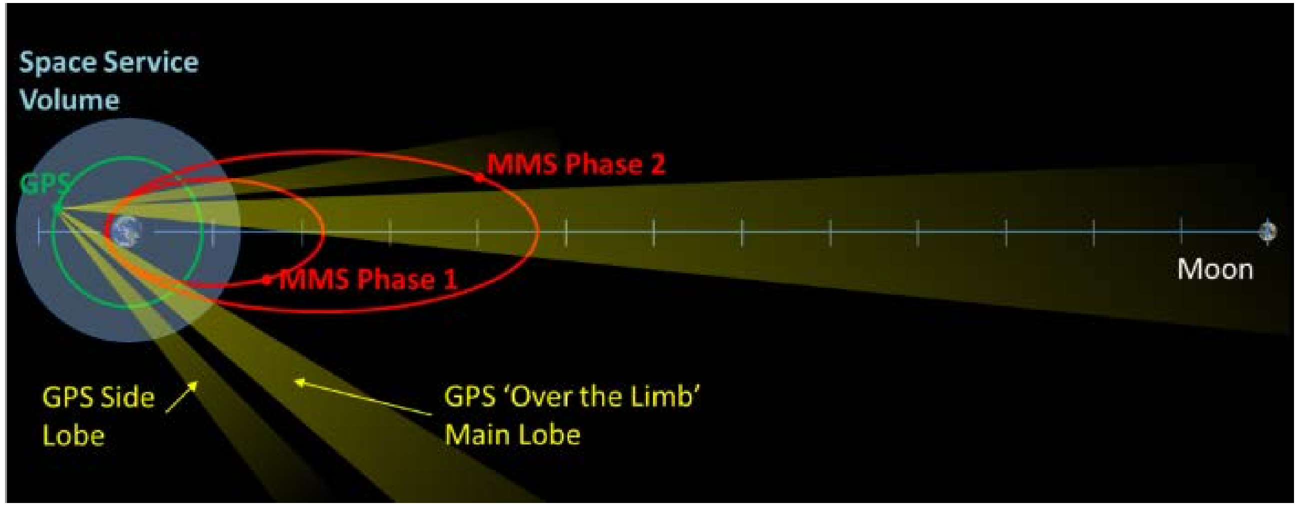
Source: Winkler, S., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D., Krimchansky, A., and Concha, M., “GPS Receiver On-Orbit Performance for the GOES-R Spacecraft,” ESA GNC 2017, 29 May-2 Jun 2017, Salzburg, Austria.

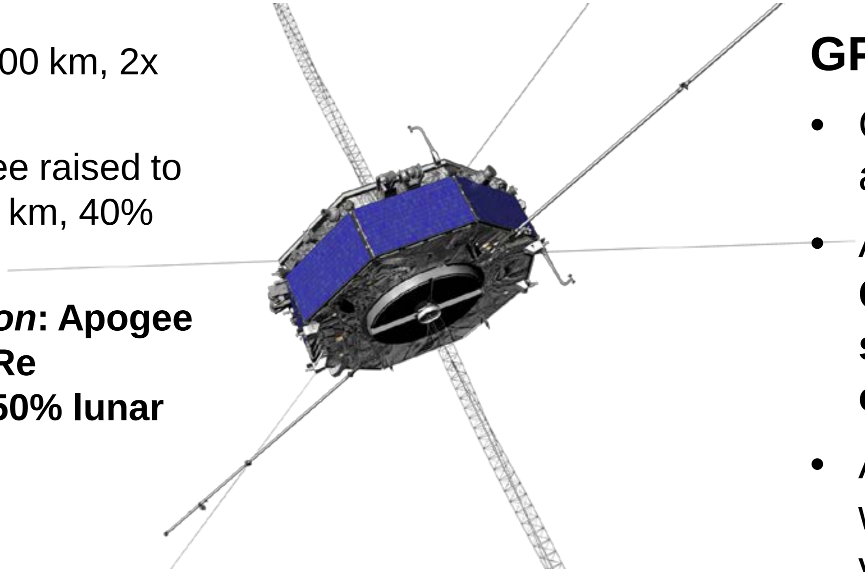
Flight Example: NASA MMS Mission

Magnetospheric Multi-Scale (MMS)

- Launched March 12, 2015
- Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
- Four spacecraft in highly eccentric orbits



- *Phase 1*: 1.2 x 12 Earth Radii (Re) Orbit (7,600 km x 76,000 km, 2x GEO alt.)
- *Phase 2B*: Apogee raised to 25 Re (~150,000 km, 40% lunar distance)
- ***Extended Mission*: Apogee raised to 29.34 Re (>180,000 km) (50% lunar distance)**



GPS Receiver: MMS Navigator System

- GPS enables onboard (autonomous) navigation and near autonomous station-keeping
- At the highest point of the MMS orbit Navigator **set Guinness world record for the highest reception of signals and onboard navigation solutions by an operational GPS receiver in space**
- At the lowest point of the MMS orbit Navigator set Guinness world for fastest operational GPS receiver in space, at velocities over 35,000 km/h

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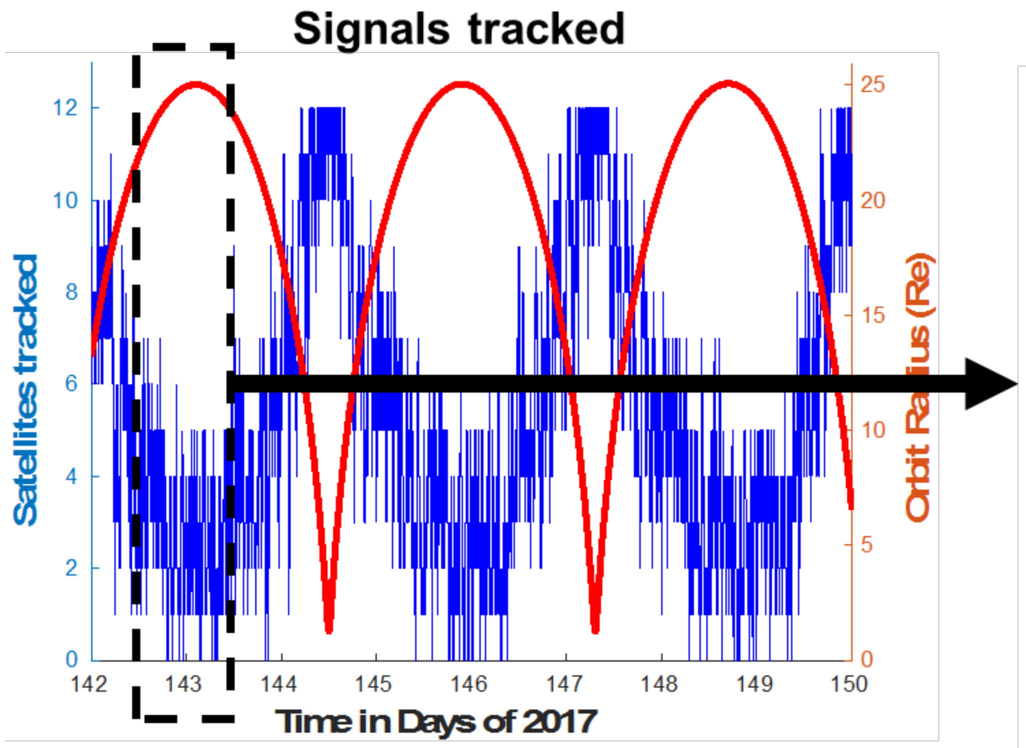
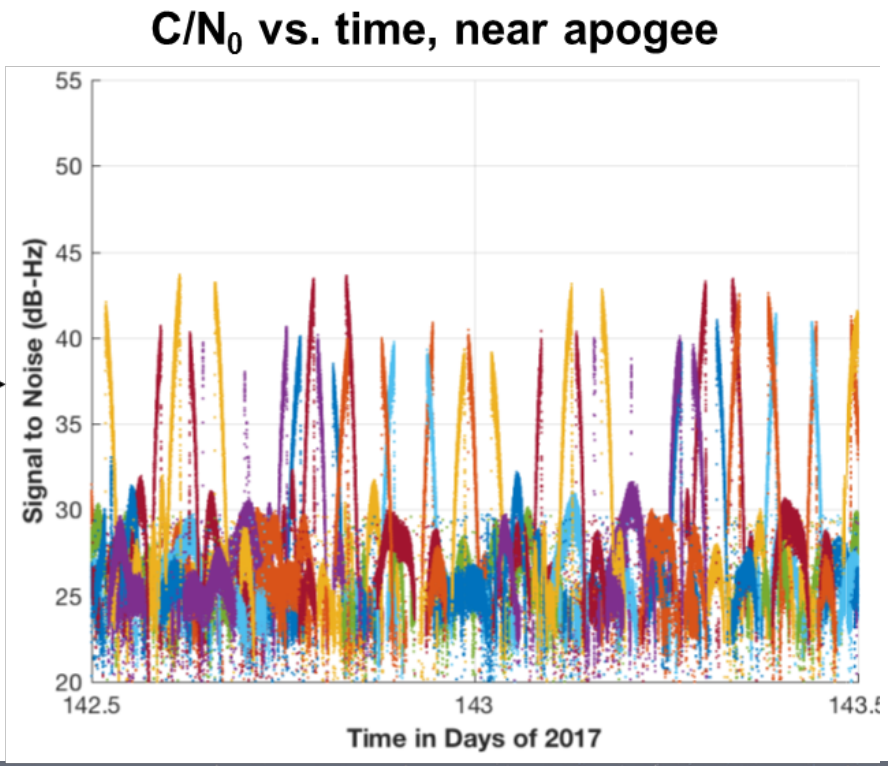
Flight Example: NASA MMS Mission

