NASA Update: GNSS Space Service Volume

Providers' Forum

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NASA Space Communication and Navigation (SCaN) Program
NASA Human Exploration and Operations Mission Directorate (HEOMD)
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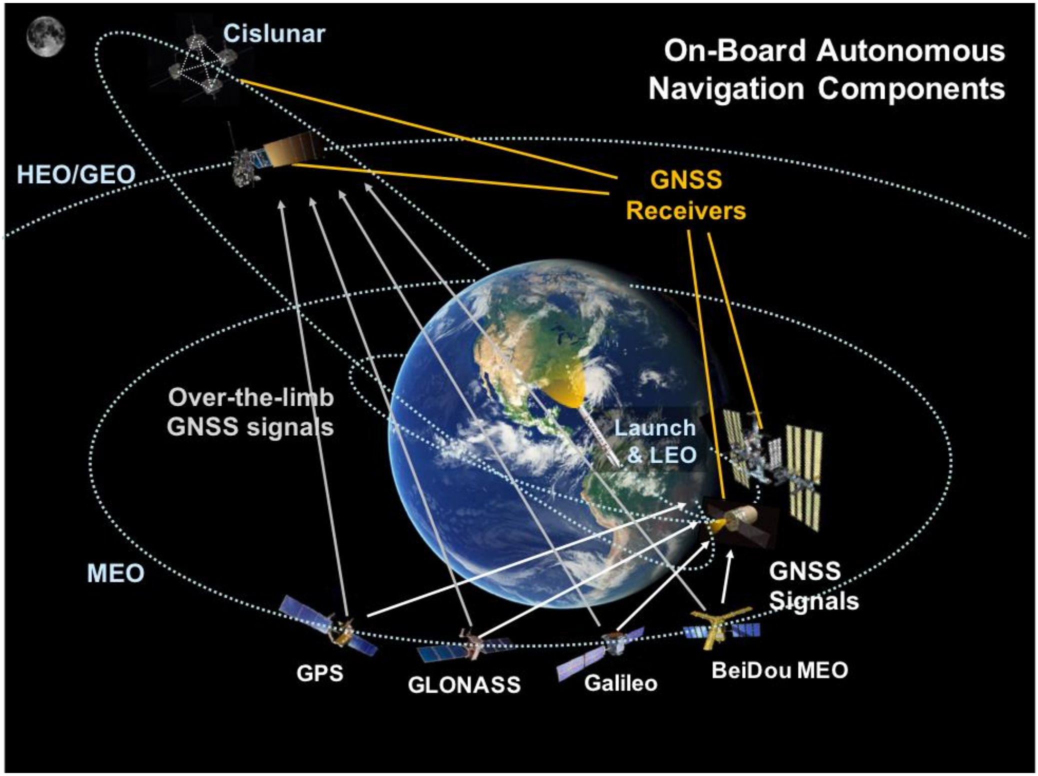
Space Uses of Global Positioning System (GPS) & Global Navigation Satellite Systems (GNSS)

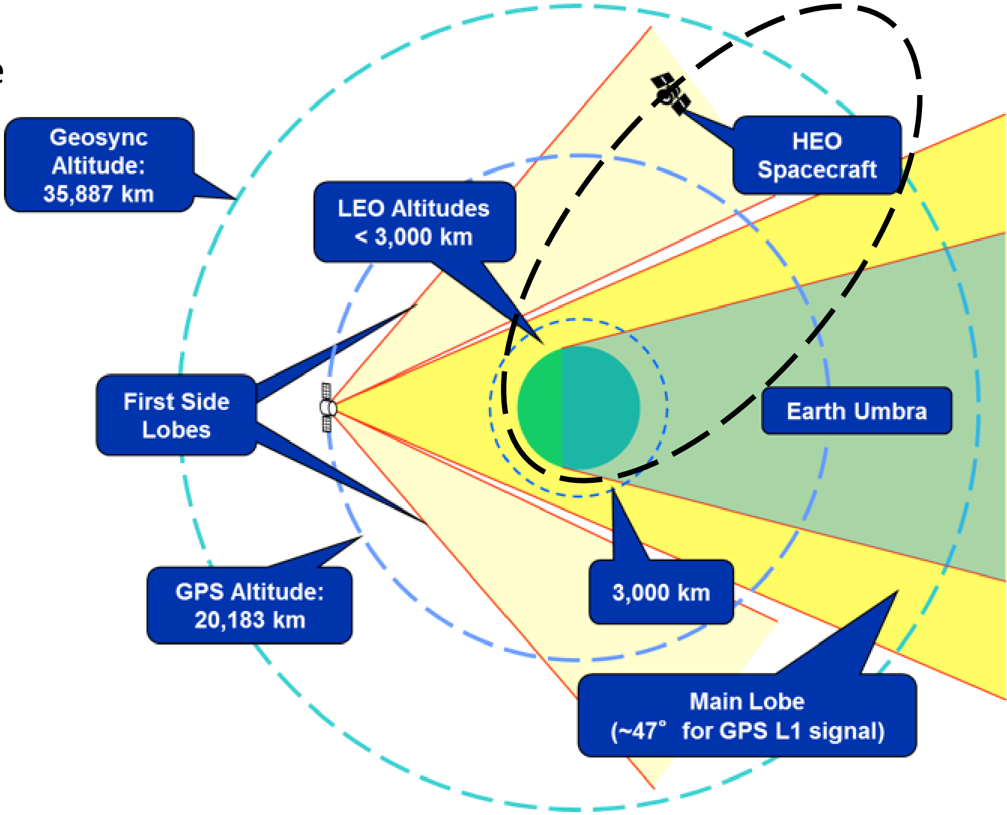
- **Real-time On-Board Navigation:** Precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **Earth Sciences:** GPS as a measurement for atmospheric and ionospheric sciences, geodesy, and geodynamics
- **Launch Vehicle Range Operations:** Automated launch vehicle flight termination; providing safety net during launch failures & enabling higher cadence launch facility use
- **Attitude Determination:** Some missions, such as the International Space Station (ISS) are equipped to use GPS/GNSS to meet their attitude determination requirements
- **Time Synchronization:** Support precise time-tagging of science observations and synchronization of on-board clocks



GPS capabilities to support space users will be further improved by pursuing compatibility and interoperability with GNSS

GNSS Signals in the Space Service Volume (SSV)

- The Terrestrial Service Volume (TSV) is defined as the volume of space including the surface of the Earth and LEO, i.e., up to 3,000 km
- The Space Service Volume (SSV) is defined as the volume of space surrounding the Earth from the edge of LEO to GEO, i.e., **3,000 km to 36,000 km altitude**
- The SSV overlaps and extends beyond the GNSS constellations, so use of signals in this region often requires signal reception from satellites on the opposite side of the Earth – main lobes and sidelobes
- Use of GNSS in the SSV increasing despite geometry, Earth occultation, and weak signal strength challenges
- Spacecraft use of GNSS in TSV & SSV enables:
    - reduced post-maneuver recovery time
    - improved operations cadence
    - increased satellite autonomy
    - more precise real-time navigation and timing performance

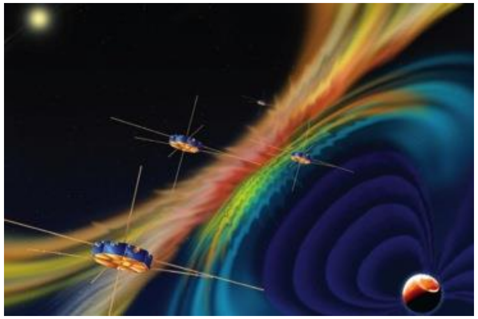


The Promise of using GNSS for Real-Time Navigation inside the SSV

Benefits of GNSS use inside the SSV:

- 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 **HEO and GEO missions,** such as:

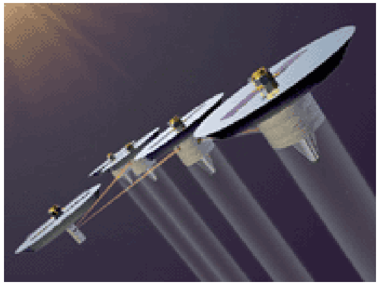
Earth Weather Prediction using Advanced Weather Satellites



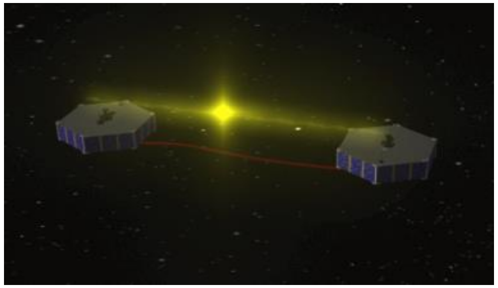
Space Weather Observations

Precise Relative Positioning

Launch Vehicle Upper Stages and Beyond-GEO applications



Formation Flying, Space Situational Awareness, Proximity Operations



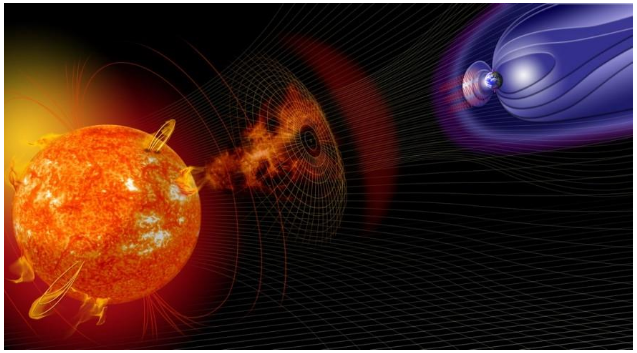
Precise Position Knowledge and Control at GEO

The Promise of using GNSS for Real-Time Navigation beyond the SSV

Benefits of GNSS use beyond the SSV:

- **Supports real-time navigation performance** (from: *no real time* to: real-time 1 km – 100 m position, µsec timing)
  - Improved performance with (pseudo-) satellite and clock augmentations
- Supports **quick trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- **Near-continuous navigation signals reduces DSN navigation support**
- **Increased satellite autonomy & robotic operations**, lowering ops costs (savings up to $500-750K/year)
- Supports vehicle autonomy, new/enhanced capabilities and better performance for Cis-Lunar & Gateway **mission scenarios,** including:

Earth Observations beyond GEO



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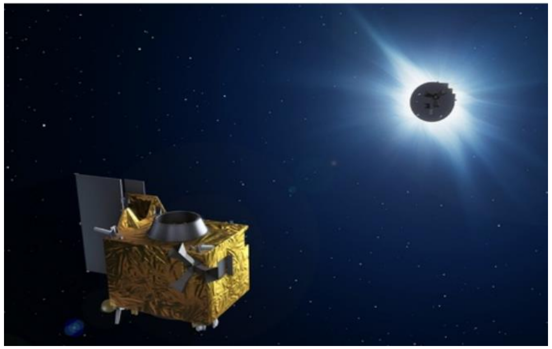
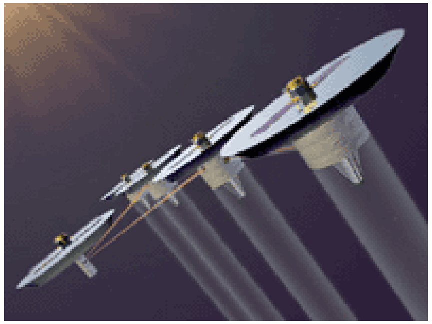


