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NASA GNSS Space Service Volume Update

WG-B—Enhancement of GNSS Performance, New Services & Capabilities

Joel Parker, NASA Goddard Space Flight Center

ICG-11, Sochi, Russian Federation, November 9, 2016



Benefits of GPS/GNSS to NASA

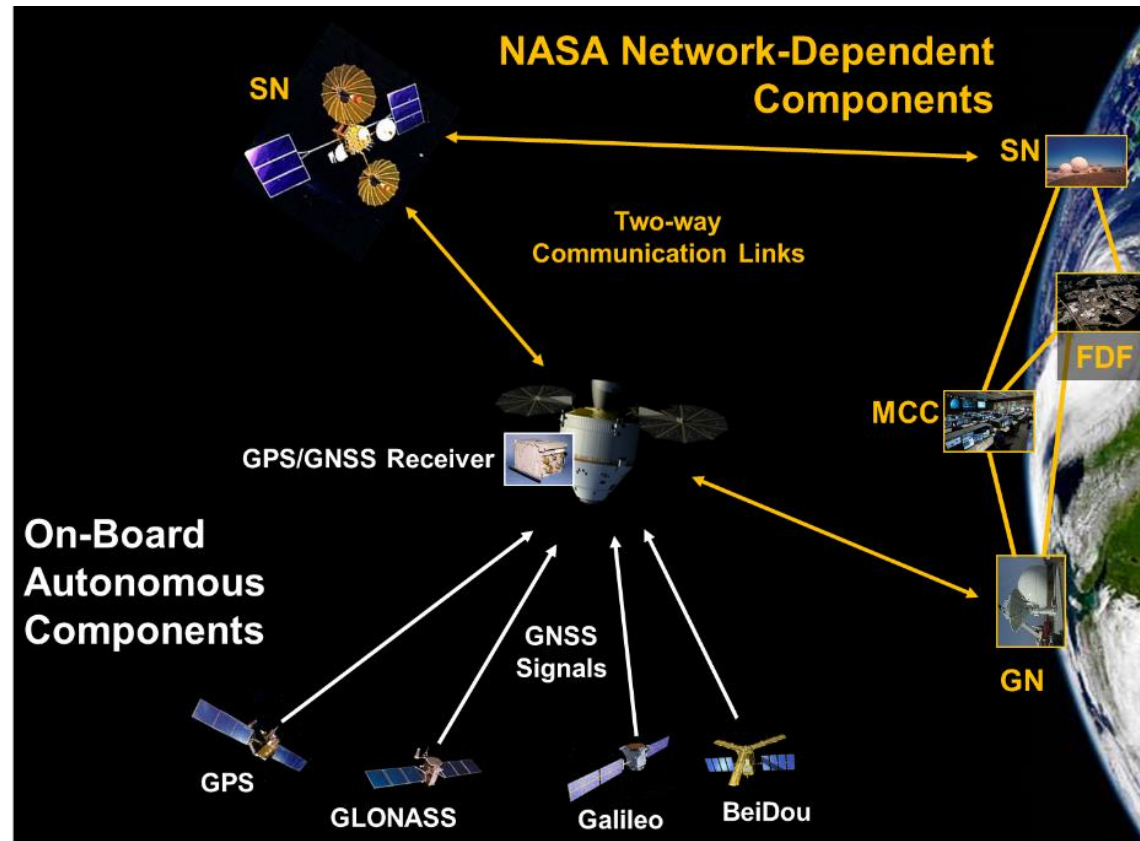


Real-time On-Board Navigation:

Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, GEO satellite servicing

Earth Sciences: GPS used as a remote sensing tool supports atmospheric and ionospheric sciences, geodesy, and geodynamics -- from monitoring sea levels & ice melt to measuring the gravity field

Attitude Determination: Use of GPS/GNSS enables some missions to meet their attitude determination requirements, such as ISS



NASA is investing approximately \$130M over the next 5 years on GPS R&D and its implementation in support of space operations and science applications

GPS capabilities to support space users may be further improved by **pursuing compatibility and interoperability with GNSS** (Global Navigation Satellite Systems), such as the Russian GLONASS, European Galileo, and China's BDS



GPS SSV Specification

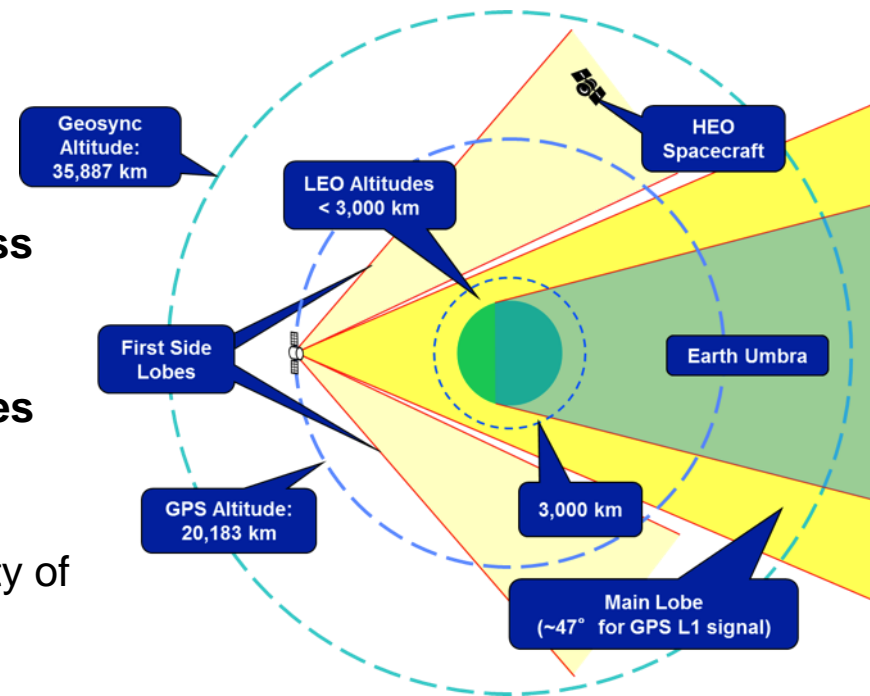
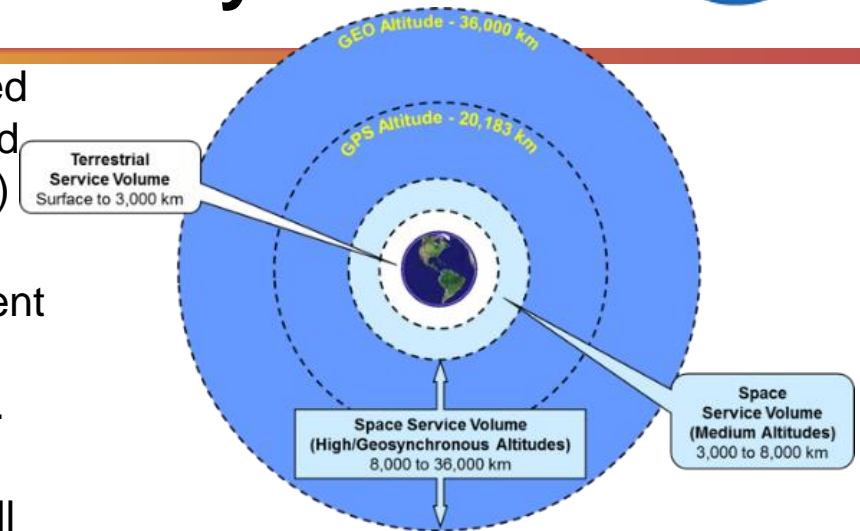
Status Update



GPS SSV Status and Lessons Learned: Executive Summary



- Current GPS SSV specifications, developed with limited on-orbit knowledge, only capture performance provided by signals transmitted within 23.5° (L1) or 26° (L2/L5) off-nadir angle (**Main Lobe Signal**).
- On-orbit data & lessons learned since spec development **show significant PNT performance improvements** when aggregate (**Main and Side Lobe**) signal is used.
- **Numerous** Civil operational missions in High & Geosynchronous Earth Orbit (HEO/GEO) utilize the full signal to enhance vehicle PNT performance
 - **Multiple** civil stakeholders **require** this enhanced PNT performance to meet mission requirements.
- **Failure to protect** aggregate signal performance in future GPS designs creates the risk of **significant loss of capability**, and **inability to further utilize performance** for civil space users in HEO/GEO
- Protecting GPS aggregate signal performance **ensures GNSS parity in the SSV**
- NASA-sponsored initiative underway to **augment current SSV specification** to ensure future availability of capability now achieved via **full, aggregate signal**





Progress Since November 2015 ICG Meeting, Boulder, Colorado, USA



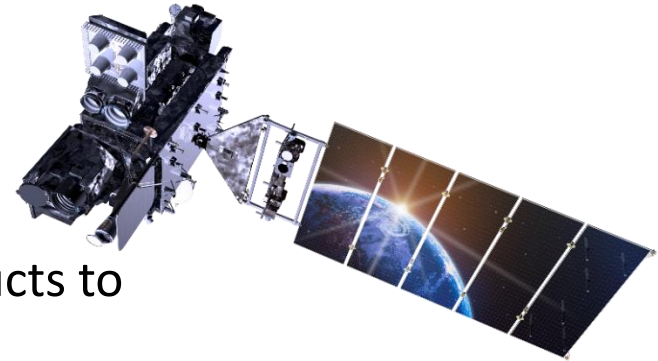
- **Oct 2015–Feb 2016:** NASA and Air Force coordinate through Integrated Forum for Operational Requirements (IFOR) process
 - Monthly IFOR WG meetings w/ NASA and USAF
 - Major deliverables provided by NASA:
 1. **Requirement language**
 2. **Statement of Need**
 3. Analysis of Alternatives (AoA)
 - NASA coordinating with interagency stakeholders for letters of support/commitment
- **8 Feb 2016:** Publication of SSV Conference Paper (AAS GN&C, Breckenridge, CO, USA)
 - Paper: <http://hdl.handle.net/2060/20160001406>
 - Presentation: <http://hdl.handle.net/2060/20160001694>
- **9 Feb 2016:** Final IFOR WG Meeting
 - NASA delivers final products
 - USAF delivers ROM cost estimate for impact to GPS system
- **22 Mar 2016:** IFOR Co-Chair preliminary recommendation meeting
 - USAF requests for clarification on AoA and forward plan leads to IFOR-requested HPT (High Power Team)
- **12–13 Apr 2016:** NASA/USAF HPT
 - Drafting of USAF/NASA Memorandum of Agreement (MoA)
 - Clarification of AoA items
 - Agreement on forward engagement in SV11+ procurement process
- **19 Apr 2016:** Formal NOAA endorsement of NASA requirement
- **18 May 2016:** Brief to PNT Advisory Board
 - Commitment from USAF leadership to reengage
- **TBD:** Final IFOR Co-Chair recommendation meeting



