National Aeronautics and
Space Administration

Advancing Space Use of GNSS

to Cislunar Space and Beyond

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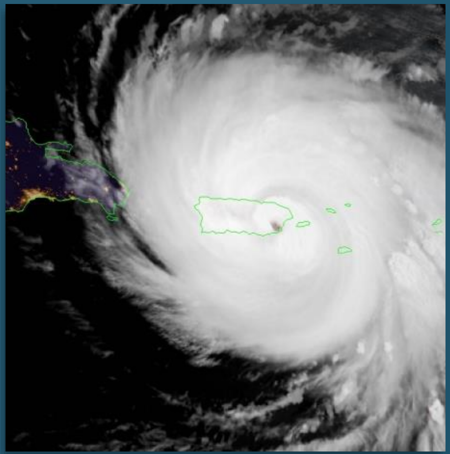
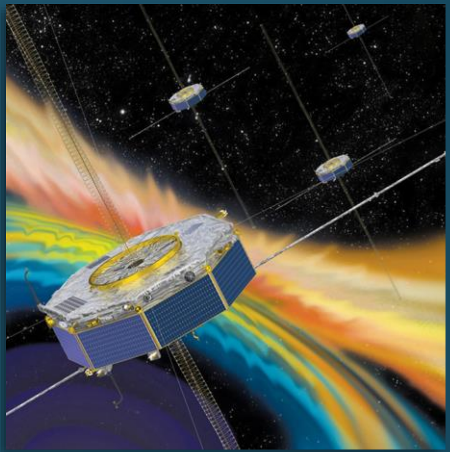
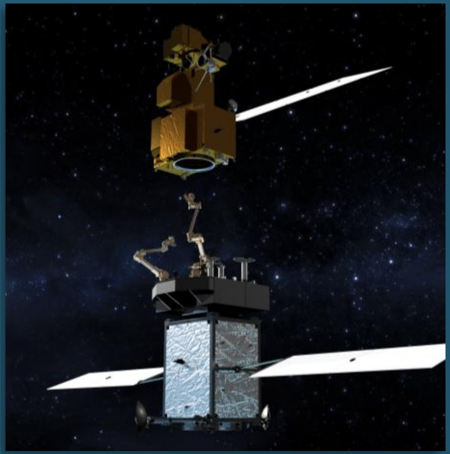
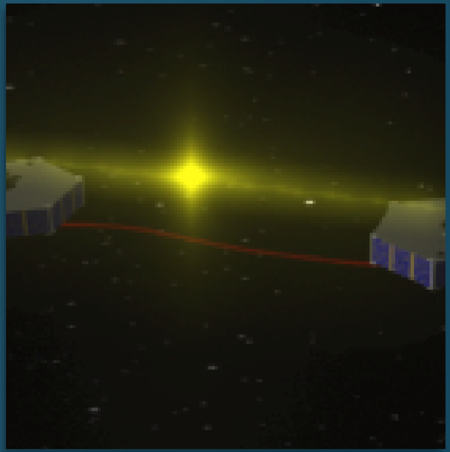
Cocoa Beach, FL

Benefits of GNSS Use in Space

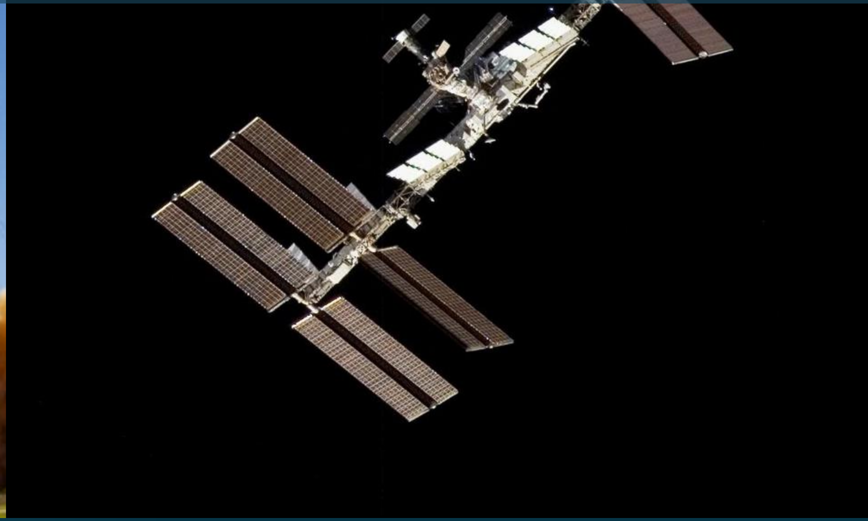





- Significantly **improves real-time navigation performance** (from km-class to meter-class)
- Supports **quick trajectory maneuver recovery** (from 5-10 hours to minutes)
- GNSS timing **reduces need for expensive on-board clocks** (from $100sK-$1M to $15K-$50K)
- Supports **increased satellite autonomy**, lowering mission operations costs (savings up to $500-$750K/year)
- Enables new/enhanced capabilities and better performance for High Earth Orbit (HEO) and Geosynchronous Earth Orbit (GEO) missions