Precise Relative Positioning

Launch Vehicle Upper Stages & Cislunar applications



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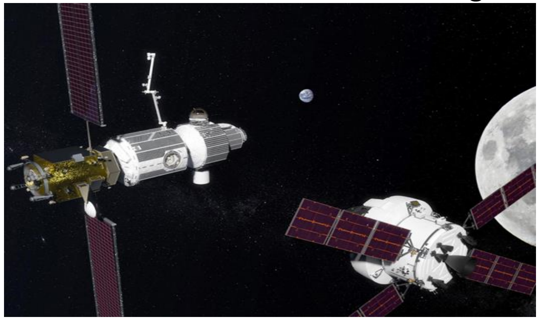

Lunar Orbiting Platform-Gateway Human & Robotic Space Applications

Operational Challenges, Mitigations and Use of GPS/GNSS in Space

Ops Scenario	Altitude Range (km)	Challenges & Observations (Compared to previous scenario)	Mitigations	Operational Status
Terrestrial Service Volume	100- 3,000	Acquisition & Tracking: Higher Doppler, faster signal rise/set; accurate ephemeris upload required; signal strength & availability comparable to Earth use	Development of Space Receivers; fast acquisition algorithm eliminates ephemeris upload	Extensive Operational use
SSV Medium Altitudes	3,000-8,000	More GPS/GNSS signals available; highest observed Doppler (HEO spacecraft)	Max signals require omni antennas; receiver algorithms must track higher Doppler	Operational (US & foreign)
SSV High-GEO Altitudes	8,000-36,000	Earth obscuration significantly reduces main lobe signal availability; frequent ops w/ <4 signals; periods of no signals; weak signal strength due to long signal paths	Nav-Orbit Filter/Fusion algorithms (e.g. GEONS) enables ops w/ <4 signals and flywheel through 0 signal ops; use of signal side lobes and/or other GNSS constellations; higher gained antennas, weak signal receivers	Operational (US & foreign)
Beyond the SSV	36,000-360,000+	Even weaker signals & worse signal geometry	Use higher gain, small footprint antenna; accept geometric performance degradation or augment with signals of opportunity to improve	Operational to 150,000 km (MMS), Orion Lunar perf. experiment

GNSS SSV Observations and Forward Priorities

Observations:

- The International Committee on GNSS (ICG) WG-B is establishing an interoperable GNSS SSV through pre-work, analyses and meetings
- Analyses continue to solidify our understanding of an SSV that combines the capabilities of all GNSS and regional navigation systems
- Despite this, SSV users should not rely on **unspecified capabilities** from any particular GNSS
  - SSV capabilities that are currently available may not be available in the future unless they are documented in specifications for that GNSS

Forward Priorities:

GNSS service providers, supported by space agencies & research institutions encouraged to:

- Support SSV in future generation of satellites, preferably through the baseline of SSV specifications
- Measure and publish GNSS antenna gain patterns to support SSV understanding & use of the GNSS aggregate signal
- Share SSV user experiences and lessons learned to improve SSV responsiveness to emerging needs

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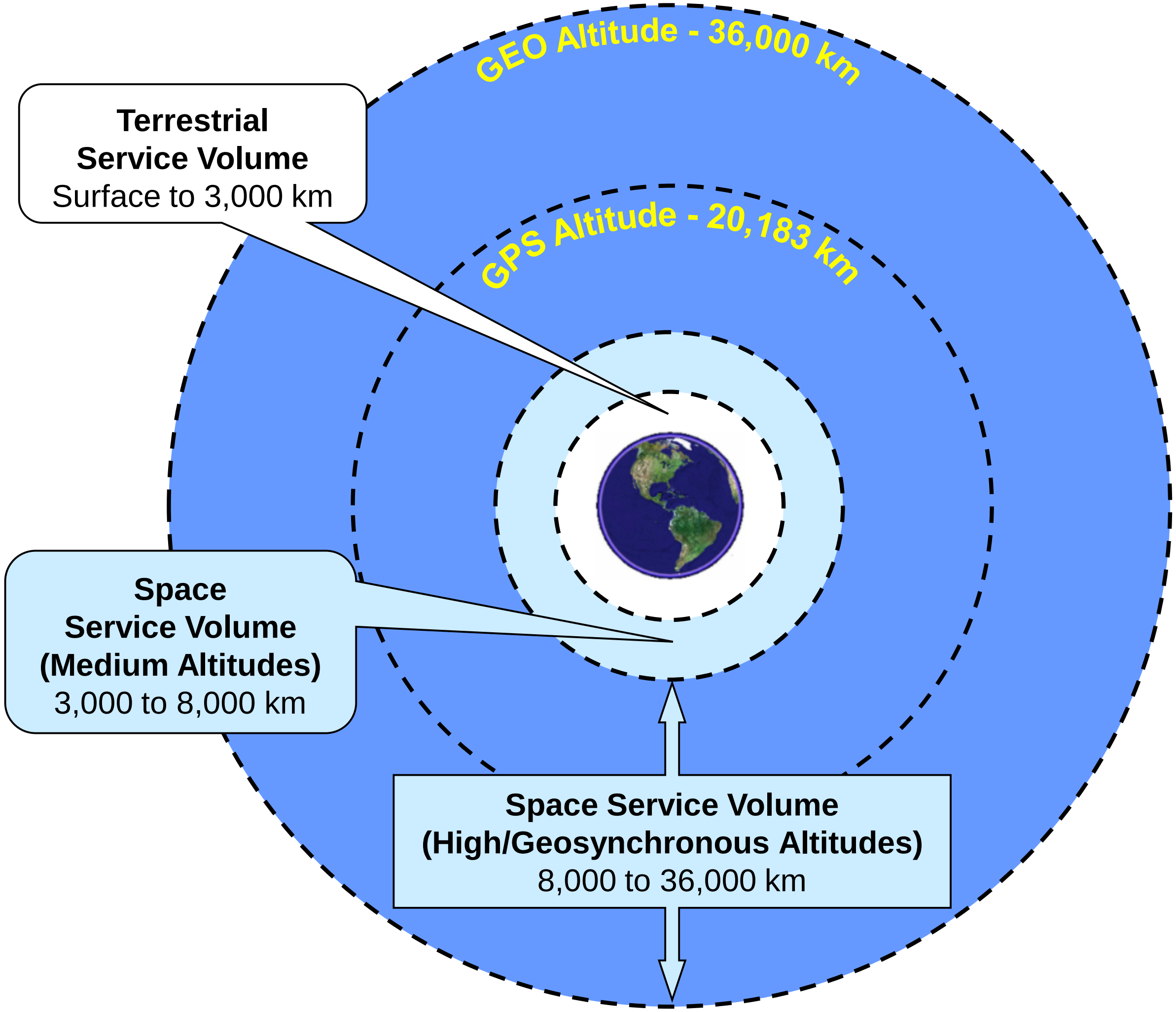
Current GPS SSV Specification



The GPS SSV is <u>specified</u> by three interrelated performance metrics for the SSV Medium Altitudes and the SSV High/Geosynchronous altitudes:

- Availability
- Minimum received power
- Pseudorange accuracy

USAF –NASA Collaboration on SSV

- **Oct 13 2017: Joint NASA-USAF Memorandum of Understanding (MOU) signed on civil Space Service Volume (SSV) Requirements**
  - Scope relevant to future GPS-III SV11+ (GPS IIIF) block build
- **MOU Resultant effects:**
  - US Civil Space representative, Jennifer Donaldson/NASA, supported GPS IIIF source selection team as SSV technical expert
  - Provided civil space insight into GPS IIIF procurement, design and production from an SSV capability perspective
  - NASA received released GPS IIF antenna pattern measurements to support NASA Space Launch System need

MOU supports SSV signal continuity goals for future space users

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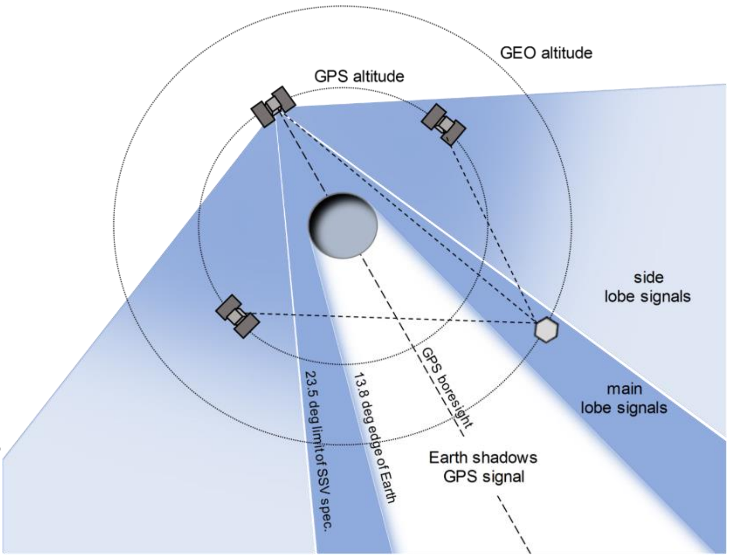
GPS Antenna Characterization Experiment (ACE)*