Key Civil Stakeholder: GOES-R



- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellite series
- 2016 Launch; Series operational through 2030s
- Improved Imager (ABI) combined with GPS PNT will be **societal game-changers** delivering data products to substantially improve public and property safety
- PNT driving requirements:
 - **Orbit position knowledge** requirement (right)
 - All performance requirements **applicable through maneuvers**, <120 min/year allowed exceedances
 - Stringent **navigation stability** requirements

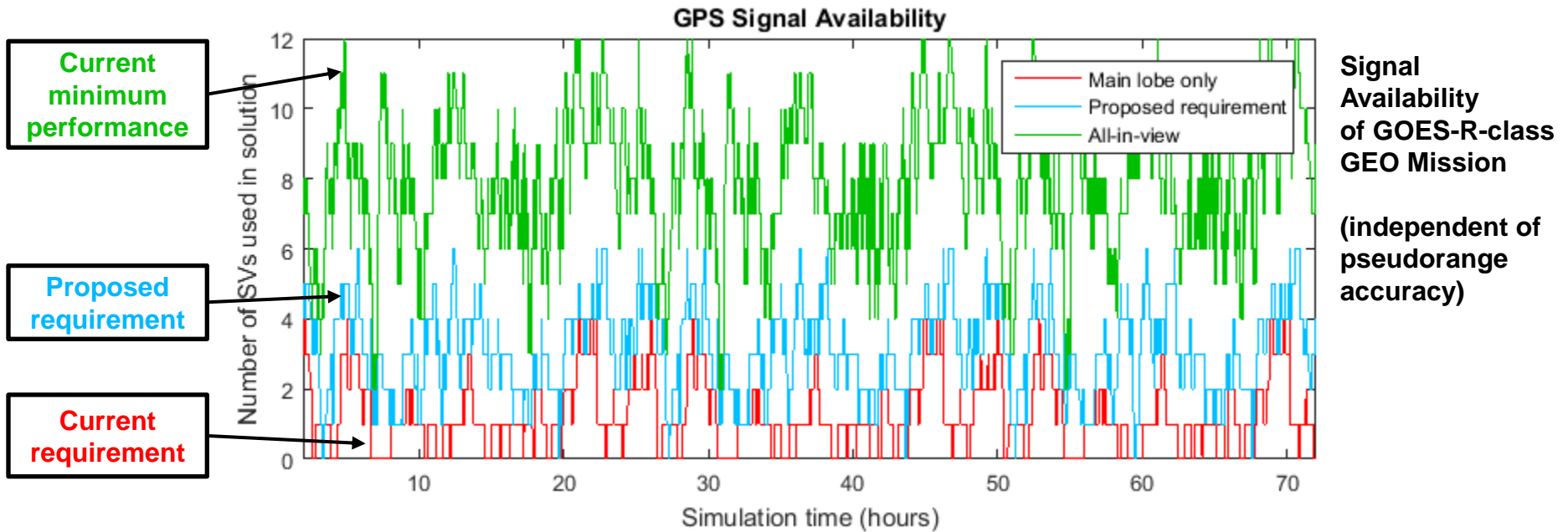


Parameter	Requirement (m, 1-sigma)
Radial	33
In-track	25
Cross-track	25

- GOES-R series **cannot** meet stated mission requirements **with SSV coverage as currently documented**
- NASA-proposed requirement is minimum-impact solution to meet GOES-R performance needs
- NOAA also identifies **EUMETSAT (EU) and Japanese weather satellites** as reliant on increased GNSS signal availability in the SSV



NASA Proposed SSV Requirement Language (in-work)



Signal Availability of GOES-R-class GEO Mission
(independent of pseudorange accuracy)

- Current requirement is a “triad” of three interrelated components:
 1. Signal availability (% of time that 1 or 4 GPS signals are available; max outage time)
 2. Minimum received signal power at GEO
 3. Maximum pseudorange accuracy (equivalent to user range error)
- Proposed requirement adds second tier of capability specifically for HEO/GEO users
 - Increased signal availability to nearly continuous for at least 1 signal
 - Relaxed pseudorange accuracy from 0.8m RMS to 4m RMS
 - No change to minimum received signal power
 - Applies to all signals (L1/L2/L5), all codes

PR acc. (rms)	0.8 m	4m
1+ signal	≥ 80%	≥ 99%
4+ signals	≥ 1%	≥ 33%
Max outage	108 min	10 min

SSV L1 HEO/GEO availability (L2/L5 not shown)



NASA SSV User Segment Status Update



U.S. Initiatives & Contributions to Ensure an Interoperable, Sustained, Quantified GNSS Capability for Space Users






- Receiver development:
 - Developing new weak signal GPS/GNSS receivers for spacecraft in cis-Lunar space through government technology developments (e.g. NASA Goddard Navigator, NavCube) and commercial procurements
- Mission usage:
 - Performing additional flight experiments above the constellation to characterize signals in cis-Lunar space
 - Developing missions and systems to utilize GNSS signals in the SSV (e.g. MMS, GOES, Orion)
 - Educating potential users on capabilities and opportunities available with multi-GNSS SSV
 - GEO Earth-sensing
 - Heliophysics and solar-occulting
 - Commercial SATCOM
 - Formation flying, proximity operations, satellite servicing
 - Beyond-SSV, cis-lunar spacecraft



NASA SSV Users



Mission	Purpose	Orbit Regime	Launch Date
AMSAT-OSCAR 40	Experimental	HEO (1,000×58,000 km)	November 2000
Magnetospheric Multiscale (MMS)	Heliophysics, formation flying	HEO (8,000×77,000 km)	March 2015
GOES-R	Terrestrial & space weather	GEO	November 2016
GOES-S		GEO	2017
Exploration Mission 1 (EM-1)	Lunar technology demonstration	Lunar	September 2018
GOES-T		GEO	2019
GOES-U		GEO	2024




-  Historical
-  On-orbit
-  Future



NASA SSV Users



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GOES-U		GEO	2024

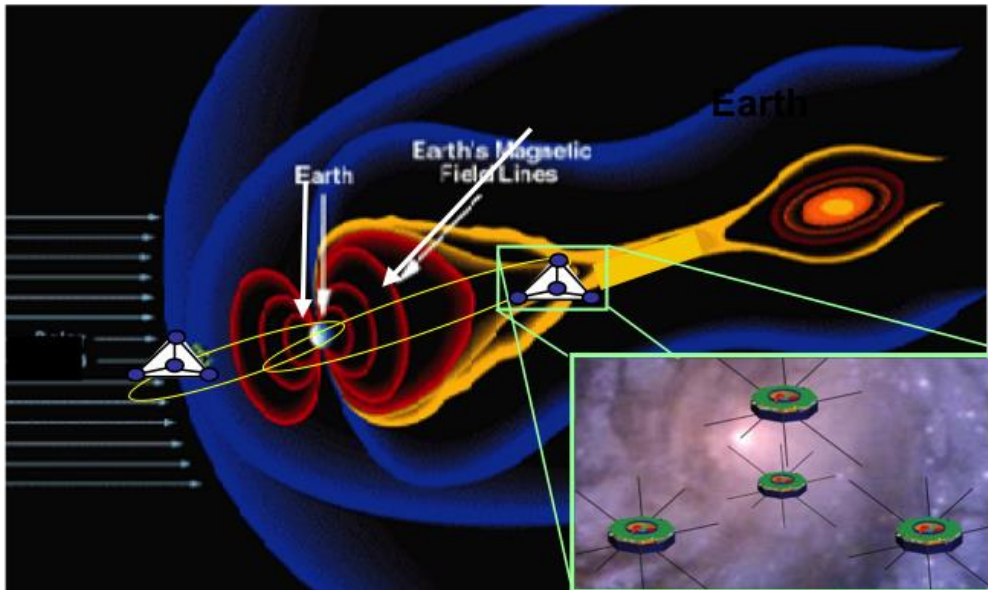
-  Historical
-  On-orbit
-  Future



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 2015
 - Phase 2B 1.2x25 R_E (magnetotail) – Dec/Jan 2017





MMS Navigator GPS Hardware

- MMS uses NASA-developed Navigator weak-signal GPS receiver. Altogether, 8 electronics boxes, 8 USOs, 32 antennas and front ends

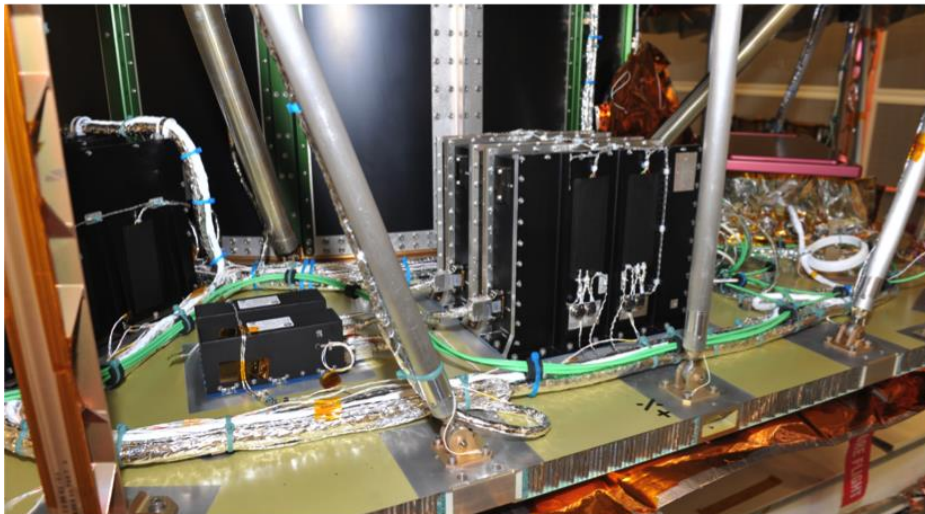
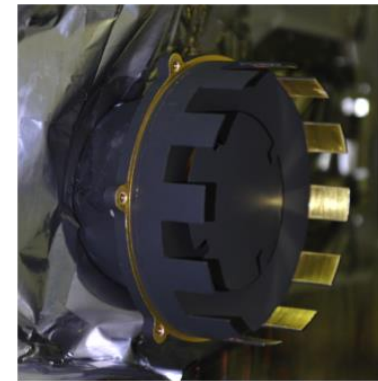
Ultra Stable Osc.



