National Aeronautics and
Space Administration

The GNSS Frontier

Advancing Space Use of Global Navigation Satellite Systems

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30 October 2019
ISGNSS/IPNT
Jeju Island, Korea

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Advancing Space Use of Global Navigation Satellite Systems

Use of GNSS in Low Earth Orbit is now common and higher altitude applications are rapidly emerging. We stand at a moment of great potential, as several trends converge:

- Improvement and expansion of GNSS constellations
- Advancements in receiver technology
- Increased global interest in space exploration

This talk surveys the current state of GNSS, discusses the most ambitious space applications, and charts a way forward to the new frontier of GNSS-based navigation.

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GNSS Providers

NASA's Role in US PNT Policy

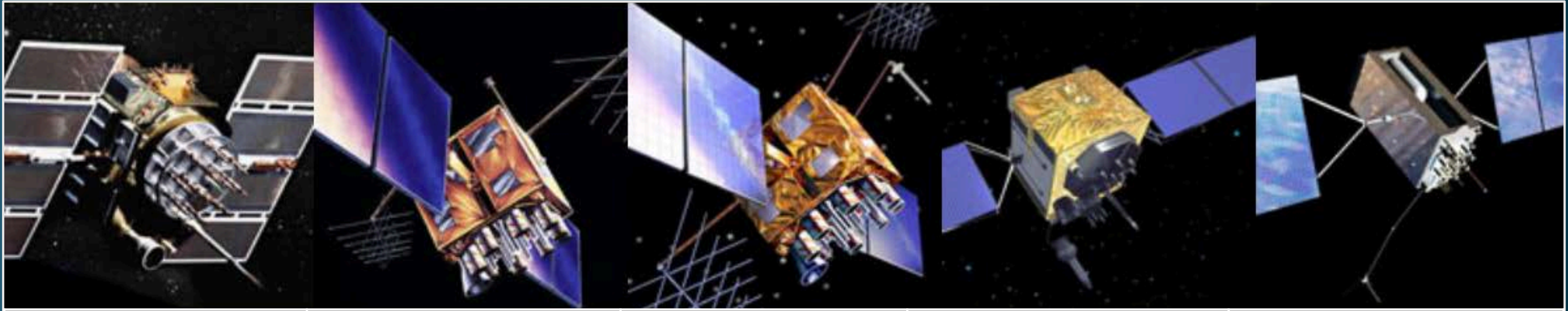
- White House
  - National Space Council
    - Users' Advisory Group
      Sponsor: NASA
  - **National Executive Committee**
    for Space-based PNT
    Executive Steering Group
    Co-chairs: Defense, Transportation
    - Stakeholder Agencies (e.g., Defense, Transportation, State, NASA)
    - PNT Advisory Board
      Sponsor: NASA
    - **National Coordination Office**
      Host: Commerce
      - Civil GPS Service Interface Committee
      - GPS International Working Group
      - Engineering Forum
      - Ad Hoc Working Groups

GNSS Constellations: Status

From “Global Navigation Satellite Systems: What’s Up?” by Dr. Oliver Montenbruck [1]

System	Blocks	Signals	Sats (May 2019)
GPS	IIA, IIR IIR-M IIF III	L1 C/A, L1/L2 P(Y) +L2C +L5 +L1C	1, 11 7 12 (1)*
GLONASS	M M+ K1	L1/L2 C/A+P L1/L2 C/A+P, L3 (CDMA) L1/L2 C/A+P, L3 (CDMA)	21+(1) 2 1+(1)
BeiDou	BDS-2 MEO, IGSO, GEO BDS-3S MEO, IGSO BDS-3 MEO, IGSO, GEO	B1-2, B2b, B3 B1, B1-2, B2a/b/ab, B3 B1, B1-2, B2a/b/ab, B3	3, 7, 5 (2), (2) 18, (1), (1)
Galileo	IOV FOC	E1, E6, E5a/b/ab E1, E6, E5a/b/ab	3+(1) 19+(3)
QZSS	Block I Block II IGSO, GEO	L1 C/A, L1C, L2C, L5, SAIF, E6 LEX L1 C/A, L1C, L2C, L5, L1S, E6, L5S	1 2, 1
NavIC	IGSO, GEO	L5, S	4+(1), 3

*parenthesis indicate non-operational



Block IIA	Block IIR	Block IIR-M	Block IIF	GPS III/IIF
1 Operational	11 Operational	7 Operational	12 Operational	1 in Checkout
• Coarse Acquistion (C/A) code on L1 frequency for civil users • Precise P(Y) code on L1/L2 frequencies for military users • 7.5-year design lifespan • Launched in 1990 -1997	• C/A code on L1 • P(Y) code on L1 & L2 • On-board clock monitoring • 7.5-year design lifespan • Launched in 1997-2004	• All legacy signals • 2nd civil signal on L2 (L2C) • New military M code signals for enhanced jam resistance • Flexible power levels for military signals • 7.5-year design lifespan • Launched in 2005-2009	• All Block 11R-M signals • 3rd civil signal on L5 frequency (L5) • Advanced atomic clocks • Improved accuracy, signal strength, and quality • 12-year design lifespan • Launched in 2010-2016	• All Block 11F signals • 4th civil signal on L1 (L1C) • Enhanced signal reliability, accuracy and integrity • No selective availability • 12-year design lifespan • 111F: laser reflectors; search and rescue payload • First launch in 2018

GPS Status

- New civilian signals
- Flex power
- GPS III

GPS Status

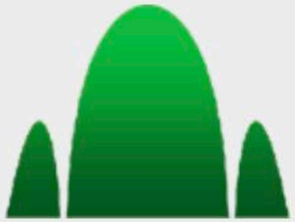
- New civilian signals: L2C, L5, L1C
  - 3 frequencies
  - Modern signal design, CNAV
  - Designated channels for codeless tracking
- Flex power
  - Transmit power variation for jamming resistance
  - Available on IIR-M and IIF satellites

L2C Features

1227.60 MHz

- Radio Navigation Satellite Services (RNSS) radio band
- Modern signal design (CNAV), including multiple message types and forward error correction
- Bi-Phase Shift Key (BPSK) modulation
- Includes dedicated channel for codeless tracking

L5 Features



1176.45 MHz

- Highly protected Aeronautical Radio Navigation Services (ARNS) radio band
- Higher transmitted power than L1 C/A or L2C
- Greater bandwidth for improved jam resistance
- Modern signal design (CNAV), including multiple message types and forward error correction
- Bi-Phase Shift Key (BPSK) modulation
- Includes dedicated channel for codeless tracking

L1C Features

1575.42 MHz

- Aeronautical Radio Navigation Services (ARNS) radio band
- Designed for international GNSS interoperability
- Modern signal design (CNAV-2), including forward error correction
- Multiplexed Binary Offset Carrier (MBOC) modulation

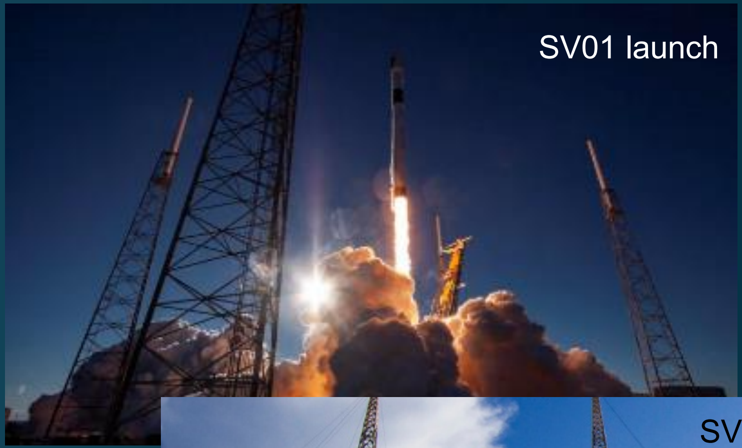
GPS Status: GPS III

GPS III (SV01-10)

- New Lockheed Martin spacecraft, digital signal generation
- Includes L1C civil signal
- SV01 launched 23 Dec. 2018 (PRN4, currently set unhealthy during checkout)
- SV02 launched 22 Aug. 2019

GPS IIIF (SV11-32)

- Follow-on Block III production
- Contract awarded to Lockheed Martin Sept. 2018
- Will include Laser Retro-reflector Arrays (LRA) and Search and Rescue payloads


SV01 launch


SV02 launch


SV11-32

A Global System:

GLONASS Status:

- 27 sats, 24 operational (2 in maintenance, 1 spare, 1 testing)
- Fleet predominantly block M, block K1 upcoming (2 launched)

BeiDou Status:

- BDS-3S: 5 experimental sats (2015-2016), inactive
- BDS-3: Global Constellation, 18 MEO sats (2017-2018), testing 1 IGSO and 1 GEO

Galileo Status:

- 22 operational sats, 5+ above 5° Elevation, 2 in eccentric orbits (set unhealthy)
- High accuracy (SISRE ~20 cm RMS, ~40 cm 95%)

Regional Systems

QZSS Status

- 4 operational sats
- Fully operational since November 2018

NavIC Status (previously IRNSS)

