GPS Space Service Volume (SSV)

Ensuring Consistent Utility Across GPS Design Builds for Space Users

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15th PNT Advisory Board Meeting
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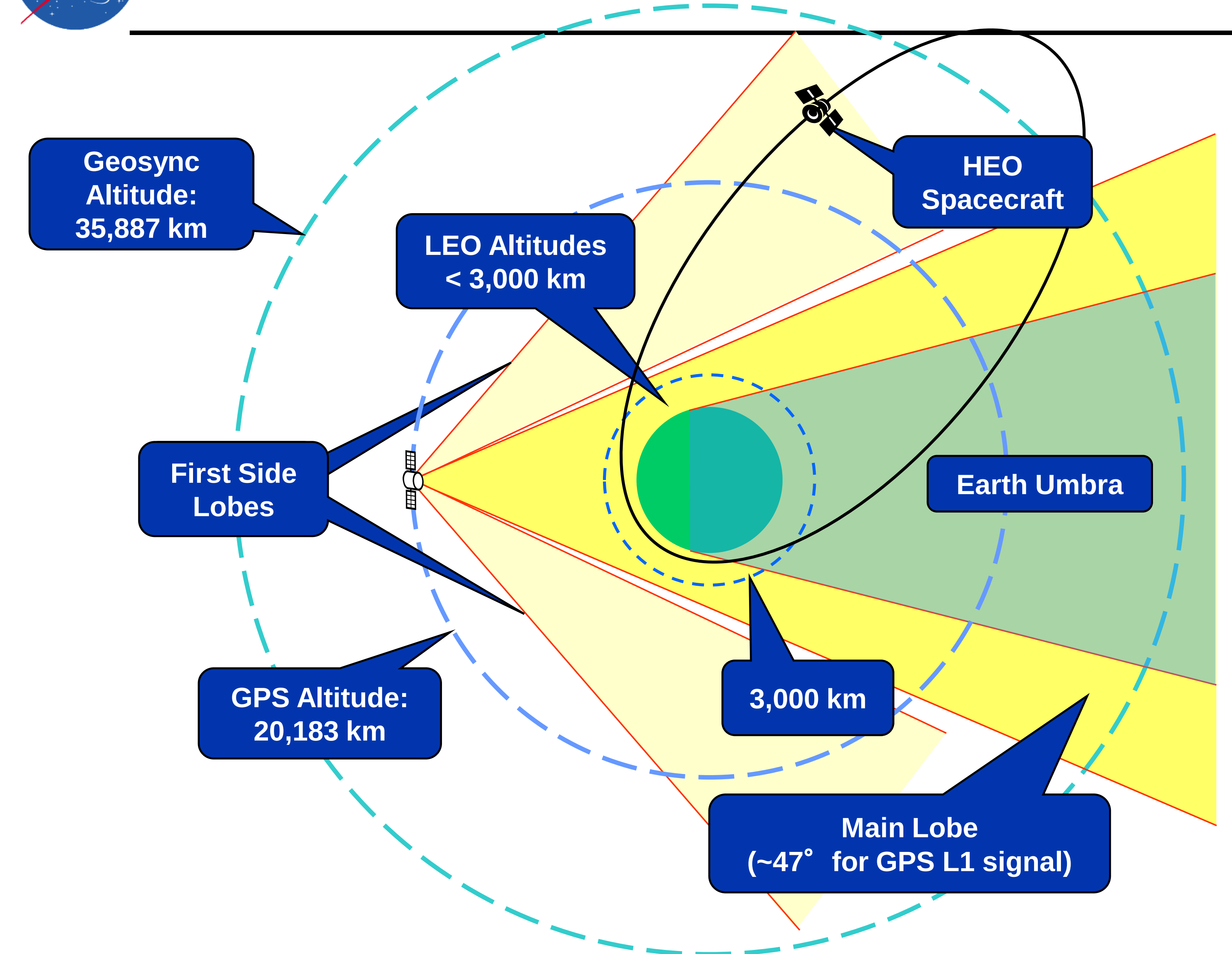
Agenda