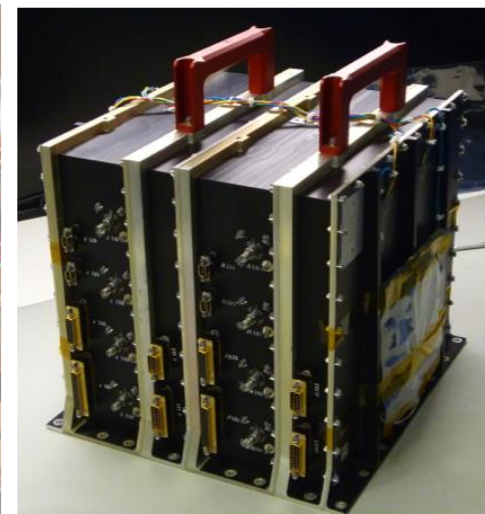
Front end electronics assembly



GPS antenna



Receiver and USO on spacecraft deck



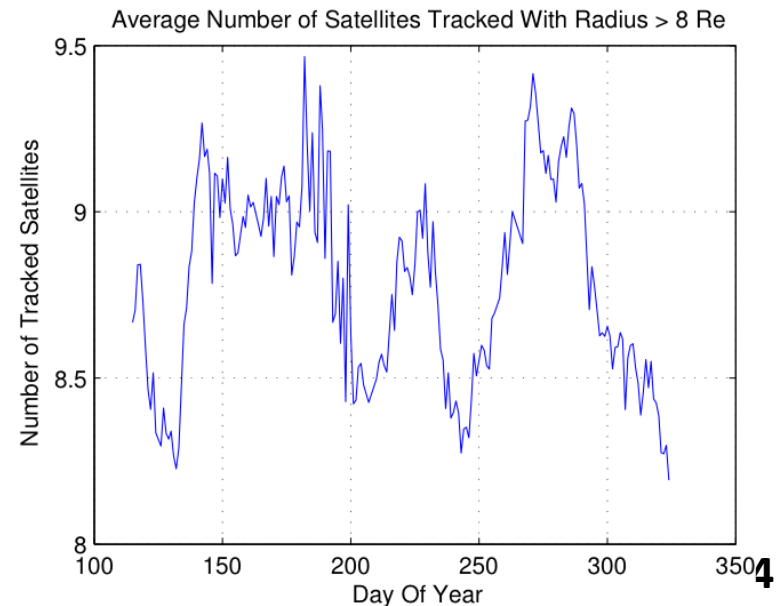
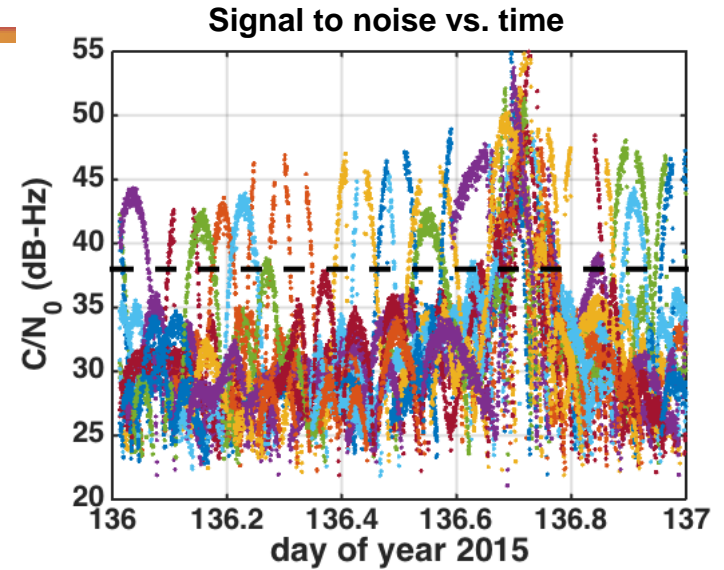
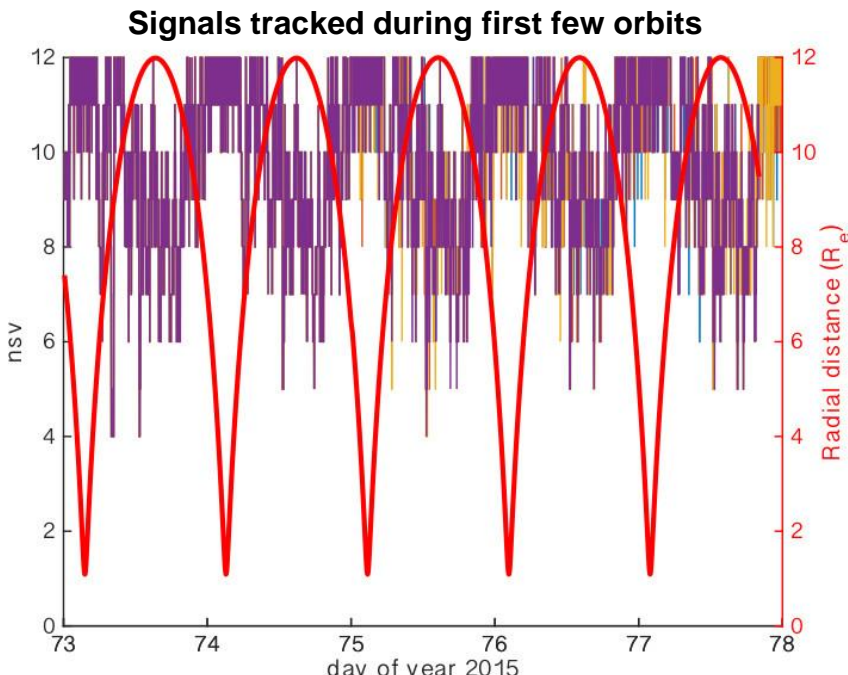
Redundant receiver electronics



Phase 1 Performance: Signal Tracking



- Once powered, receiver began acquiring weak signals and forming point solutions
- Long term trend shows average of >8 signals tracked above $8R_E$
- Above GPS constellation, vast majority of these are sidelobe signals
- Visibility exceeded preflight expectations

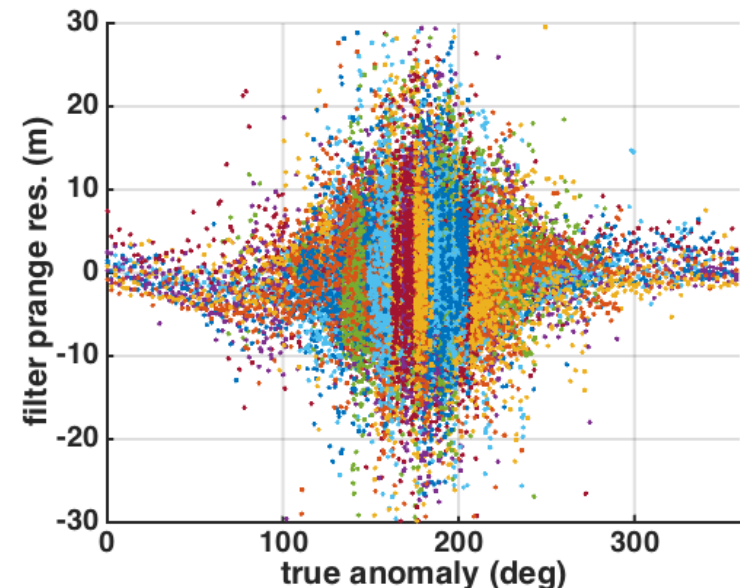
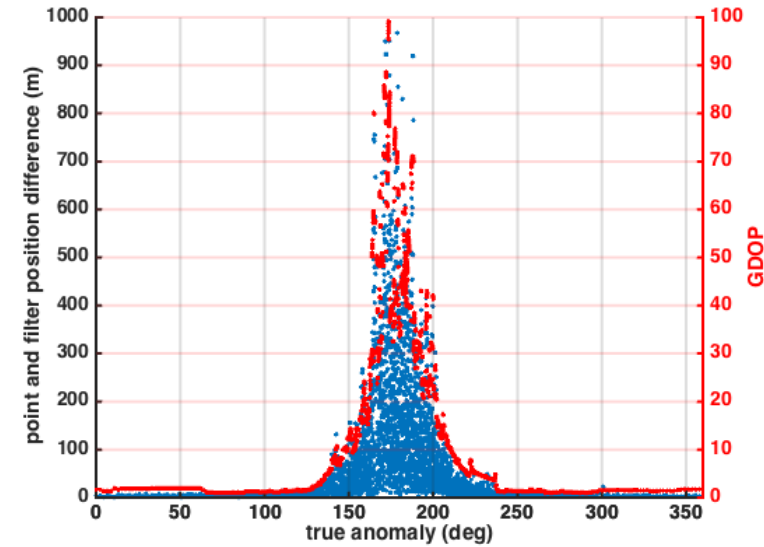
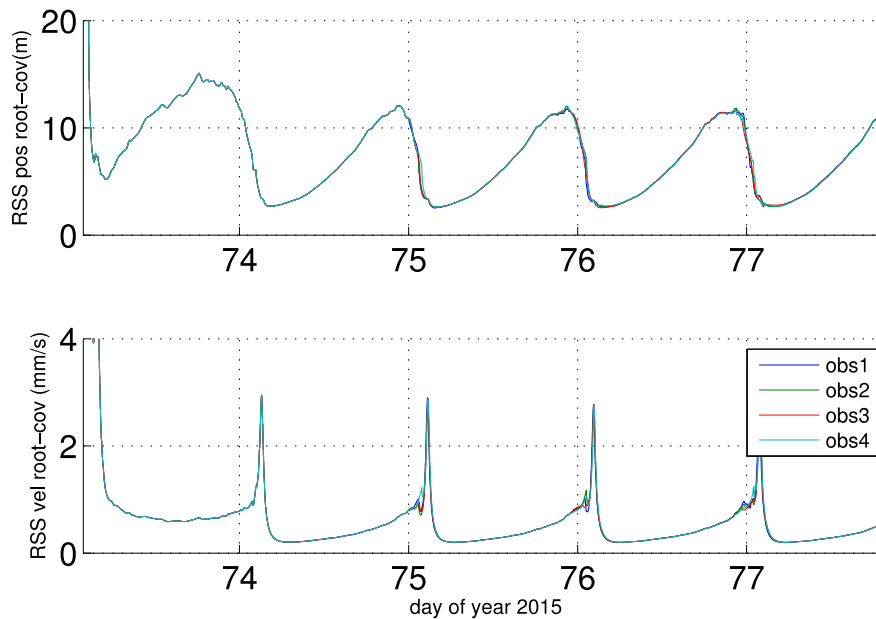