MMS Phase 2B on-orbit signal tracking results

- Consider 8-day period early in Phase 2B, apogee ~150,000 km
- Above GPS constellation, majority of signals are sidelobes
- Long term trend shows average of ~3 signals tracked near apogee, with up to 8 observed.
- Visibility exceeds preflight expectations significantly





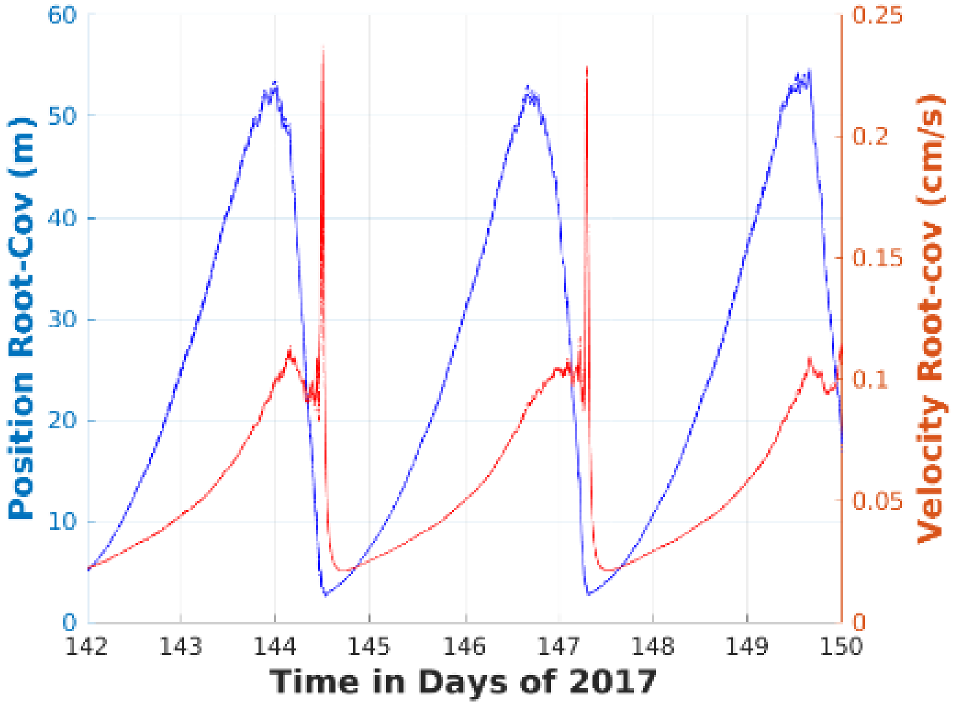
Flight Example: NASA MMS Mission

MMS Phase 2B on-orbit navigation performance

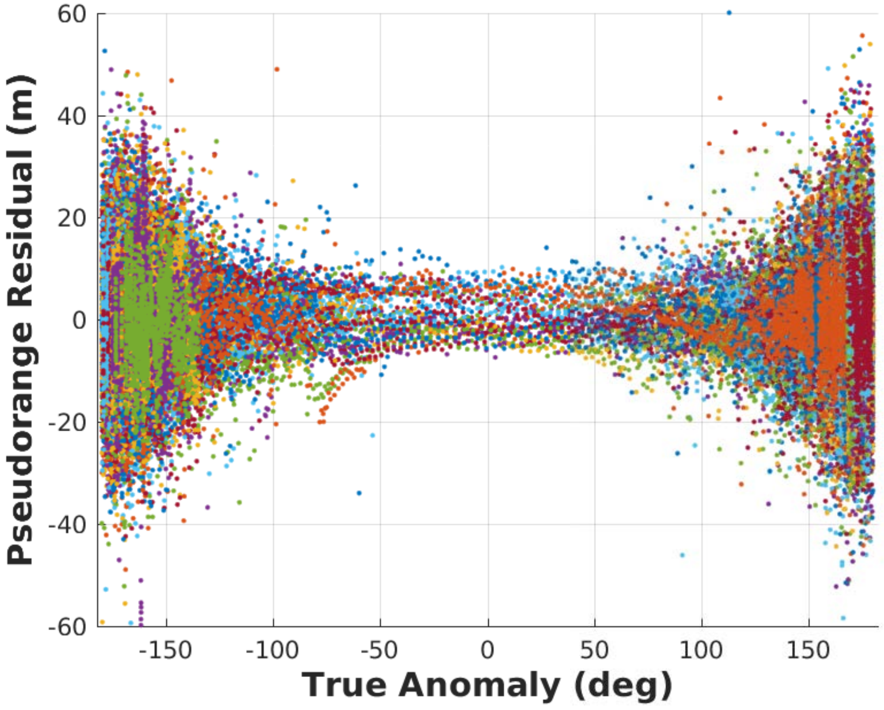
- Onboard Kalman filter RSS 1-sigma formal errors reach maximum of ~55m (165m 3σ) and briefly 2.5mm/s (typically <1mm/s)
- Measurement residuals are zero mean, of expected variation <10m 1-sigma.
  - ~5 m at perigee, ~20 m at apogee
  - Suggests sidelobe measurements are of high quality.

Description	Requirement
Semi-major axis est. under 3 R_E (99%)	50 m (Phase 1) 100 m (Phase 2B)
Orbit position estimation (99%)	100 km RSS

Filter formal pos/vel errors (1σ root cov)