Earth Sciences

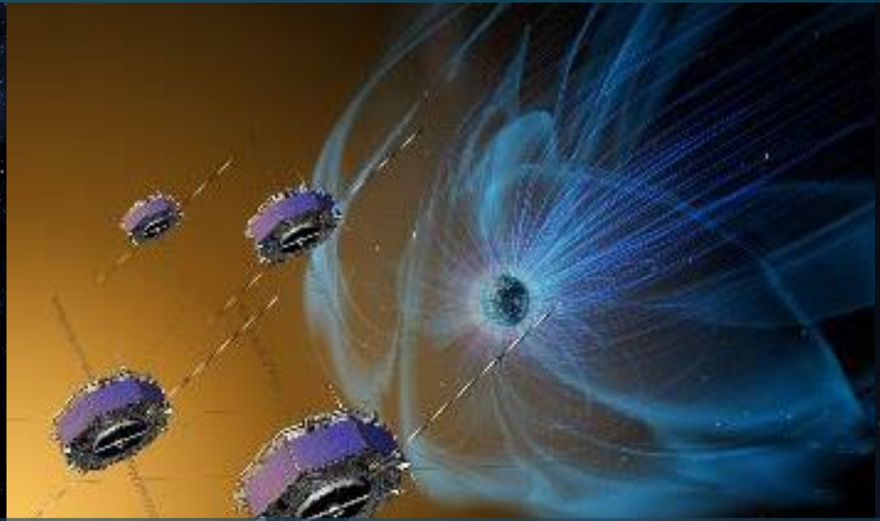
Launch Vehicle Range Ops

Attitude Determination

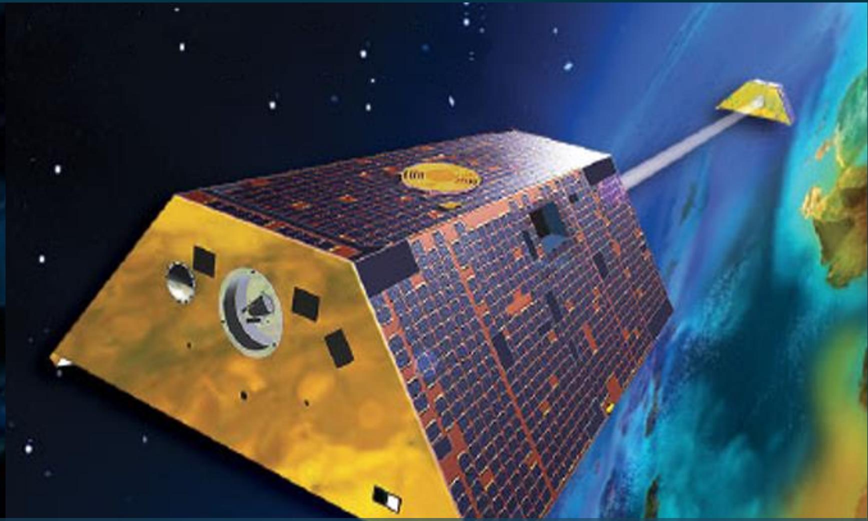


Active Space Use Cases

Time Synchronization



Real-Time On-Board Nav



Precise Orbit Determination

Space Use Case Example: AFTS

Autonomous Flight Termination (AFTS) concept

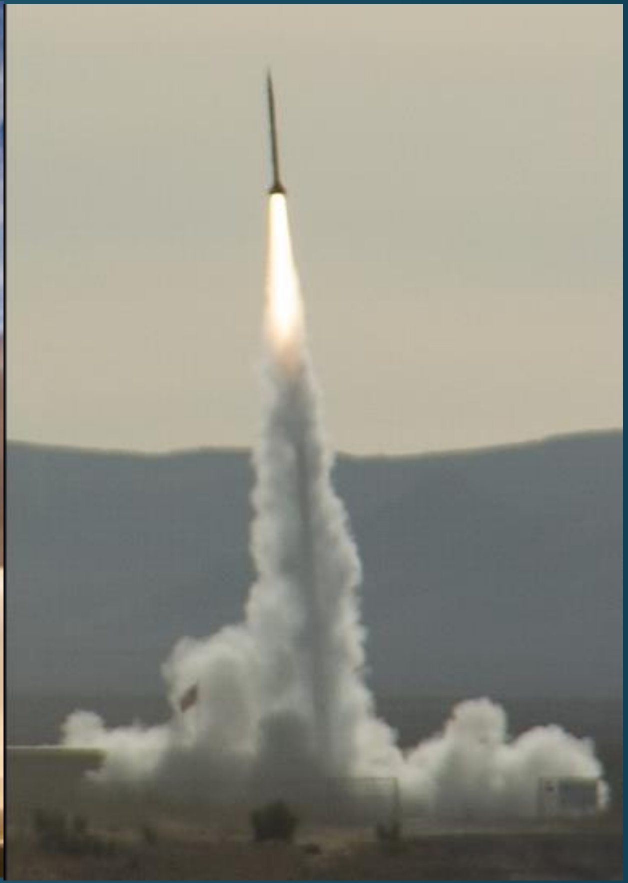
- Independent, self-contained subsystem onboard launch vehicle that automatically makes flight termination / destruct decisions
- Box on the vehicle (AFTU)
  - Tracking from GPS and INS sensors
  - Rule set built in pre-flight period; rule violation terminates flight
- Radar and command stations recede into the past
- Telemetry down-link drops from safety critical to situational awareness, post-flight, and mishap investigation

Development

- NASA wrote original AFTS Core Autonomous Safety Software (CASS), USAF rewrote to make it safety critical and distributes to users via SUA within ITAR
- NASA KSC wrote example AFTS wrapper software, released as Class E software within ITAR, will release as Class B after IV&V
- NASA KSC released hardware design reference via commercialization office to Range Users within ITAR

Kennedy Space Center AFTS Flight Tests

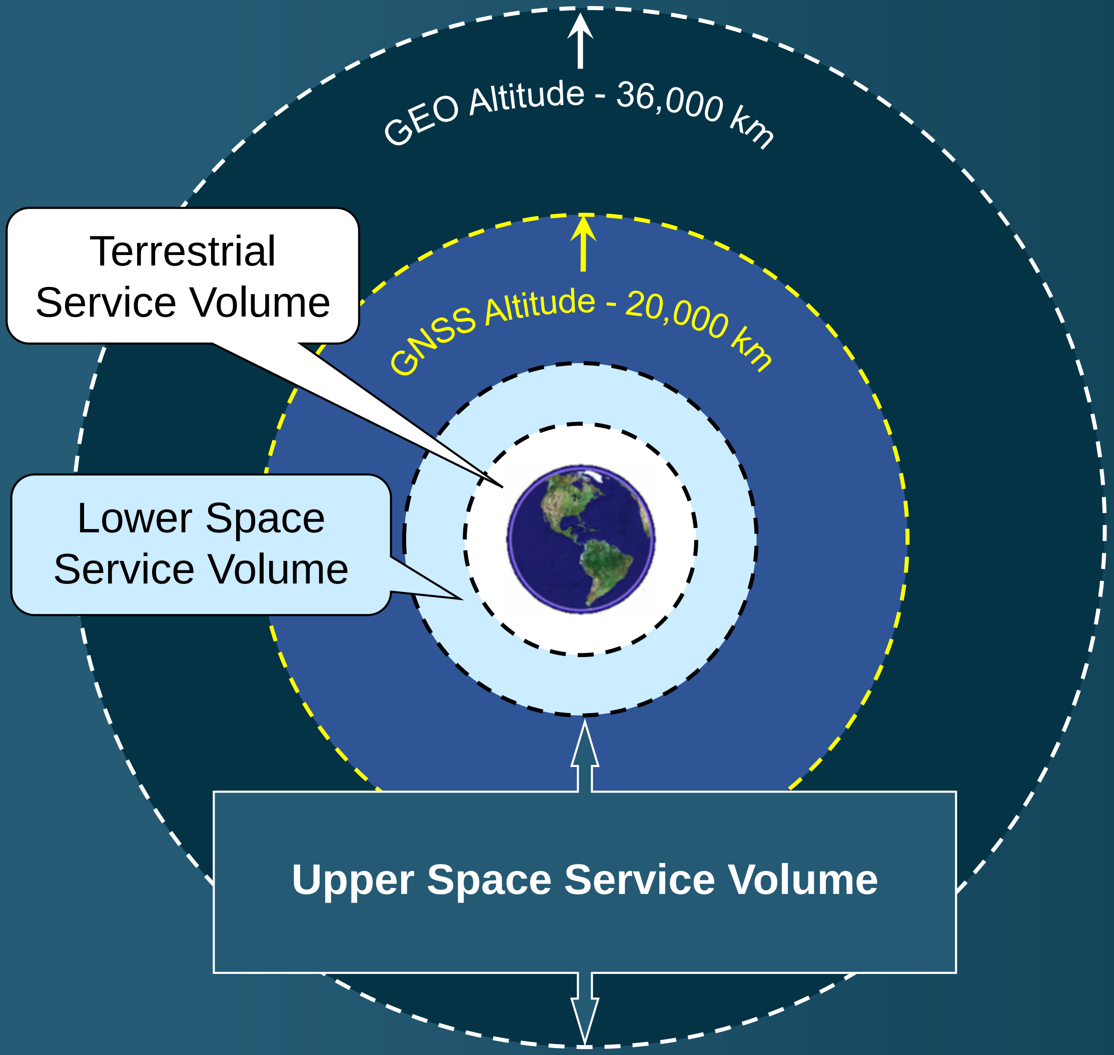
Rocket Lab Electron Launch



UP Aerospace Spaceloft Launch

- DARPA initiated partnership with NASA on a low cost, flight demo to flight test KSC's AFTS Reference Design Hardware
  - demonstrated AFTS system (with validated CASS SW)
  - doesn’t require traditional 30th or 45th Range support for vehicle tracking and command destruct
- DARPA funded, NASA AFTS payload launched on Rocket Lab’s Electron Launch Vehicle from New Zealand in May 2017
- Three certification Rocket Lab flights been completed
- NASA AFRC purchased 6 units
- First launch using the DARPA/NASA AFTU for primary operations is scheduled for Nov 25
- Several launch vehicles have baselined NASA AFTS units into their vehicles for future operational use