*J. Donaldson, J. Parker, M. Moreau, P. Martzen, D. Highsmith

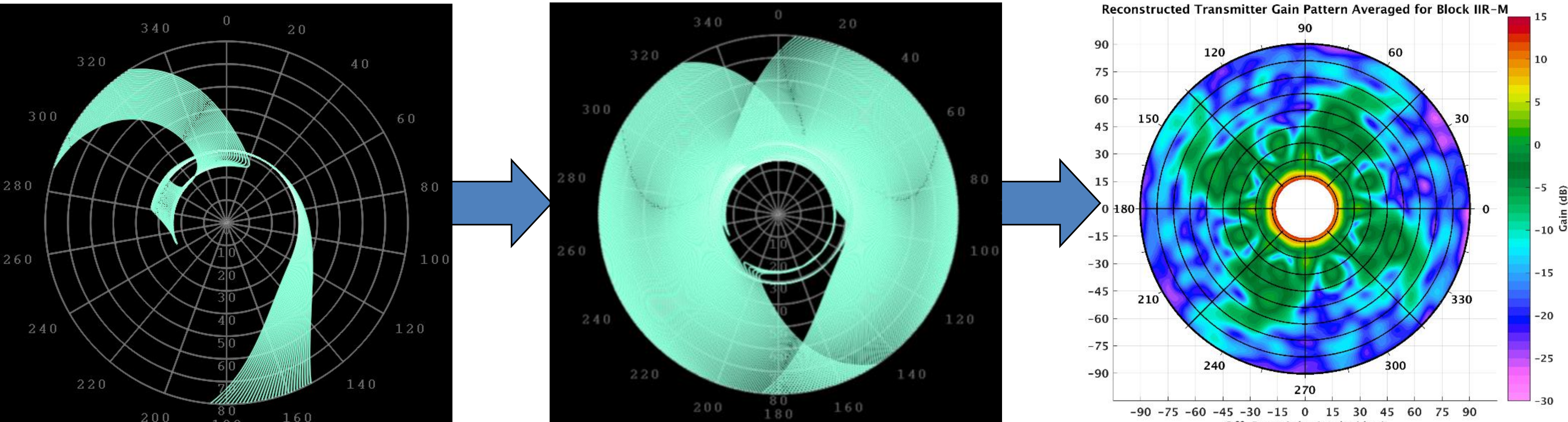
Overview

- 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



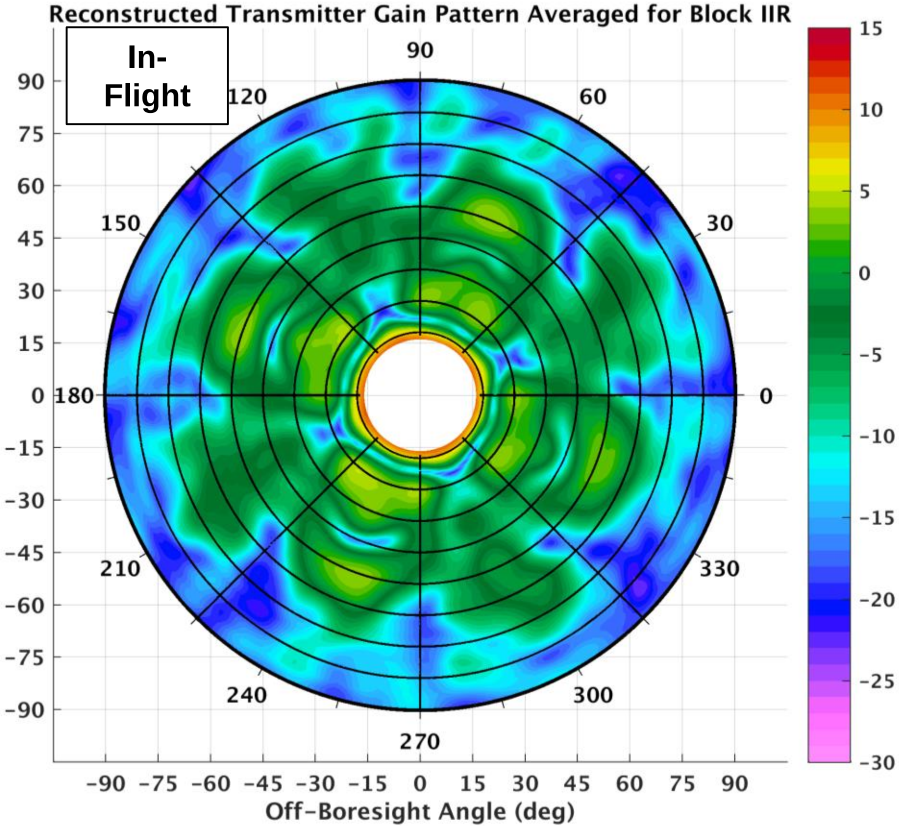
Data Collection & Visualization

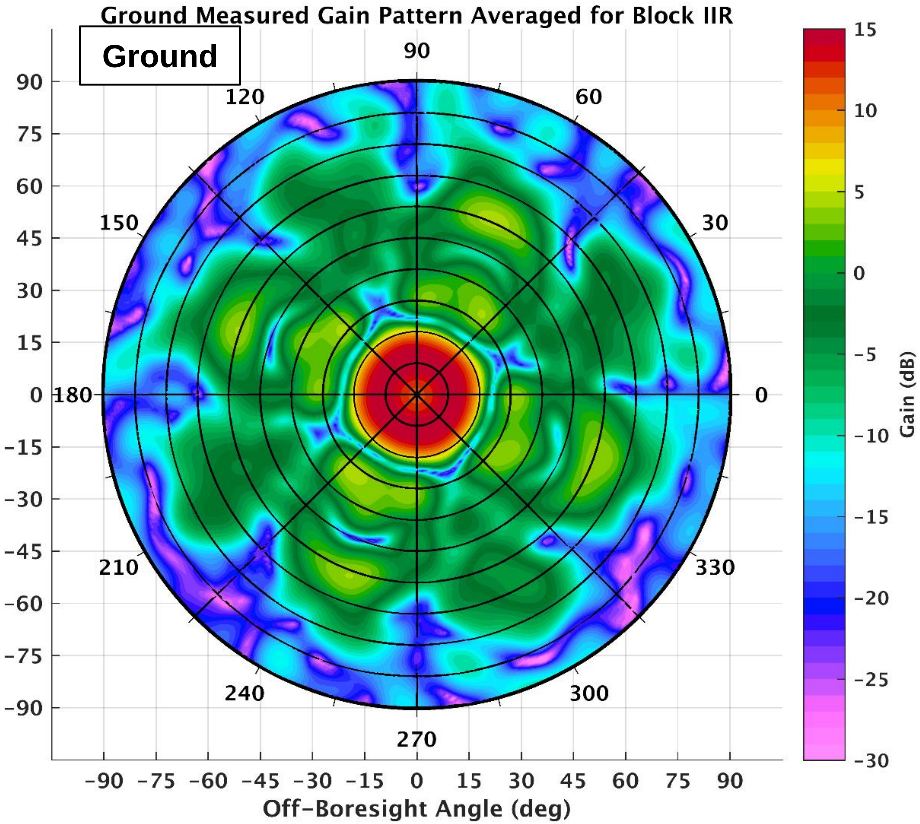
- Trace path of GEO vehicle in antenna frame of each GPS vehicle
- Reconstruct full gain pattern after months of tracking



ACE Results
Average Transmit Gain – Block IIR

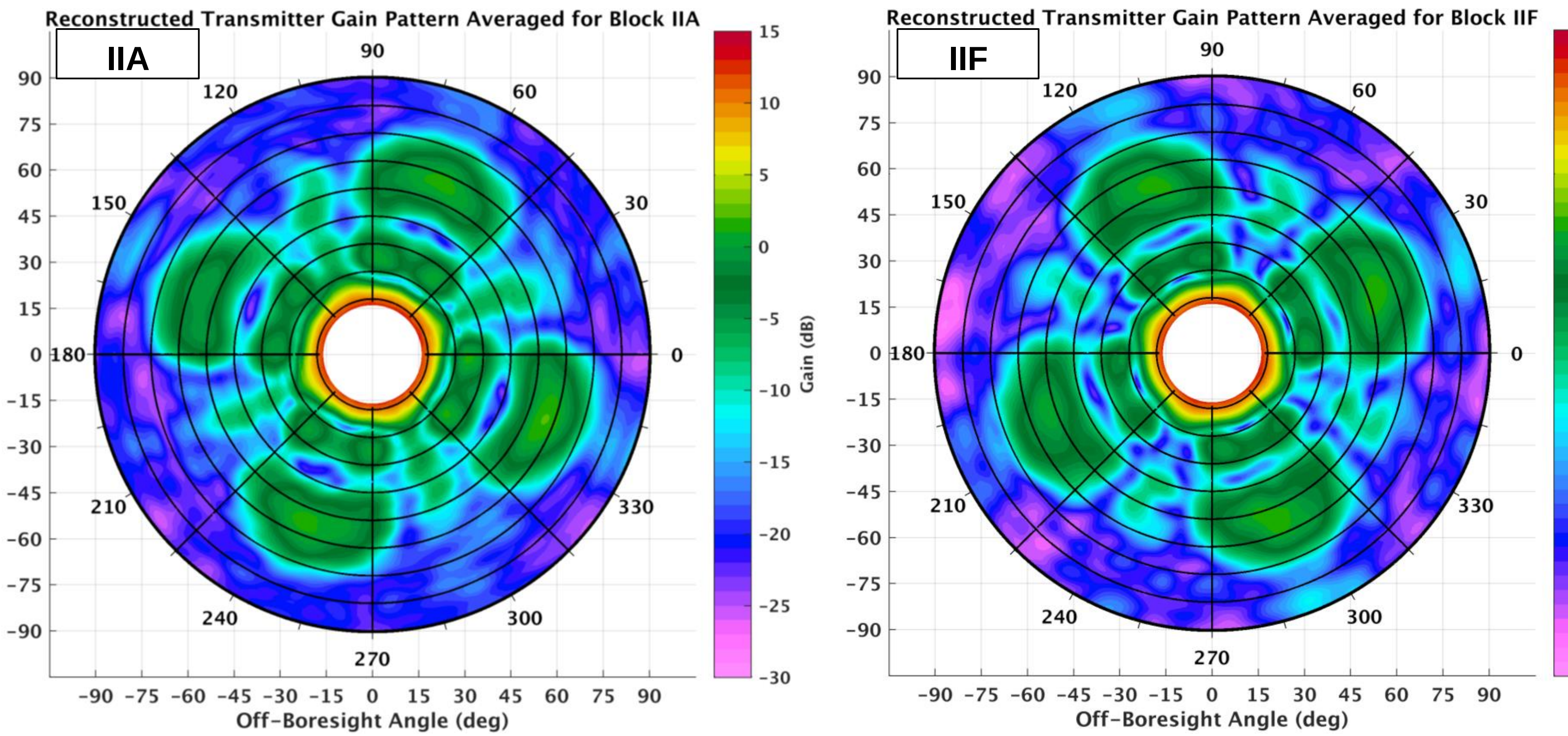
- In-flight averaged over all SVNs in block in 1 deg x 1 deg bins
- Remarkable similarity between average flight and ground measurements
  - Note matching patterns in nulls around outer edge





ACE Results
Average Transmit Gain – Block IIA/IIF

- Averaged over all SVNs in block in 1 deg x 1 deg bins
- IIF side lobes are shifted 45 deg in azimuth from other blocks



GPS ACE Conclusions

- **GPS ACE architecture permits tracking of extremely weak signals over long duration**
  - MGPSR produces signal measurements well into back lobes of GPS vehicles
  - 24/7 GPS telemetry provides near continuous tracking of each PRN
- **First reconstruction of full GPS gain patterns from flight observations**
  - Block averages of IIR, IIR-M show remarkable consistency with ground patterns
    - Demonstrates value in extensive ground testing of antenna panel
  - Characterized full gain patterns from Blocks IIA, IIF for the first time
  - Patterns permit more accurate simulations of GPS signal availability for future HEO missions
- **Additional analysis of pseudorange deviations indicate usable measurements far into side lobes**

Dataset available at: **https://esc.gsfc.nasa.gov/navigation**

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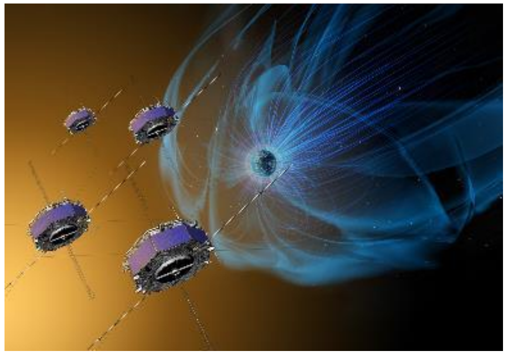
- **Share SSV user experiences and lessons learned to improve SSV responsiveness to emerging needs—US Response**

U.S. Initiatives & Contributions to Develop & Grow an Interoperable GNSS SSV Capability for Space Users

Operational Users

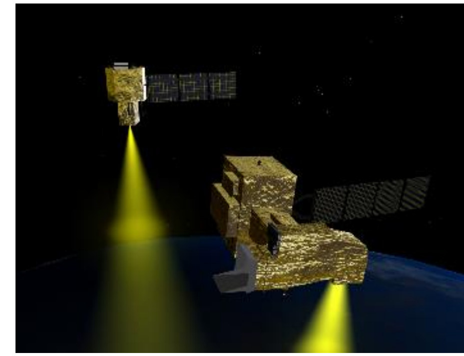
- MMS
- GOES-R, S, T, U
- EM-1 (Lunar en-route)
- Satellite Servicing