- 8 sats, 7 operational
- Launches 2013-2018
- Fully operational

2

Space Use of GNSS

Routine Use of GNSS in Space

Hundreds of satellites have likely used GNSS in space since the 1980s

Interagency Operations Advisory Group (IOAG) shows 102 current or upcoming civil missions utilizing GNSS

- 7 international space agencies

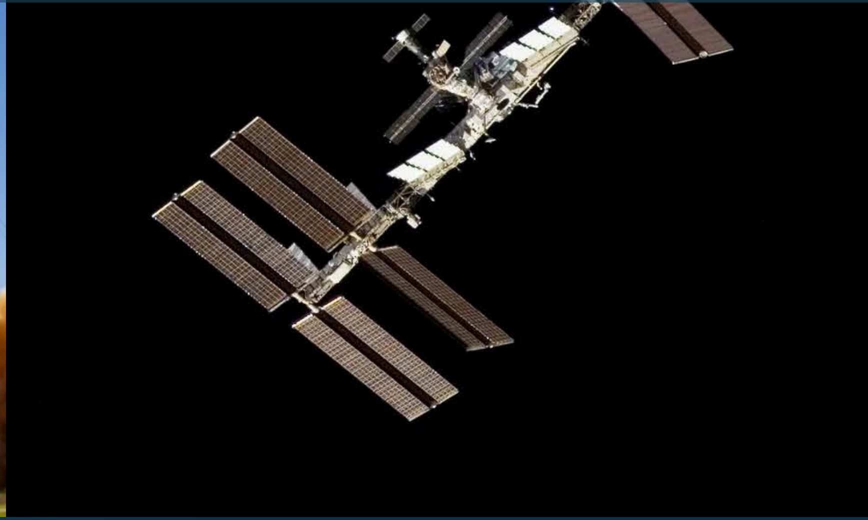
This data does not include:

- Commercial users
- Other government space agencies
- Military users

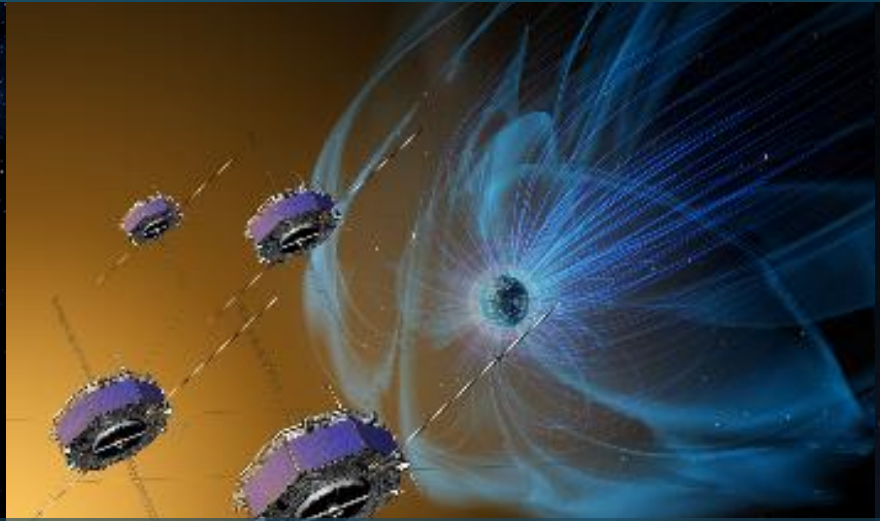
Earth Sciences

Launch Vehicle Range Ops

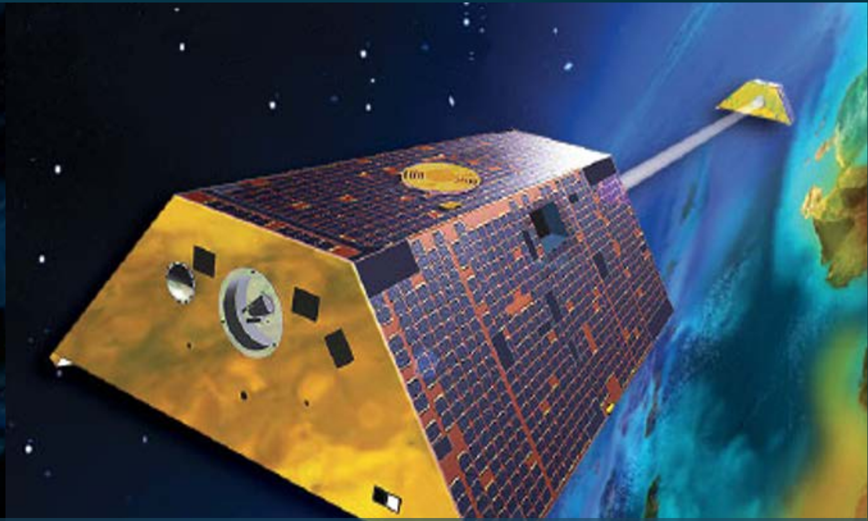
Attitude Determination



Active Space Use Cases

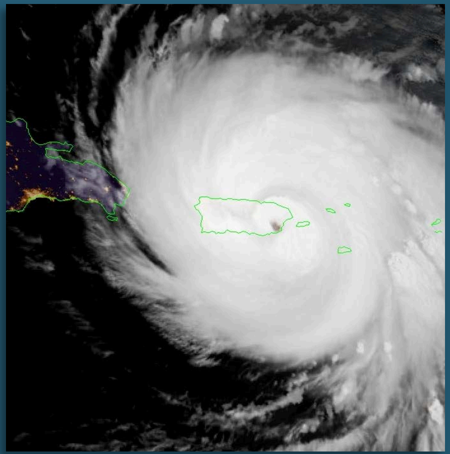
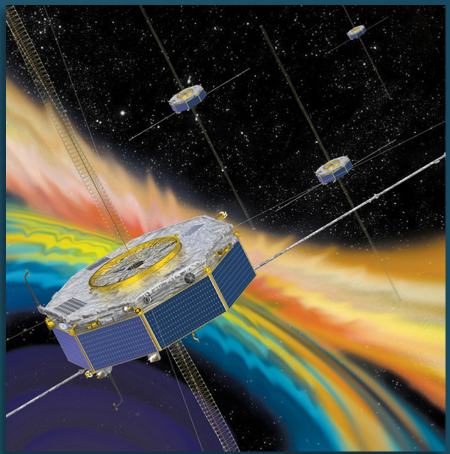
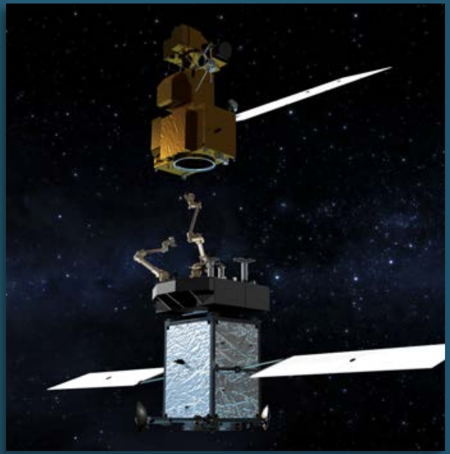
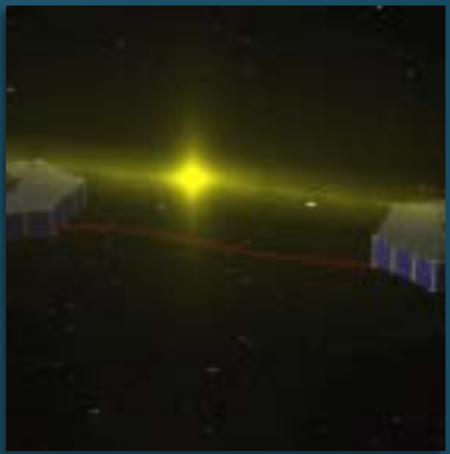