GNSS Service Volumes



Terrestrial Service Volume (surface to 3,000 km altitude)

- GNSS utilization similar to Earth surface use
- Accounts for vast majority of space users

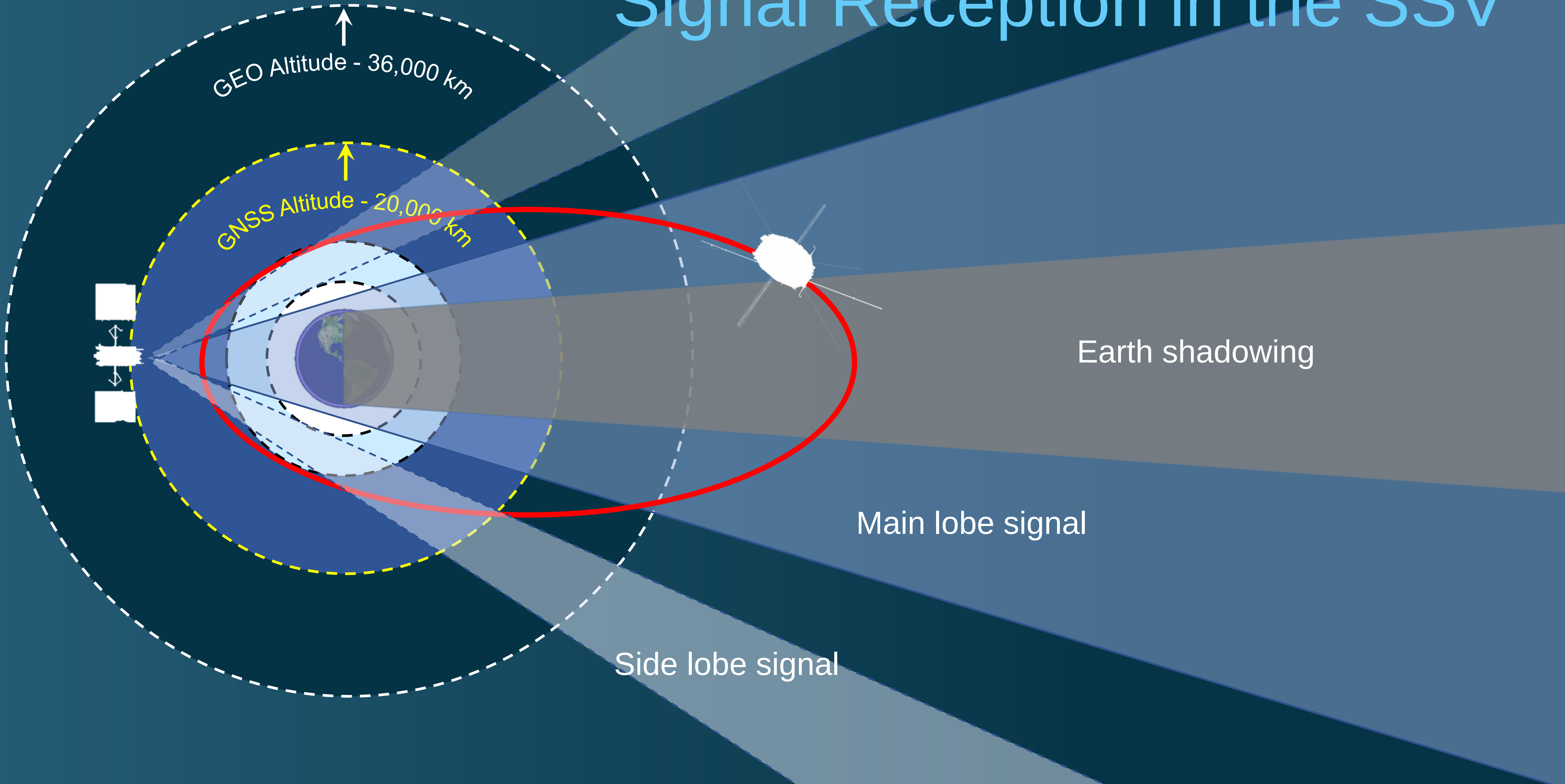
Lower Space Service Volume (3,000 km to 8,000 km)

- Navigation performance impaired by poor geometry, Earth occultation, and weak signal strength

Upper Space Service Volume (8,000 km to 36,000 km)

- Overlaps and extends beyond the GNSS constellations
- Navigation beyond constellations dependent on reception of signals from the opposite side of Earth

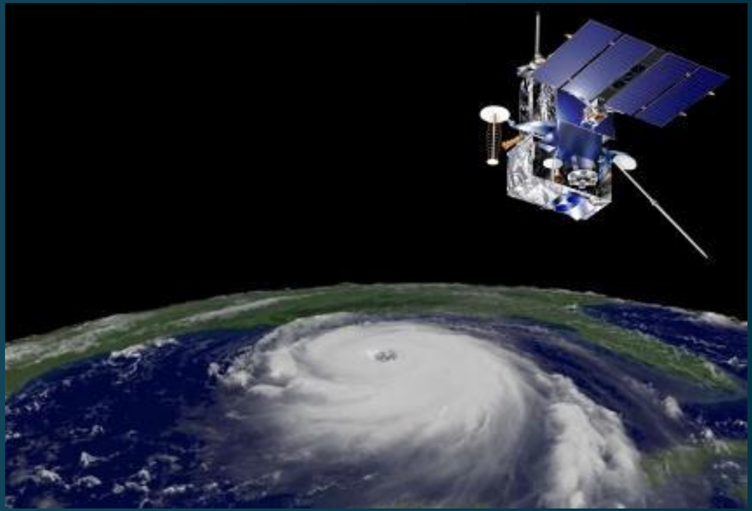
Signal Reception in the SSV



U.S. Missions using GNSS in the SSV & Beyond

GOES-R Weather Satellite Series:

- Next-generation U.S. operational GEO weather satellite series
- First series to use GPS for primary navigation
- GPS provides rapid maneuver recovery, enabling continual observation with <2 hour outage per year
- Introduction of GPS and new imaging instrument are **delivering data products to substantially improve public and property safety**



GOES-16 GPS Visibility [5]:

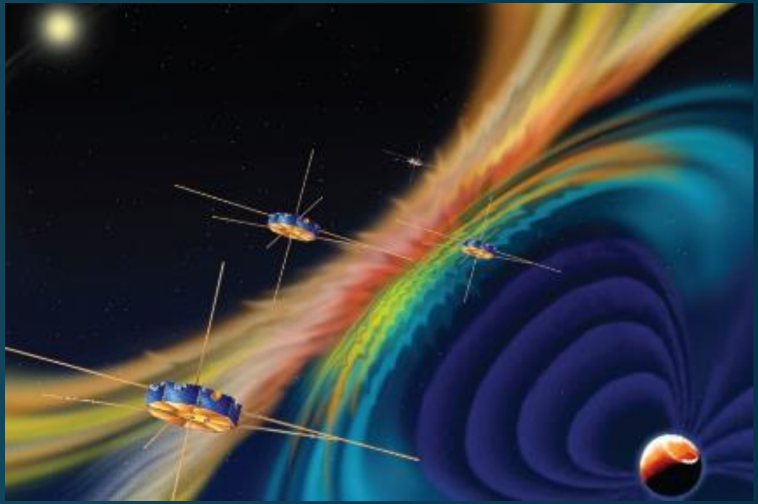
- Minimum SVs visible: 7
- DOP: 5–15

Nav Performance (3σ):

- Radial: **14.1 m**
- In-track: **7.4 m**
- Cross-track: **5.1 m**
- Compare to requirement: (100, 75, 75) m

Magnetospheric Multi-Scale (MMS) Mission:

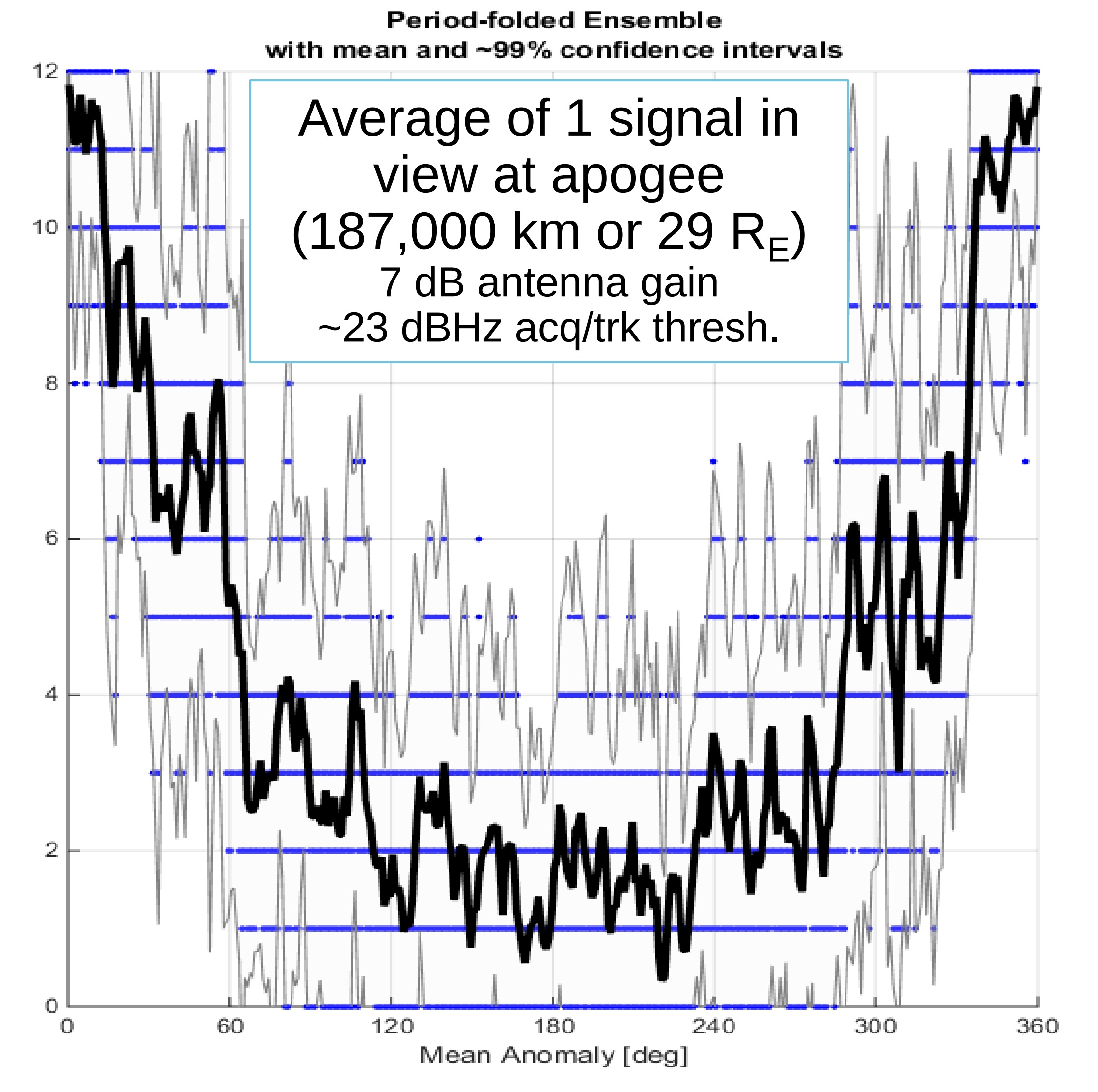
- Four spacecraft form a tetrahedron near apogee for magnetospheric science measurements (space weather)
- Highest-ever use of GPS
  - Phase 1: 12 Earth Radii (RE) apogee (76,000 km)
  - Phase 2B: 25 RE apogee (~150,000 km) **(40% lunar distance)**
  - Apogee raising beyond 29 RE **(50% lunar distance)** completed in February 2019
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping



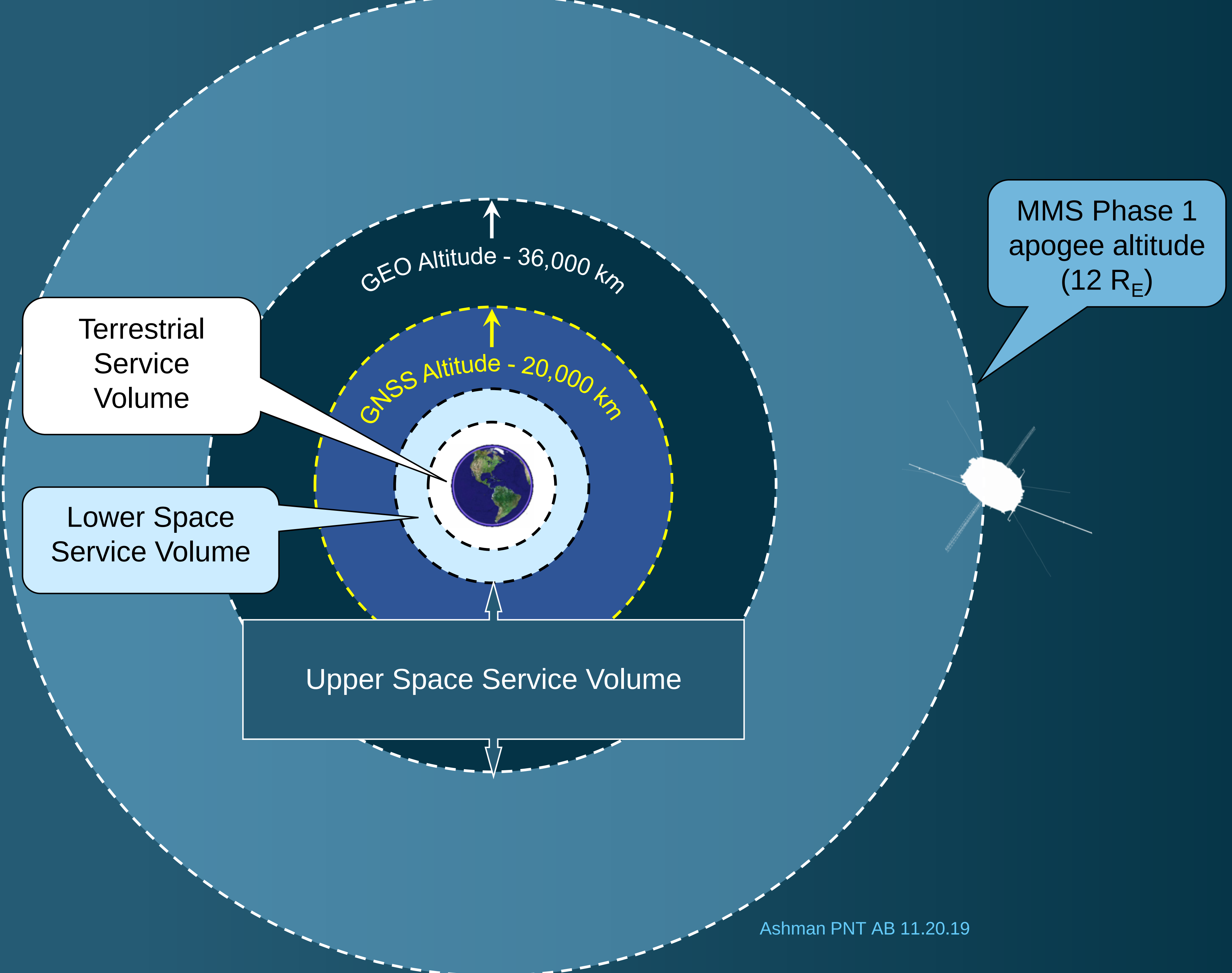
MMS Nav Performance (1σ) [7]