Operational Use Demonstrates Future Need

Space Flight Experiments

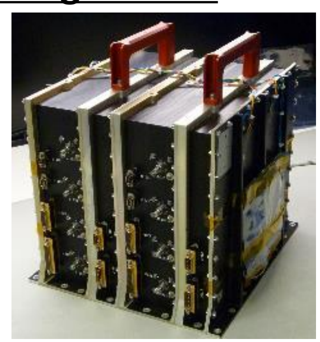
- Falcon Gold
- EO-1
- AO-40
- GPS ACE
- EM-1 (Lunar vicinity)



Breakthroughs in Understanding; Supports Policy Changes; Enables Operational Missions

SSV Receivers, Software & Algorithms

- GEONS (SW)
- GSFC Navigator
- General Dynamics
- Navigator commercial variants (Moog, Honeywell)



Develop & Nurture Robust GNSS Pipeline

SSV Policy & Specifications

- SSV definition (GPS IIF)
- SSV specification (GPS III)
- ICG Multi-GNSS SSV common definitions & analyses

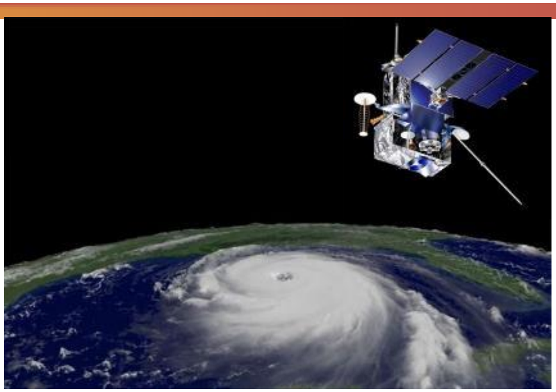
Operational Guarantees Through Definition & Specification

From 1990's to Today, U.S. Provides Leadership & Guidance Enabling Breakthrough, Game-changing Missions through use of GNSS in the SSV

Current U.S. Missions using GPS above the GPS Constellation

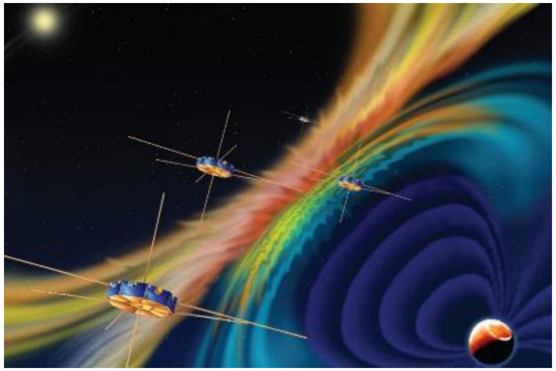
GOES-R Weather Satellite Series:

- Next-generation U.S. operational GEO weather satellite series
- Series is first to use GPS for primary navigation
- GPS provides quicker maneuver recovery, enabling continual science operations with <2 hour outage per year
- Introduction of GPS and new imaging instrument are game-changers to humanity, delivering data products to substantially improve public and property safety



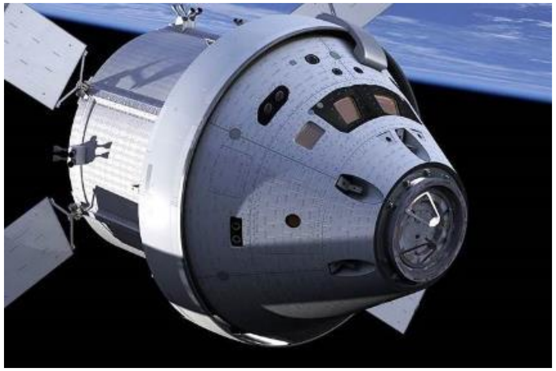
Magnetospheric Multi-Scale (MMS) Mission:

- Four spacecraft form a tetrahedron near apogee for magnetospheric science measurements (space weather)
- Highest-ever use of GPS; Phase I: 12 Earth Radii (RE) apogee; Phase 2: 25 RE apogee ***(40% of way to the moon)***
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping
- **Additional apogee raising to 29.34 RE (50% of way to moon) planned for February 2019**



Exploration Mission 1 (EM-1):

- First cis-lunar flight of NASA Space Launch System (SLS) with an Orion crew vehicle equipped with a Honeywell high-altitude GPS receiver as an experiment



US Contributions to ICG WG-B Multi-GNSS SSV Efforts

US Team Supporting Multiple WG-B Multi-GNSS Initiatives Including:

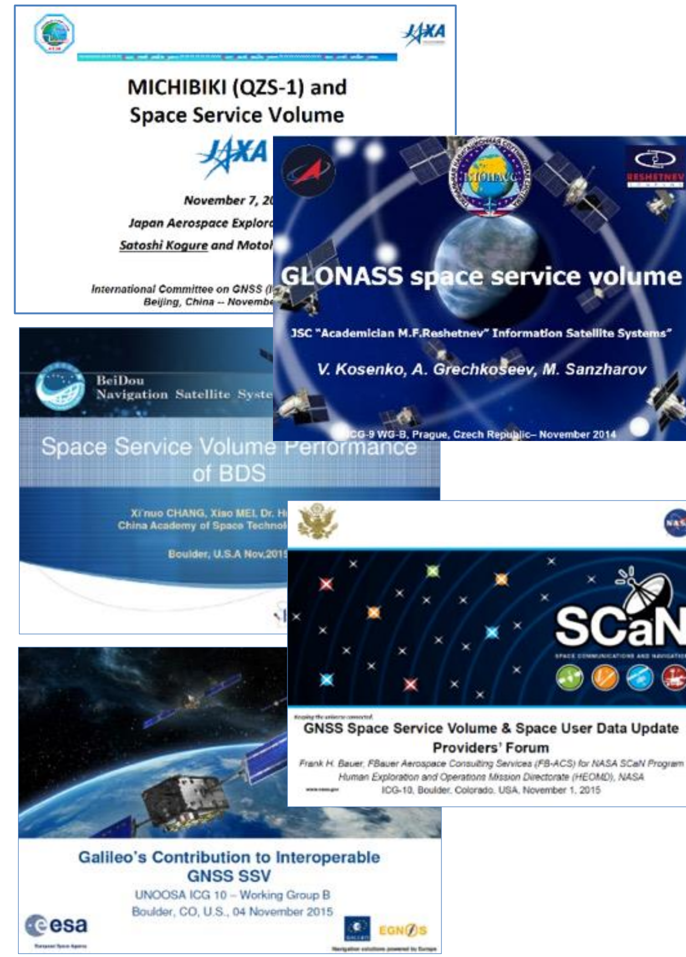
SSV Booklet Development

- Documents and publishes SSV performance metrics for each individual constellation
- Includes internationally coordinated SSV analyses and simulations
- Communicates assumptions & analysis results
- Supports international space user characterization of PNT performance in SSV
- Booklet publication: Nov 2018

Companion SSV Outreach Video being produced by NASA on behalf of ICG

Coordinated Outreach Initiative to communicate capabilities of SSV to future SSV users

ICG-approved Recommendation to examine use of GNSS SSV for exploration activities in cis-Lunar space



ICG-12 (Kyoto) Recommendation:
Use of GNSS for Exploration Activities in Cislunar Space and Beyond

Background/Brief Description of the Issue:
During the WG-B GNSS SSV Working Group activities associated with the generation of the GNSS SSV Booklet, it became clear that the use of GNSS signals in support of missions within and beyond cis-Lunar space is possible and could contribute to improved on-board navigation capabilities.

Discussion/Analyses:
It is essential to understand the user needs for missions to cis-Lunar space and beyond, and to perform detailed analyses of the GNSS SSV capabilities and potential augmentations related to the support of missions to cis-Lunar space and beyond.

Recommendation of Committee Action:
WG-B will lead and Service providers, Space Agencies and Research Institutions are invited to contribute to investigations/developments related to use of the full potential of the GNSS SSV, also considering the support of exploration activities in cis-Lunar space and beyond.

NASA Lunar GPS Visibility Simulation*

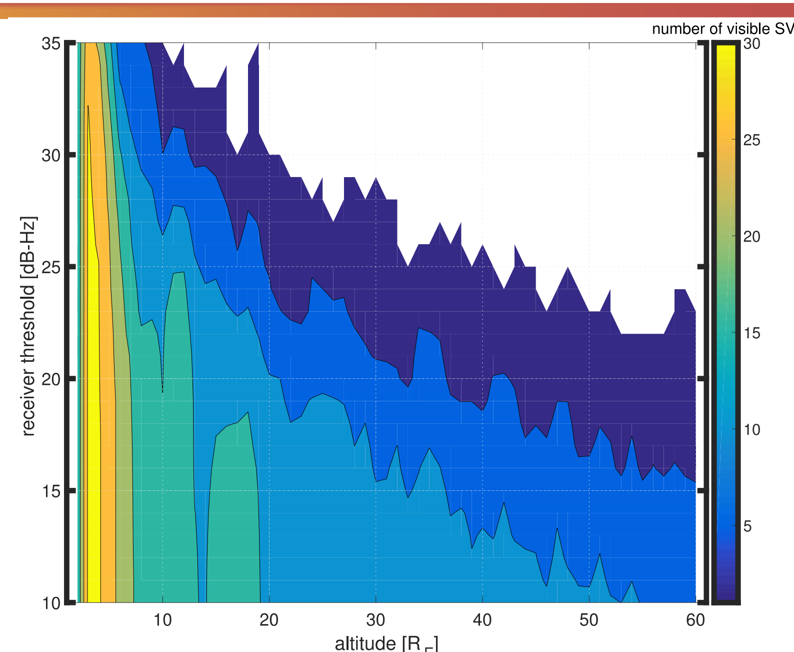
*B. Ashman, F. Bauer, J. Parker, J. Donaldson

Lunar Simulation Results

- Outbound lunar NRHO GPS receiver reception with 22 dB-Hz acq/trk threshold

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

- A modest amount of additional antenna gain or receiver sensitivity increases coverage significantly



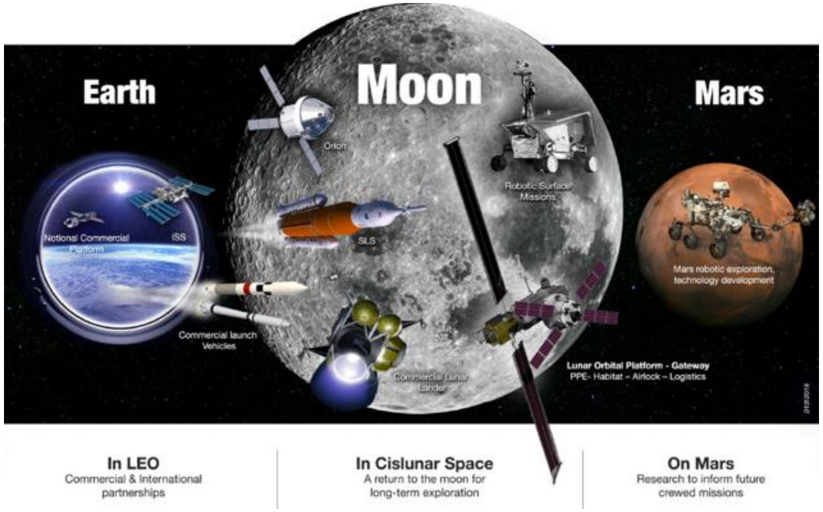
Number of satellites visible by altitude and receiver threshold

