National Aeronautics and Space Administration

NASA GNSS Space User Update

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ICG-14 Working Group B
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Space Uses of Global Navigation Satellite Systems (GNSS)

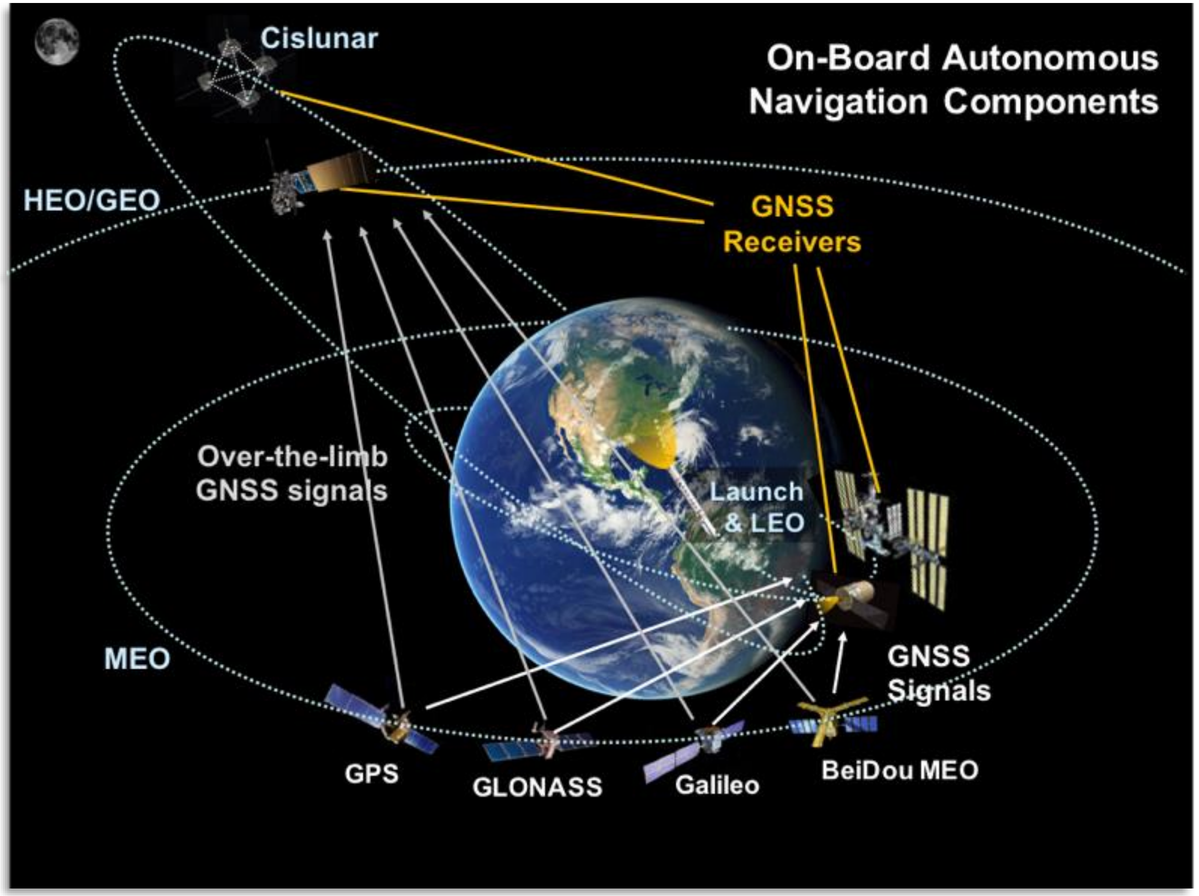
<u>Real-time On-Board Navigation</u>: Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing

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

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

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

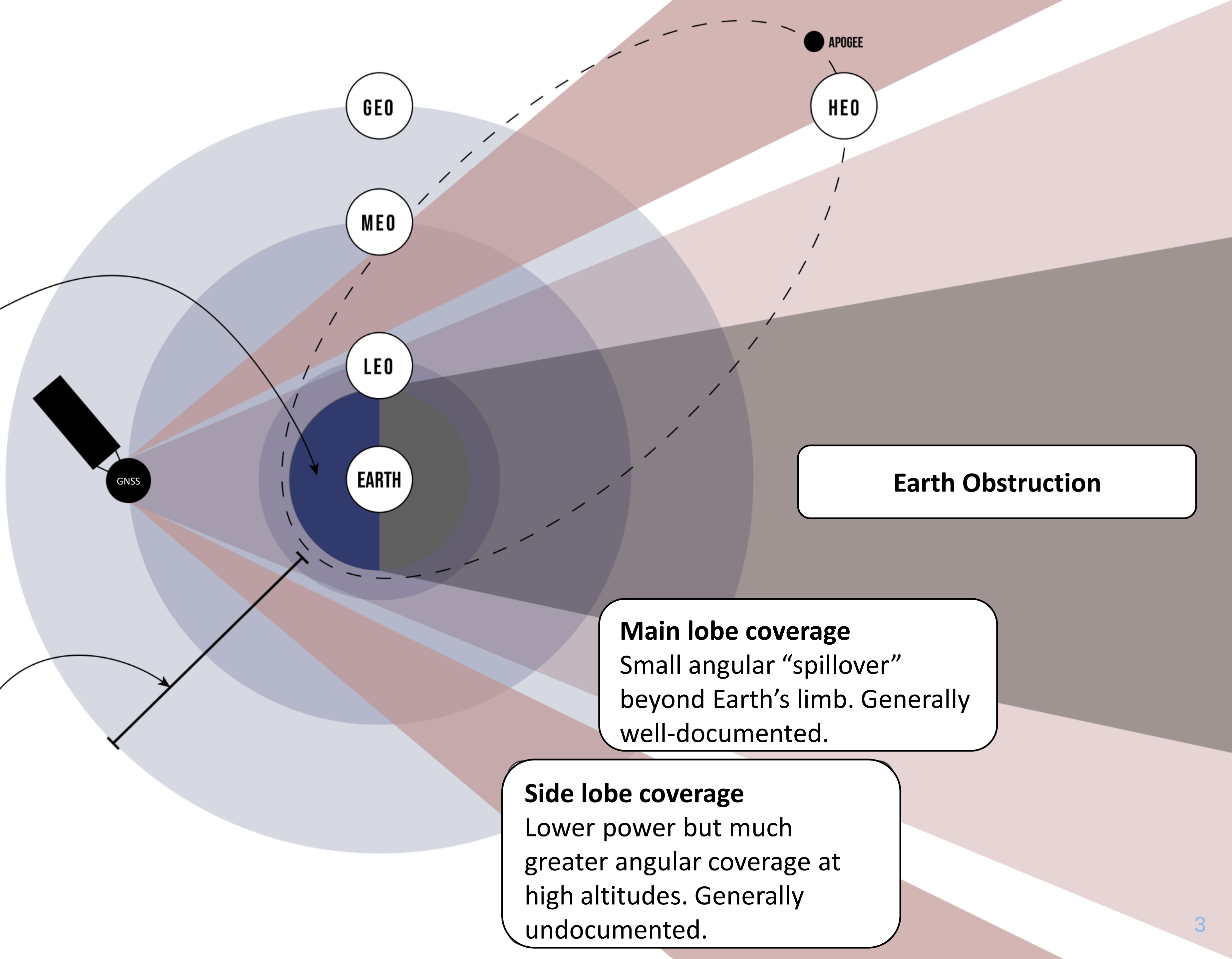
<u>Time Synchronization</u>: Support precise time-tagging of science observations and synchronization of on-board clocks