Real-Time On-Board Navigation



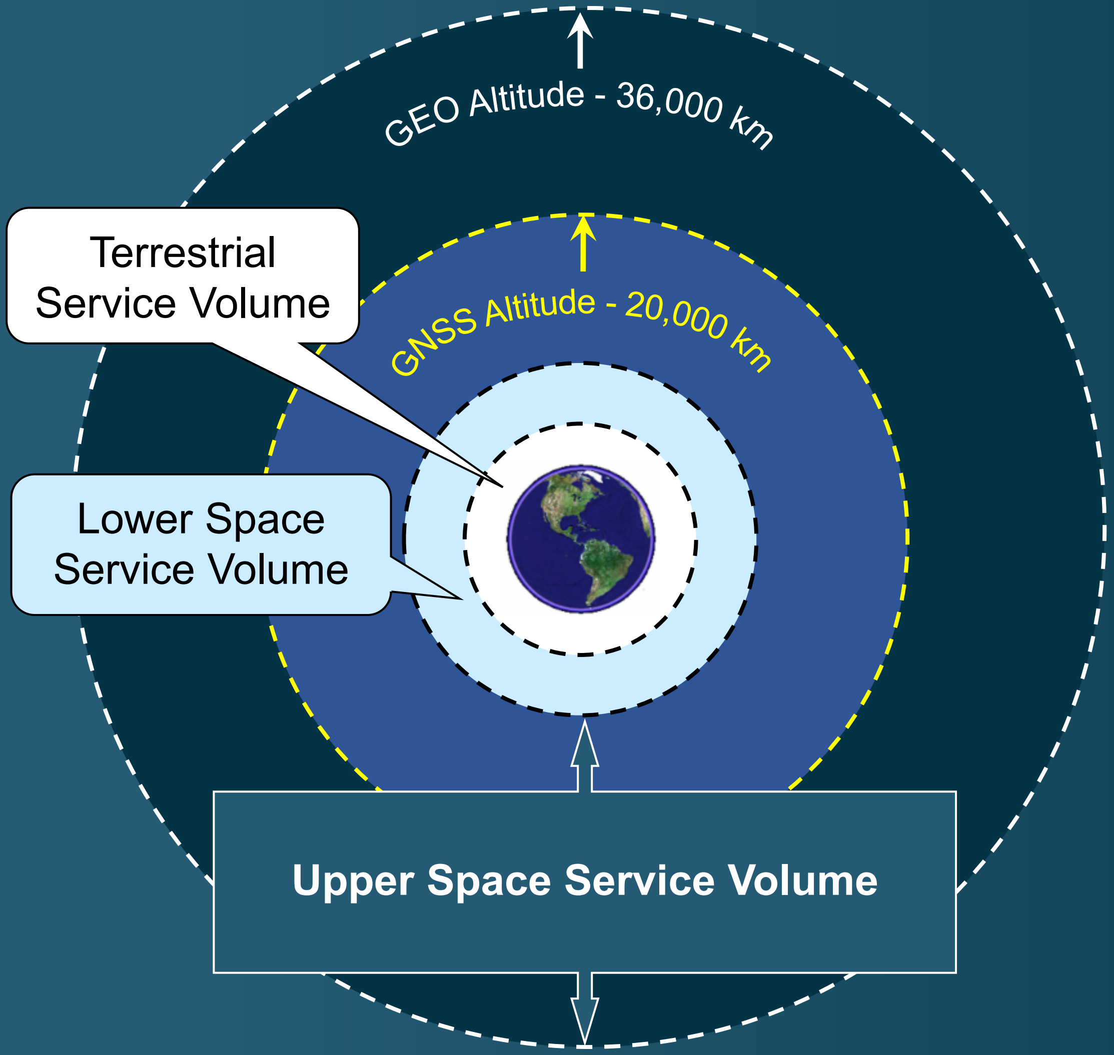
Time Synchronization

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

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

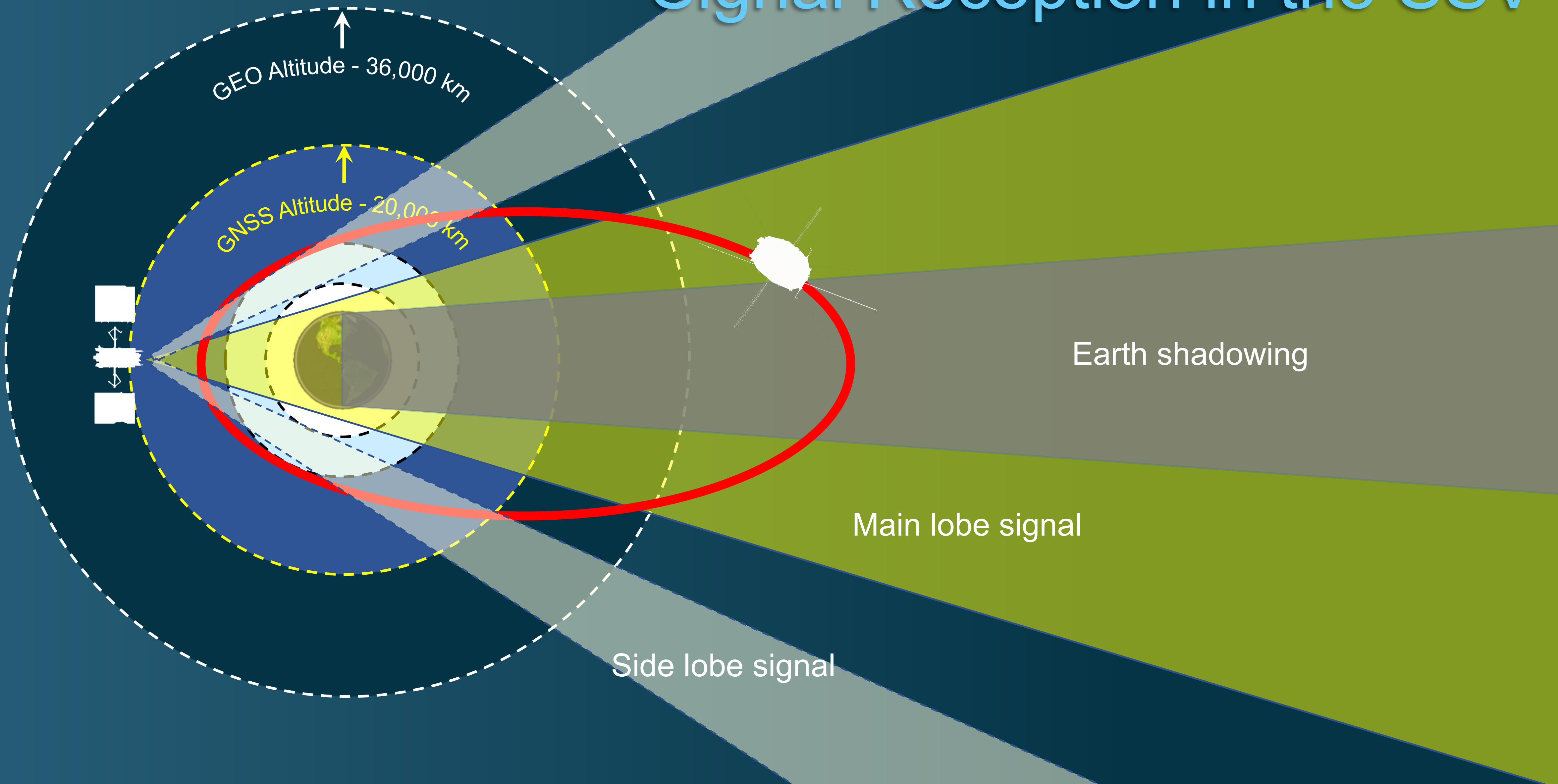
Lower Space Service Volume (3,000 km to 8,000 km)

- 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

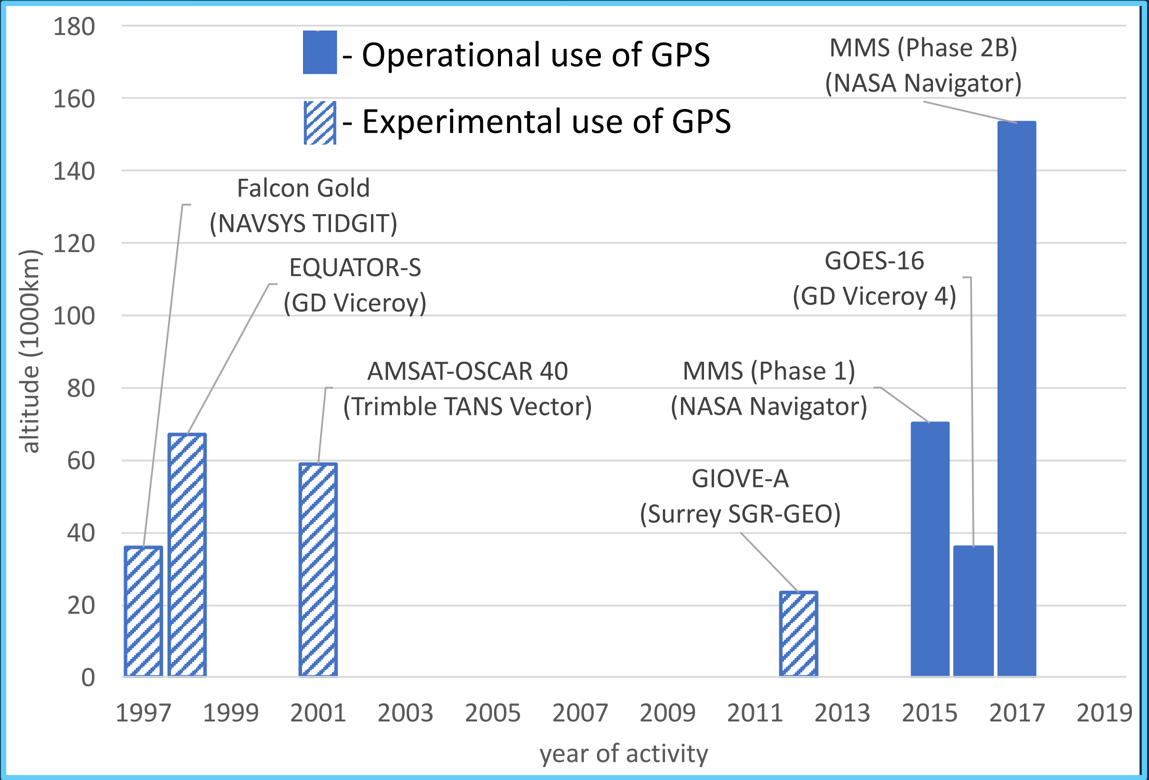


The Rise of High Altitude GNSS

	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

Transition from experimentation to operational use:

- **1990s**: Early flight experiments demonstrated basic feasibility-–Equator-S, Falcon Gold
- **2000**: Reliable GPS OD at GEO employing a bent pipe architecture and ground-based receiver (Kronman 2000 [4])
- **2001**: AMSAT OSCAR-40 mapped GPS main and sidelobe signals (Davis et al. 2001 [5])
- **2015**: MMS employed GPS operationally at 76,000 km (recently increased to 187,000 km)
- **2016–2017**: GOES-16/17 employed GPS operationally at GEO



Flight Example: GOES-R Series Weather Satellites

GOES-R, -S, -T, -U: 4^{th} generation NOAA operational weather satellites

GOES-R/GOES-16 Launch: 19 Nov 2016

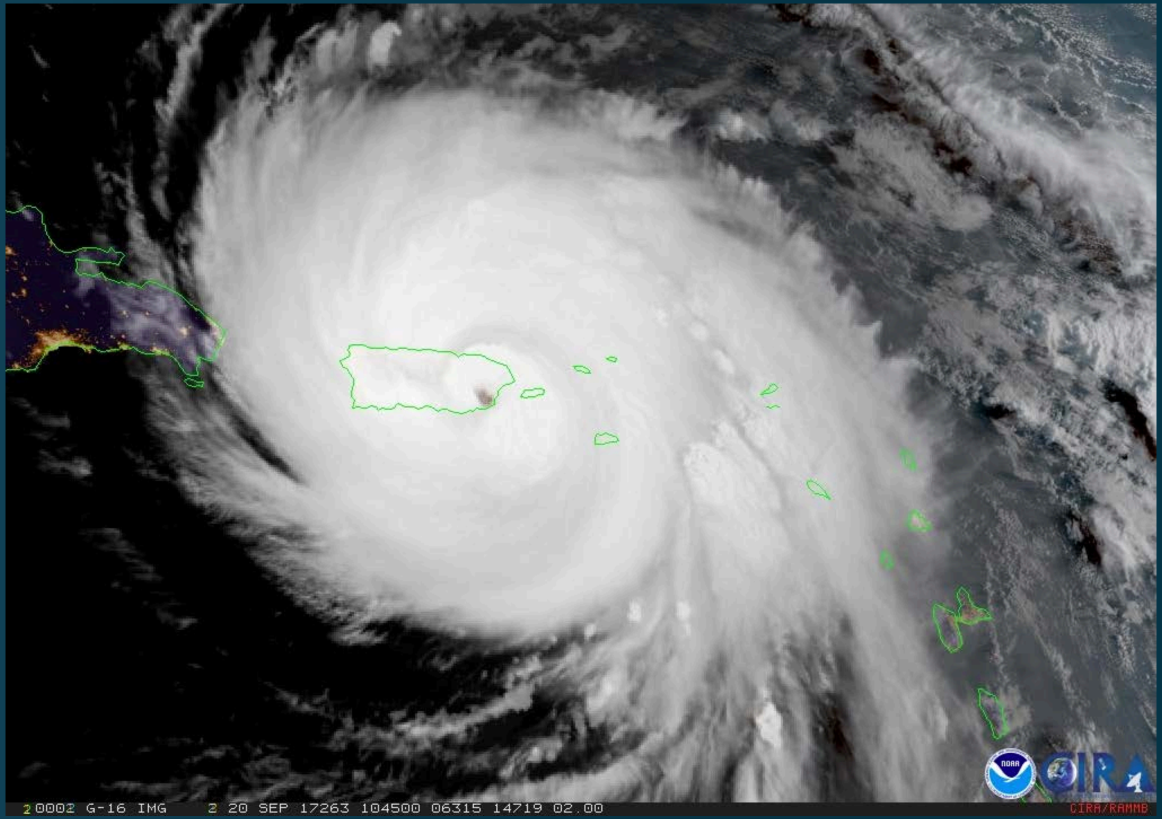
GOES-S/GOES-17 Launch: 1 Mar 2018

15-year lifespan, 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, <2 hr of outage per year
- Tighter navigation accuracy requirements and faster cadence needed to support highly increased operational tempo

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

Features unique signal reception characteristics

- General Dynamics Viceroy GPS receiver
- Custom receive antenna designed for above-the-constellation use: max gain at 20° off-nadir
- Tuned to process main lobe spillover and first side lobe

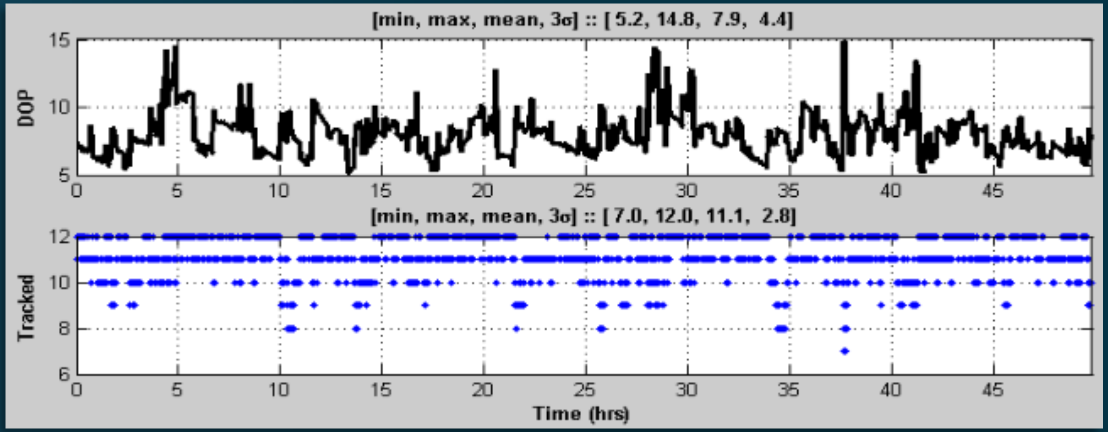
GOES-16 GPS Visibility:

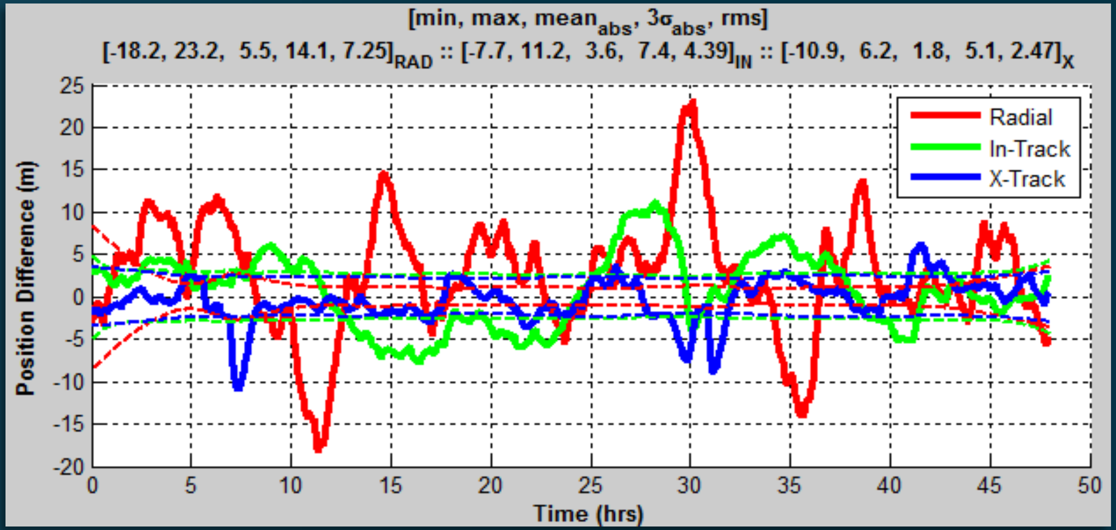
- Minimum SVs visible: 7
- DOP 5-10

GOES-16 Navigation Performance (3-sigma)