Pseudorange residuals

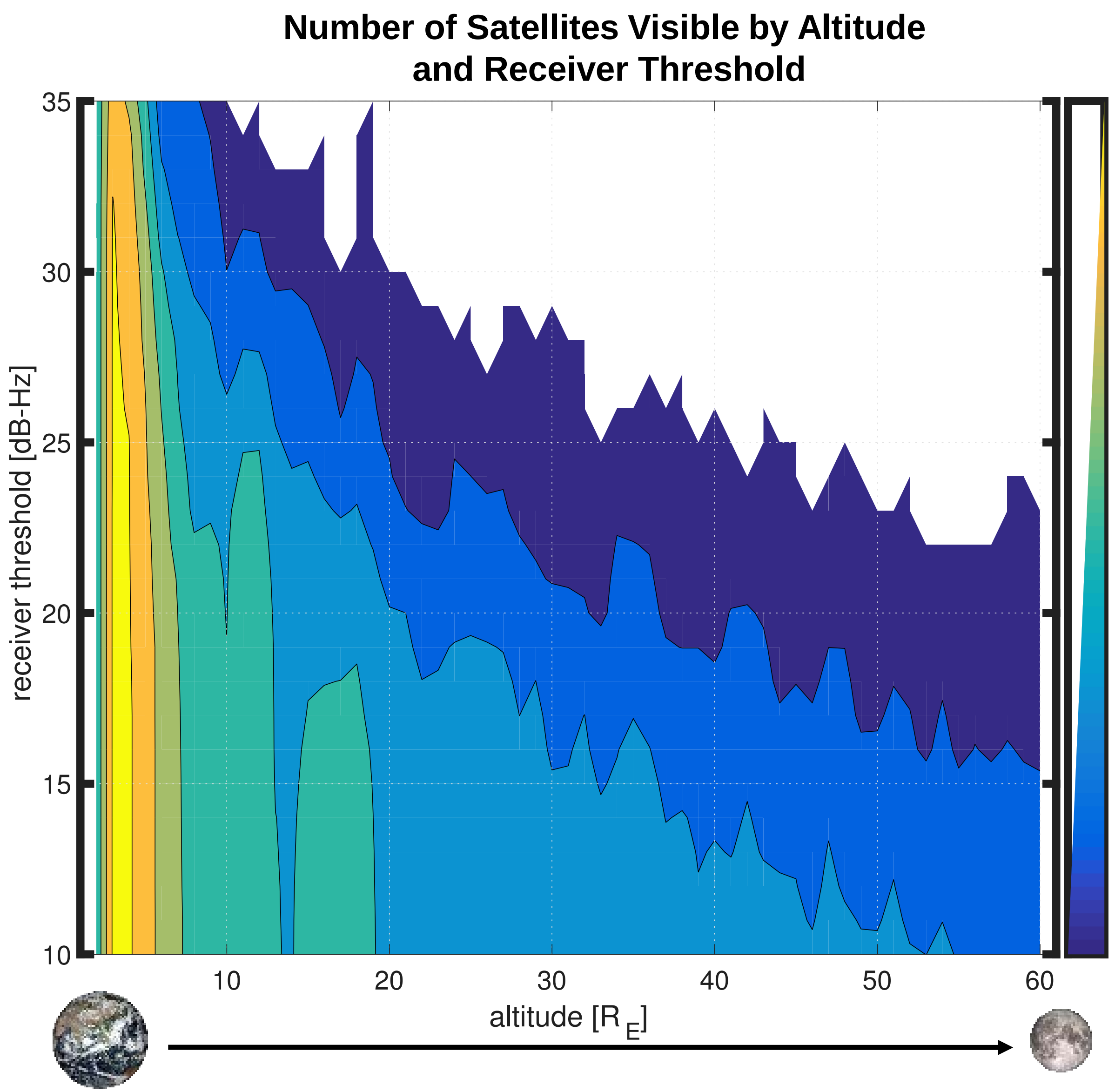


2018 Lunar GPS Visibility Study

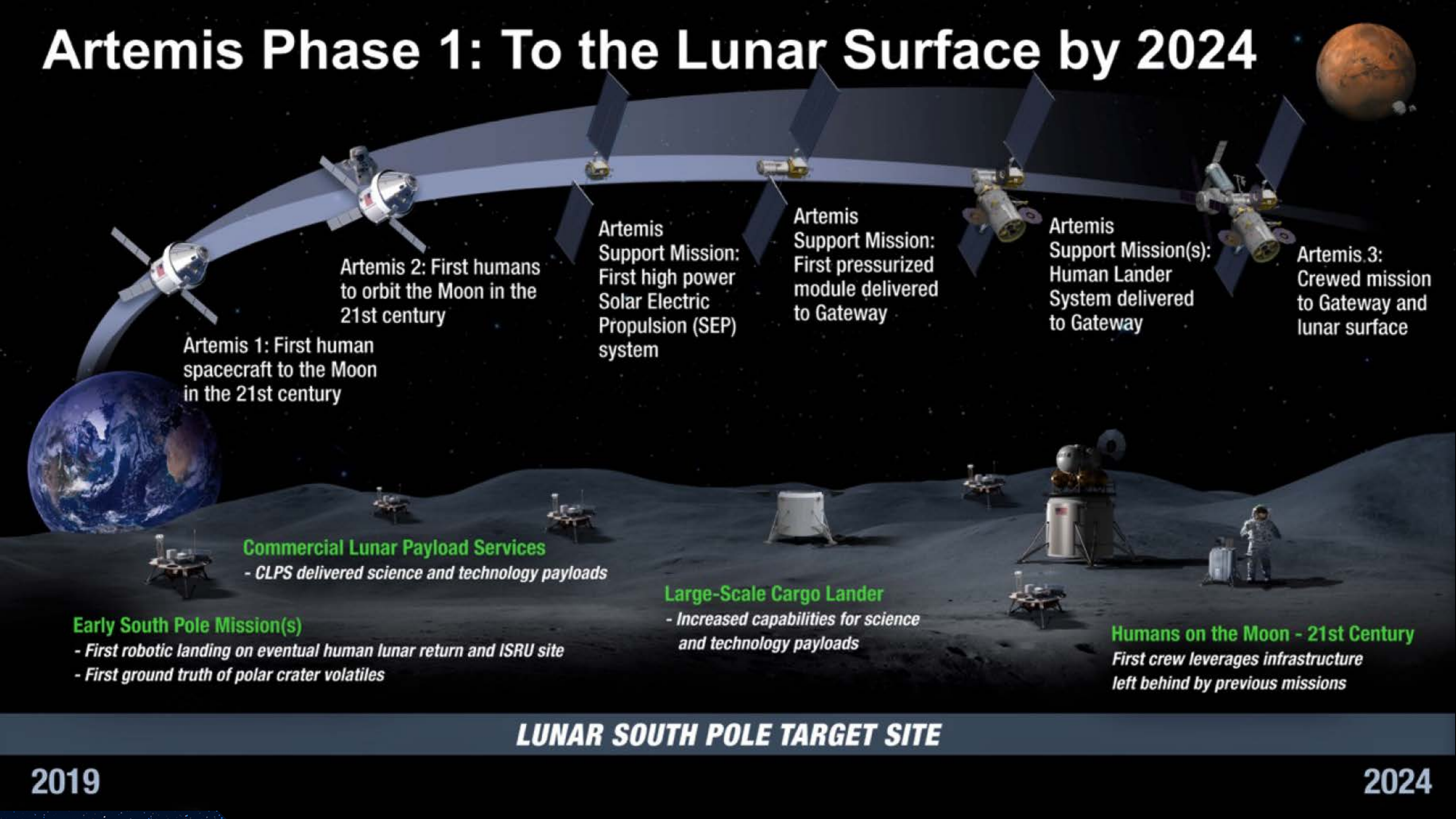
- GPS constellation modeled as accurately as possible, **including sidelobe signals**; validated with GOES-16 and MMS flight data.
- Calibrated models applied to outbound lunar near-rectilinear halo orbit (NRHO) GPS receiver reception with 22 dB-Hz C/N_0 threshold.

Peak Antenna Gain	1+ Vis.	4+ Vis.	Maximum Outage
7 dB	63%	8%	140 min
10 dB	82%	17%	84 min
14 dB	99 %	65%	11 min

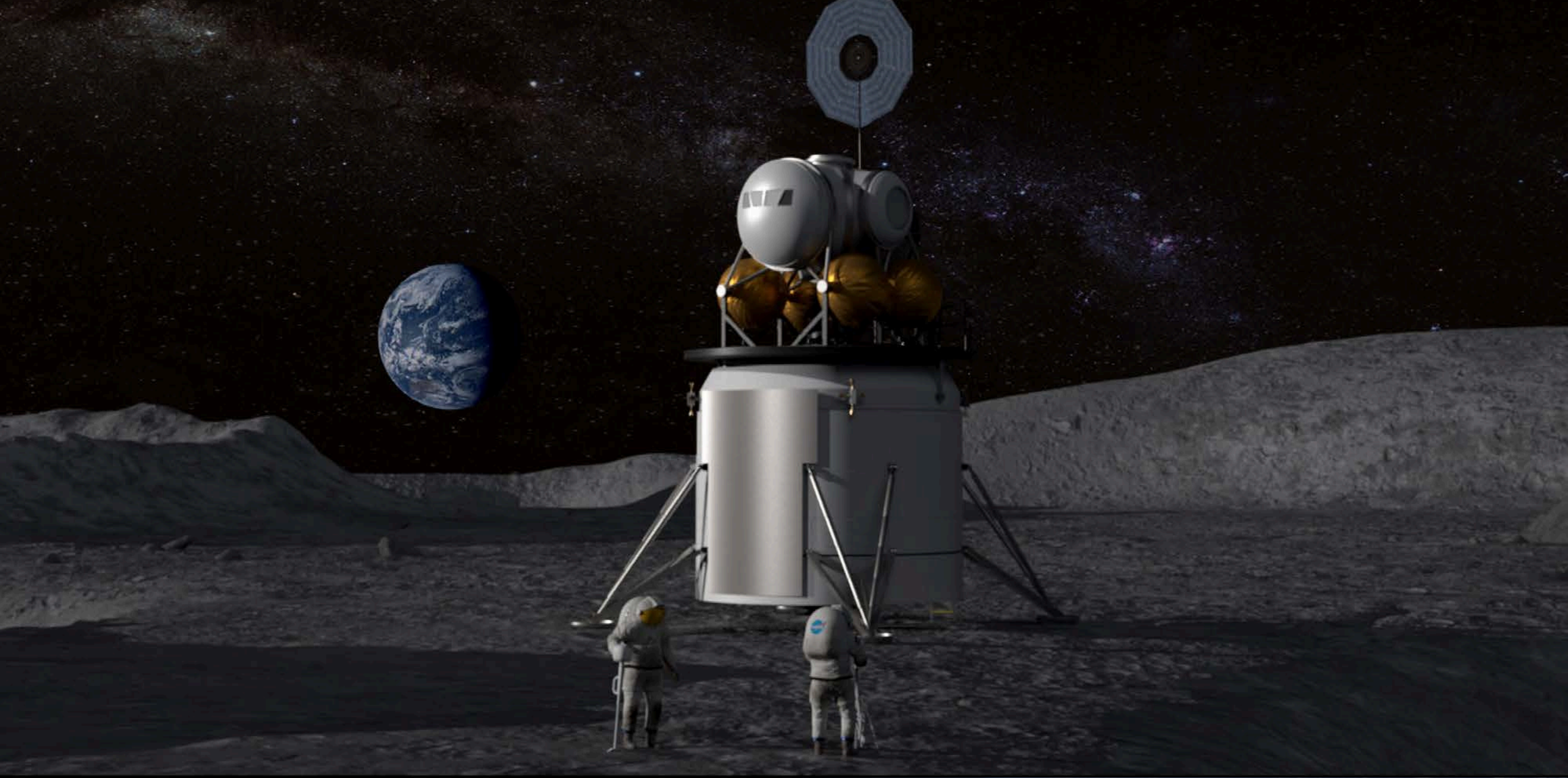
- Use of sidelobes and a modest amount of additional antenna gain or receiver sensitivity increases coverage greatly.
- **Results show useful onboard GPS navigation at lunar distances is achievable *now* using *currently-available* signals and *flight-proven* receiver technology.**