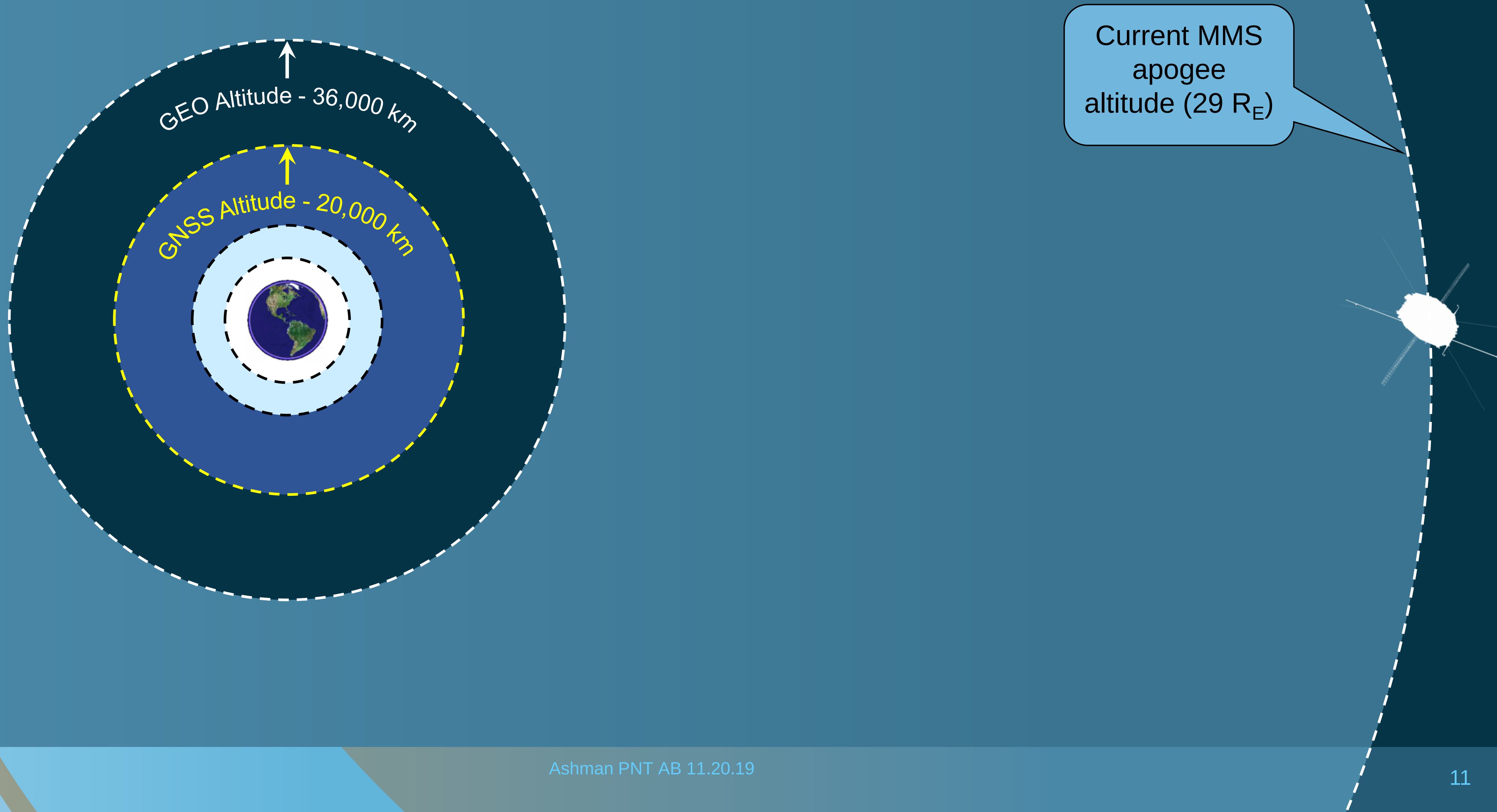
Description	Phase 1	Phase 2B
Semi-major axis est. under 3 R_E	2 m	**5 m**
Orbit position estimation	12 m	**55 m**

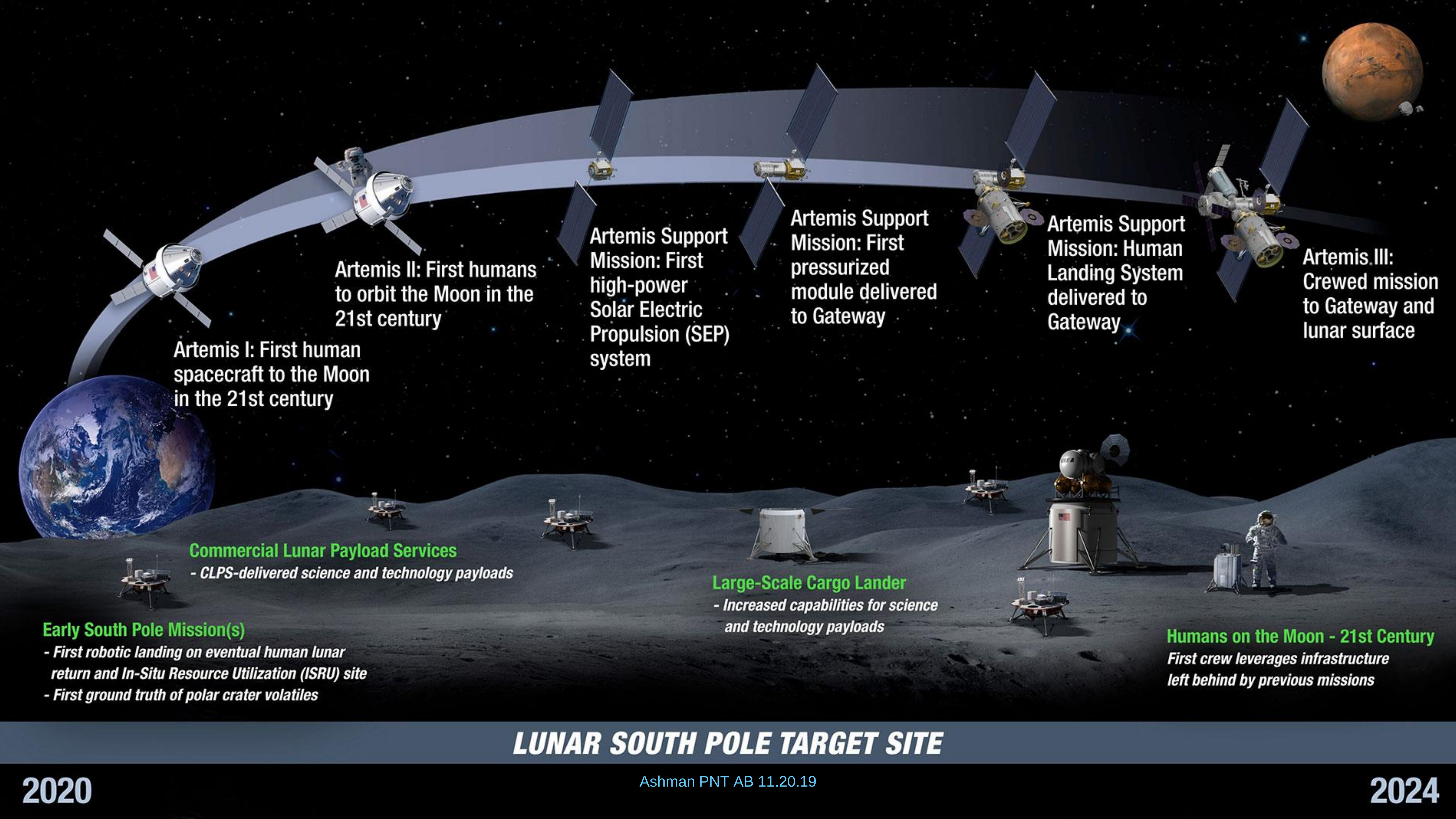
Recent MMS Navigation Performance



- 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


GEO Altitude - 36,000 km
GNSS Altitude - 20,000 km
Terrestrial Service Volume
Lower Space Service Volume
Upper Space Service Volume
MMS Phase 1 apogee altitude ($12\ R_E$)