- Radial: 14.1 m
- In-track: 7.4 m
- Cross-track: 5.1 m

Compare to requirement: (100, 75, 75) m



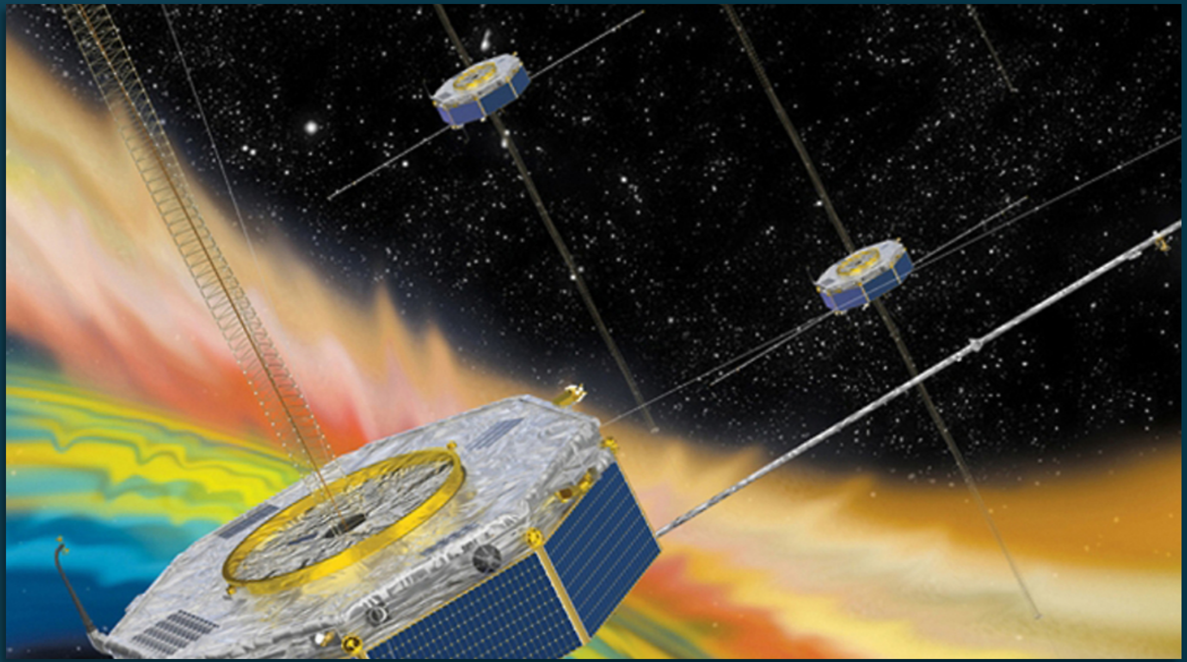


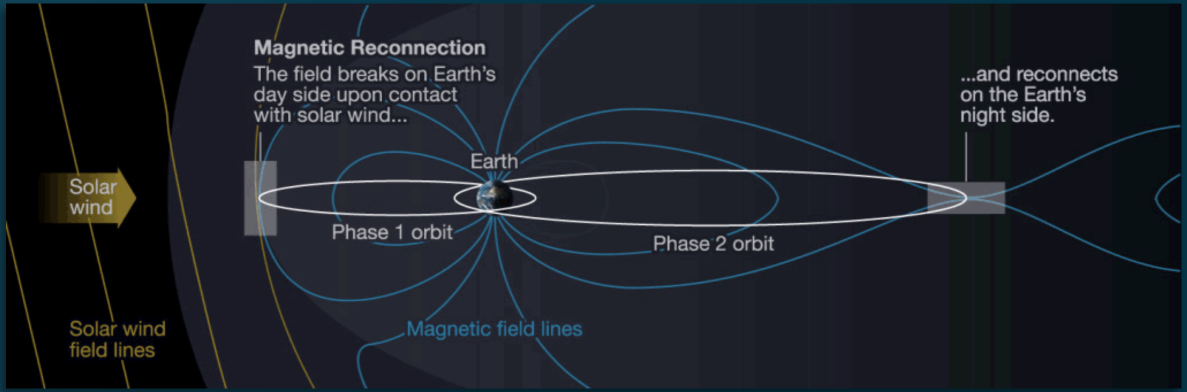
Initial GOES-16 performance Winkler et al. 2017 [5]

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 R_E apogee (~150,000 km)
  - 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

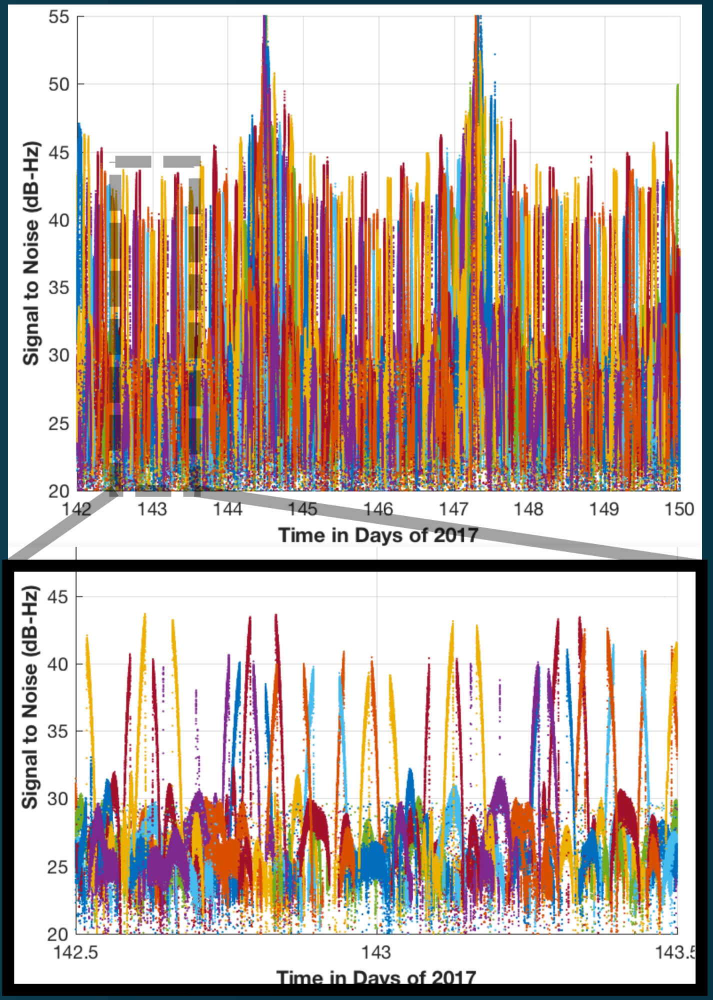
MMS Navigator System:

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

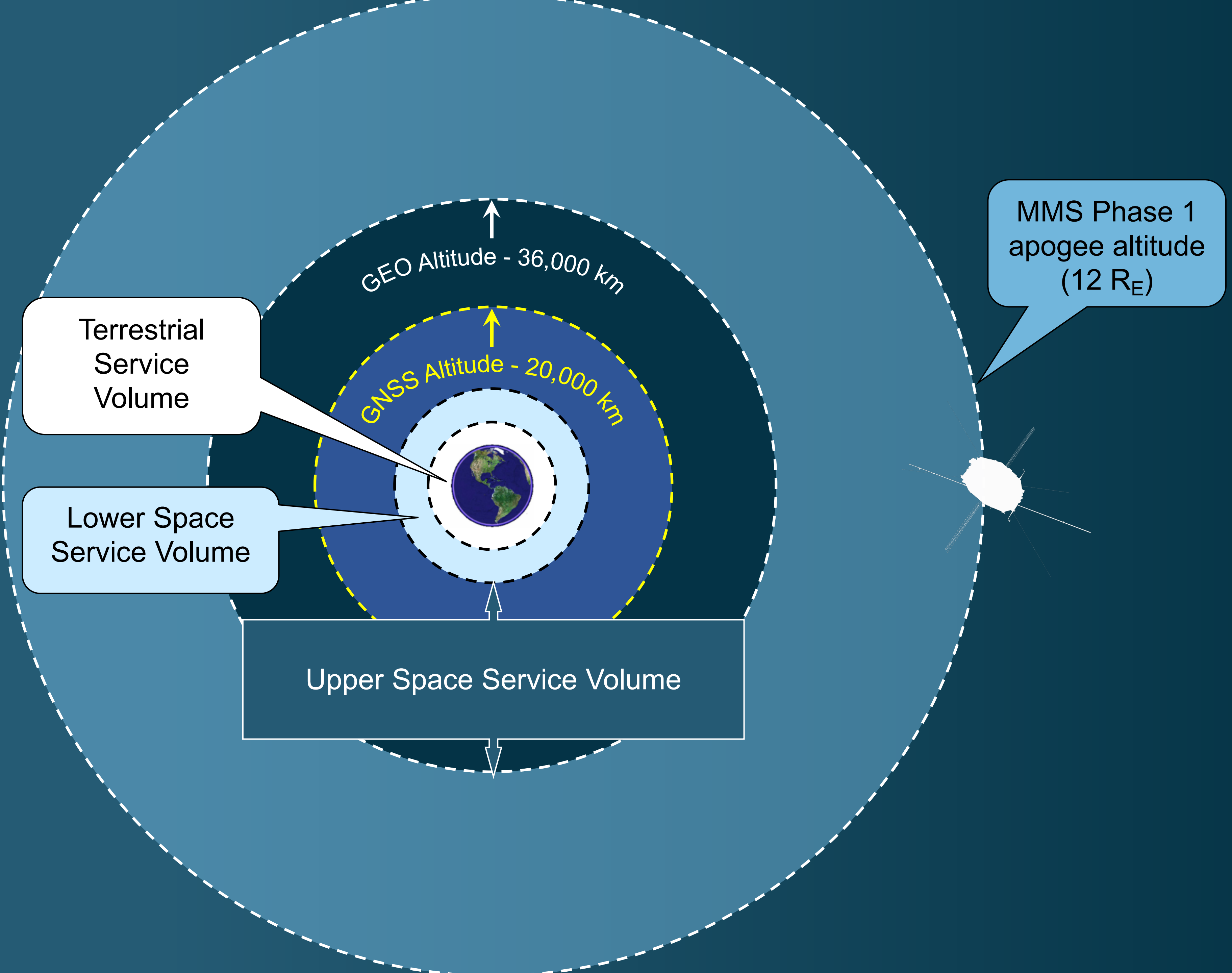
MMS GPS Visibility

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



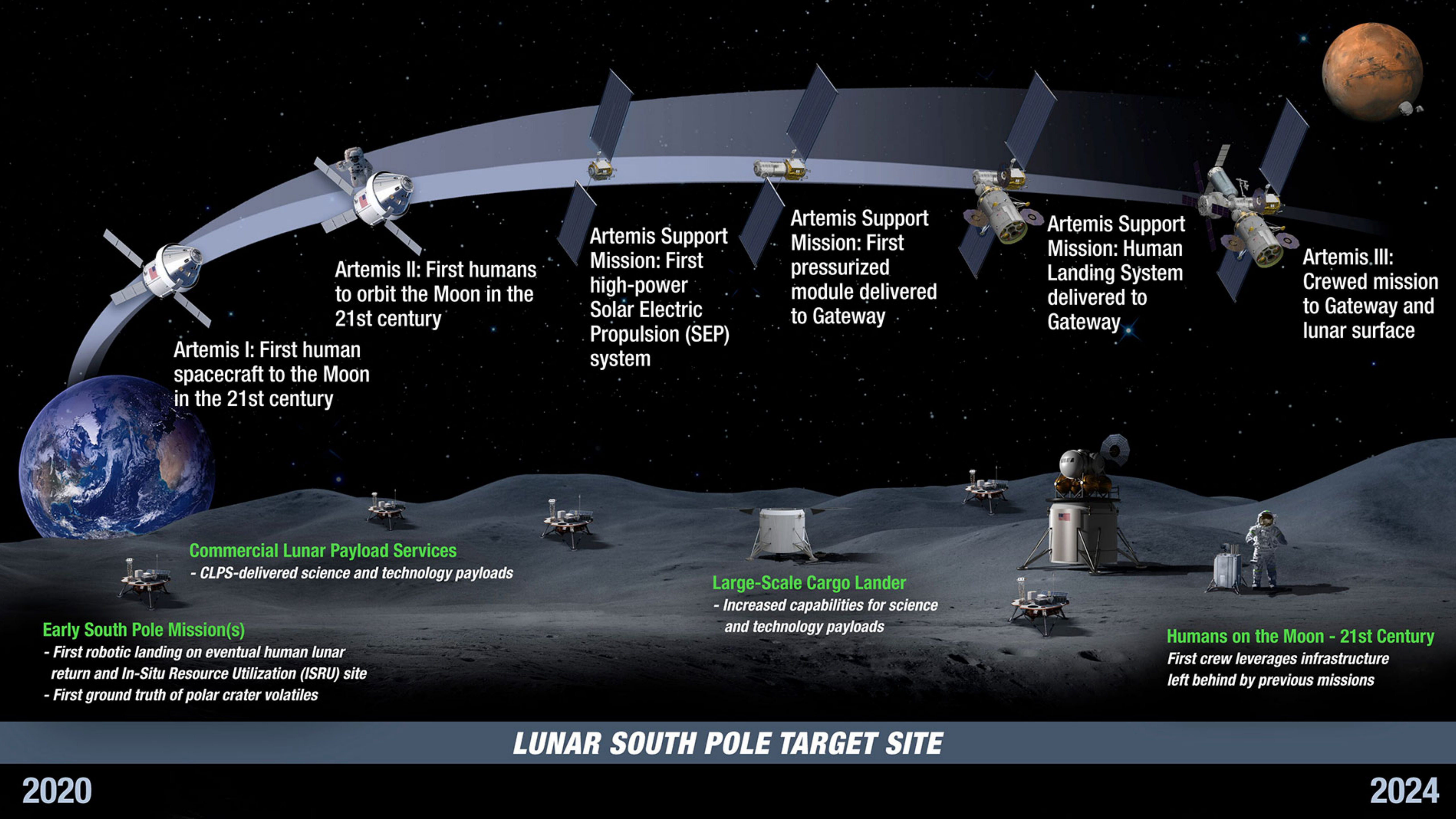
MMS Phase 2B results Winternitz et al. 2017 [7]


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)

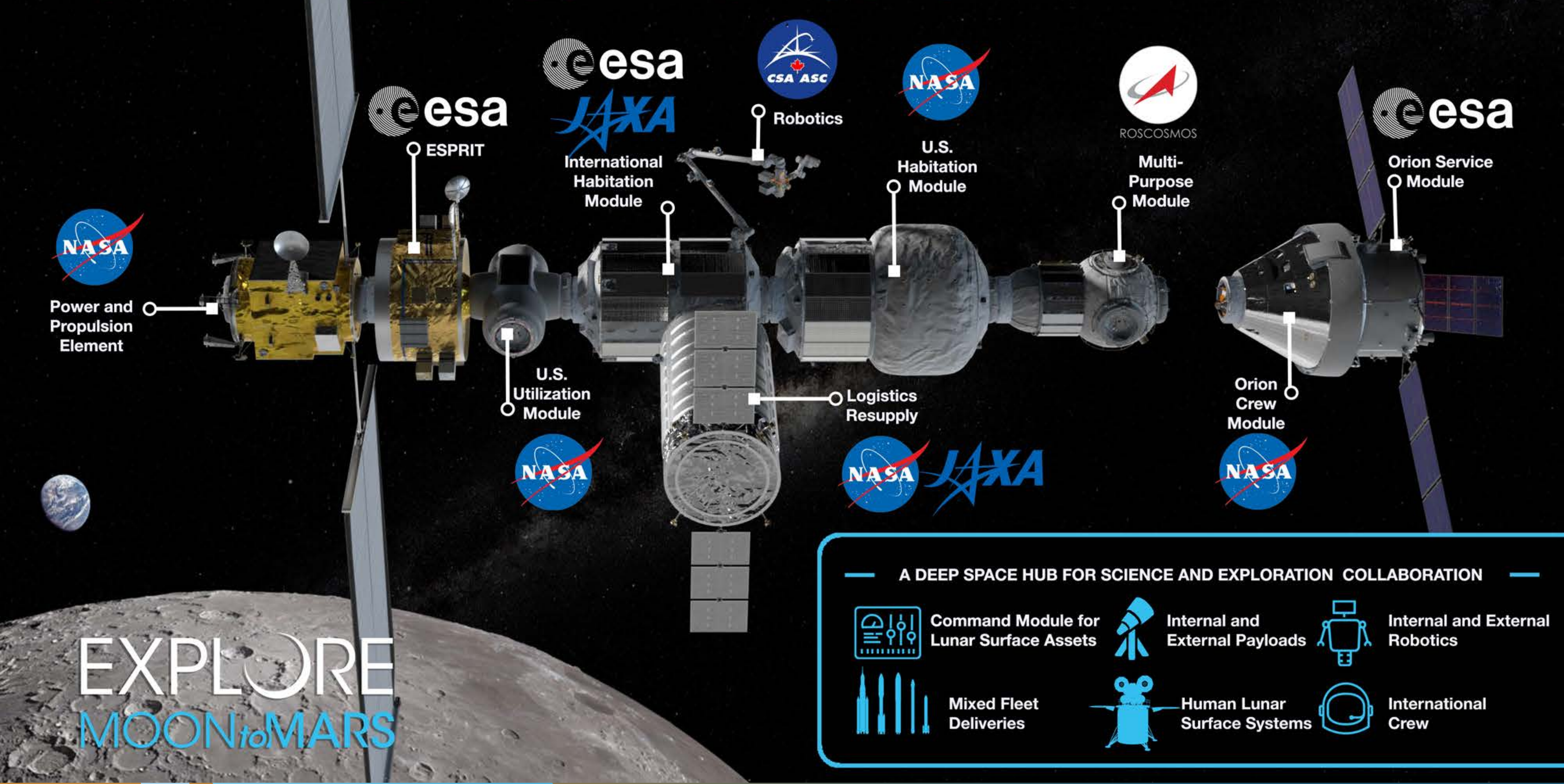
Where is the GNSS frontier?