The Opportunity: Moon to Mars

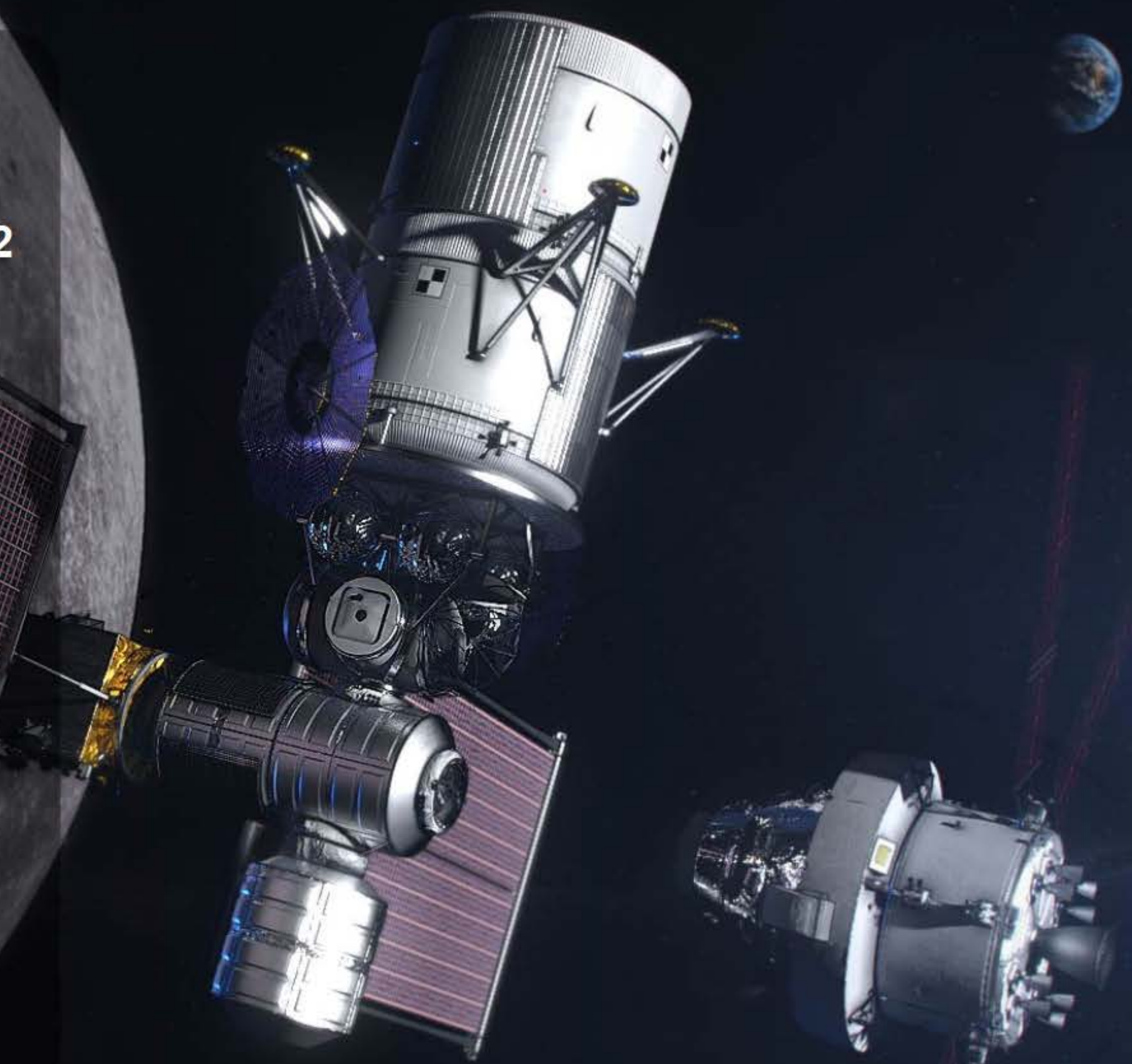

Artemis Phase 1: To the Lunar Surface by 2024
Artemis 1: First human spacecraft to the Moon in the 21st century
Artemis 2: First humans to orbit the Moon in the 21st century
Artemis Support Mission: First high power Solar Electric Propulsion (SEP) system
Artemis Support Mission: First pressurized module delivered to Gateway
Artemis Support Mission(s): Human Lander System delivered to Gateway
Artemis 3: Crewed mission to Gateway and lunar surface
Commercial Lunar Payload Services
- CLPS delivered science and technology payloads
Early South Pole Mission(s)
- First robotic landing on eventual human lunar return and ISRU site
- First ground truth of polar crater volatiles
Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads
Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
LUNAR SOUTH POLE TARGET SITE
2019
2024

HUMAN LANDING SYSTEM



Gateway is Essential for 2024 Landing

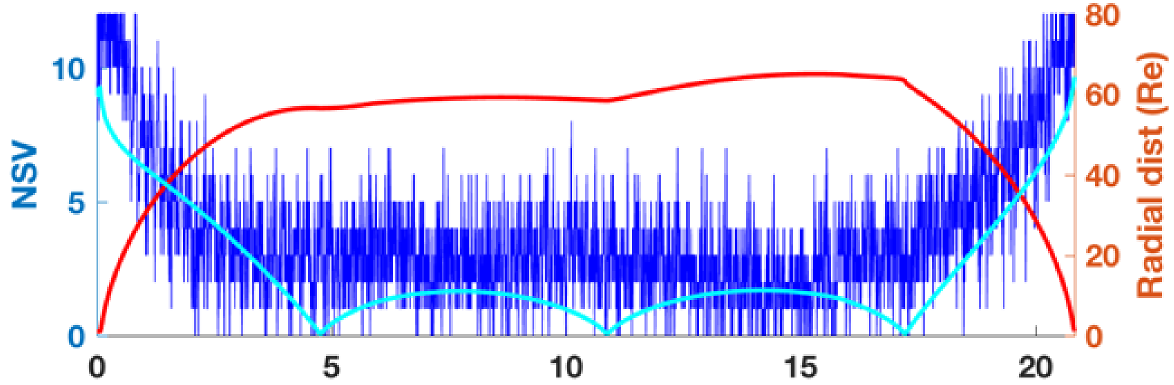
- Initial Gateway focuses on the minimum systems required to support a 2024 human lunar landing while also supporting Phase 2
- Provides command center and aggregation point for 2024 human landing
- Establishes strategic presence around the Moon – US in the leadership role
- Creates resilience and robustness in the lunar architecture
- Open architecture and interoperability standards provides building blocks for partnerships and future expansion



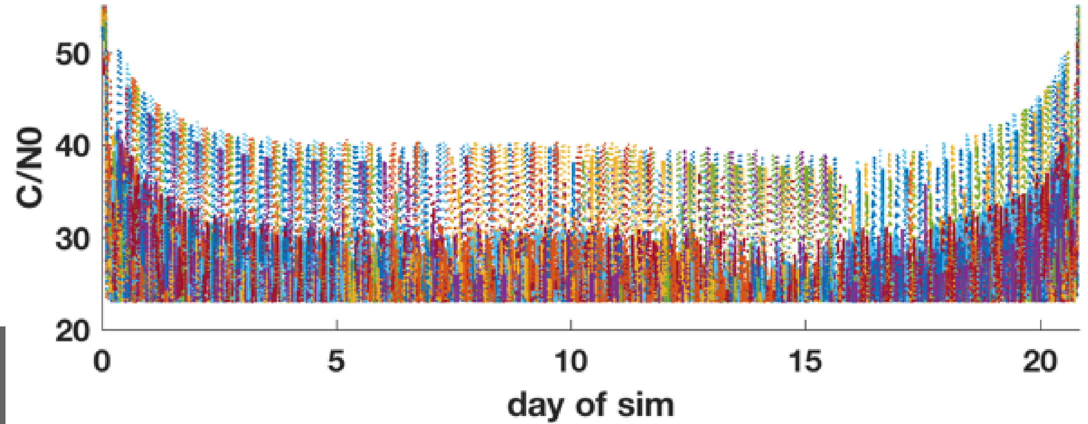
MMS Navigator Lunar Study

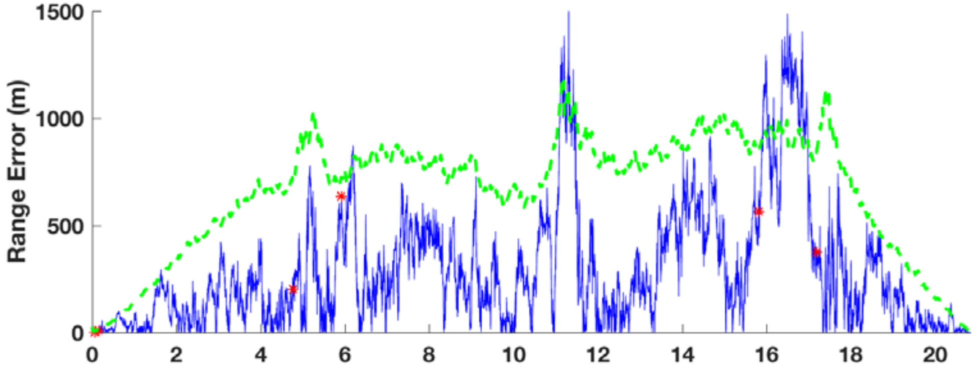
Study: How will MMS receiver perform if used on a conceptual Lunar mission with 14dBi high-gain antenna?

- Concept lunar trajectory similar to Artemis: LEO -> translunar -> Lunar (libration) orbit -> return
- **Visibility similar to MMS2B, as high-gain antenna makes up for additional path loss**
  - Avg visibility: ~3 SVs; C/N0 peaks > 40dB-Hz (main lobes) or > 30 dB-Hz (side lobes)
- Range/clock-bias errors dominate – order of 1-2 km; lateral errors 100-200 m
  - With atomic clock, or, e.g., periodic 2-way range/Doppler, could reduce range errors to meas. noise level

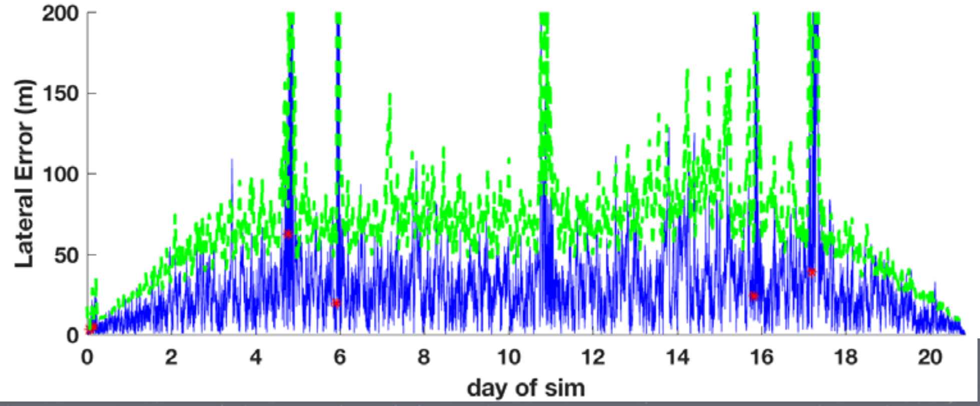


Top: Signals tracked and radial dist to Earth (red) and Moon (cyan); Bottom: C/N_0