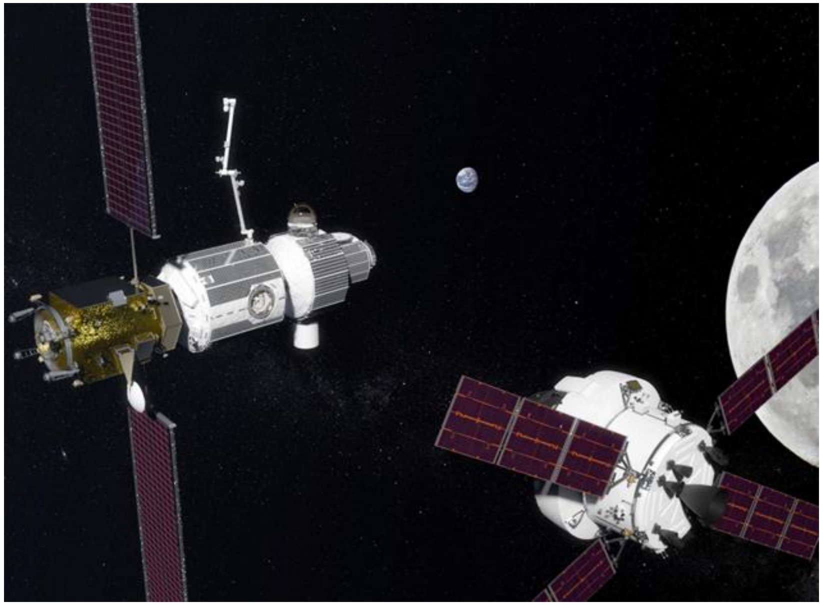
Conclusions

- GOES and MMS data have enabled the development of high altitude GPS simulation models that match flight data to within a few percent in overall visibility metrics
- These results show useful onboard GPS navigation at lunar distances is achievable *now* using *currently-available* signals and *flight-proven* receiver technology
- A modest increase in antenna gain or receiver sensitivity increases visibility significantly
- Future work must extend these specific studies to full navigation analysis of cis-lunar spacecraft, including effects of DOP, and utilizing the *full capability* of multi-GNSS signals
- ICG WG-B is a natural forum for these discussions and analyses, in keeping with the ICG-12 recommendation for analysis for cis-lunar missions and beyond.

Potential Future Application: Lunar Orbital Platform - Gateway

- NASA Exploration Campaign: Next step is deployment and operations of US-led Lunar Orbital Platform – Gateway (previously known as Deep Space Gateway)
- Step-off point for human cislunar operations, lunar surface access, missions to Mars
- Features include:
  - Power and propulsion element (PPE) – targeted for 2022
  - Human habitation capability
  - Docking/rendezvous capability
  - Extended uncrewed operations (not continuously crewed)
  - Lunar near-rectilinear halo orbit (NRHO)
- Gateway conceptual studies are continuing with ISS partners
  - Requirements to be baselined in 2018
  - To be followed by Broad Agency Announcement for partnerships
- **Gateway represents a potential application for on-board GNSS navigation**
- NASA will continue providing updates to WG-B as plans develop.

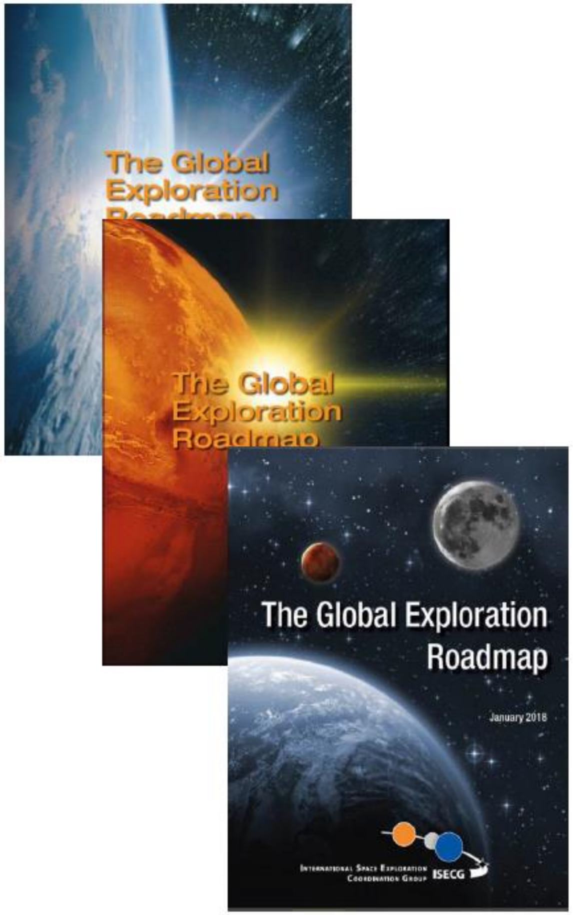




https://www.nasa.gov/feature/nasa-s-lunar-outpost-will-extend-human-presence-in-deep-space

Global Exploration Roadmap

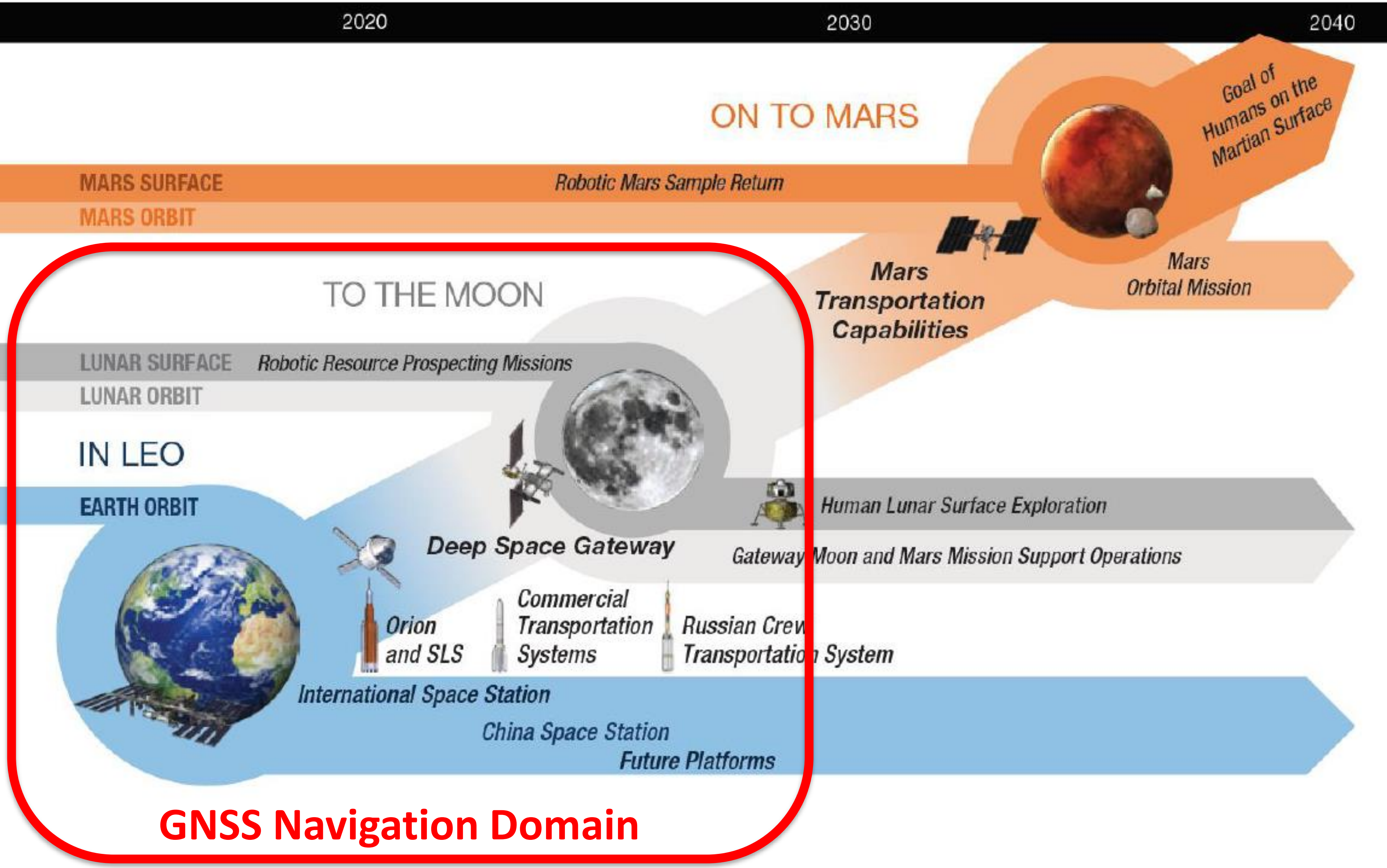
- **The GER is a human space exploration roadmap developed by 14 space agencies participating in the International Space Exploration Coordination Group (ISECG)**
  - First released in 2011. Updated in 2013 and 2018.