Phase 1 Results: Measurement and Navigation Performance



- GEONS filter RSS 1-sigma formal errors reach maximum of 12m and 3mm/s (typically <1mm/s)
- Although geometry becomes seriously degraded at apogee, point solutions almost continuously available
- Measurement residuals are zero mean, of expected variation. Suggests sidelobe measurements are of high quality.

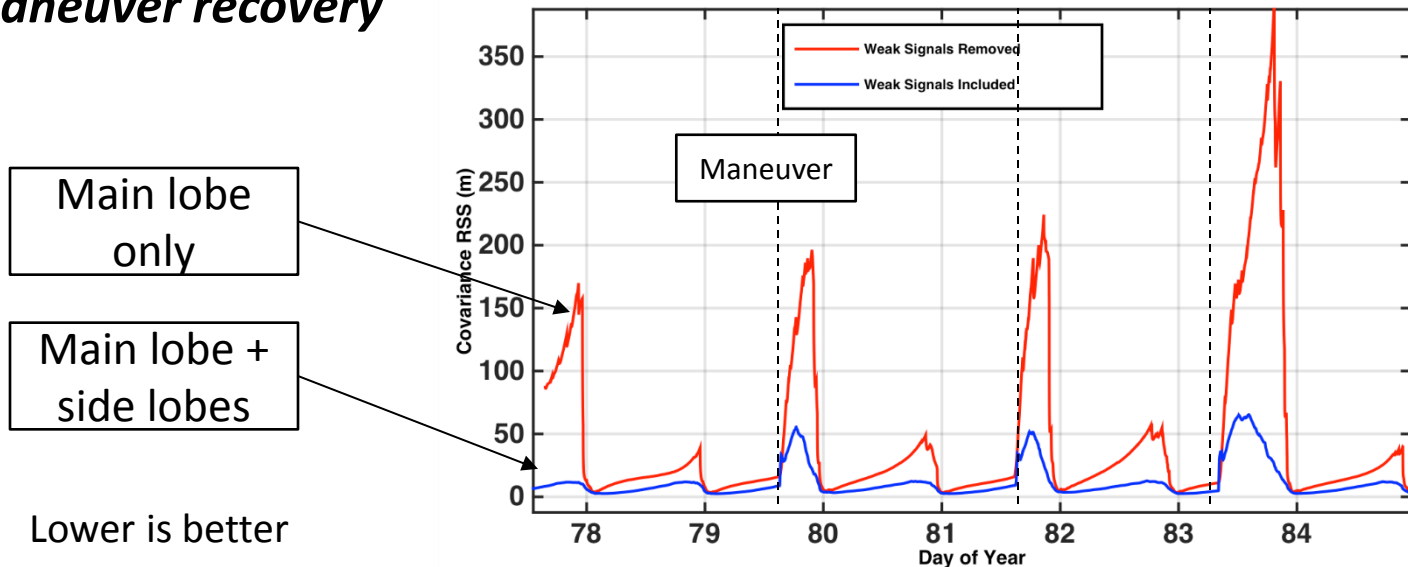




Value of Sidelobes for MMS



- **Simulation study looked at reprocessing flight measurements from MMS Phase 1 through Navigator FSW (w/GEONS) on ground, compared:**
 - Processing all data (matching on-orbit results) **in blue**
 - Removed signals below 38dB-Hz simulating removal of side-lobes **in red**
- **Dataset includes early sequence of four perigee raising maneuvers**
 - Process noise inflated during maneuver window, accelerometer data passed to GEONS
- ***Sidelobes significantly improve initial convergence, peak errors at apogee and maneuver recovery***

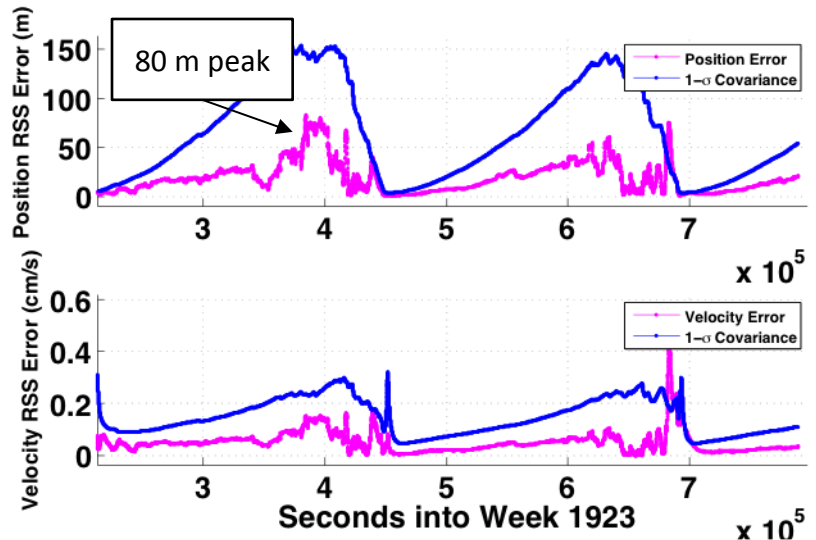
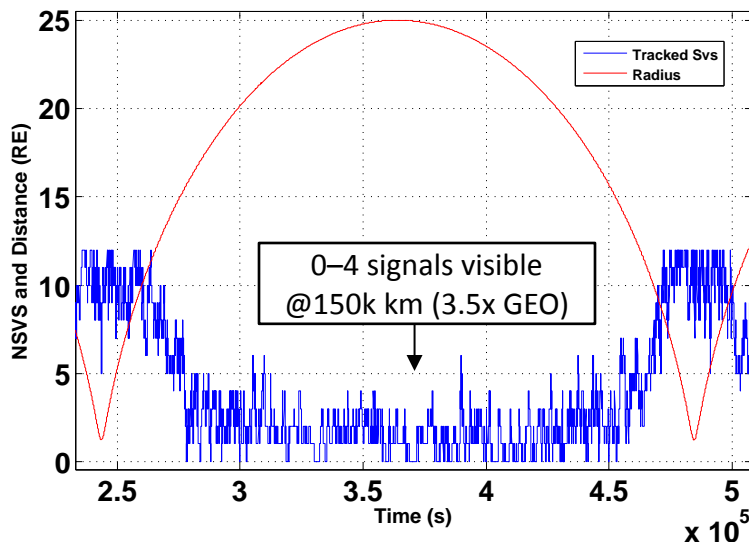




Phase 2B (150K km Apogee) Predicted Performance



- It has become apparent that the MMS preflight simulations had significant conservatism built in.
- Recalibrated MMS Phase 2B hardware-in-the-loop simulations conducted in GPS test lab (FFTB) with MMS EM show improved performance





Interoperable GNSS SSV

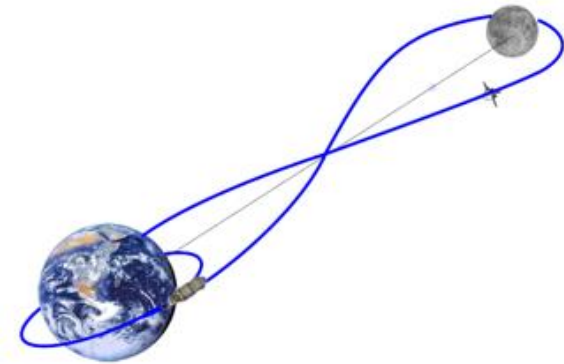
Status and Recommendations



Phase 3 Lunar Mission Setup



Mission	Simplified lunar transfer, similar to Apollo 11, Exploration Mission 1 (EM-1)
Description	Free-return lunar trajectory with optional lunar orbit and return phases
Earth Periapsis	185 km alt
Moon Periapsis	100 km alt
Earth Inclination	32°
Duration	4 d
Attitude profile	Nadir-pointing
Receive antennas	Patch (zenith) + High-gain (nadir)