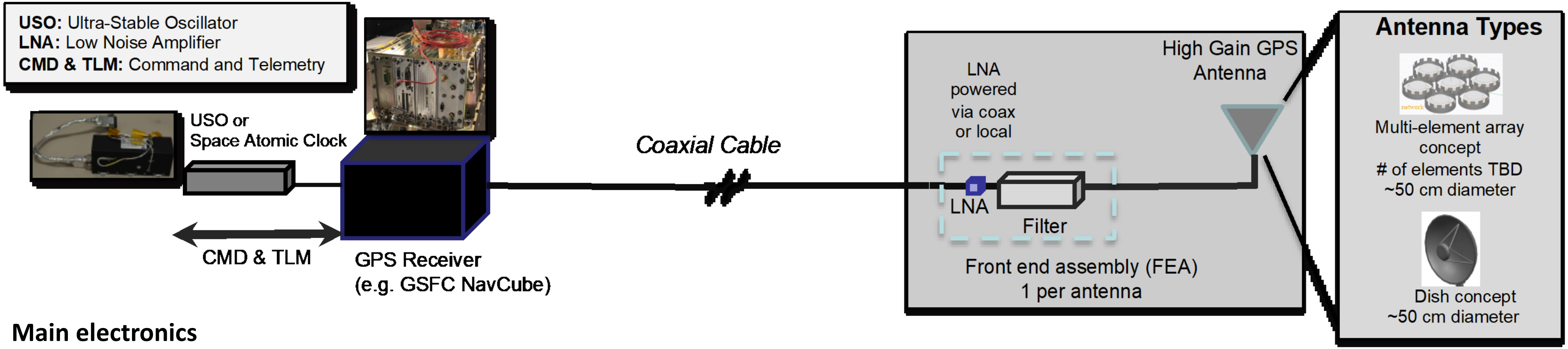


Filter position formal (3σ) and actual errors



A conceptual Gateway onboard GPS navigation system

Our study predicts that an MMS-like GPS navigation system, with an Earth pointed high-gain antenna (~14dBi) would provide strong onboard navigation for Gateway



Main electronics

- GSFC NavCube – Next Gen MMS Navigator GPS
  - Reprogrammable Software Defined Receiver (SDR)
    - Upgradable to multi-GNSS, etc.
  - Updated MMS GPS baseband processor logic
  - GEONS navigation filter software tuned for NRHO

External oscillator

- MMS USO or space-rated atomic clock
  - Could significantly enhance performance

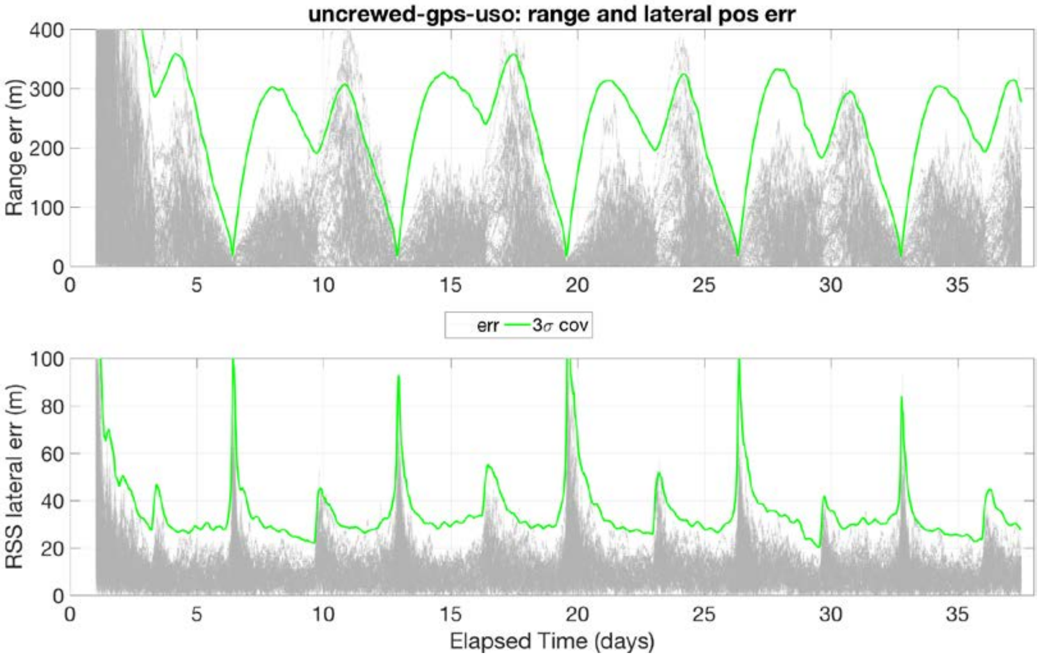
Antenna and Front End Assembly (FEA)

- 1 FEA with cables per antenna
- 1 High gain GPS Antenna ~14dBi
  - *a small dish or multi-element array*
  - *Earth pointed, gimbal*

Following slide shows results from Winternitz, L., Bamford, W., Long, A., and Hassouneh, M., “GPS Based Autonomous Navigation Study for the Lunar Gateway,” AAS GN&C Conference, Breckenridge, CO, Feb 2019, AAS 19-096.

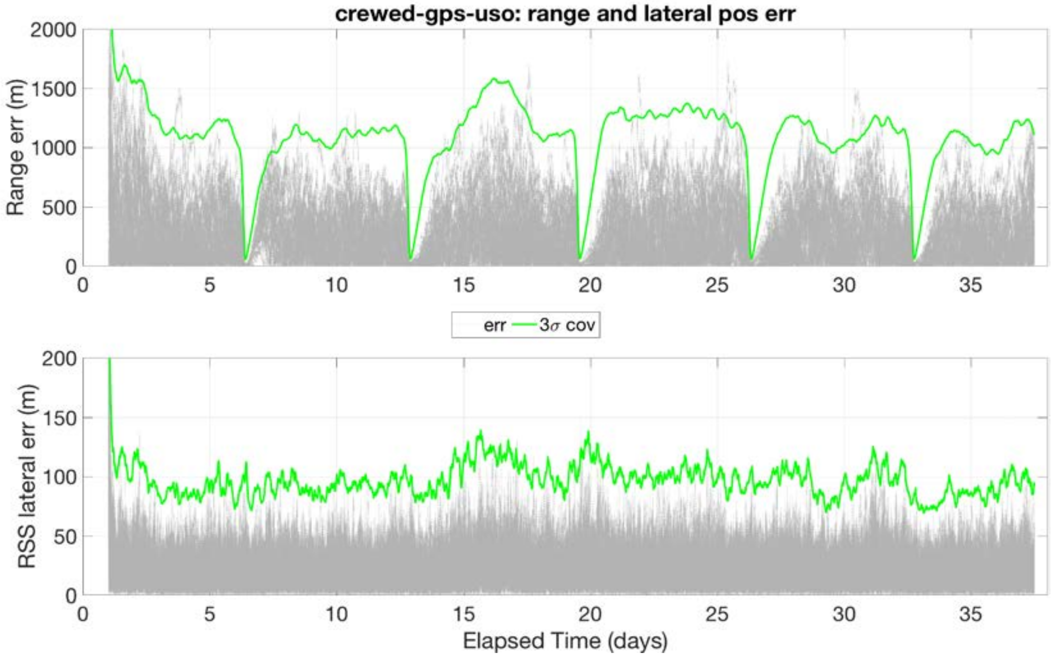
Lunar Gateway Navigation Performance: Crewed and Uncrewed

No Crew



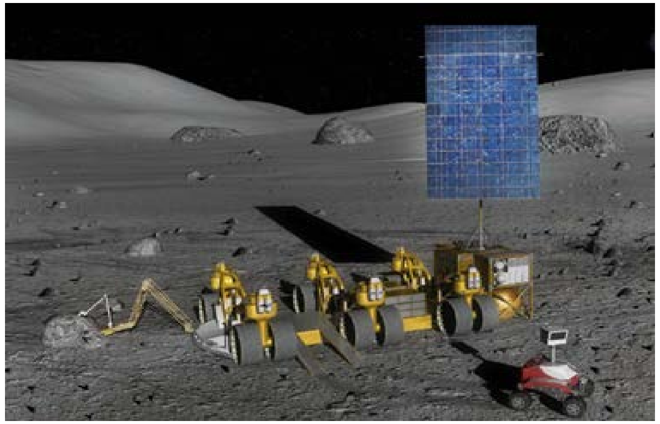
GPS Mean of 3-rms value over last orbit				
	Position (m)		Velocity (mm/sec)	
	Range	RSS Lateral	Range	RSS Lateral
USO	202.9	31.3	1.9	1.4
Atomic Clock	8.5	30.5	0.2	1.2

With Crew

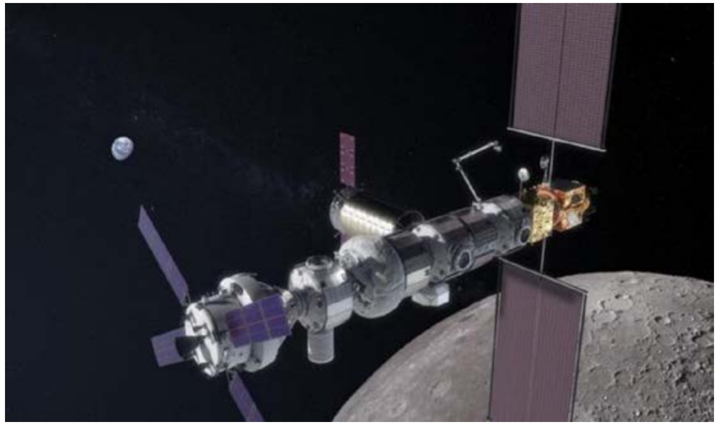


GPS Mean of 3-rms value over last orbit				
	Position (m)		Velocity (mm/sec)	
	Range	RSS Lateral	Range	RSS Lateral
USO	909.7	79	18.9	12.3
Atomic Clock	21.4	76.9	3.5	11.9