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

US Civil Space User Updates

In response to Recommendation
ICG/WGB/2016-2:
GNSS Space User Database

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: GPS/GNSS Space User Database

- IOAG has secured 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 Oct. 8, 2019 for ICG-14
- Key changes since previous update (Sep. 20, 2018):
  - Korea Aerospace Research Institute (KARI) added
  - Total number of entries* increased from 102 to 108

    (*) Some entries cover multiple vehicles
- 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	2018	2019
ASI	Italy	4	4
CNES	France	10	10
CSA	Canada	5	5
DLR	Germany	11	7
ESA	Europe	17	18
JAXA	Japan	12	12
KARI	Republic of Korea	-	8
NASA	USA	43	44

US Mission Status Updates

Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
~~NASA~~	~~SCAN Testbed on ISS~~	~~GPS, Galileo~~	~~L1 CA, L2C, L5, Galileo E1 and E5A~~	~~Demo of Software Defined Radio~~	~~LEO~~	~~2012~~	"Blackjack-based SDR. Monitoring of GPS CNAV testing began in June 2013. Development of Galileo E5a/GPS L5 waveform through agreement with ESA began in October 2016 2018 Update: Decommissioned 6/3/19 (incinerated during SpaceX Dragon CRS-17 re-entry). See URL <https://www.nasa.gov/feature/communications-testbed-leaves-legacy-of-pioneering-technology>.
NASA	COSMIC IIA (6 satellites)	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Occultation	LEO	6/25/2019	TriG receiver, 8 RF inputs, hardware all-GNSS capable, will track GPS + GLONASS at launch. Mission is NASA collaboration with USAF and National Space Program (NSPO).
NASA	DSAC	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Time transfer	LEO	6/25/2019	TriG lite receiver
NASA	ICESat-2	GPS	-	-	LEO	2018	RUAG Space receiver
NASA/DLR	GRACE FO	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Occultation, precision orbit, time	LEO	5/22/2018	TriG receiver with microwave ranging, joint mission with DLR

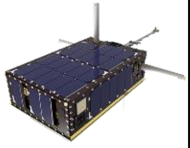
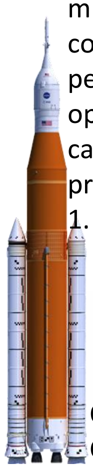
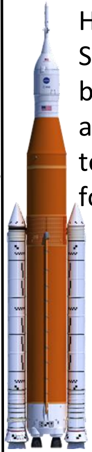
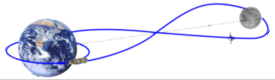
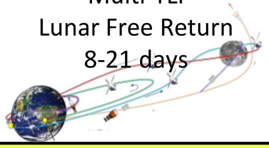
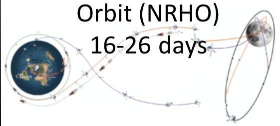
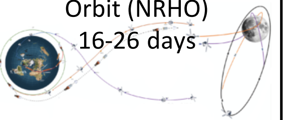
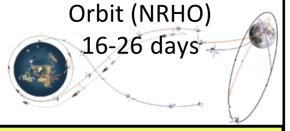
US Mission Status Updates

Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
NASA	NICER (ISS)	GPS	L1 C/A	Orbit	LEO	6/3/2017	Moog/Navigator receiver
NASA/CNES	SWOT	GPS, GLONASS FDMA, Galileo	L1 C/A, L2C, L5, Galileo, GLONASS FDMA	Precise Orbit Determination - Real Time	LEO	September 2021	TriG receiver with MIL-STD-1553 interface
NASA	Restore-L	GPS	L1 C/A	Orbit determination, spacecraft timing, GNSS measurements part of multi-sensor nav filter for AR&D with Landsat 7	LEO (Earth Polar)	2023	RUAG
NASA	PACE	GPS	L1 C/A	Orbit Determination	LEO	2022	RUAG LEORIX

US Newly-Added Missions

Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
AFRL	NTS-3	GPS, Galileo	GPS L1 C/A, L2C, L5 Galileo E1, E5a	Autonomous navigation in GEO with sub-m URE. Onboard ensemble time and clock integrity monitoring. Characterization and exploitation of dual frequency GPS space service volume.	GEO	2022	JPL collaboration with Harris Corporation Space and Intelligence Systems. JPL's Cion GNSS receiver, JPL's RTGx orbit determination and prediction software, NRL's Ensemble Timescale Filter (ETF) software.
NASA	STP-H6 XCOM Demo	GPS	L1 C/A, L2C	Orbit, time	Ei (ISS)	2019	NASA NavCube receiver