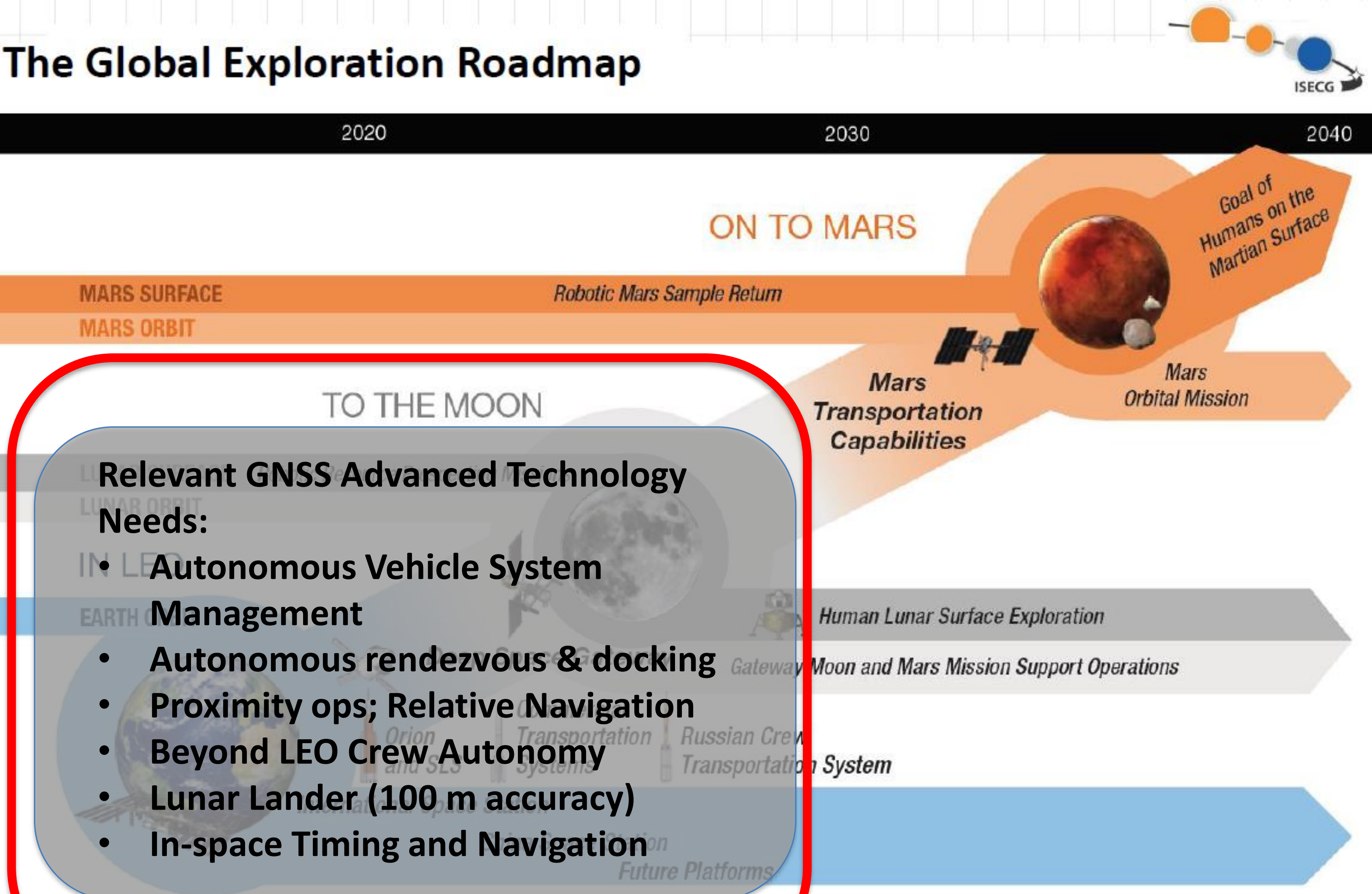
- **The non-binding strategic document reflects consensus on expanding human presence into the Solar System, including**
  - Sustainability Principles, spaceflight benefits to society
  - Importance of ISS and LEO
  - The Moon: Lunar vicinity and Lunar surface
  - Mars: The Driving Horizon Goal

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

The Global Exploration Roadmap



The Global Exploration Roadmap



Relevant GNSS 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

GNSS Navigation Domain

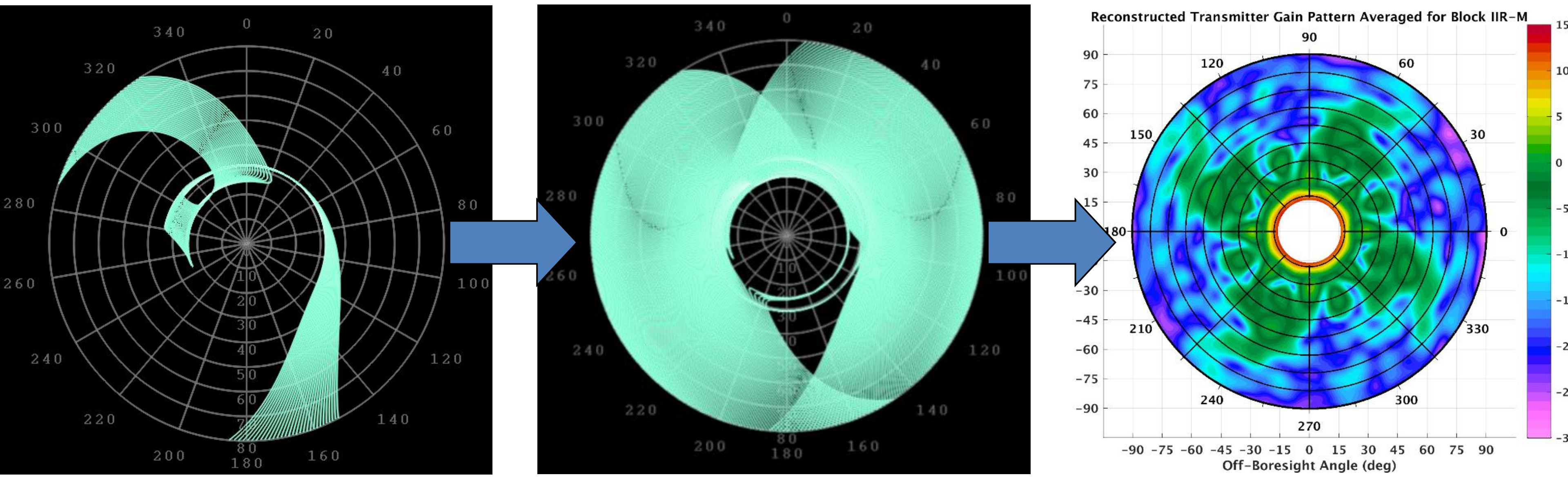
Conclusions

- The SSV, first defined for GPS Block IIF, **continues to evolve** to meet user needs. **GPS has led the way** with a formal specification for GPS Block III, requiring that GPS provides a core capability to space users
- Current and future space missions within the SSV are **becoming increasing reliant** on near-continuous GNSS availability to improve their mission performance; **mission use is expanding into cislunar space**
- Today, we **continue to work** to ensure that the SSV keeps pace with user demands:
  - For GPS, we are working with the Air Force to understand how future GPS block builds will continue to support the needs of emerging GPS-only users like the Geostationary Operational Environmental Satellite - R Series (GOES-R)
  - In partnership with foreign GNSS providers, we are working to characterize, analyze, document, and publish the capabilities of an **interoperable multi-GNSS SSV** with ultimate goal of provider specification
- **Both approaches** are equally critical: (1) a robust GPS capability enables and enhances new missions in applications that only rely on GPS signals; while (2) an interoperable GNSS SSV improves on-board PNT resilience & ensures that wider capabilities are available as needed
- NASA and the U.S. Government are **proud to work** with the GNSS providers to contribute making GNSS services more accessible, interoperable, robust, and precise for all users, for the **benefit of humanity**. We encourage all providers to continue to support this essential capability

Backups

Visualization of Data Collection

- Trace path of GEO vehicle in antenna frame of each GPS vehicle
- Reconstruct full gain pattern after months of tracking



View from GPS Antenna Frame

- Shows path of GEO vehicle in azimuth & off-boresight angle relative to GPS frame
- Path changes due to Sun-relative yaw of GPS vehicle attitude
- Azimuth is from SV +X-axis about SV +Z-axis

IOAG-ICG Collaboration: Space User Database

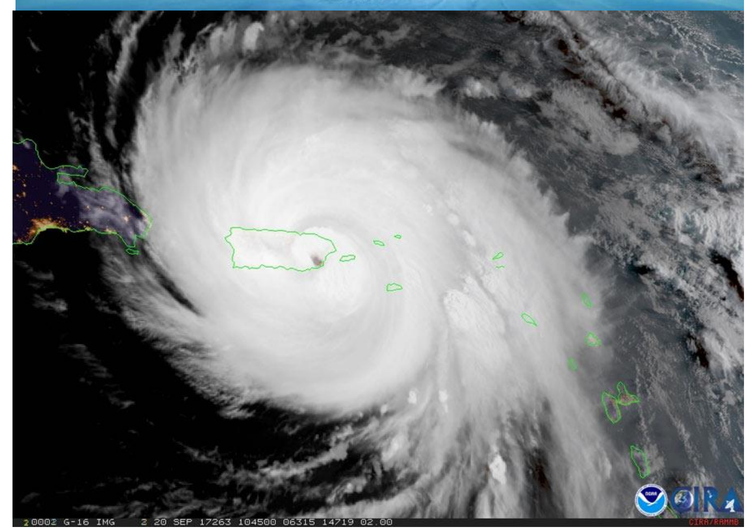
- ICG-11 recommendation encourages providers, agencies, and research organizations to publish details of GNSS space users to contribute to IOAG database.
- IOAG database of GNSS space users updated on November 14, 2017 (IOAG-21)
- Please encourage your service providers, space agencies and research institutions to contribute to the GNSS space user database via your IOAG liaison or via WG-B.

Number of Missions / Programs by Agency

ASI	Agenzia Spaziale Italiana	4
CNES	Centre national d'études spatiales	10
CSA	Canadian Space Agency	5
DLR	German Aerospace Center	12
ESA	European Space Agency	17
JAXA	Japan Aerospace Exploration Agency	12
NASA	National Aeronautics and Space Administration	38

GOES-R Series Weather Satellites

- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellites
- GOES-R/GOES-16 Launch: 19 Nov 2016
- 15 year life, series operational through mid-2030s
- Employs GPS at GEO to meet stringent navigation requirements
- Relies on beyond-spec GPS sidelobe signals to increase SSV performance
- Collaboration with the USAF (GPS) and ICG (GNSS) expected to ensure similar or better SSV performance in the future
- NOAA also identifies **EUMETSAT (EU) and Himawari (Japan) weather satellites** as reliant on increased GNSS signal availability in the SSV