Lunar Exploration: Roles for GNSS Navigation & Timing

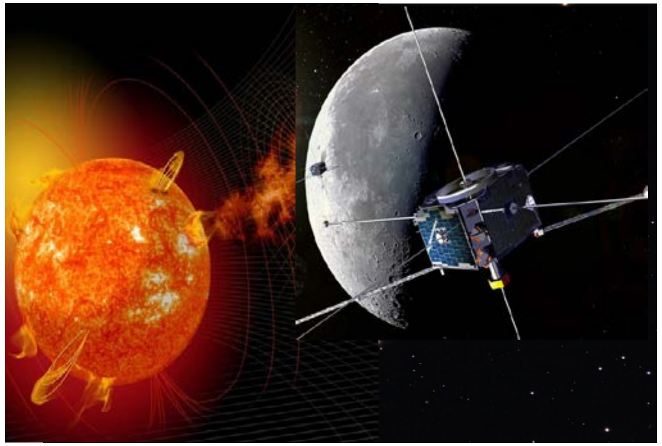


Lunar Surface Operations,
Robotic Prospecting,
& Human Exploration

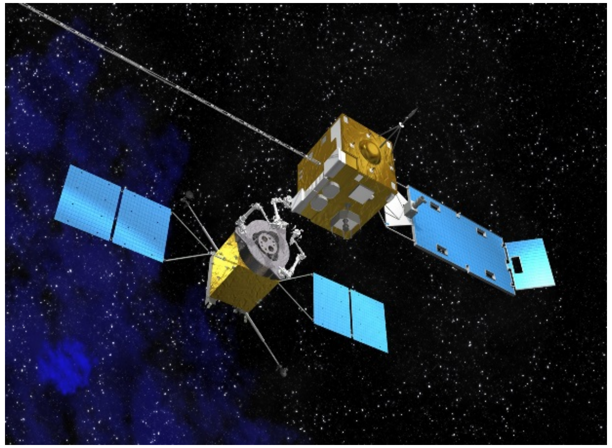


Human-tended Lunar Vicinity
Vehicles (Gateway)

Robotic Lunar Orbiters,
Resource & Science Sentinels



Earth, Astrophysics, & Solar
Science Observations



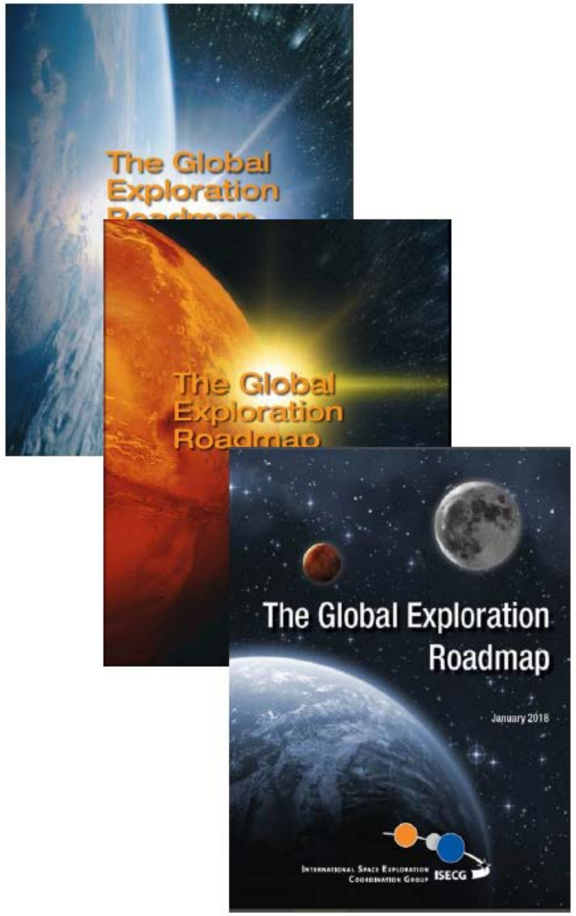
Satellite Servicing

Lunar Exploration Infrastructure

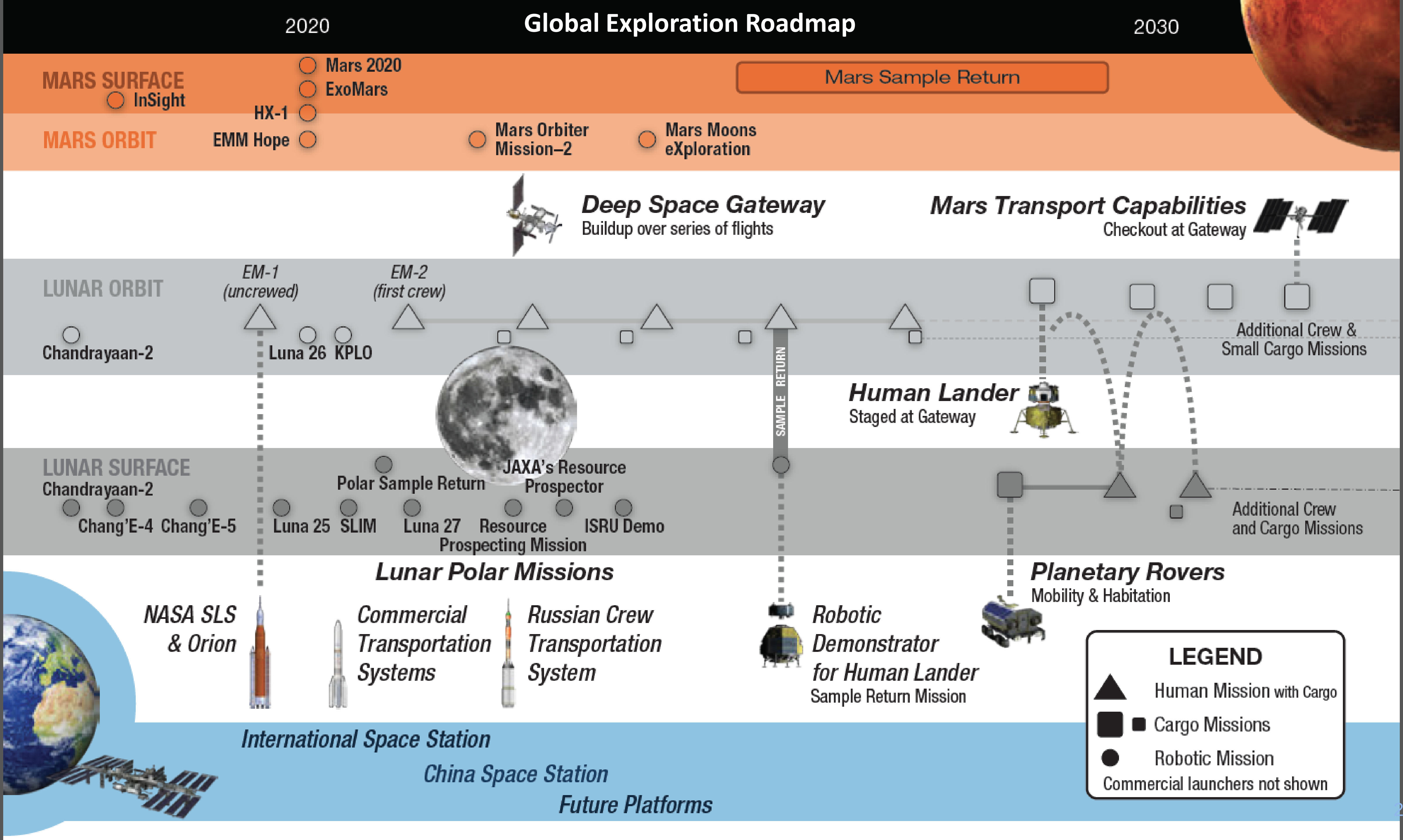
The Global Picture: ISECG Global Exploration Roadmap

- The GER is a human space exploration roadmap developed by 14 space agencies participating in the International Space Exploration Coordination Group (ISECG)
  - First released in 2011. Updated in 2013 and 2018.