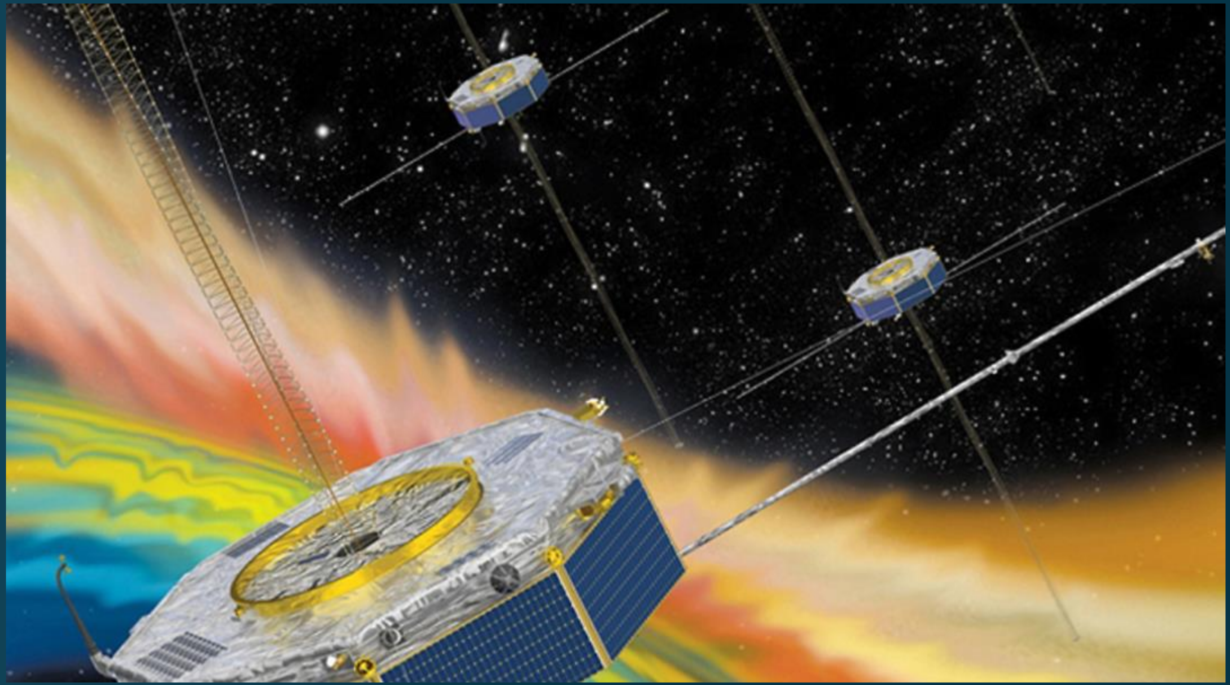
GPS use aboard Space Launch System

Artemis-1 Formerly: Exploration Mission 1 (EM1)	Artemis-2 Formerly: Exploration Mission 2 (EM2)	Artemis-3 Formerly: Exploration Mission 3 (EM3)	SLS SM-1 Science Mission 1	Artemis-4 Formerly: Exploration Mission 4 (EM4)	Artemis-5 Formerly: Exploration Mission 5 (EM5)
June 2021	Oct 2022	Oct 2024	Sep 2025	Dec 2025	Dec 2026
Block 1: ICPS	Block 1: ICPS	Block 1: ICPS	Block 1B Cargo	Block 1B: EUS	Block 1B: EUS
Cargo	4 Crew	4 Crew	Europa Clipper	4 Crew	4 Crew
 Cis-Lunar Space Mission to confirm vehicle performance and operational capability.  13 CubeSat Payloads	 First crewed mission, to confirm vehicle performance and operational capability, same profile as Artemis 1.  Orion Capsule + Crew	 Orion Docks to Gateway and Human Landing System (HLS) brings first woman and next man back to lunar surface for 6.5 days.  Orion Capsule + Crew	 First cargo mission configuration.  Europa Clipper to Jupiter	 Orion Docks to Gateway and HLS brings second Crew of two back to lunar surface for 6.5 days.  Orion Capsule + Crew	 Orion Docks to Gateway and HLS brings full Crew of four to lunar surface for sustainable missions.  Orion Capsule + Crew
Cis-Lunar Trajectory 11-21 days 	Multi-TLI Lunar Free Return 8-21 days 	Near-Rectilinear Halo Orbit (NRHO) 16-26 days 	Jupiter Direct 2.5 years 	Near-Rectilinear Halo Orbit (NRHO) 16-26 days 	Near-Rectilinear Halo Orbit (NRHO) 16-26 days 
Orbit: Honeywell SIGI with SPS Trimble Force 524D (L1 C/A Code Only) for Orbit Determination, Trans-Lunar Injection Burn and End-of-Mission disposal burn.	**Ascent**: M-Code L1/L2 in Shadow Mode for Range Safety Metric Tracking during Ascent. **Oribt**: SIGI w/SPS Force 524D	**Ascent**: M-Code L1/L2 in Shadow Mode for Ascent Tracking and Autonomous FTS. **Orbit**: Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	**Ascent**: M-Code L1/L2 as Primary for Ascent Track and Autonomous FTS. **Orbit**: Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	**Ascent**: M-Code L1/L2 as Primary for Ascent Track and Autonomous FTS. **Orbit**: Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	**Ascent**: M-Code L1/L2 as Primary for Ascent Track and Autonomous FTS. **Orbit**: Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.

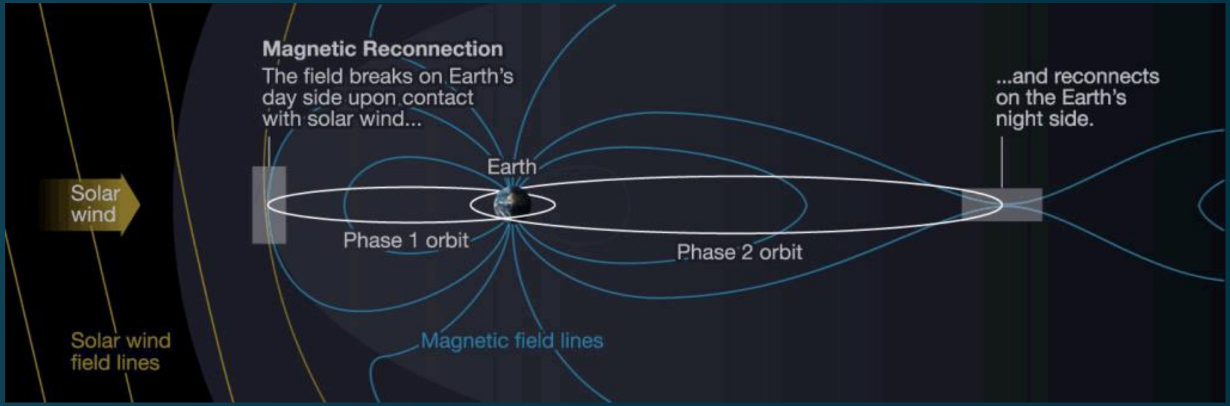
SLS Mission Data is based upon ESD-DM-13034, *ESD Internal Planning Manifest*, October 2019.