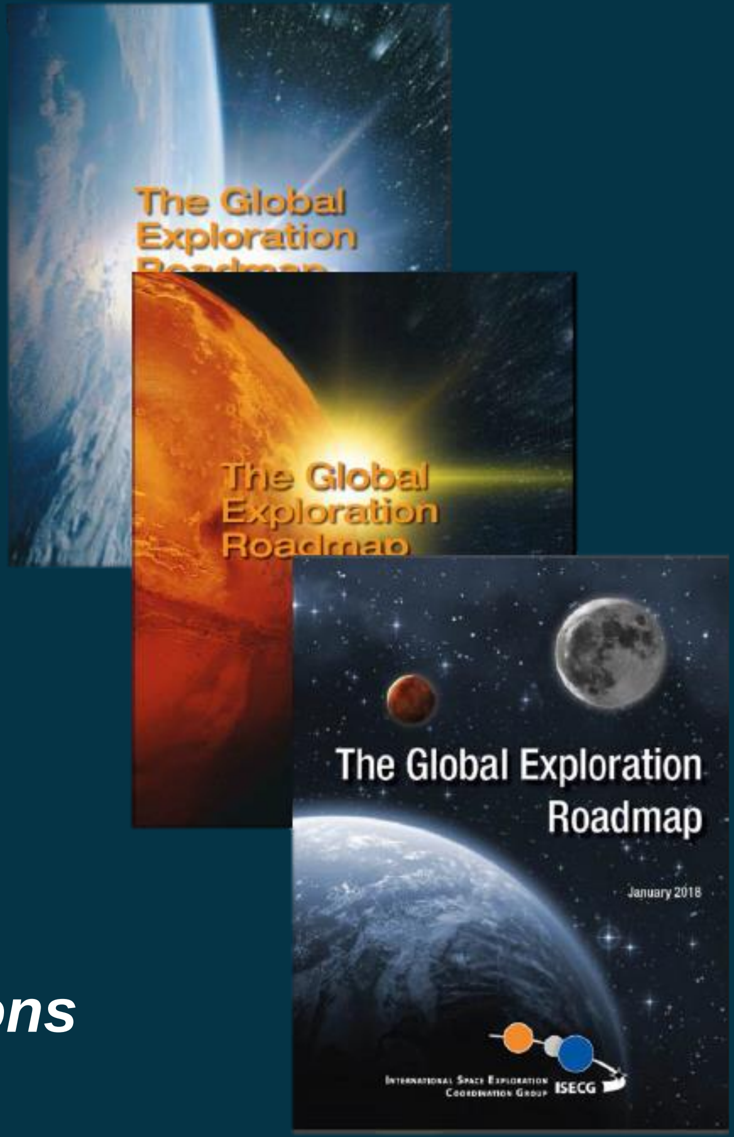

GEO Altitude - 36,000 km
GNSS Altitude - 20,000 km
Current MMS apogee altitude (29 R_E)



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

Global Interest in Lunar Exploration

The 14 space agencies of the International Space Exploration Coordination Group (ISECG) state a desire to return to the Moon in the next decade in the 2018 Global Exploration Roadmap (GER)



GER lists more than 20 upcoming lunar missions

The Role of GNSS

Critical technology gaps identified by the GER:

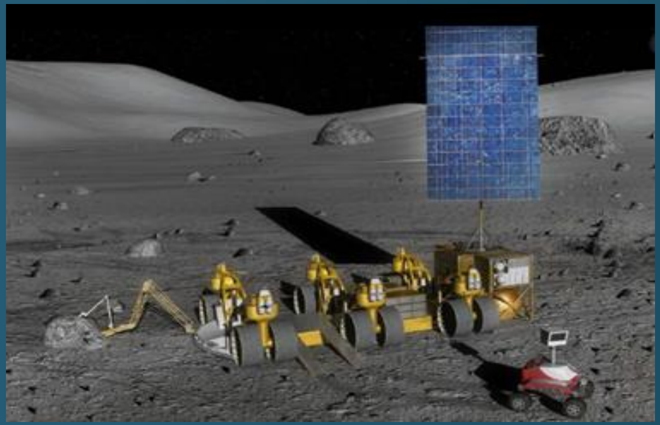
- AR&D Proximity Operations, Target Relative Navigation
- Beyond-LEO crew autonomy

GNSS on lunar missions would:

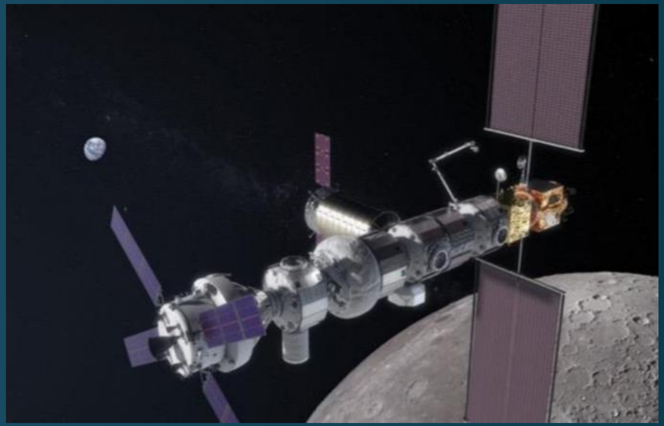
- enable autonomous navigation
- reduce tracking and operations costs
- provide a backup/redundant navigation for human safety
- provide timing source for hosted payloads
- reduce risk for commercial development

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

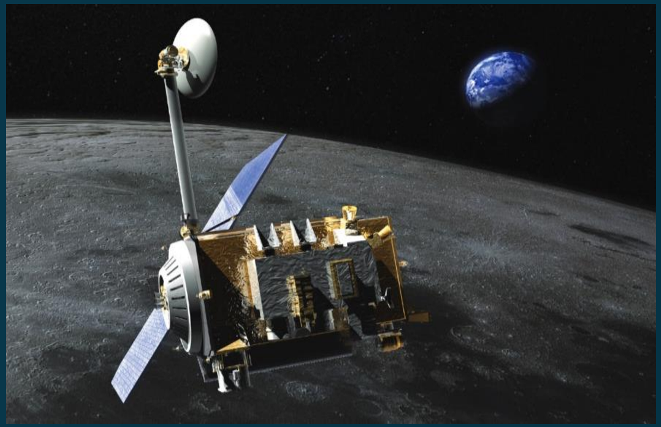
Lunar Exploration: Roles for GNSS



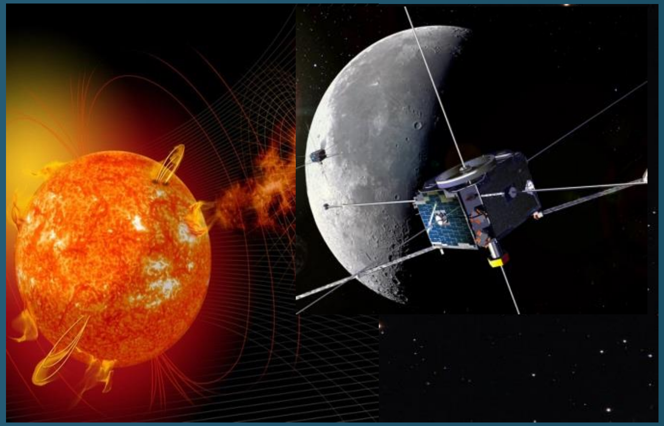
Lunar Surface Operations, Robotic Prospecting,& Human Exploration