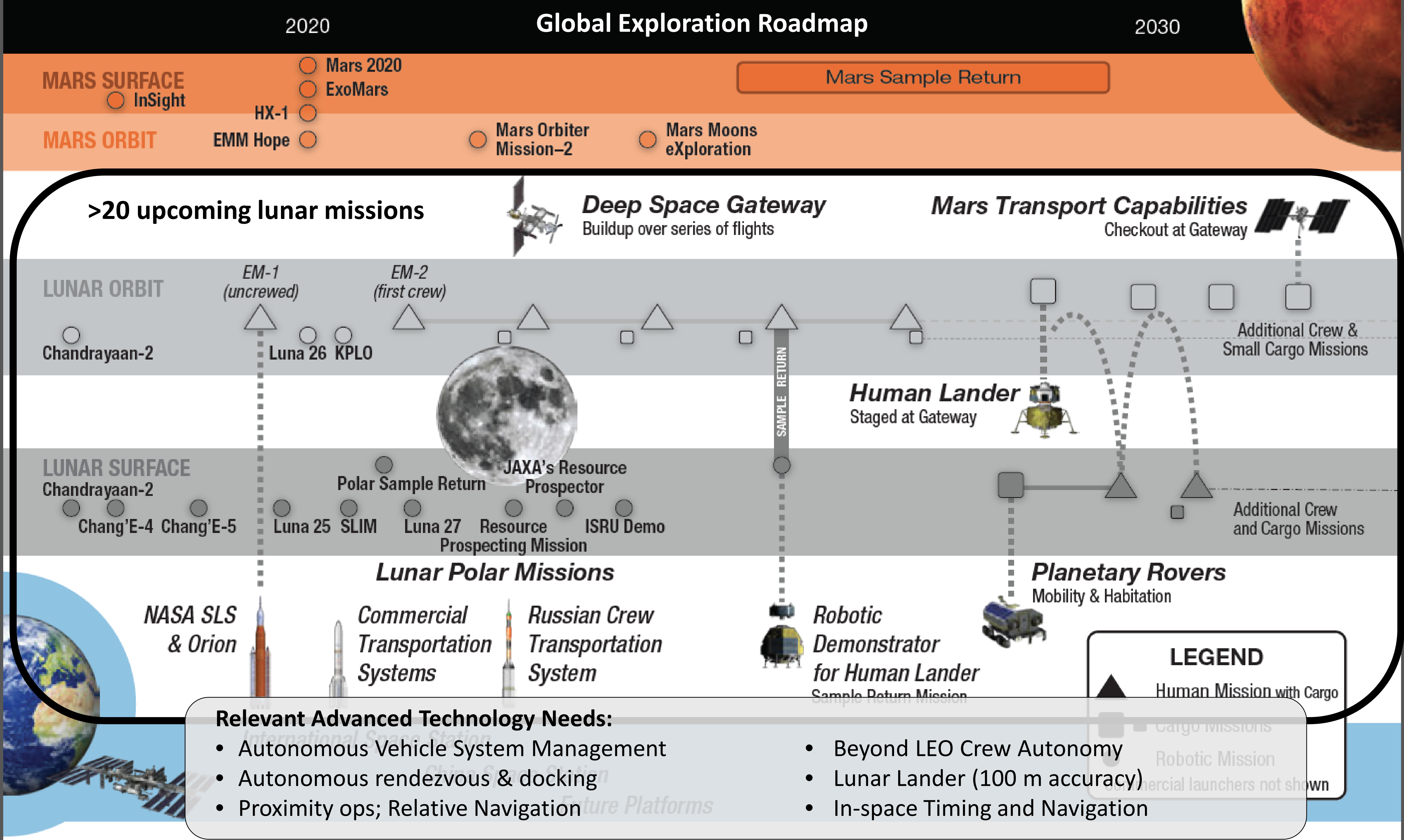
- The non-binding strategic document reflects consensus on expanding human presence into the Solar System, including
  - Sustainability Principles, spaceflight benefits to society
  - Importance of ISS and LEO
  - The Moon: Lunar vicinity and Lunar surface
  - Mars: The Driving Horizon Goal



www.globalspaceexploration.org
www.nasa.gov/isecg



Global Exploration Roadmap
2020
2030
MARS SURFACE
InSight
Mars 2020
ExoMars
HX-1
Mars Sample Return
MARS ORBIT
EMM Hope
Mars Orbiter Mission–2
Mars Moons eXploration
Deep Space Gateway
Buildup over series of flights
Mars Transport Capabilities
Checkout at Gateway
LUNAR ORBIT
EM-1 (uncrewed)
EM-2 (first crew)
Chandrayaan-2
Luna 26
KPLO
Additional Crew & Small Cargo Missions
SAMPLE RETURN
Human Lander
Staged at Gateway
LUNAR SURFACE
Chandrayaan-2
Chang'E-4
Chang'E-5
Luna 25
SLIM
Polar Sample Return
Luna 27
JAXA's Resource Prospector
Resource Prospecting Mission
ISRU Demo
Additional Crew and Cargo Missions
Lunar Polar Missions
Planetary Rovers
Mobility & Habitation
NASA SLS & Orion
Commercial Transportation Systems
Russian Crew Transportation System
Robotic Demonstrator for Human Lander
Sample Return Mission
LEGEND
Human Mission with Cargo
Cargo Missions
Robotic Mission
Commercial launchers not shown
International Space Station
China Space Station
Future Platforms



Relevant Advanced Technology Needs:

- Autonomous Vehicle System Management
- Autonomous rendezvous & docking
- Proximity ops; Relative Navigation
- Beyond LEO Crew Autonomy
- Lunar Lander (100 m accuracy)
- In-space Timing and Navigation

Building the Lunar GNSS Future: Collaboration and Development

International Committee on GNSS (ICG)

- **The ICG emerged from 3rd UN Conference on the Exploration and Peaceful Uses of Outer Space July 1999 to:**
  - Promote the use of GNSS and its integration into infrastructures, particularly in developing countries
  - Encourage compatibility & interoperability among global and regional systems
- **Members:** GNSS Providers (U.S., EU, Russia, China, India, Japan), Other Member States of the United Nations, and International organizations/associations (including the Interagency Operations Advisory Group) & others
- **Annual Meetings**:
  - 13th ICG hosted by China in Xi'an, November 4-9, 2018 (http://icg13.beidou.gov.cn/)
  - 14th ICG to be hosted by India in Bangalore, 2019 (https://www.icg14.org/)
  - 15th ICG to be held at the UN in Vienna, Austria, 2020

http://www.oosa.unvienna.org/oosa/en/SAP/gnss/icg.html

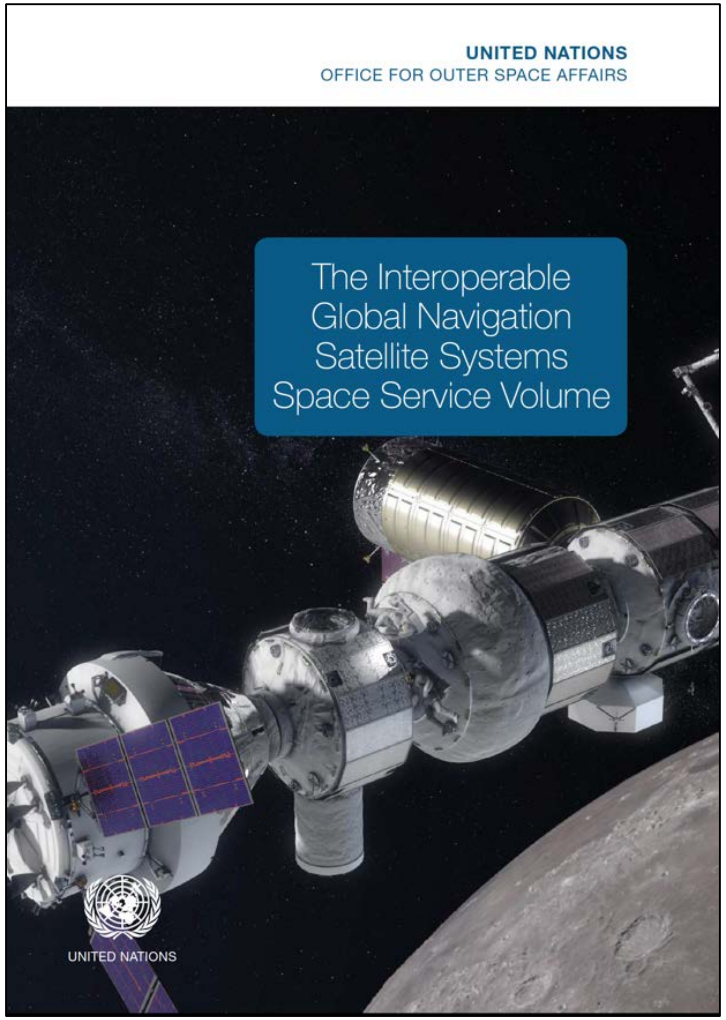
International Multi-GNSS SSV Activities in the ICG WG-B

The **United Nations International Committee on GNSS (ICG) Working Group B (WG-B) on Enhancement of GNSS Performance, New Services and Capabilities** leads development of the Multi-GNSS Space Service Volume (SSV) concept and related activities.

This is being accomplished via several initiatives:

Initiative	Status
• **SSV Definition/Assumption Maturation**: Adopting the formal definition of the Multi-GNSS SSV	Completed 2017
• **Constellation-Specific SSV Performance Data**: Publishing high-altitude performance characteristics for each GNSS constellation	Completed 2015
• **Multilateral SSV Analysis**: Conducting an internationally-coordinated analysis of simulated multi-GNSS SSV performance	Completed 2017
• **Multi-GNSS SSV Booklet**: Development of a formal UN publication (ST/SPACE/75) defining the Multi-GNSS SSV, its characteristics, benefits, and applications.	Completed 2018
• **Space Users Subgroup**: Establishing dedicated subgroup focusing on space user development.	Completed 2018
• **Beyond SSV studies**: Lunar vicinity GNSS performance and augmentation architecture studies	Ongoing
• **SSV Capabilities Outreach**: Coordinating a joint international outreach activity to raise awareness of the final policy.	Ongoing

ICG SSV Booklet & Ongoing Development



https://undocs.org/ST/SPACE/75

- **First publication of SSV performance characteristics for each GNSS constellation**
  - Received signal power, signal availability, pseudorange accuracy to GEO distance for each band
  - Conservative performance for main lobe signals only
- **Global and mission-specific visibility analyses**
  - GEO
  - Highly-elliptical
  - Lunar
- **Proposed expansion in 2nd edition:**
  - Addition of DOP analysis
  - Release and analysis of high-fidelity antenna patterns
  - Inclusion of real-world flight experiences
- **Future "Beyond-SSV" complementary activities:**
  - Identification and analysis of major Moon and Mars use cases
  - Analysis of benefits of GNSS augmentations for lunar activities
  - Collaboration with international exploration community