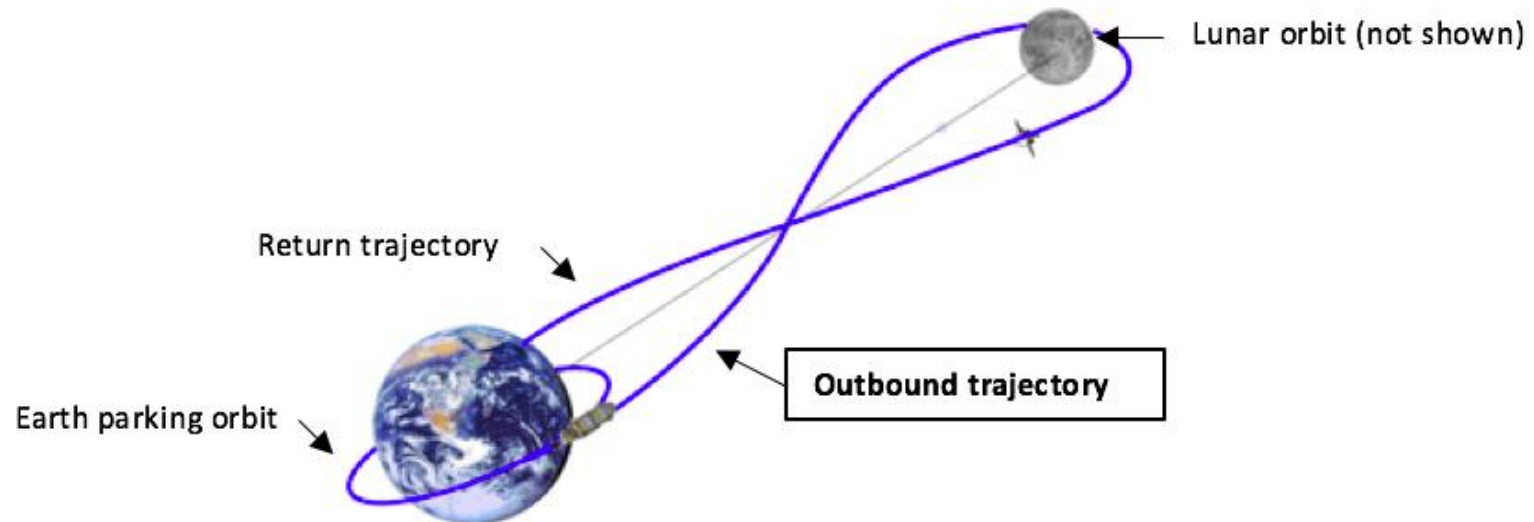




Outbound Trajectory



- Four phases available for analysis:
 - Earth park orbit
 - Lunar transfer
 - Lunar orbit
 - Earth return
- **Recommendation:** Model only outbound trajectory (lunar transfer).
- **Rationale:** Visibility is function of altitude in this scenario; closed orbits are not germane, and return trajectory is expected to show similar behavior as outbound.

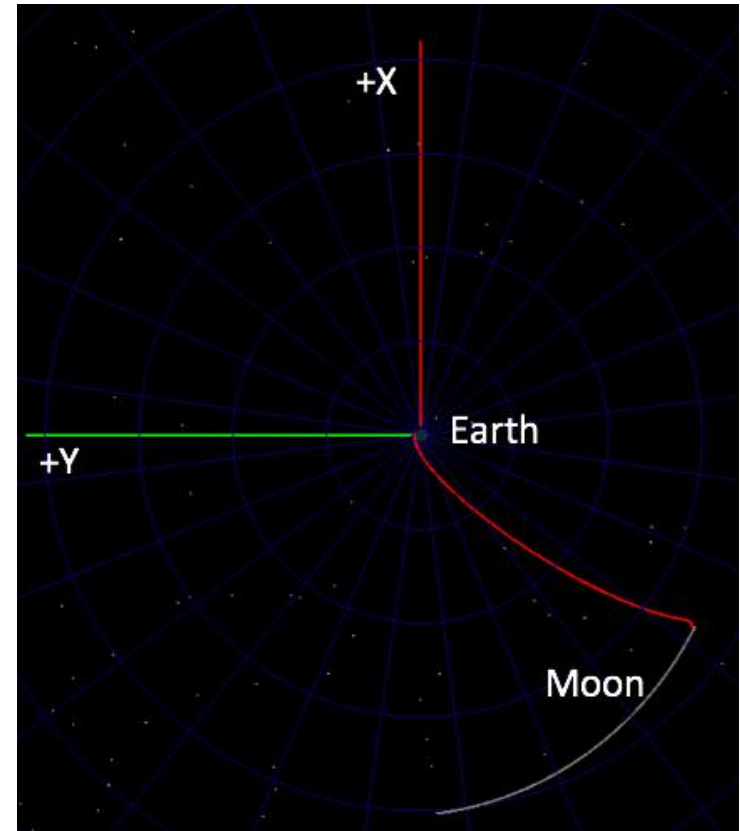




Trajectory & Attitude Ephemerides



- Trajectory
 - Delivered as CCSDS-OEM ephemeris file
 - Can be used with CCSDS-OEM reader, or as a simple 7-column tabular text format with a 21-line header.
 - Fixed-step, 600s, Cartesian pos/vel
 - Modeling and propagating multi-body scenario directly would add unnecessary complexity
- Attitude
 - Body-fixed frame is inertially nadir-pointing
 - Delivered as table of quaternions at 600s interval
 - Simple fixed-width tabular text format
- Both files available on FTP, as well as formal setup document





CCSDS-OEM Example



```
CCSDS_OEM_VERS = 1.0  
CREATION_DATE  = 2016-11-04T14:41:16  
ORIGINATOR     = GMAT USER
```

```
META_START  
OBJECT_NAME      = MoonSat  
OBJECT_ID        = LunarMission  
CENTER_NAME      = Earth  
REF_FRAME        = EME2000  
TIME_SYSTEM      = UTC  
START_TIME       = 2016-01-01T12:00:00.000  
USEABLE_START_TIME = 2016-01-01T12:00:00.000  
USEABLE_STOP_TIME  = 2016-01-05T23:55:45.759  
STOP_TIME        = 2016-01-05T23:55:45.759  
INTERPOLATION    = Lagrange  
INTERPOLATION_DEGREE = 7  
META_STOP
```

```
2016-01-01T12:00:00.000    3.282519067056595e+03    5.360307815880745e+03    ...  
2016-01-01T12:10:00.000   -2.462125251295503e+03    6.273902300408525e+03    ...  
...
```

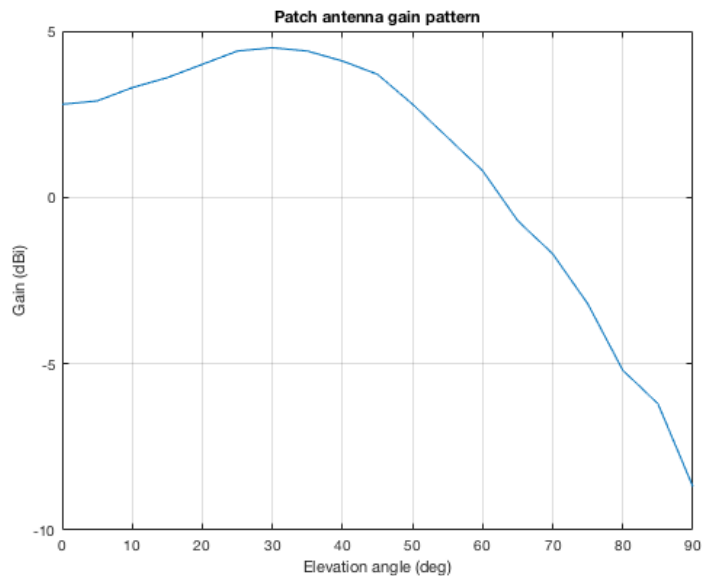


Receiver & Antenna Parameters

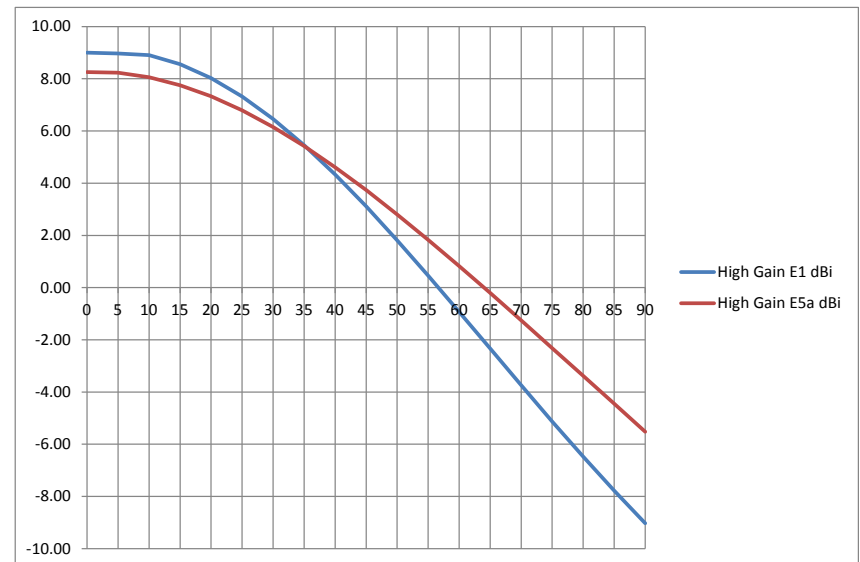


- Two antennas: zenith-pointing for LEO/MEO phase, nadir-pointing for cis-lunar phase
- Acquisition threshold: 20 dBHz

Zenith-pointing patch antenna



Nadir-pointing high-gain antenna





ICG WG-B Observations



- WG-B is making significant progress in establishing an interoperable Global Navigation Satellite System (GNSS) Space Service Volume (SSV) through pre-work, analyses and regularly held teleconferences.
- Co-chair leadership has kept the WG-B team at a high momentum.
- WG-B Analyses underway to solidify understanding of expected HEO/GEO user performance using all provider's SSV signals (BDS, Galileo, GLONASS, GPS, IRNSS, QZSS).
- NASA encourages all providers to support, and continue to support, WG-B initiatives, particularly the current analysis effort. We will go far, if everyone participates.
- Recent ICG WG-B initiatives have led some providers (e.g. EU) to perform government studies to investigate best approaches for development and specification of SSV within their constellations. This should be encouraged and expanded to all providers.
- WG-B is “home” to critical development, specification, and outreach of the SSV, a truly revolutionary concept that is just beginning to be realized.