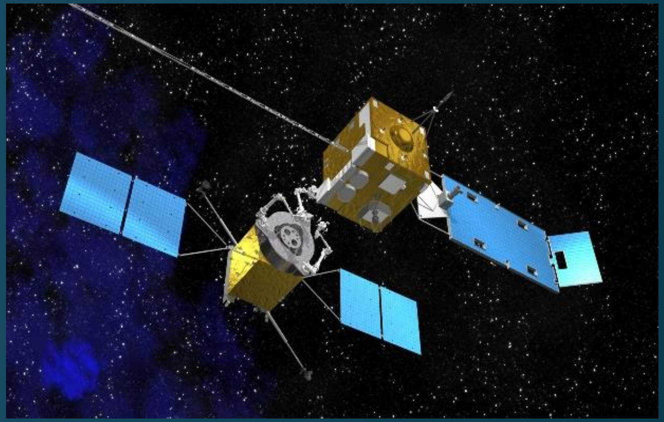
Human-tended Lunar Vicinity Vehicles (Gateway)



Robotic Lunar Orbiters, Resource & Science Sentinels



Earth, Astrophysics, & Solar Science Observations



Satellite Servicing

Lunar Exploration Infrastructure

Projected GNSS Performance at the Moon

"GPS Based Autonomous Navigation Study for the Lunar Gateway"

Winternitz et al. 2019 [8]

- 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

- Ground baseline: fewer tracks, larger gaps than GPS
- Average of 3 GPS signals tracked in NRHO
- 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
- **GPS can provide a simple, high-performance, on-board 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**

*Rubidium Atomic Frequency Standard

Projected GNSS Performance at the Moon

"Lunar Navigation Beacon Network Using GNSS Receivers"

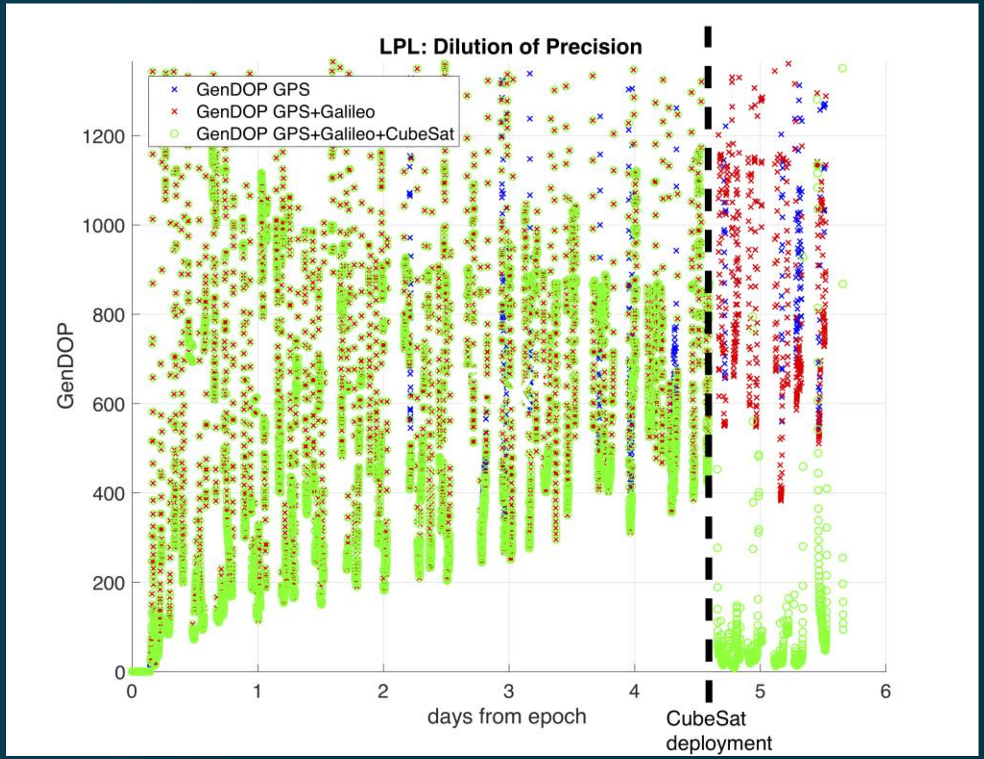
Anzalone et al. 2019 [9]

- 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 [10]

- Considered same scenario as Anzalone et al. 2019 but focused on signal availability and geometry and included other GNSS
- ~1 GPS signal available in lunar orbit, ~1 Galileo



Generalized Dilution of Precision for GPS only, GPS+Galileo, and GPS+Galileo+CubeSat [10]

Enabling the SSV

GPS Antenna Characterization Experiment [11]

- First complete mapping of GPS L1 side lobes for all GPS satellites via GEO-based bent pipe
- Data set available at https://esc.gsfc.nasa.gov/navigation

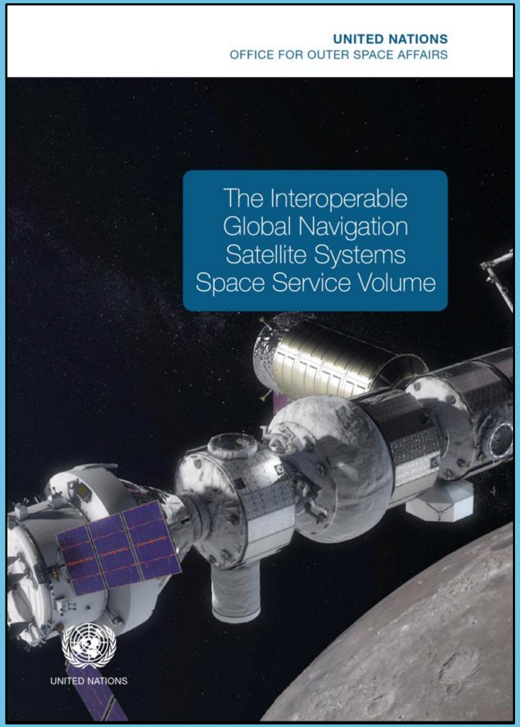
United Nations International Committee on GNSS

- SSV booklet (first edition published November 2018)
  - First publication of SSV performance characteristics for each GNSS constellation
  - Conservative performance for main lobe signals only
- Working Group B subgroup on space users established in 2018 at ICG-13
  - U.S., China, and ESA are co-chairs; India, Russia, Japan members

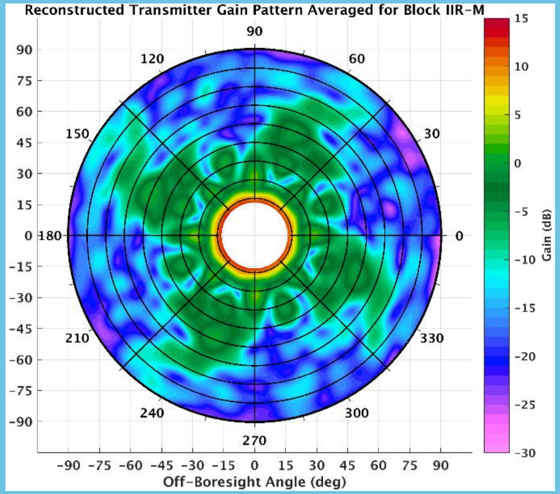
Galileo, QZSS have released extensive calibrated satellite data