Flight Example: NASA MMS Mission

- **Magnetospheric Multi-Scale (MMS) Mission**
- Four spacecraft in a HEO form a tetrahedron near apogee to study magnetic reconnection energy
- Launched 12 March 2015



- Fastest-ever use of GPS
  - Velocities over 35,000 km/hr at perigee
- Highest-ever use of GPS
  - Phase 1: 12 Earth Radii (R_E) apogee (76,000 km)
  - Phase 2B: 25 RE apogee (~150,000 km)
  - **Phase 2E: Additional apogee raising beyond 29 R_E (50% lunar lunar distance) completed Feb 2019**
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping



Flight Example: NASA MMS Mission

MMS Navigator System

- Ultra-stable crystal oscillator (US)
- Navigator-GPS receiver
  - Rad-hard C/A code receiver with fast unaided weak signal acq (<25 dB-Hz)
- Goddard Enhance Onboard Navigation System (GEONS)
  - UD-factorized Extended Kalman Filter
  - Also flying on Terra, GPM, NICER/SEXTANT

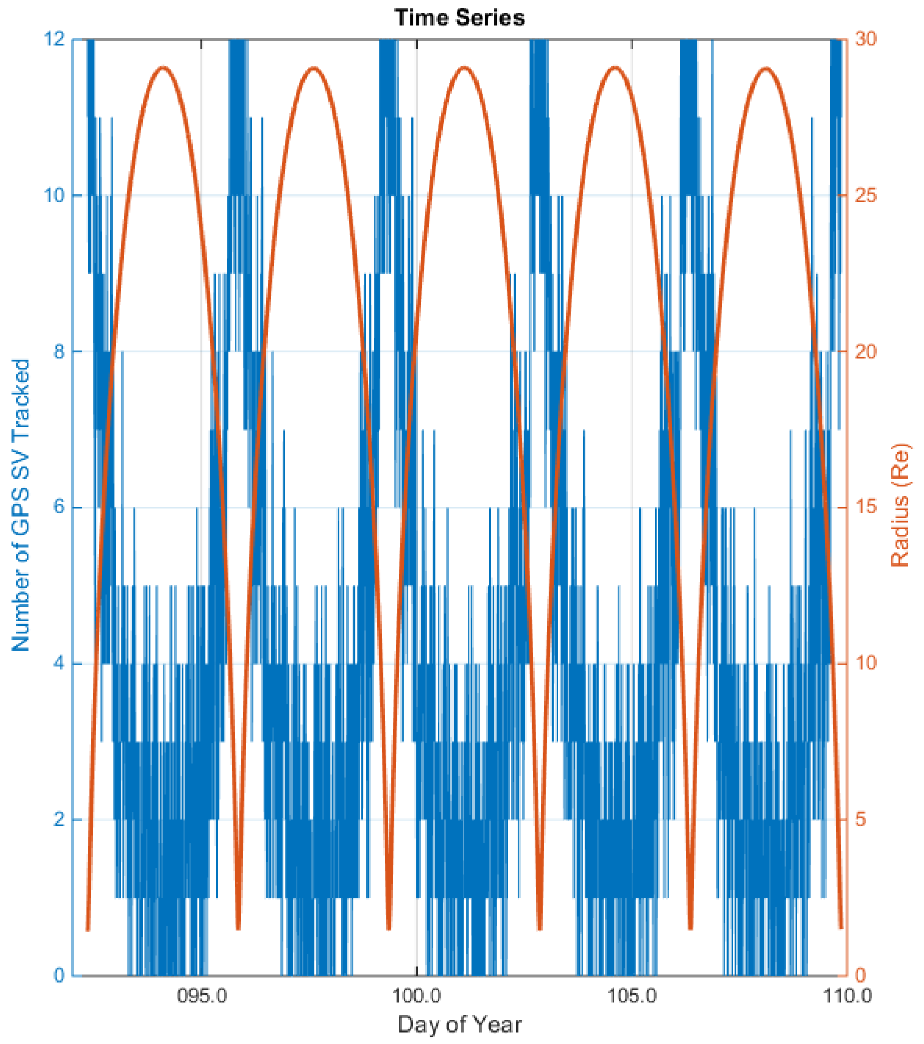
MMS GPS Visibility

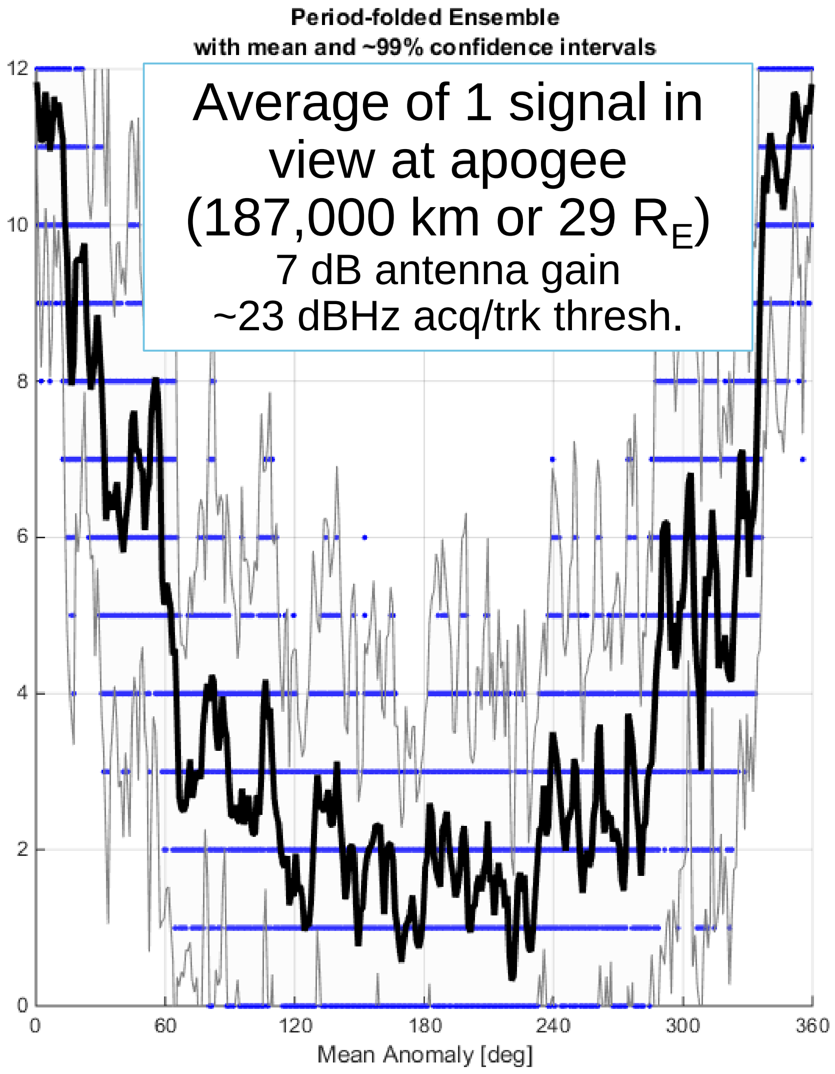
- Average of 3 signals tracked near apogee, up to 8

MMS Navigation Performance (1-sigma)

Description	Phase 1	Phase 2B
Semi-major axis est. under 3 R_E (99%)	2 m	5 m
Orbit position estimation (99%)	12 m	55 m