ICG SSV Outreach Activities



- 31 Dec 2016: SSV Booklet v1.0
- 14–18 Mar 2017: Munich Satellite Navigation Summit
- 25–29 Sep 2017: (Proposed) International Astronautical Congress

- Proposal: joint conference paper on SSV capabilities and analysis
- Venue: International Astronautical Congress 2017, Adelaide, Australia
- Milestones:

Abstract development	14	31-Jan-17
Final abstract for review	14	14-Feb-17
Abstract due		28-Feb-17
Paper development	60	27-Apr-17
Peer review	14	26-Jun-17
Paper revisions	30	10-Jul-17
Final paper for review	30	9-Aug-17
Paper submission		8-Sep-17



US Team Recommendations to GNSS Providers



Recommendation #1:

WG-B should maintain and publish a database of GNSS space users, including those within the Space Service Volume, with contributions from all WG-B providers and observers, and externally via the IOAG liaison.

The data included in the database should include:

- Basic details:
 - Mission name & agency
 - Actual or planned launch date
 - Development phase (planned, in development, on-orbit, historical)
 - Orbit regime (LEO, HEO, GEO, cis-lunar, etc.)
- GNSS usage:
 - GNSS constellations used
 - GNSS signals used
 - GNSS application (navigation, POD, time, radio occultation, etc.)
 - Acquisition methods used (traditional, carrier phase)
 - Solution method (point solution, filtered solution, etc.)



Example:

IOAG GNSS Missions Reference Tables



- The GNSS Missions Reference Tables were initially prepared for the Interagency Operations Advisory Group (IOAG), and last updated for the International Committee on GNSS (IGS) on May 13, 2014
- These tables include: (1) Sponsoring Agency; (2) Mission Name; (3) GNSS System/s used; (4) GNSS Signal/s Used; (5) GNSS Applications; (6) Orbit, and; (7) Launch Date

– Example - International Space Station (ISS):

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
51	NASA	ISS	GPS	L1 CIA	Attitude Dynamics	LEO	Since 1998	Honeywell SIGI receiver

- **We are now requesting** that IOAG member agencies confirm and/or update the mission data in these tables in preparation for the upcoming ICG-10 meeting
- The objective for these reference tables is to ensure the space user community has access to GNSS signal performance data for mission planning
- Space agency stakeholders have the opportunity to provide user requirements to GNSS/PNT service providers now -- before Performance Standards and Interface Specifications are finalized.
- Space agencies are positioned to help GNSS service providers plan for provision of PNT signals to support space users out to GeoSynchronous Orbit altitudes
- NASA recommends that space agencies define and communicate their space user performance needs to their respective GNSS constellations service providers
- Providing this information to the ICG helps to document user needs, furthers IOAG objectives on interoperability, and provides a forum with policy makers on implementation of such capabilities



US Team Recommendations to GNSS Providers



Recommendation #2:

Recognizing the success of WG-B in encouraging all providers to provide basic SSV service details in templates for their constellations, global mission users now have the data necessary to determine if the SSV service is applicable to their needs. In order to fully support mission-specific navigation studies utilizing GNSS, WG-B further encourages the providers to publicly document the following additional data:

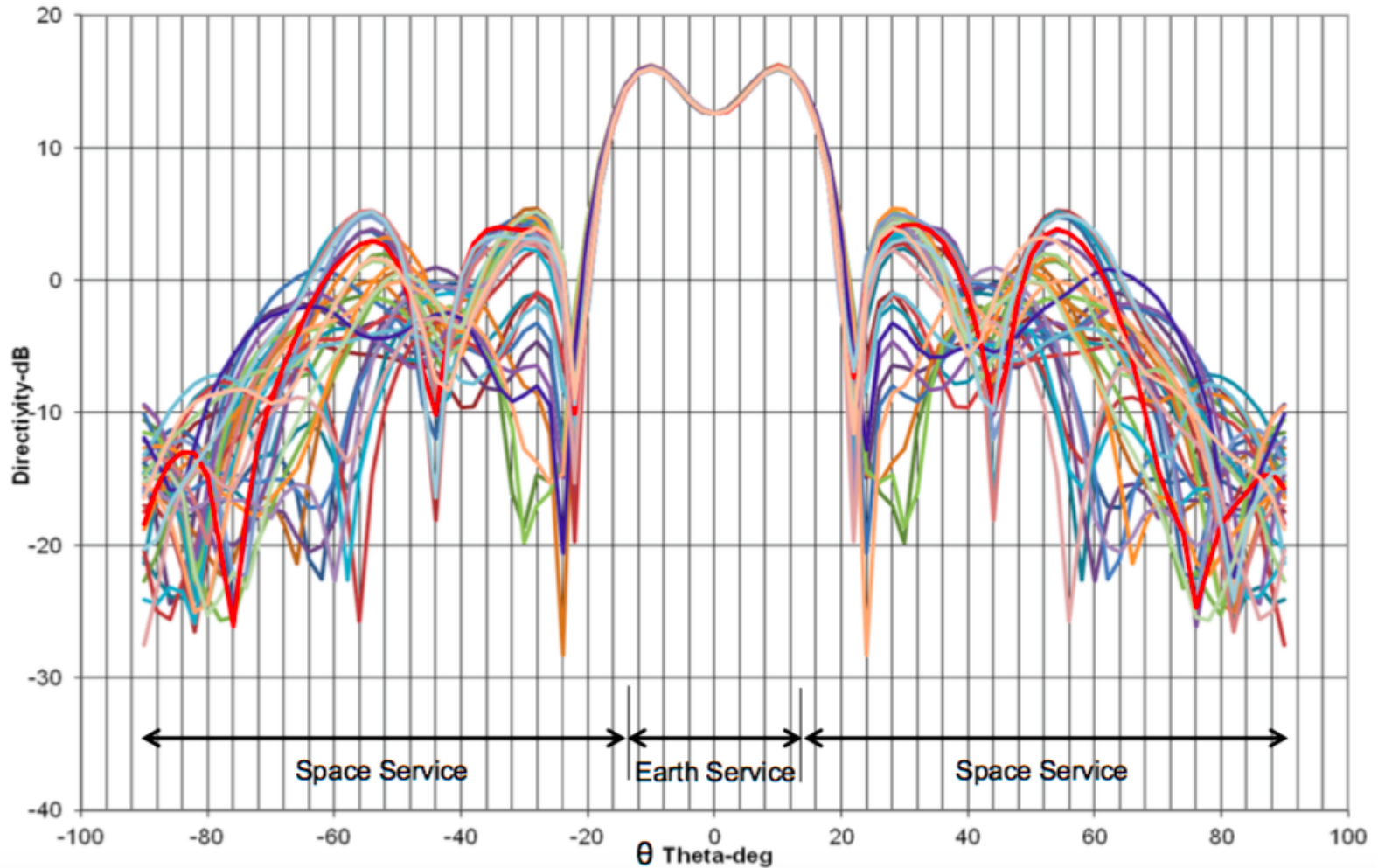
- GNSS transmit antenna gain patterns for each frequency, measured by antenna panel elevation angle at multiple azimuth cuts, at least to the extent provided in each constellation's SSV template
- GNSS transmit antenna phase center and group delay patterns for each frequency
- GNSS nominal or minimum transmit power, without considering the antenna gain, but after considering any transmission losses inherent to the system



Gain Pattern Example



Average IIR L1 roll pattern, Phi cuts every 10 deg





US Team Recommendations to GNSS Providers



Long-term recommendations:

1. Baseline SSV specifications as part of all future constellation developments with definitions and parameters that are common across all provider constellations
 - Specification should strive to capture near-continuous availability such as what may be provided by the aggregate GNSS signal (main & side lobes)
2. Providers should perform a comprehensive series of antenna tests and power output measurements, pre-flight, to:
 - Characterize constellation gain and pseudorange accuracy for the full antenna pattern and to facilitate understanding of SSV specification margins
 - Enable mission designers to derive mission PNT performance of spacecraft in the SSV through mathematical models developed from antenna/power data
3. Perform on-orbit characterization & testing of SSV specified signal parameters through dedicated flight experiments and mission data evaluation
4. Encourage development of spacecraft and formation flying missions in the SSV
5. Encourage active and consistent participation in all ICG SSV activities and initiatives, including the current interoperable GNSS analyses



Closing Remarks



- NASA and all other space users increasingly rely on GNSS over an expanding range of orbital applications to serve Earth's population in countless ways
- Current and future space missions in SSV orbits are becoming increasingly reliant on near-continuous PNT sensing using GNSS
- To ensure stable, robust PNT in the SSV, providers should:
 - Baseline SSV specifications as part of all future constellation developments using ICG-developed common definitions & parameters
 - Specification should strive to capture near-continuous availability such as what may be provided by the aggregate GNSS signal (main & side lobes)
- WG-B is making significant progress in establishing an interoperable Global Navigation Satellite System (GNSS) Space Service Volume (SSV) through pre-work, analyses and regular meetings
- NASA and the USG is 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