3

The Way Forward

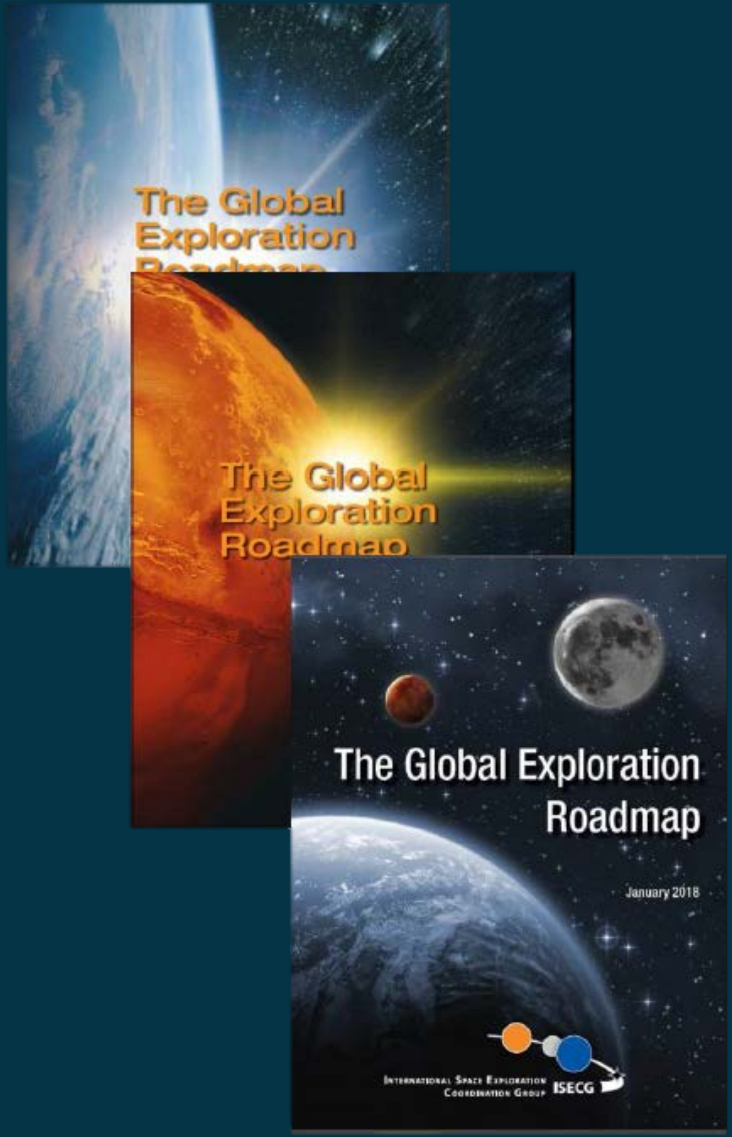

Artemis I: First human spacecraft to the Moon in the 21st century
Artemis II: First humans to orbit the Moon in the 21st century
Artemis Support Mission: First high-power Solar Electric Propulsion (SEP) system
Artemis Support Mission: First pressurized module delivered to Gateway
Artemis Support Mission: 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

GATEWAY CONFIGURATION CONCEPT as of May 2019



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:

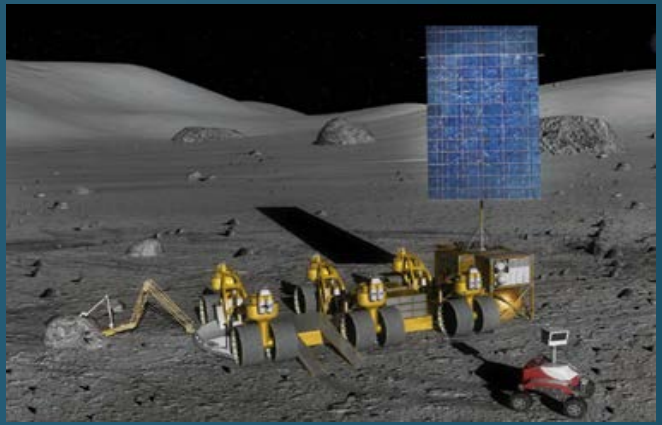
- AR&D Proximity Operations, Target Relative Navigation
- Beyond-LEO crew autonomy

GNSS on lunar missions would:

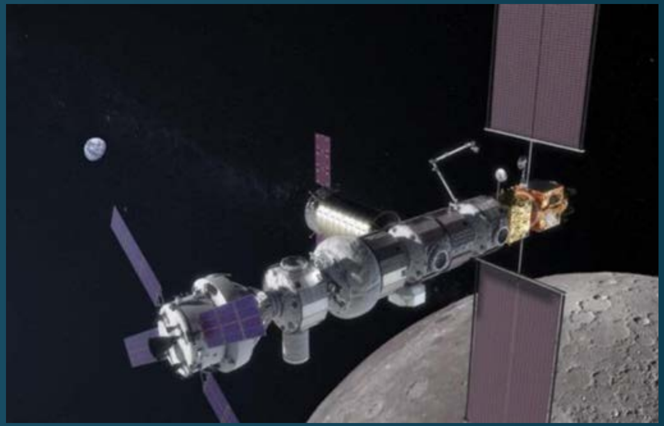
- enable autonomous navigation
- reduce tracking and operations costs
- provide a backup/redundant navigation for human safety
- provide timing source for hosted payloads
- reduce risk for commercial development

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

Lunar Exploration: Roles for GNSS

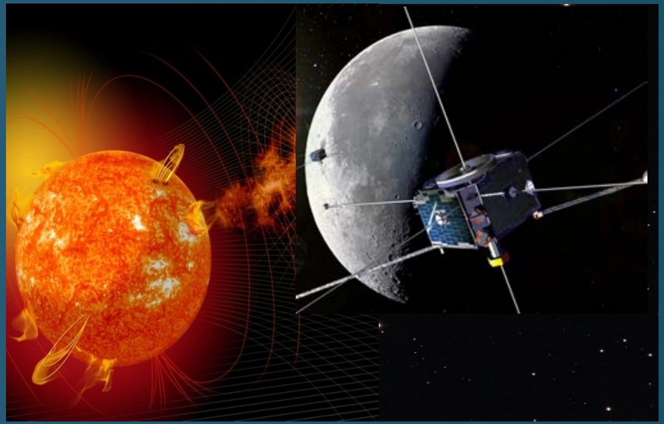


Lunar Surface Operations, Robotic Prospecting,& Human Exploration

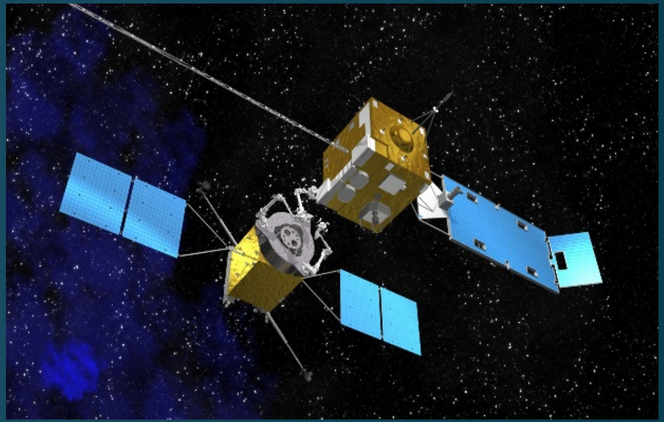


Human-tended Lunar Vicinity Vehicles (Gateway)

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 mean of 3-sigma RMS value 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
- **GPS can provide a simple, high-performance, on-board navigation solution for Gateway**

	Pos Range	Pos RSS Lateral	Vel Range	Vel RSS Lateral
Ground Tracking	32.9 m	467.4 m	1.0 mm/s	10.6 mm/s
GPS with USO	202.9 m	31.3 m	1.9 mm/s	1.4 mm/s
GPS with space atomic clock	8.5 m	30.5 m	0.2 mm/s	1.2 mm/s

Projected GNSS Performance at the Moon

"Lunar Navigation Beacon Network Using GNSS Receivers"

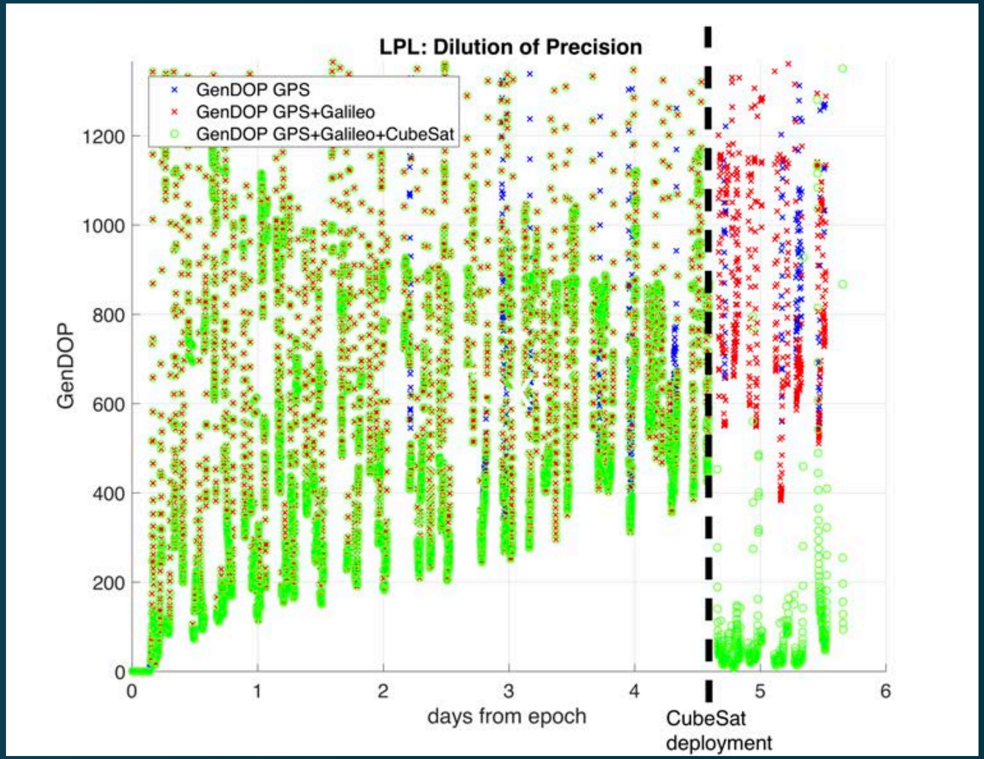
Anzalone et al. 2019 [9]