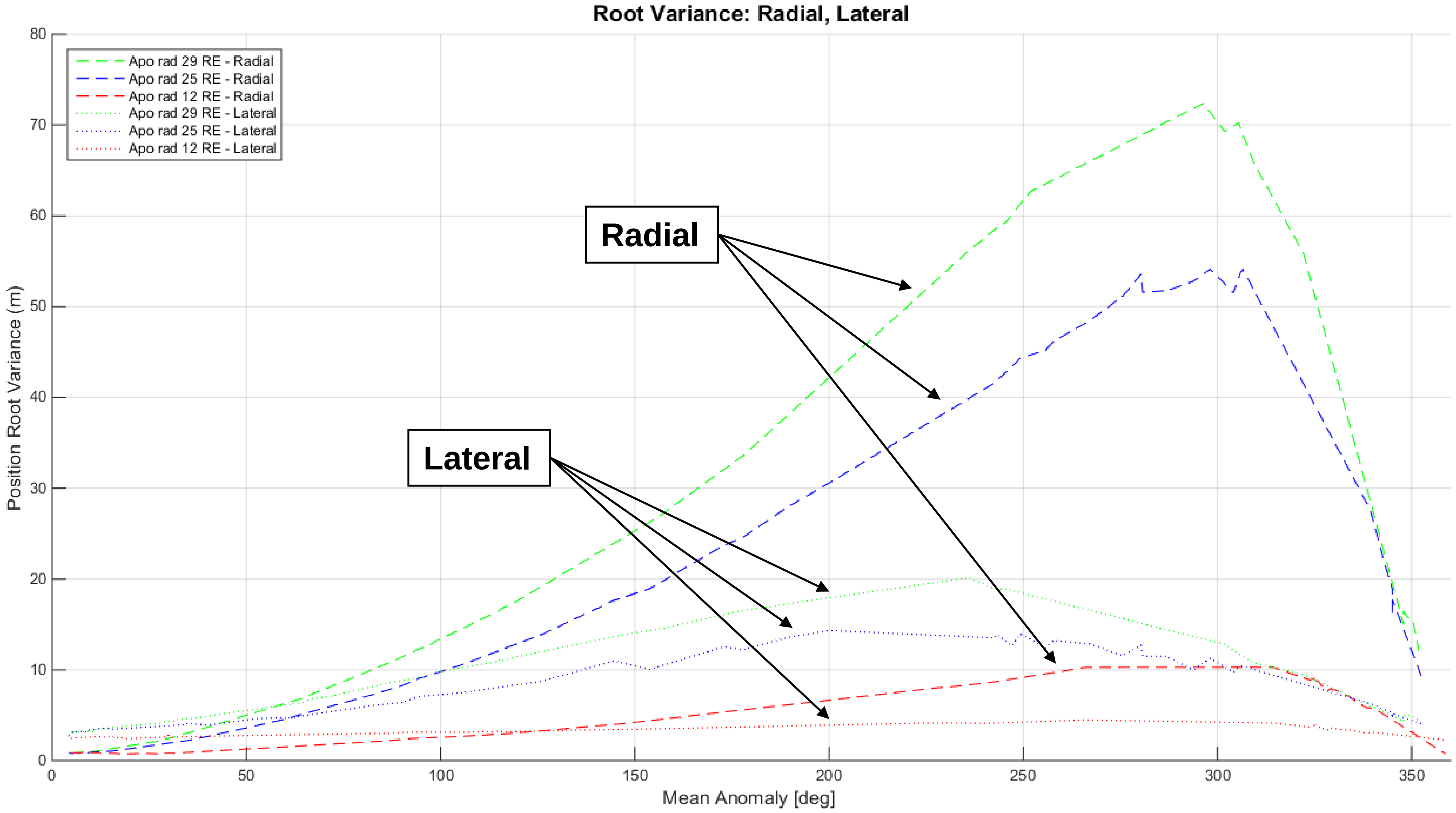
Signal Tracking Performance: 29.34 Re





- **GPS mean outage per orbit: 345 min (~7% of orbit period)**
- **Signal availability: ~93%**
- **GPS maximum individual outage: ~35 min**

Position Navigation Performance
12 Re, 25 Re, 29 Re



- Continued outstanding GPS performance
- Root variance: Radial < 70m, lateral <20m

NASA-USAF Collaboration on SSV

2017 SSV MOU:

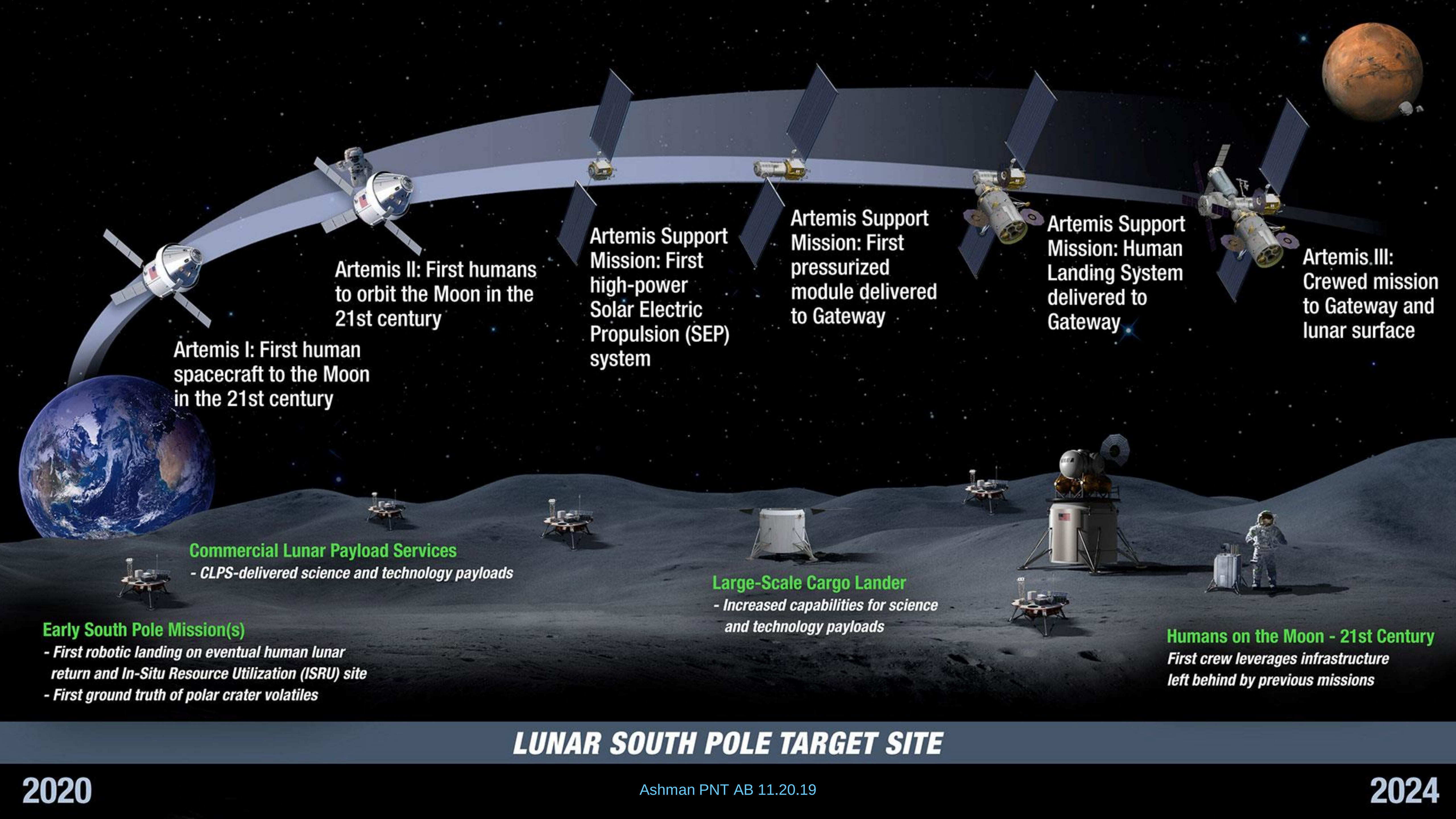
- 2017 joint NASA-USAF Memorandum of Understanding signed on GPS civil SSV requirements
  - as US civil space representative, provides NASA insight into GPS IIIF satellite procurement, design and production of new satellites from an SSV capability perspective
  - intent is to ensure SSV signal continuity for future space users
  - currently working on release to NASA of GPS III (SV1-10) antenna data