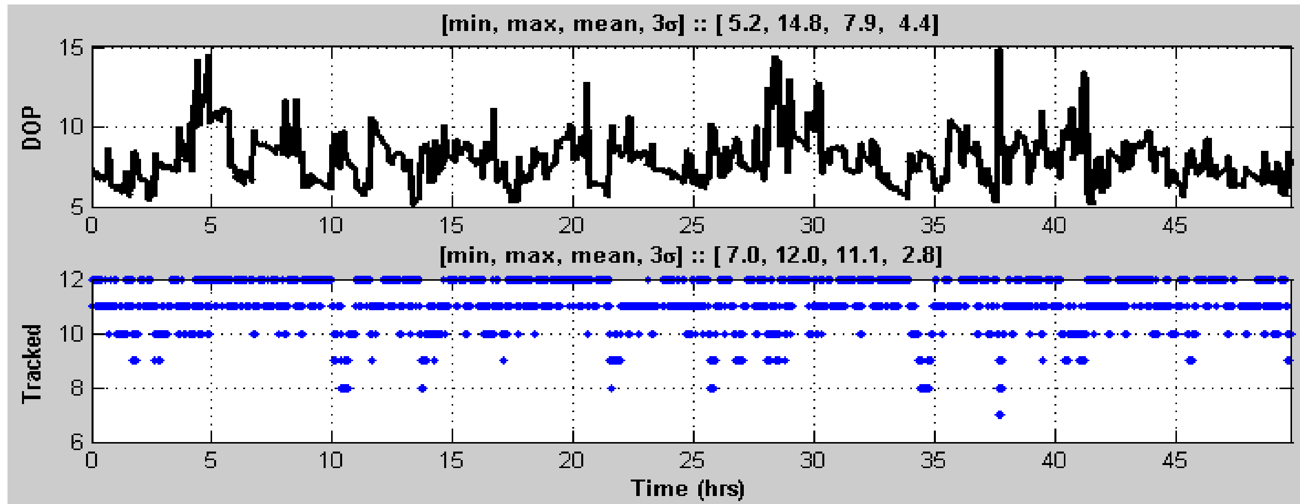


GOES-16 Image of Hurricane Maria Making Landfall over Puerto Rico

GOES-R/GOES-16 In-Flight Performance

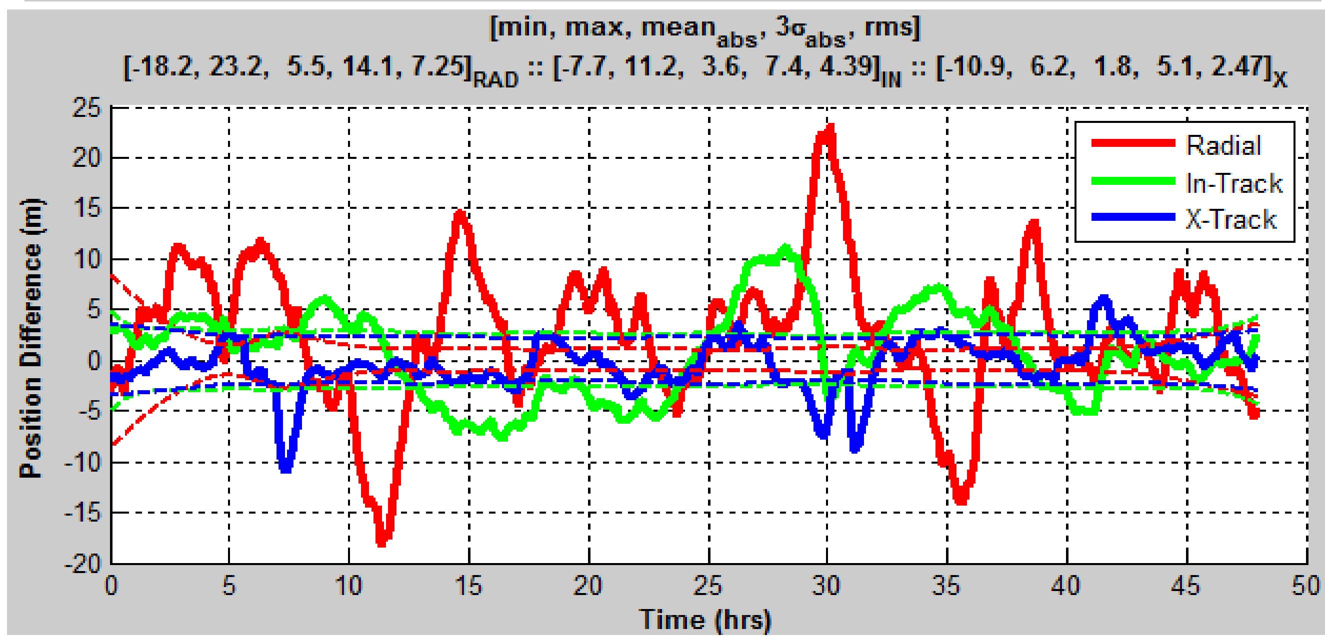
GPS Visibility

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



Navigation Performance

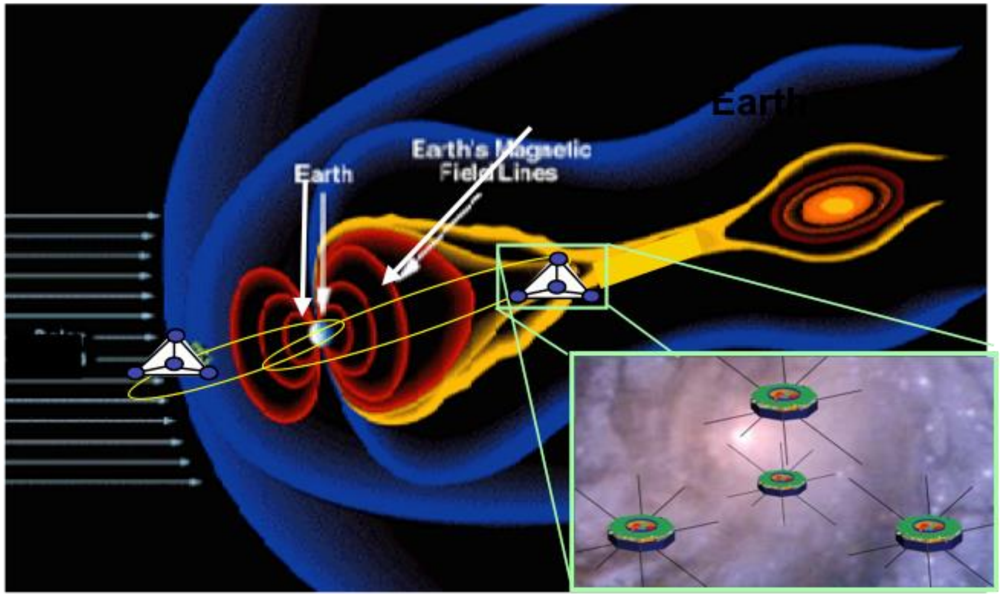
- 3σ position difference from smoothed ground solution (~3m variance):
  - Radial: 14.1 m
  - In-track: 7.4 m
  - Cross-track: 5.1 m
- Compare to requirement: (100, 75, 75) m



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.

NASA's Magnetospheric MultiScale (MMS) Mission

- Discover the fundamental plasma physics process of reconnection in the Earth's magnetosphere.
- Coordinated measurements from tetrahedral formation of four spacecraft with scale sizes from 400km to 10km
- Flying in two highly elliptic orbits in two mission phases
  - Phase 1 1.2x12 R_E (magnetopause) Mar '14-Feb '17
  - Phase 2B 1.2x25 R_E (magnetotail) **May '17-present**



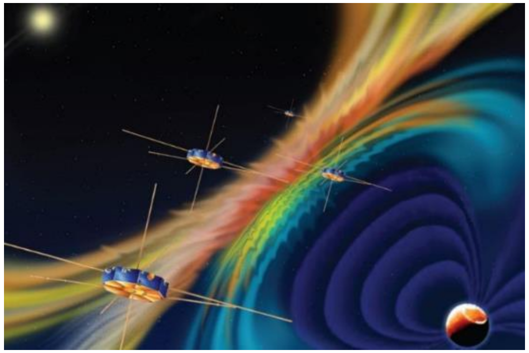
Using GPS above the GPS Constellation: NASA GSFC MMS Mission

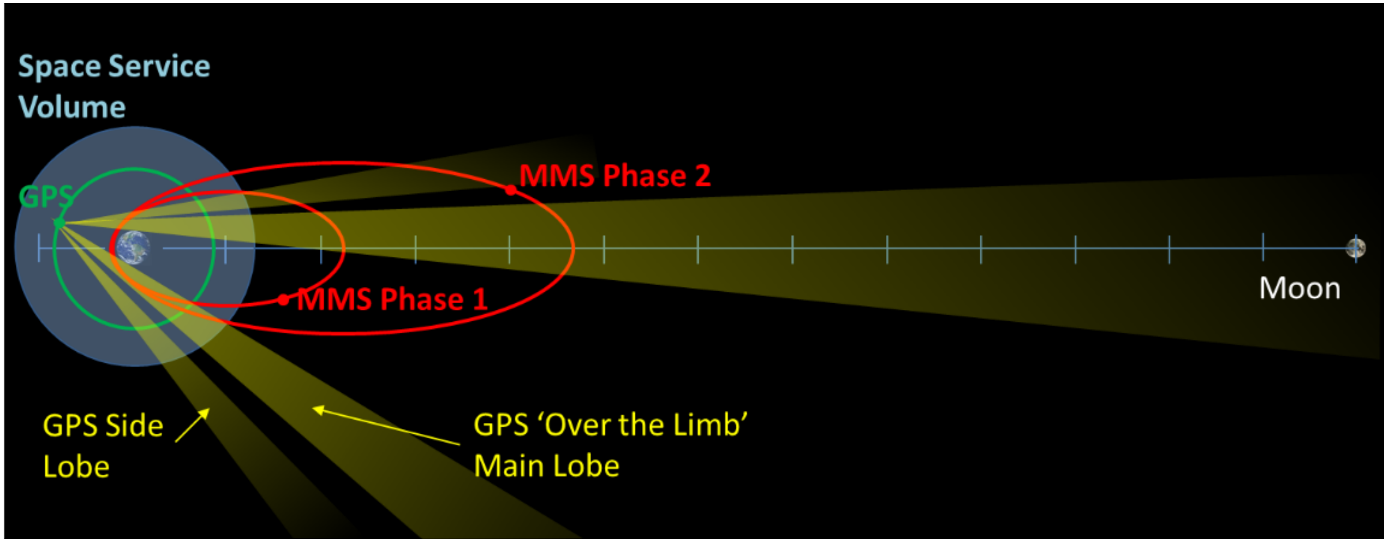
Magnetospheric Multi-Scale (MMS)

- 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)
  - Phase 2: Extends apogee to 25 Re (~150,000 km) **(40% of way to Moon!)**