Backup Charts



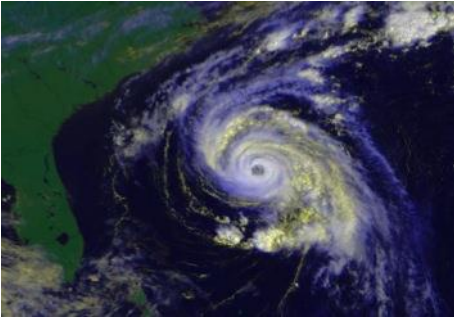


The Promise of using GNSS for Real-Time Navigation in the Space Service Volume

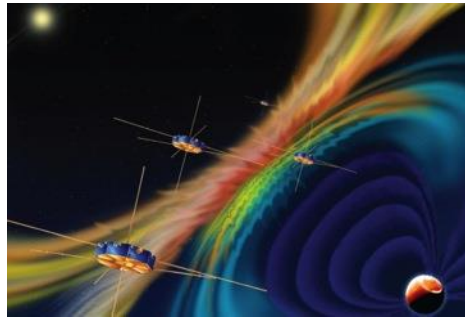


Benefits of GNSS use in SSV:

- 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



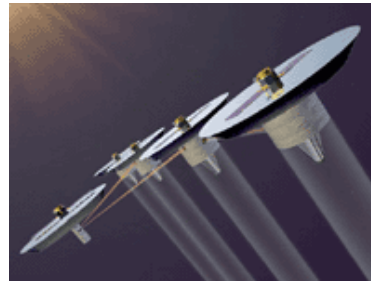
Space Weather Observations



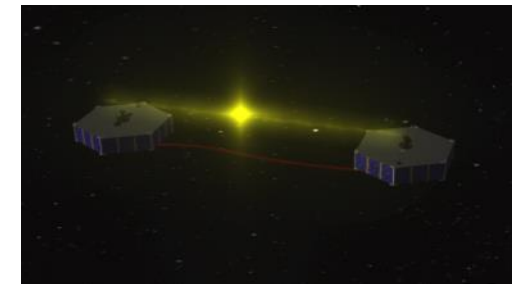
Precise Relative Positioning



Launch Vehicle Upper Stages
and Beyond-GEO applications



Formation Flying, Space Situational
Awareness, Proximity Operations



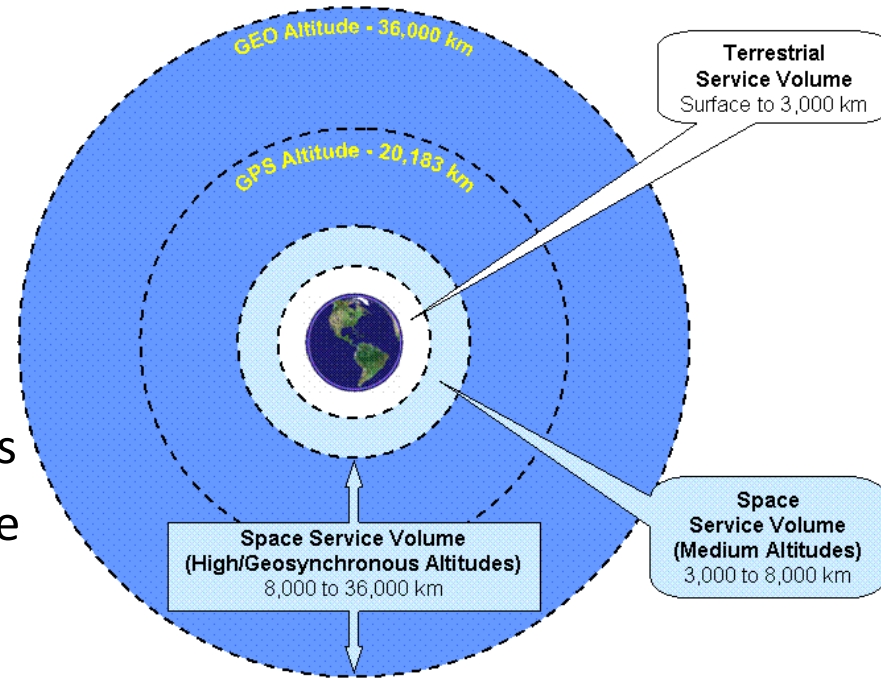
Precise Position Knowledge
and Control at GEO



More Resilient PNT Solutions In-Space through an Interoperable Multi-GNSS SSV



- At least four GNSS satellites in line-of-sight are needed for on-board real-time autonomous navigation
 - GPS guarantees this up to 3,000 km altitude
 - Meter-class real-time position accuracy
- At GEO altitude, an average of 1-2 GPS satellites will be available using only GPS main lobe signal with some long data outages
- GPS-only positioning possible using main lobe signal-only with on-board filtering, but very limited and with long waits for navigation recovery after trajectory maneuvers
- **GPS + Galileo + GLONASS + BDS + IRNSS + QZSS** would enable near-continuous visibility of four main-lobe GNSS signals on L1 frequency band or continuous visibility using L5 frequency band with 10 meter-class real-time position accuracy



To accomplish this requires:

- GNSS interoperability; and
- Common definitions & specifications for use of GNSS signals within the SSV
- **Further improvements could be realized if GNSS systems specify aggregate (Main and Side lobe) signal availability**



Statement of Need: GOES-R Spacecraft Series Issue Summary

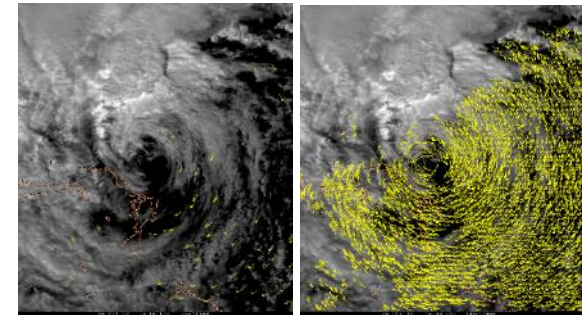


- GOES-R-U series operational weather satellites of national importance, protecting people and property through weather prediction and severe event warnings
- New, improved Imager (ABI) combined with near-continuous GPS PNT will have **game-changing** societal benefits with enhanced temporal, spatial, spectral & radiometric attributes
- GPS/GOES nav. stability & geolocation requirements critical to derive first & second derivative wind measurements, significantly improving wind velocity estimations
- Safety of people/property data products **requiring** the NASA-proposed (improved) SSV specification include:
 - Improved wind vector measurements—significantly enhancing convective (severe) storm prediction & danger zone warning time
 - Exact location & volume of mountain downpours—improves flash flood warnings
 - Timely, precise location of wild fires—enables safe placement of firefighters & equipment
 - More accurate prediction of early morning fog for aviation
 - Better prediction of mountain weather where radar is ineffective
 - Blending GEO-sat (high temporal resolution), LEO-sat (high spatial resolution) & ground-based radars for more accurate prediction
 - Improved weather forecasting from 3-5 days (now) to 5-7 days (GOES-R)

Assembled GOES-R Spacecraft



Wind Vector Measurements
Hurricane Sandy



Current

GOES-R

Safety of People/Property Data Products Will Not Be Operationally Delivered if GPS Degrades Capability to Current GPS SSV Spec; Minimally Met Through Proposed SSV Spec



Progress on Key Issues



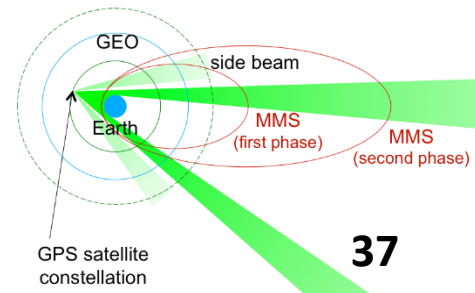
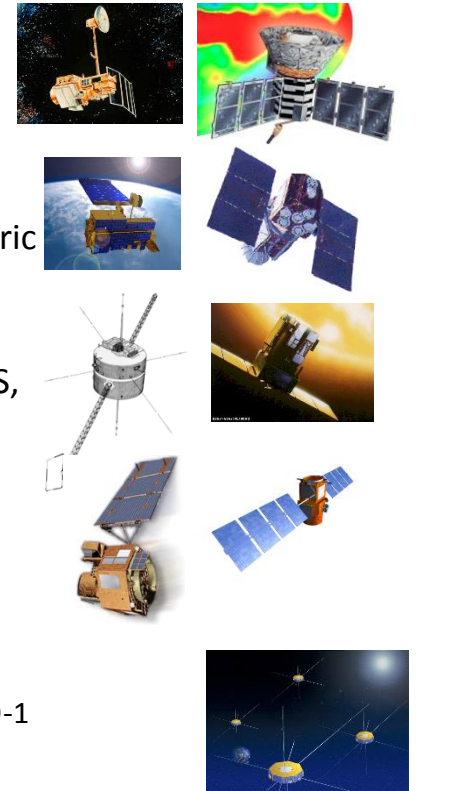
- **NASA & USAF partnership on implementation**
 - Joint NASA/USAF Memorandum of Agreement in coordination
 - Defines roles & responsibilities for NASA and USAF through requirements definition and acquisition process
- **Ensuring navigation resiliency**
 - NASA-proposed requirement is intended to protect use of critical GPS capabilities for space users in HEO/GEO
 - Effort is not intended to establish GPS as a space user's only navigation solution
 - Resiliency is ensured through space vehicle applications of complementary PNT solutions – RF, optical, INS, etc.