NASA-USAF Collaboration on SSV

Public Data Availability:

- NASA is engaging with USAF on ICG recommendations for system technical data availability:
  - ICG/WGB/2013-01 (Dubai, UAE)
  - ICG/WGD/2014-23 (Prague, Czech Republic)
  - ICG/WGB/2016-03 (Sochi, Russia)
- Message is that public availability of technical data is essential for high-accuracy users, including space users
  - Gold standard: Flight vehicle pre-launch test measurements and public release of data
  - Reconstructed/estimated data in use for flight vehicles at reduced accuracy/confidence
  - Partial release achieved by Galileo, QZSS & BDS using measured/calibrated data (Gold standard)
- Collaboration is ongoing to secure full public release of key data to support SSV and science users.
  - Specific SSV focus: antenna gain patterns, phase center data, attitude models

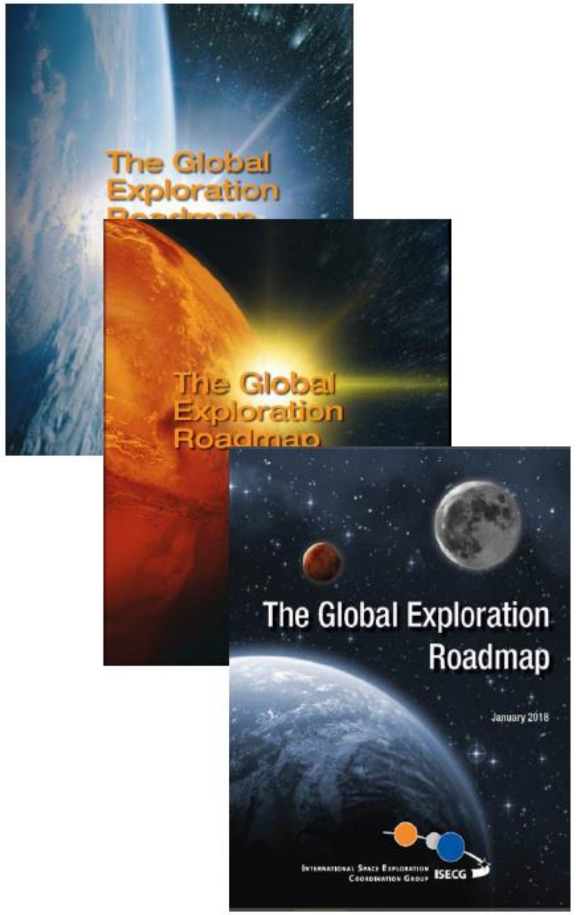
The GNSS Lunar Frontier



Artemis I: First human spacecraft to the Moon in the 21st century
Artemis II: 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: Human Landing System delivered to Gateway
Artemis III: 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 In-Situ Resource Utilization (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
2020
2024

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

GER lists more than 20 upcoming lunar missions

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

The Role of GNSS

Critical technology gaps identified by the GER:

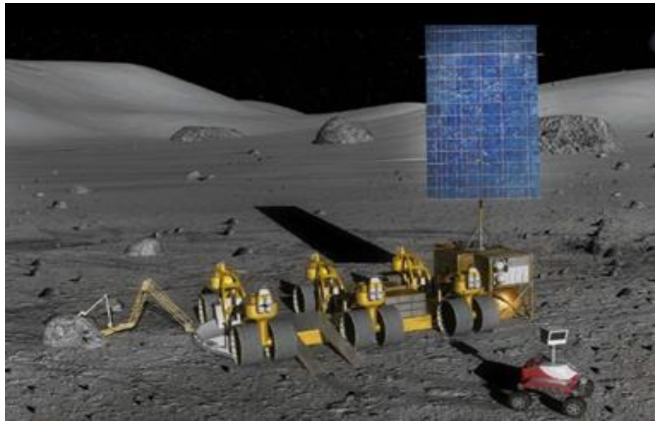
- AR&D Proximity Operations, Target Relative Navigation
- Beyond-LEO crew autonomy

GNSS on lunar missions would:

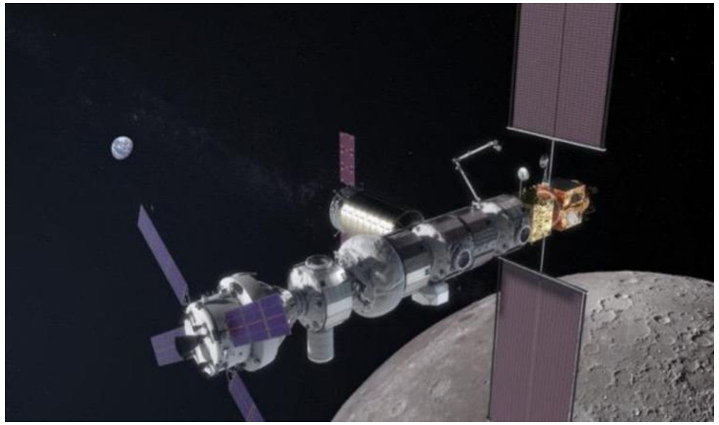
- enable autonomous navigation
- reduce tracking and operations costs
- provide a backup/redundant navigation for human safety
- provide timing source for hosted payloads
- reduce risk for commercial development