US User-Provider Collaboration on GPS SSV

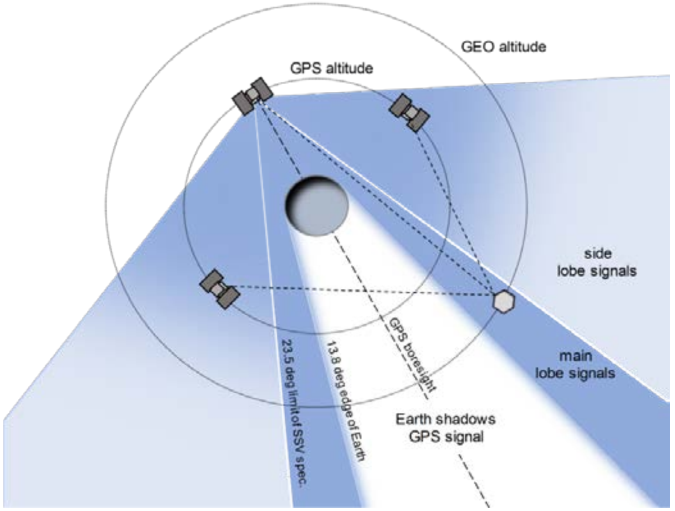
2017 Joint NASA-USAF Memorandum of Understanding signed on GPS civil Space Service Volume (SSV) requirements

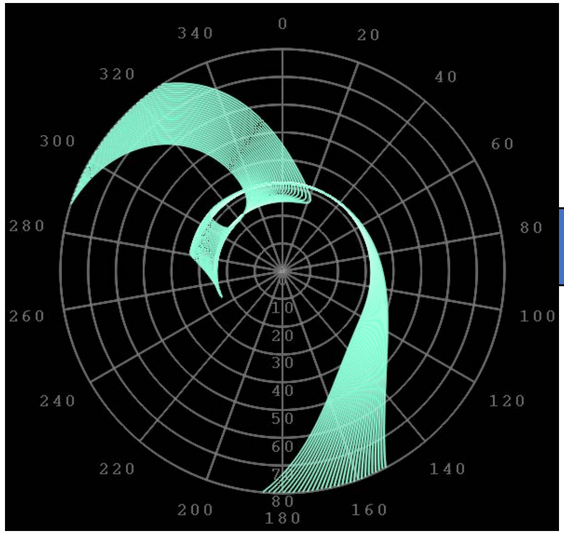
- Scope is relevant to future GPS IIIF satellites
- As US civil space representative, provides NASA insight into procurement, design and production of new satellites from an SSV capability perspective
- Intent is to ensure SSV signal continuity for future space users

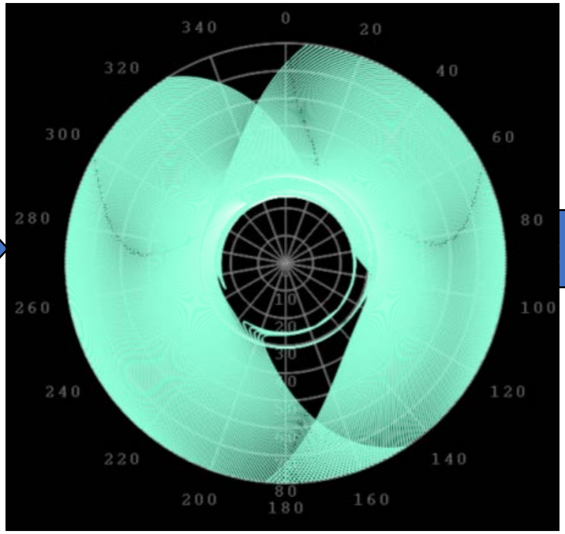
Example of productive collaboration between space user community and GNSS provider to ensure future SSV signal performance.

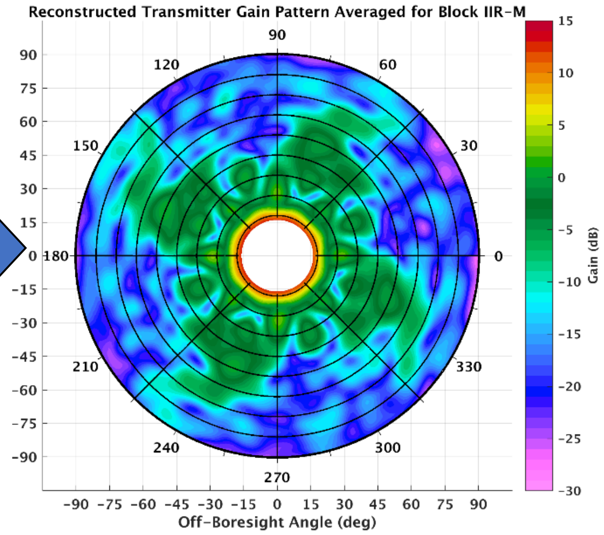
NASA Data Collection Initiative: GPS Antenna Characterization Experiment (ACE)

- GPS L1 C/A signals from GEO are available at a ground station through a “bent-pipe” architecture
- Map side lobes by inserting advanced, weak-signal tracking GPS receivers at ground station to record observations from GEO
- Trace path of GEO vehicle in antenna frame of each GPS vehicle
- Reconstruct full gain pattern after months of tracking









Full reconstructed patterns for GPS Blocks II/IIA, IIR, IIR-M, IIF available:

https://esc.gsfc.nasa.gov/navigation

Conclusions

The next frontier of GNSS in space is lunar.

To secure that future, we must continue to:

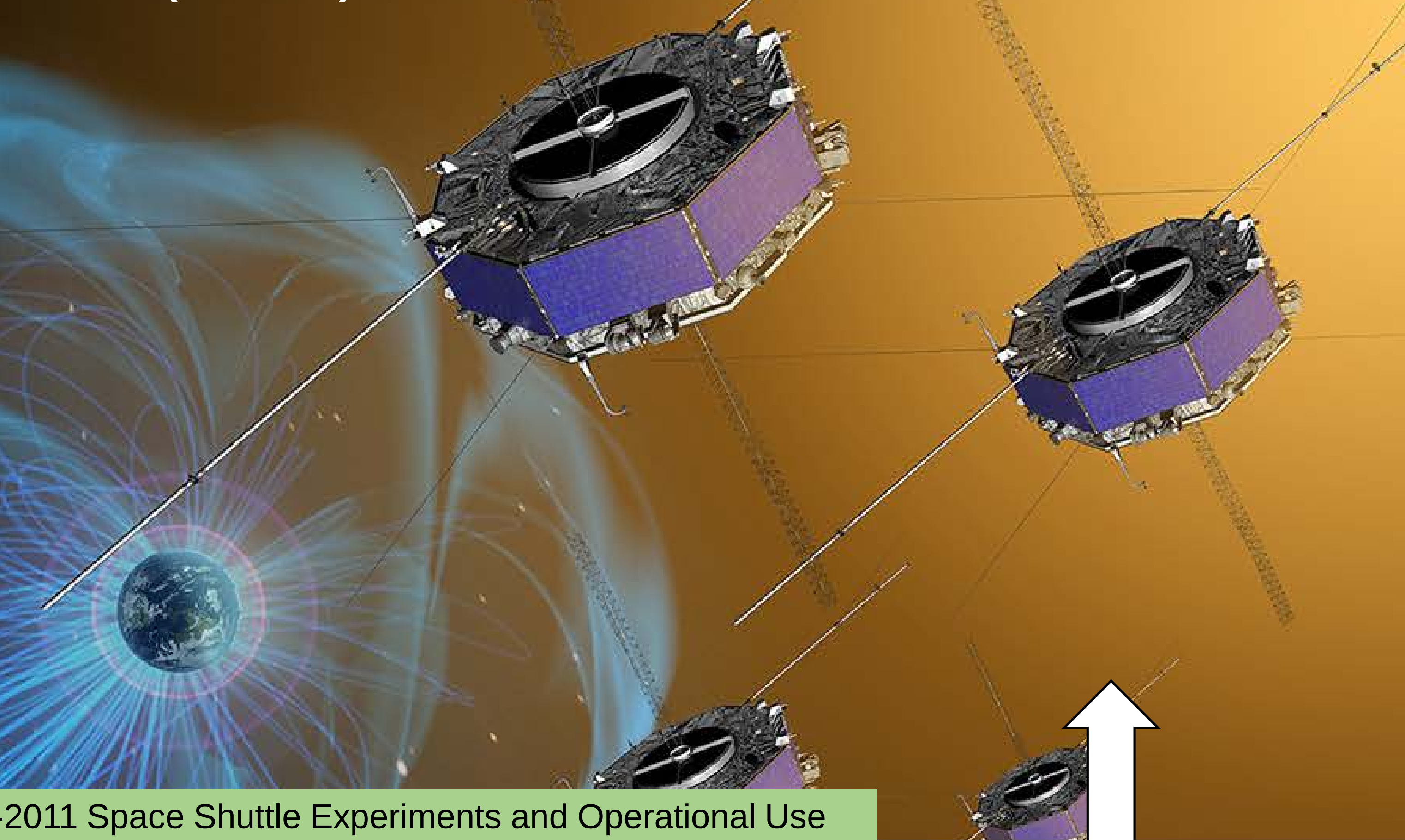
- Study the capabilities of GNSS *and augmentations* for lunar applications
- Work with user and provider community internally and via ICG to ensure signal performance and relevant data are available
- Mature receiver and antenna technology to meet technical challenges
- Secure flight demonstrations amidst global expansion in lunar exploration activities.
- Work with operational programs to maximize benefit to science and exploration.

NASA looks forward to pioneering the future in lunar GNSS—together.

Highest-Ever Use of GPS

Magnetospheric Multiscale Mission (MMS)

- **Launched**: March 13, 2015
- **Receiver**: NASA Navigator
- **Developed by**: NASA Goddard Space Flight Center
- MMS holds the record for the highest-ever use of GPS at over 29 Earth radii (50% of lunar distance), while simultaneously maintaining the tightest-ever spacecraft formation, at just over 7 km apart.



1993-2011 Space Shuttle Experiments and Operational Use

1970's	1980's	1990's	2000's	2010's

1978, GPS SV 1

1993, GPS IOC

1995, GPS FOC

2000, GPS SA Turned Off

Space Policy Directive 1: To the Moon, then Mars

"Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations…"