- 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



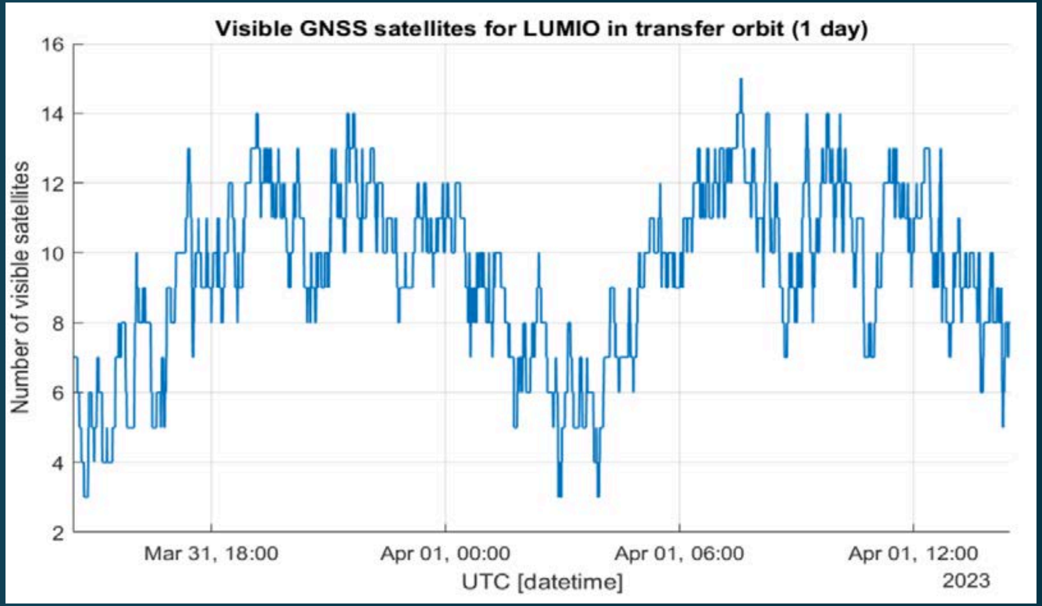
Generalized Dilution of Precision for GPS only, GPS+Galileo, and GPS+Galileo+CubeSat [10]

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

Enabling the SSV

GPS Antenna Characterization Experiment [13]

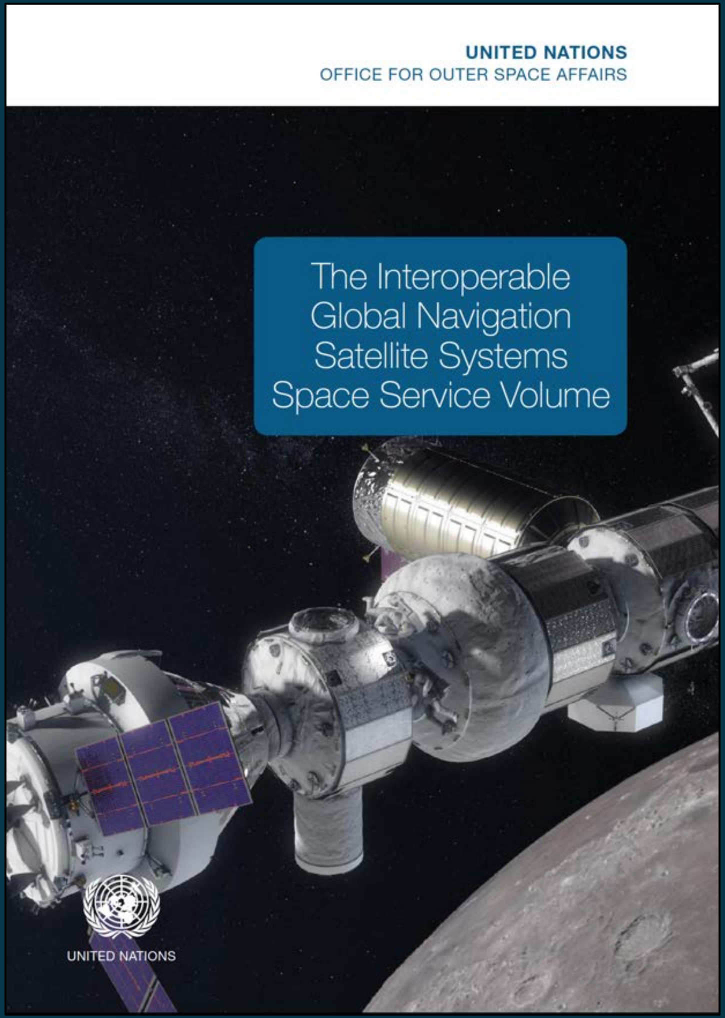
- First complete mapping of GPS L1 side lobes for all GPS satellites via GEO-based bent pipe
- Data set available at https://esc.gsfc.nasa.gov/navigation

U.S. User-Provider Collaboration on GPS SSV

- 2017 joint NASA-USAF Memorandum of Understanding signed on GPS civil SSV requirements
- Intent is to ensure SSV signal continuity for future space users

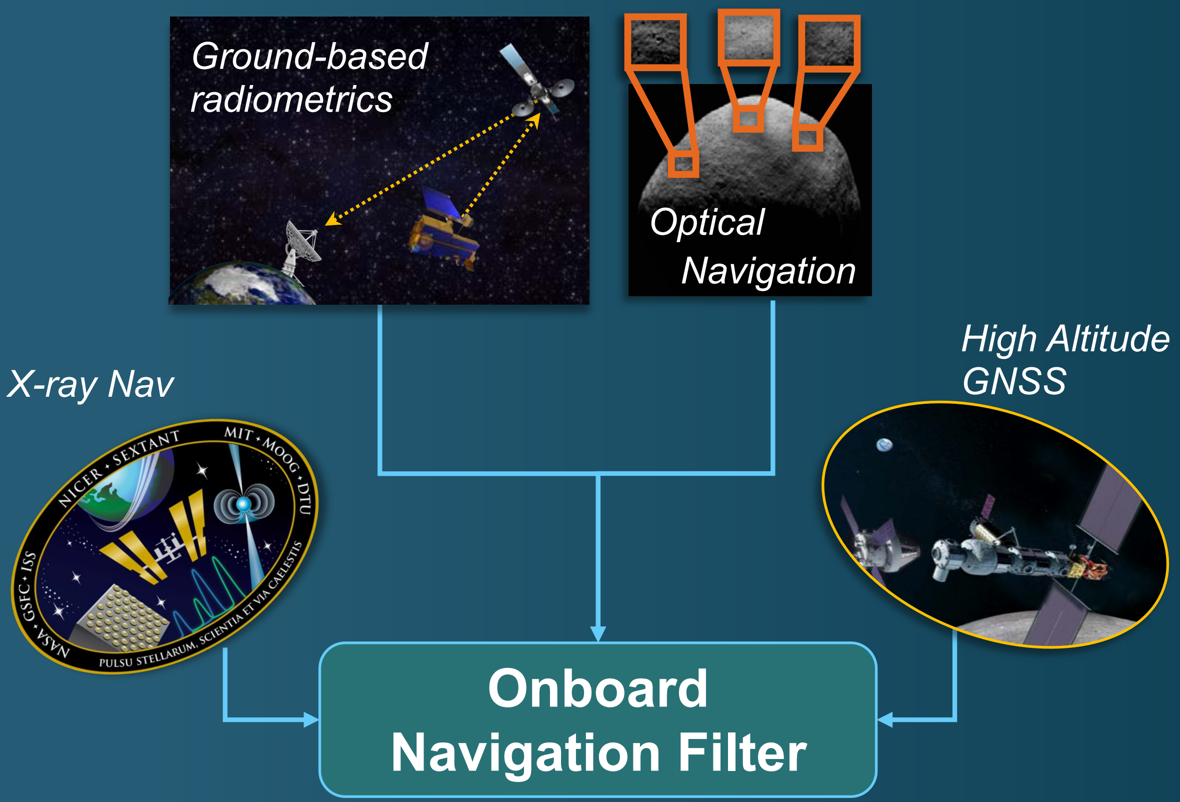
United Nations International Committee on GNSS

- 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



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

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

High-altitude space use (i.e. from 3,000 km to lunar orbit) represents the newest frontier of GNSS

High-altitude GNSS offers numerous benefits to space users, including:

- Promising new mission types and operations concepts
- Precise real-time navigation and time sensing
- Enhanced on-board autonomous operations and reduced ground support

The international GNSS community must act to realize these benefits:

- **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

The US civil space community looks forward to future collaboration, internally and externally, to advance space use of GNSS

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