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

Lunar Exploration: Roles for GNSS Navigation & Timing

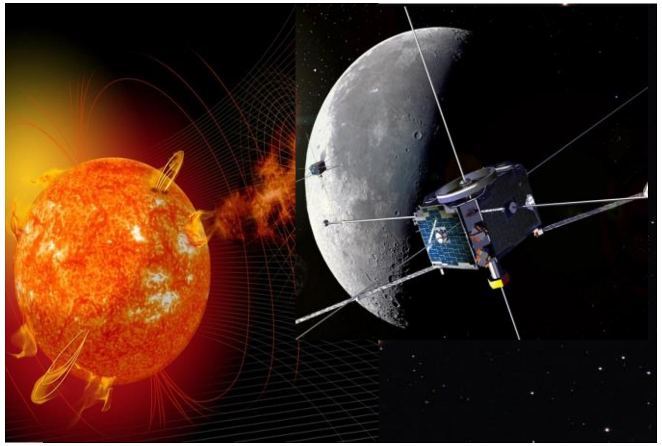


Lunar Surface Operations, Robotic Prospecting, & Human Exploration

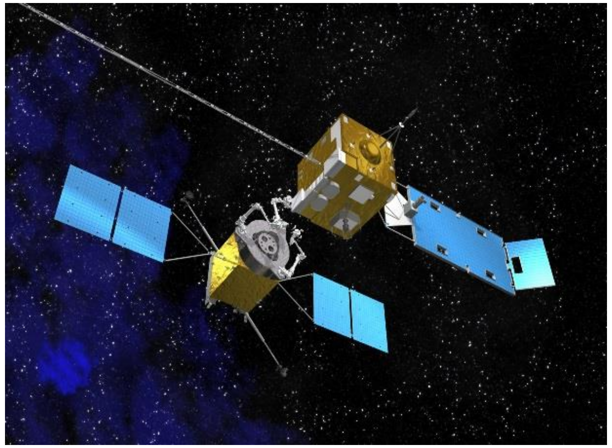


Human-tended Lunar Vicinity Vehicles (Gateway)

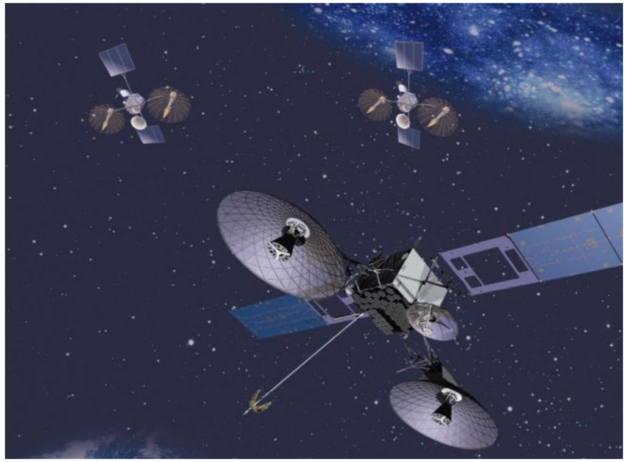
Robotic Lunar Orbiters, Resource & Science Sentinels



Earth, Astrophysics, & Solar Science Observations



Satellite Servicing



Lunar Exploration Infrastructure

Projected GNSS Performance at the Moon

“GPS Based Autonomous Navigation Study for the Lunar Gateway”

Winternitz et al. 2019 [1]

- Considered performance on Gateway of MMS-like navigation system with Earth-pointed high-gain antenna (~14 dBi) and GEONS flight filter software
- Calibrated with flight data from MMS Phase 2B
- L2 southern Near Rectilinear Halo Orbit (NRHO), 6.5 day period
- 40 Monte Carlo runs for cases below, w/ & w/o crew
- Uncrewed & crewed (w/ disturbance model) 3 x RMS average over last orbit:

Conclusions

- Average of 3 GPS signals tracked in NRHO
- Fewer Ground Station tracks, larger gaps than GPS
- GPS shows additional improvement over typical ground-based tracking when crew perturbations are included
- Ground tracking Nav: ***Hours***; GNSS Nav: ***Seconds***
- Beacon augmentations can further improve nav performance
- ***GNSS can provide a simple, high-performance, onboard, real-time navigation solution for Gateway***

Uncrewed	**Position (m)**		**Velocity (mm/s)**		**Update Rate**
	Range	Lateral	Range	Lateral	
Ground Tracking (8 hr/pass, 3–4 passes/orbit)	**33**	**468**	**1**	**10.6**	**Hours, Ground-Based**
GPS + RAFS*	**9**	**31**	**0.2**	**1.2**	**Real-Time, Onboard**

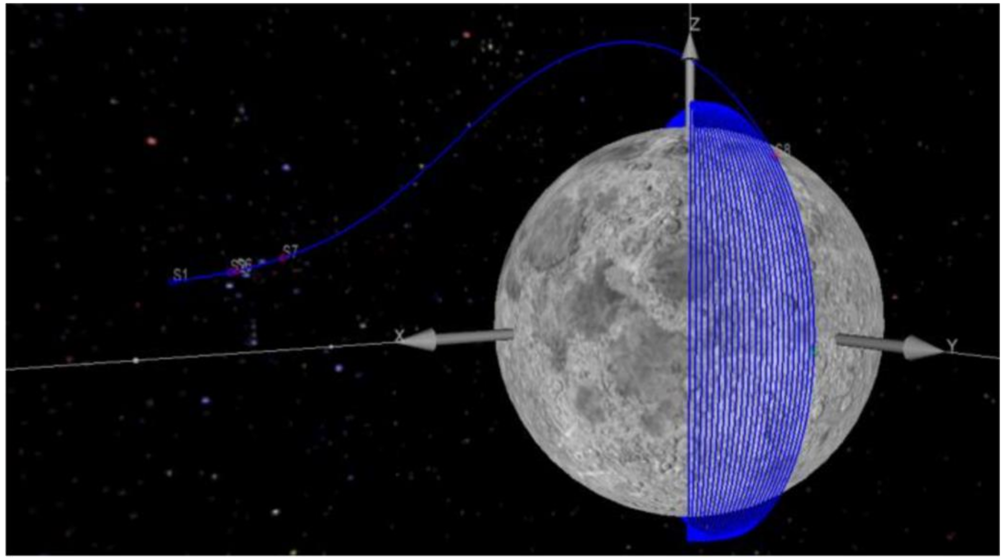
Crewed	**Position (m)**		**Velocity (mm/s)**		**Update Rate**
	Range	Lateral	Range	Lateral	
Ground Tracking (8 hr/pass, 3–4 passes/orbit)	**451**	**8144**	**18**	**155**	**Hours, Ground-Based**
GPS + RAFS*	**21**	**77**	**4**	**12**	**Real-Time, Onboard**