- Per-satellite phase center offsets & variations (PCO/PCV), group delay, etc.
- Responds to recommendation by ICG; offers tremendous science benefit

NASA recommends public release of civil GPS antenna patterns per recommendation by the ICG



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



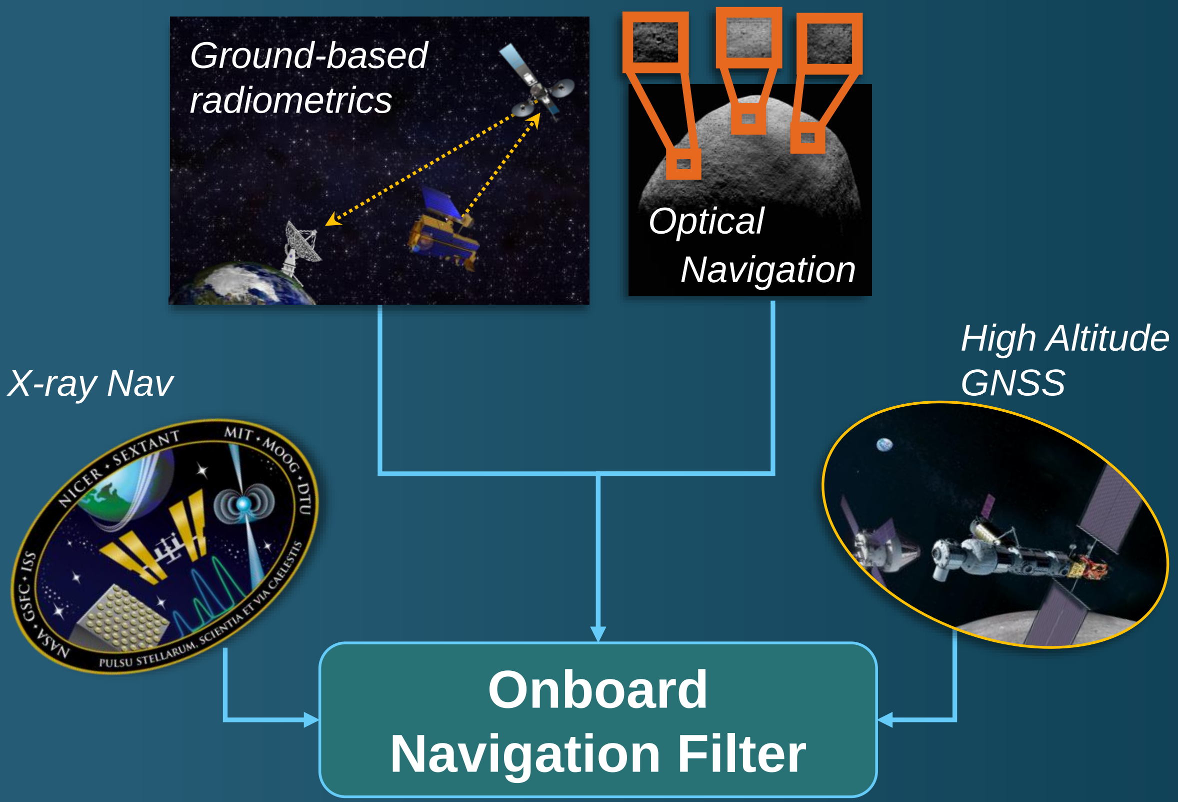
Block IIR-M reconstructed pattern from GPS ACE [11]

Enabling the SSV (continued)

NASA-USAF Collaboration on GPS SSV

- 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 of GPS III (SV1-10) antenna data

Diversifying: Robust High-Altitude PNT



Robust high-altitude PNT relies on a diversity of navigation sources, each with strengths and weaknesses:

- GPS+GNSS
- Augmentations
- Ground-based tracking
- Optical navigation
- X-ray pulsar navigation
- Other sources (signals of opportunity, etc.)

Conclusions

GNSS can be an important part of lunar exploration

- Robust high-altitude PNT relies on a diversity of navigation sources (e.g., GNSS, ground-based tracking, optical navigation, x-ray pulsar navigation)
- Increased understanding of signal performance at high altitudes has informed GNSS studies that suggest GNSS-based navigation at the Moon can offer advantages over conventional ground-based navigation in conops and performance

The GNSS community must act to seize this opportunity

- **Operationalizing** high-altitude GNSS in known regimes
- **Enabling** future development through international collaborations, data availability, and provider support
- **Extending** the boundaries of GNSS usage in space to lunar vicinity
- **Diversifying** to enable robust space-based PNT

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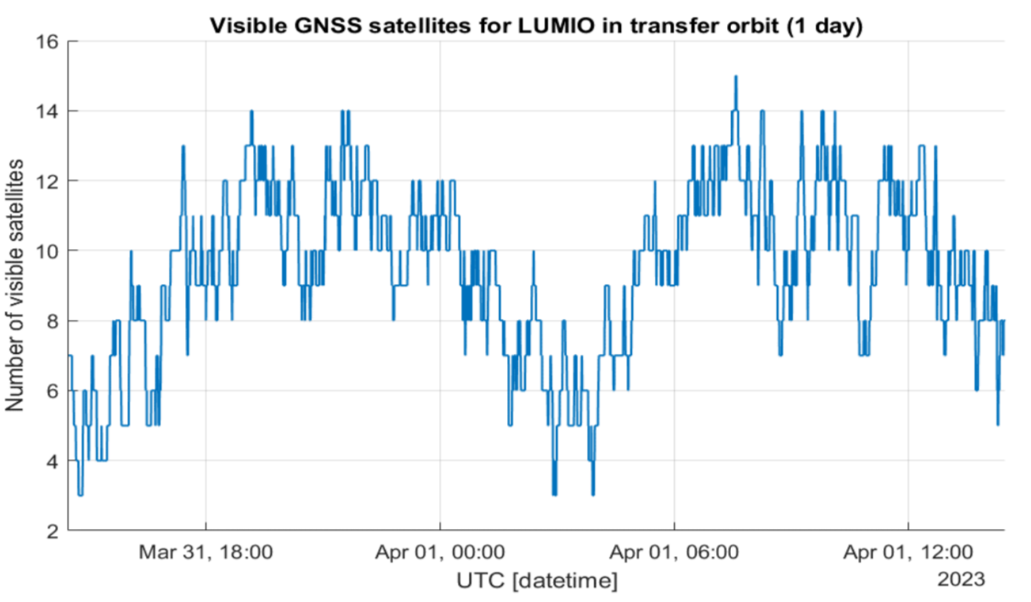
Projected GNSS Performance at the Moon

Presentation at 7th Int'l Colloquium on Scientific & Fundamental Aspects of GNSS

Delepaut et al. 2019 [11]

- Considered GPS + Galileo, receiver with 15 dBHz tracking and acquisition threshold, 14 dBi receiver antenna gain
  - Main lobes only
- Trajectory: LUMIO CubeSat mission transfer from LLO to EM L2 Halo Orbit



Visible GNSS satellites for LUMIO over transfer from LLO to NRHO [11]

"GNSS for Lunar Surface Positioning Based on Pseudo-satellites"

Sun et al. 2019 [12]

- Considers DOP for a user at 0° lat and lon on the lunar surface with GPS-only and with the addition of 1+ surface navigation beacons
- 1 beacon reduces PDOP from 1000 to 20