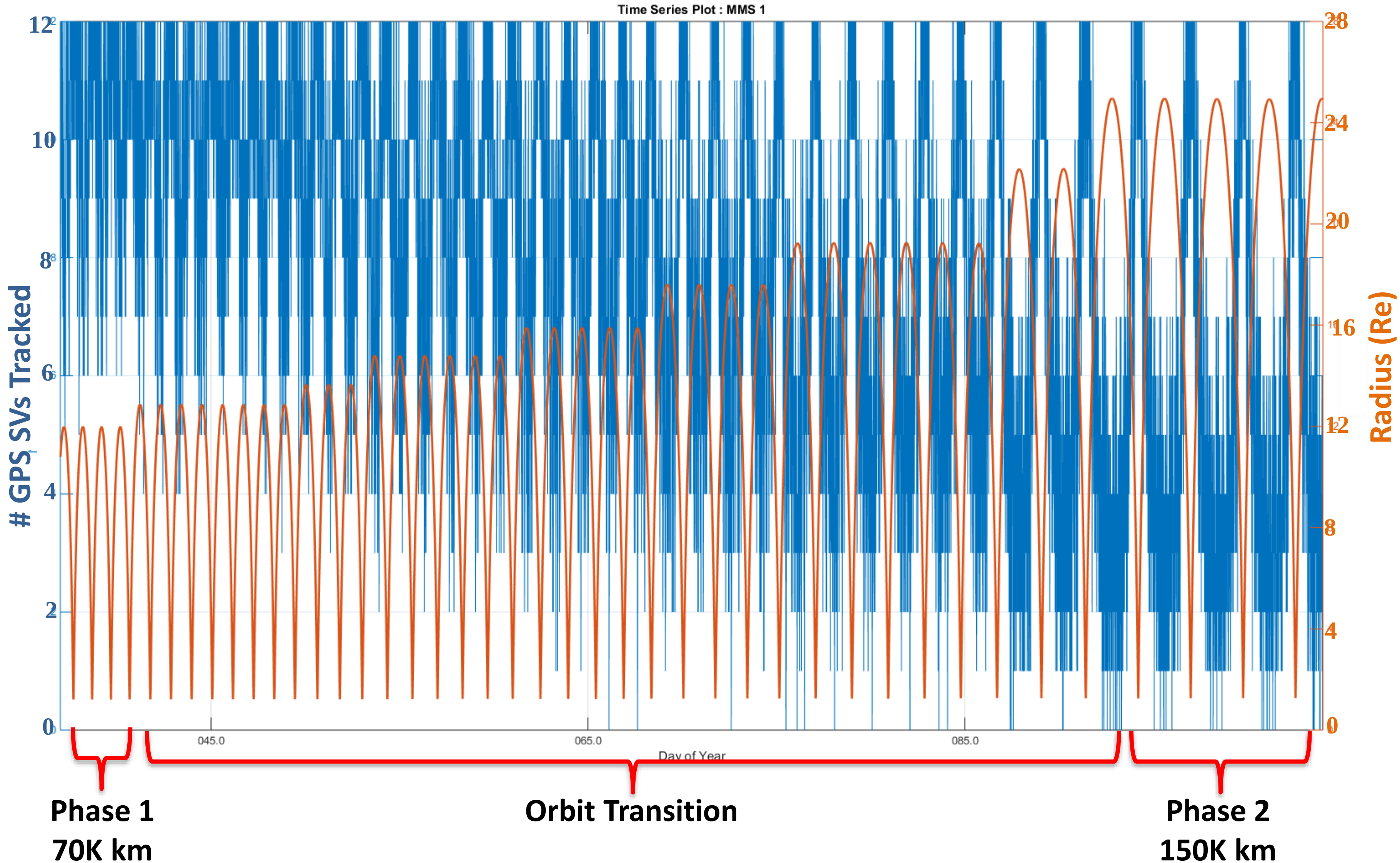
MMS Navigator System

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

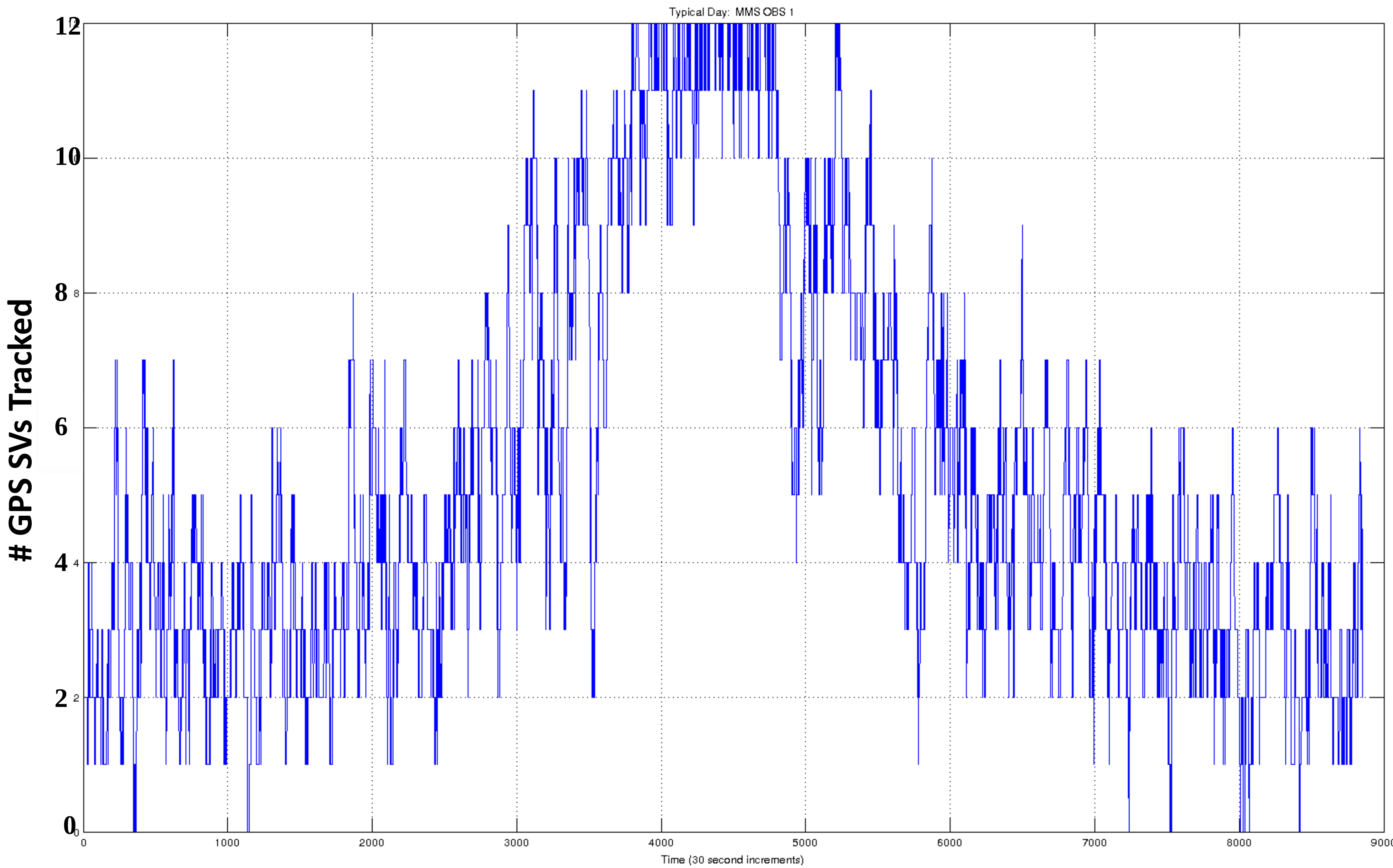




Signal Tracking Performance During Phase 1 to Phase 2 Apogee Raising (70K km to 150K km)



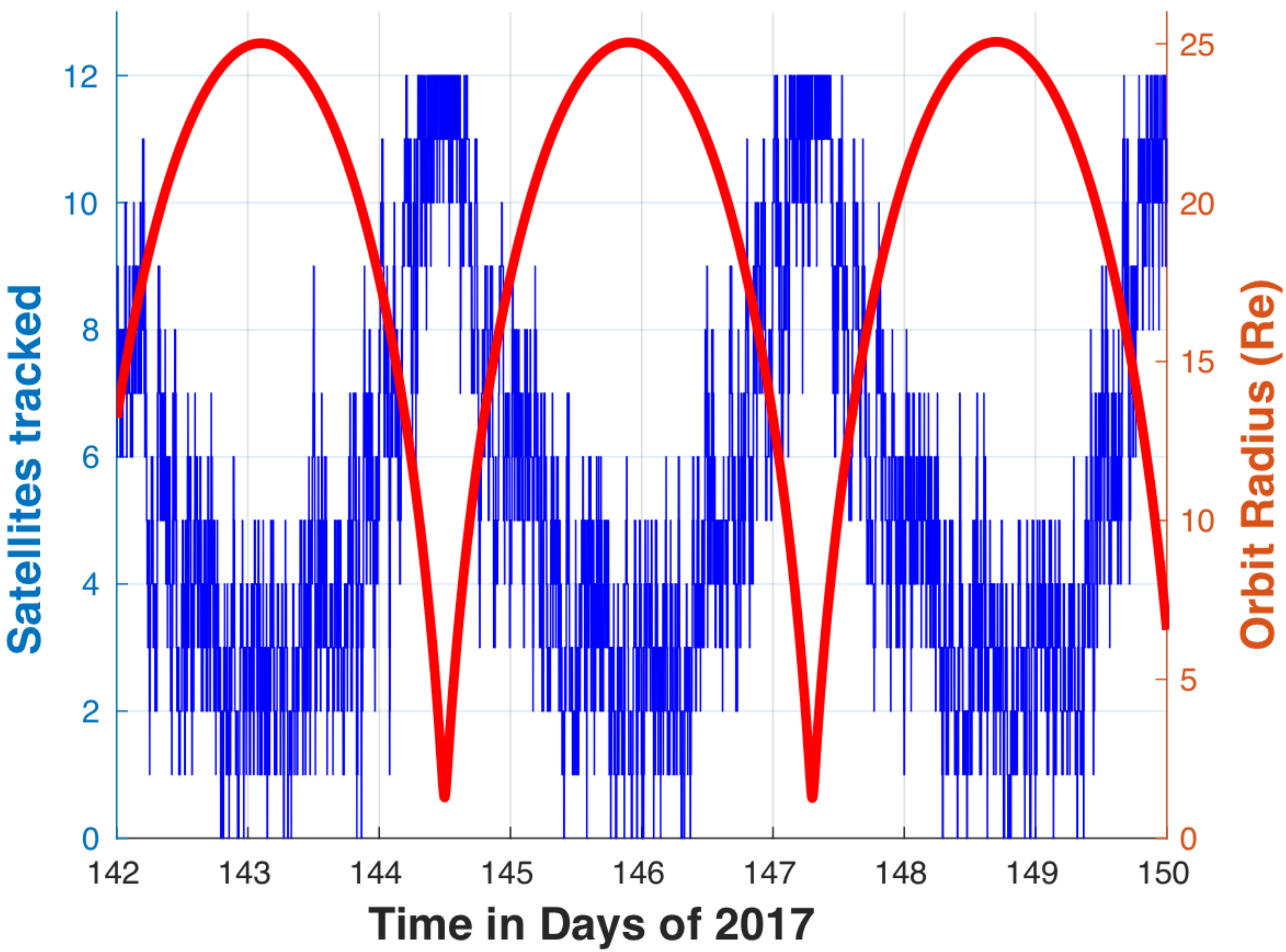
Signal Tracking Performance
Single Phase 2B Orbit (150K km Apogee)



Average Outage: 2.8 mins; Cumulative outage: 22 min over 67 hour orbit (0.5%)

Note: Actual performance is orbit sensitive

MMS GPS Signal Tracking Performance During Phase 2b (Apogee at ~160K km)

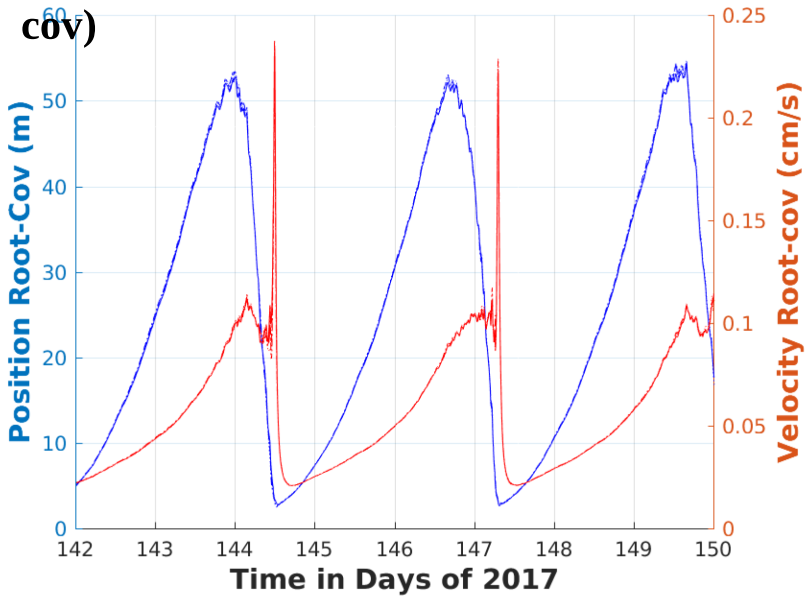


MMS On-orbit Phase 2B Results: Measurement and Navigation Performance

- GEONS filter RSS 1σ formal errors reach maximum of ~50 m and briefly 5 mm/s (typically <1 mm/s)
- Measurement residuals are zero mean, of expected variation <10m 1σ
  - Suggests sidelobe measurements are of high quality
- Science and navigation requirements met with significant margin

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

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



Pseudorange residuals