Projected GNSS Performance at the Moon

"Lunar Navigation Beacon Network Using GNSS Receivers"

Anzalone et al. 2019 [2]

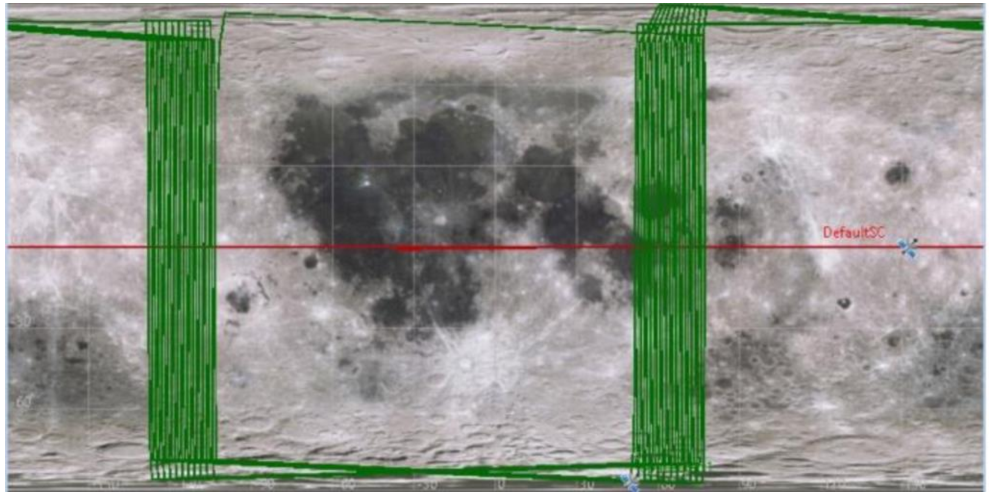
- Considered similar MMS-like navigation system for Lunar Pallet Lander (LPL)
- Added cross-links to a cubesat navigation beacon deployed into an equatorial or polar 200 km altitude lunar orbit
- Steady state errors in low lunar orbit (LLO): ~50 m position and < 5 cm/s velocity (range improved due to dynamics, lateral dominates)



"Cislunar Autonomous Navigation Using Multi-GNSS and GNSS-like Augmentations: Capabilities and Benefits"

Singam et al. 2019 [3]

- Considered same scenario as Anzalone et al. 2019 but focused on signal availability and geometry; included other GNSS
- ~1 GPS signal available in lunar orbit, ~1 Galileo
- Generalized DOP reduction from 100s to 10s by CubeSat beacon



Conclusions

The user community is making progress to realize the lunar frontier

- Detailed analyses show clear benefits for lunar applications
- Collaborations with providers are making progress with data release
- Many technology demonstration activities are ongoing globally
- ICG work to coordinate efforts is making impact

The GNSS community must act to seize this opportunity

- **Providers:**
  - **Preserve** existing capability
  - **Facilitate** user community development to realize full capabilities
- **Users:**
  - **Develop** receiver and navigation filter technology
  - **Share** details of lunar missions and associated navigation needs
  - **Collaborate** on architectures and augmentations to support global lunar ecosystem

References

1. Winternitz, L. B., Bamford, W. A., Long, A. C., & Hassouneh, M. (2019). GPS Based Autonomous Navigation Study for the Lunar Gateway.
2. Anzalone, E. J., Getchius, J. W., Leggett, J. O., Ashman, B. W., Parker, J. J. K., & Winternitz, L. B., “Lunar Navigation Beacon Network Using GNSS Receivers”, *Proceedings of the 70th International Astronautical Congress (IAC),* Washington, DC, October 2019.
3. Singam, C., Ashman, B., Schlenker, L., “Cislunar Autonomous Navigation Using Multi-GNSS and GNSS-like Augmentations: Capabilities and Benefits”, *Proceedings of the 70th International Astronautical Congress (IAC),* Washington, DC, October 2019.

Backup

NASA GNSS User Update for SLS

(Space Launch System)

Agency	Mission	GNSS Used	GNSS Signals Used	GNSS Application	Orbit	Launch	GPS Specifics
NASA	Artemis-1 (ICPS)	GPS	L1 C/A Receiver	Orbit Determination, TLI burn, End-of-Mission Disposal	Un-Crewed Cis-Lunar Trajectory	Jun 2021	Ascent: No GPS Metric Tracking. Orbit: Honeywell SIGI with SPS Trimble Force 524D.
NASA	Artemis-2 (ICPS)	GPS x 2	L1/L2 M-Code Receiver L1 C/A Receiver	Shadow-Mode Range Safety Certification for Autonomous FTS Orbit Determination, TLI burn, End-of-Mission Disposal	Crewed Multi-TLI Lunar Free Return	Oct 2022	Ascent: L1/L2 IEC Tru-Track M-Code GPS Receiver in AFTS shadow mode (passenger only, no cmd authority). Orbit: Honeywell SIGI with SPS Trimble Force 524D
NASA	Aretmis-3 (ICPS)	GPS x 2	L1/L2 M-Code Receiver L1 C/A Receiver	Shadow-Mode Range Safety Certification for Autonomous FTS Orbit Determination, TLI burn, End-of-Mission Disposal	Near-Rectilinear Lunar Halo Orbit (NRHO)	Oct 2024	Ascent: L1/L2 IEC Tru-Track M-Code GPS Receiver in AFTS shadow mode. Orbit: Honeywell Mercury L1 SPS GPS for operation at > 8,000 km altitude
NASA	Science Mission 1 (EUS)	GPS x 2	L1/L2 M-Code Receiver L1 C/A Receiver	Ascent Range Safety Tracking and Autonomous Flight Termination. Orbit Determination, TLI burn, End-of-Mission Disposal	Jupiter Direct (Science Cargo Mission)	Sep 2025	Ascent: L1/L2 IEC Tru-Track M-Code GPS Receiver for Autonomous FTS. Orbit: Honeywell Mercury L1 SPS GPS for operation at > 8,000 km altitude
NASA	Artemis-4 (EUS)	GPS x 2	L1/L2 M-Code Receiver L1 C/A Receiver	Ascent Range Safety Tracking and Autonomous Flight Termination. Orbit Determination, TLI burn, End-of-Mission Disposal	Near-Rectilinear Lunar Halo Orbit (NRHO)	Dec 2025	Ascent: L1/L2 IEC Tru-Track M-Code GPS Receiver for Autonomous FTS. Orbit: Honeywell Mercury L1 SPS GPS for operation at > 8,000 km altitude