Goddard's Enhanced Onboard Navigation System (GEONS)



- **UD-factorized Extended Kalman Filter, 4th/8th order RK integrator, realistic process noise models**
- **Estimation state:** Absolute and/or relative position and velocity vectors for multiple satellites, clock states, drag and SRP coeff corrections, measurement biases
- **Dynamic models:** High fidelity geopotential, solar system bodies, Harris-Priester atmospheric density, SRP with spherical or multi-plate area models, measured accelerations, impulsive delta-V maneuver model
- **Measurement types:** GPS differenced/undifferenced, WAAS, differential corrections, TDRSS, Ground station, Crosslink, Celestial object line of sight, XNAV
- **Development history**
 - Ground-based experiments on Landsats 4 & 5, COBE (1980s) onboard exp. EUVE (1990s)
 - TDRSS Onboard Navigation System (TONS): operational onboard OD for Terra 1999-current
 - Enhanced Onboard Navigation System (EONS) = TONS + GS meas on GD Command Receiver
 - Celnav tested on the ground with POLAR and SOHO data
 - TONS -> GPS for GPS Enhanced Orbit Determination Experiment (GEODE) on Lewis (1996), follow on EO-1 and licensed to industry flown on Microstars, Orbviews, SORCE, CALIPSO ++
 - XNAV measurement model added for NICER/SEXTANT demonstration (2016 launch)
 - **GEONS = GEODE + EONS + Celnav + XNAV**
- **MMS GEONS**
 - Estimate absolute pos/vel, clock bias, rate & accel, integrator step 10s
 - 13x13 geopotential, sun, moon point mass, SRP, drag
 - Process L1 C/A GPS undifferenced pseudorange at 30s rate
 - Accelerometer data at 10s during maneuver





Example Performance: Side Lobe Signal Availability

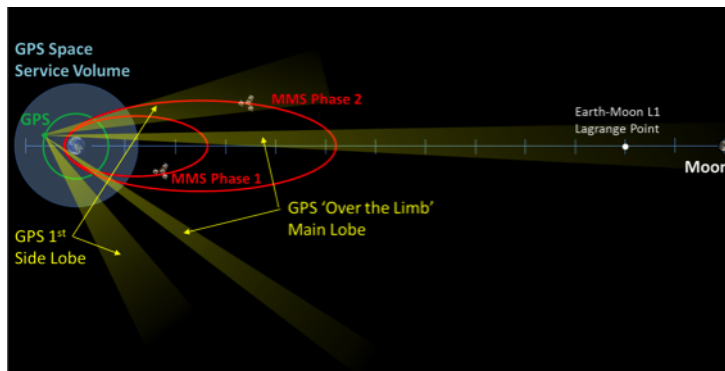


Signal Availability Contributed by Side Lobes (Assumes 24 Satellite Constellation)

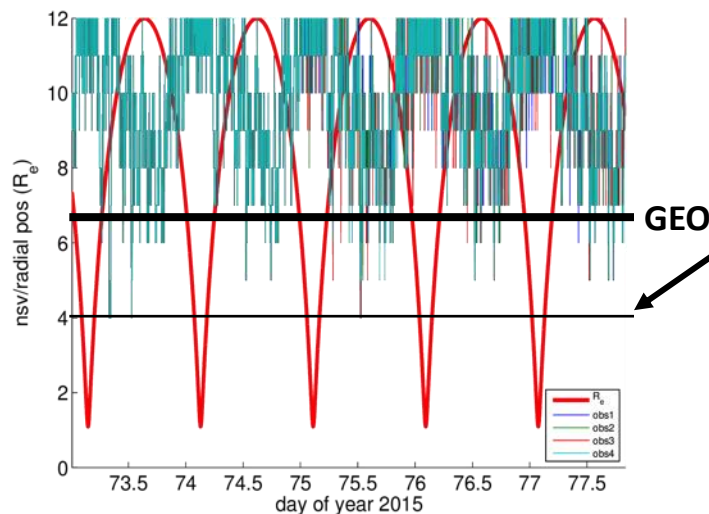
<u>L1 Signal Availability</u>	<u>Main Lobe Only</u>	<u>Main and Side Lobes</u>
4 or More SVs Visible	Never	99%
1 or More SVs Visible	59%	100%
No SVs Visible	41%	Never

Current Spec (L1 Signal Availability): 4 or more SVs visible: >1%

Recent Flight Data From Magnetosphere Multi-Scale (MMS) Mission



**MMS Phase 1: $1.2 \times 12 R_e$ orbit
(7,600 km \times 76,000 km)**



Current spec:
Four or more PRs shall be available more than or equal to 1% of the time.

MMS is seeing 100%.



GPS Space Service Volume Specification History



- **Mid-1990s**—efforts started to develop a formal Space Service Volume
 - Discussion/debate about requiring “backside” antennas for space users
 - Use of main lobe/side-lobe signals entertained as a no cost alternative
- **1997-Present**—Several space flight experiments, particularly the AMSAT-OSCAR-40 experiment demonstrated critical need to enhance space user requirements and SSV
- **February 2000**—GPS Operational Requirements Document (ORD), released with first space user requirements and description of SSV
 - Shortcomings
 - Did not cover mid-altitude users (above LEO but below GPS)
 - Did not cover users outside of the GEO equatorial plane
 - Only specified reqts on L1 signals (L2 and L5 have wider beam-width and therefore, better coverage)
- **2000-2006**—NASA/DoD team coordinated updated Space User reqmnts
 - Worked with SMC/GPE, Aerospace support staff & AFSPACE to assess impacts of proposed requirements to GPS-III
 - Government System Spec (SS-SYS-800) includes threshold & objective reqmnts
 - Shortcomings:
 - Developed with limited on-orbit experiment data & minimal understanding of GPS satellite antenna patterns
 - **Only specifies the main lobe signals, does not address side lobe signals**



Key Endorsements



USAF SMC/SY (Space Superiority Systems)

- Letter of endorsement signed by Col Garrant, 26 Feb 2016.
- SMC/SY has documented program requirement.
- Requirement is unfunded at this time.
- SY currently performing analyses to document their actual required capability levels as compared to NASA's proposed IFOR requirement.

NOAA

- Letter of endorsement from VADM Manson Brown (NOAA Deputy Administrator) to Gen Hyten & Maj Gen Thompson, 19 Apr 2016
- Confirms that GOES-R is reliant on GPS signals as captured in NASA's proposed IFOR requirement
- Additionally, identifies EUMETSAT (EU) and Japanese weather satellites as reliant on increased signal availability



Using GPS above the GPS Constellation: NASA GSFC MMS Mission

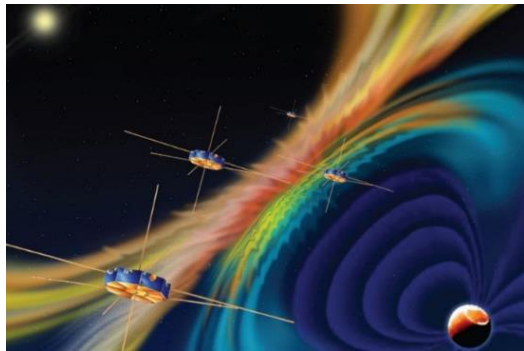
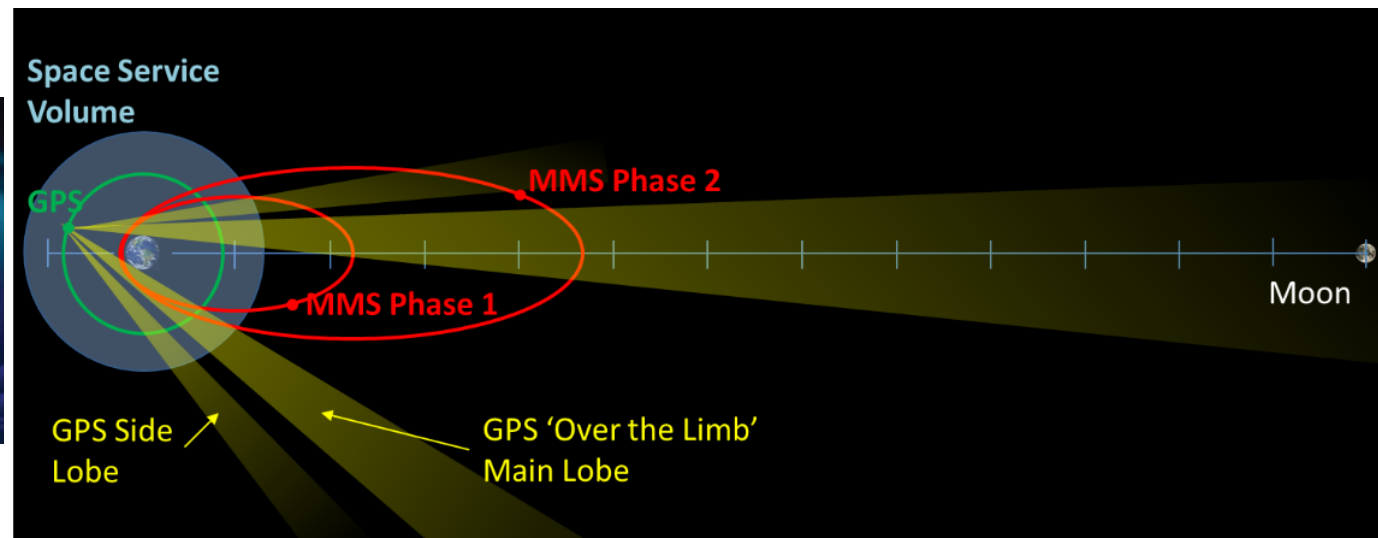


Magnetospheric Multi-Scale (MMS)

- 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 (R_E) Orbit (7,600 km x 76,000 km)
 - Phase 2: Extends apogee to 25 R_E (~150,000 km)

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 Guinness 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 Guinness world for fastest operational GPS receiver in space, at velocities over 35,000 km/h





MMS Navigation



- **MMS baselined GSFC Navigator + GEONS Orbit Determination (OD) filter software as sole means of navigation (mid 2000's)**
 - Original design included crosslink, later descoped
- **Trade vs. Ground OD (2005)**
 - Estimated >\$2.4M lifecycle savings over ground-based OD.
 - Enhanced flexibility wrt maneuver support
 - Quicker return to science after maneuvers
- **Main challenge #1: Sparse, weak, poorly characterized signal signal environment**
 - MMS Navigator acquires and tracks below 25dB-Hz (around -178dBW)
 - GEONS navigation filter runs embedded on the Navigator processor
 - Ultra stable crystal oscillator (Freq. Electronics, Inc.) supports filter propagation
- **Main challenge #2: Spacecraft are spin stabilized at 3RPM with obstructions on top and bottom of spacecraft**
 - Four GPS antennas with independent front end electronics placed around perimeter achieve full sky coverage with low noise
 - Receiver designed to hand off from one antenna to next every 5s