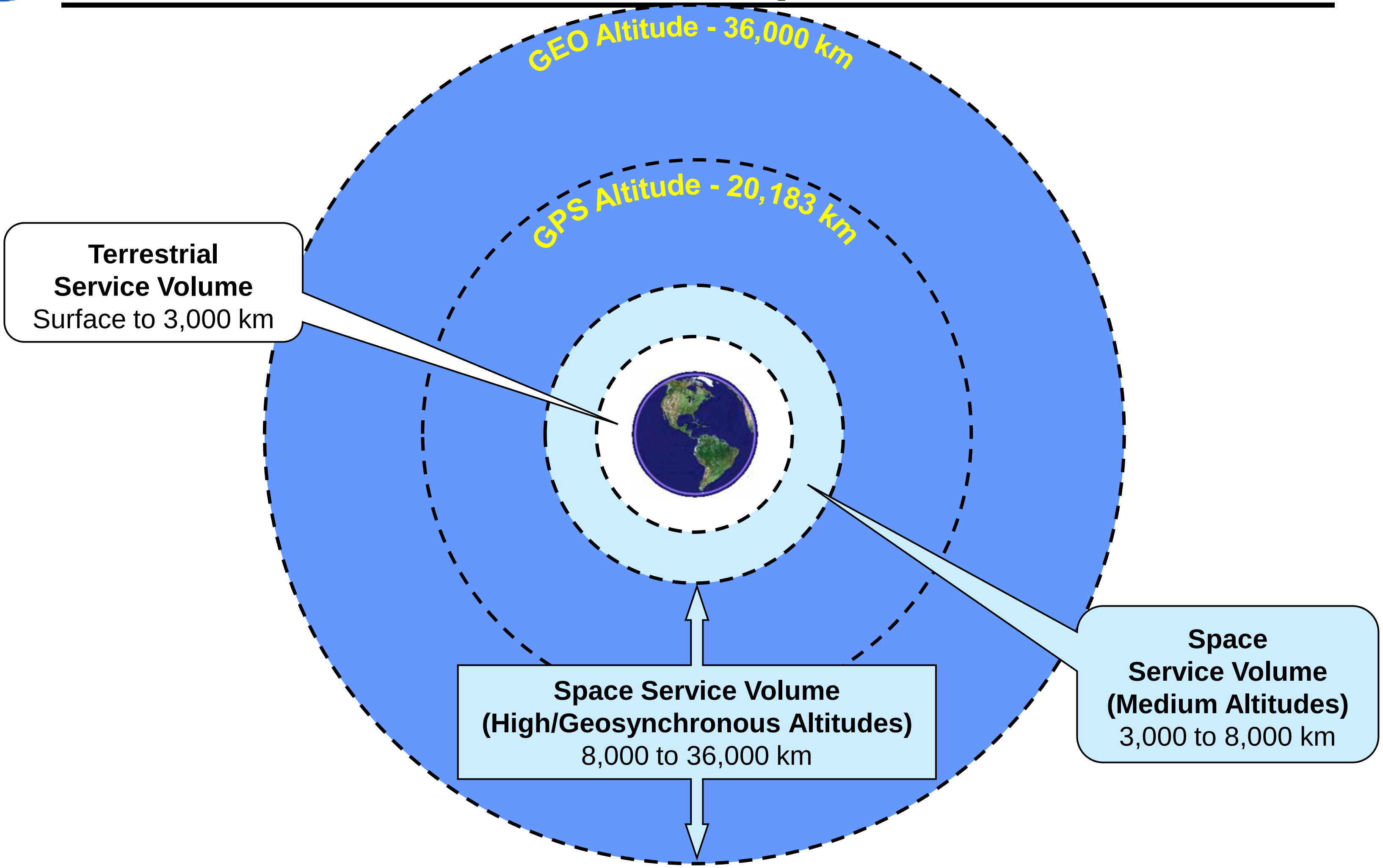
- Background
- SSV Specification History
- SSV Revisit: Knowledge Gained & Lessons Learned
- Proposed SSV Specification Updates to Ensure Minimal Degradation in Signal Strength/Availability
- Summary and Closing Remarks

Background

Reception Geometry for GPS Signals in Space



What is a Space Service Volume (SSV)? Current SSV Specification



Specification of SSV, Signal Strength and Availability Crucial for Reliable Space User Mission Designs

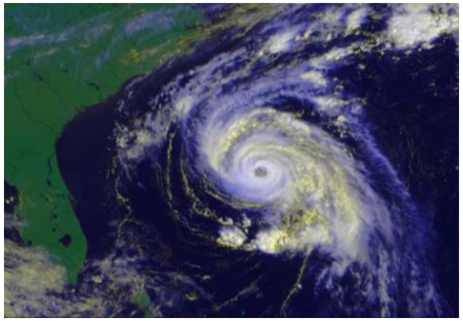
Space Service Volume Observations

- **GPS availability and signal strength originally specified for users on or near surface of Earth with transmitted power levels specified at edge-of-Earth, 14.3 degrees**
- **Prior to the SSV specification, on-orbit performance of GPS varied from block build to block build (IIA, IIRM, IIF) due to main lobe antenna gain and beamwidth variances**
  - Unstable on-orbit performance results in significant risk to space users
- **Side-lobe signals, although not specified, were expected to significantly boost GPS signal availability for users above the constellation**
- **During the GPS III Phase A specification update, NASA noted significant discrepancies in power levels specified in GPS III specification documents and measured on-orbit performance**
- **To stabilize the signal for high altitude space users, NASA/DoD team in 2003-2005 led the creation of new Space Service Volume (SSV) definition and specifications**
  - Guarantee backward compatibility
  - Identify areas for improved performance through objective requirements

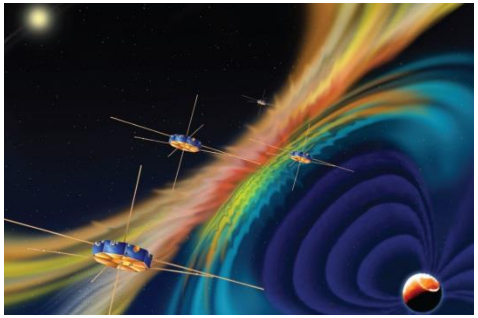
Why is the Space Service Volume Specification Important for Missions in High Earth Orbit?

SSV specifications are crucial for DoD, NASA and Commercial users, providing real-time GPS navigation solutions in High Earth Orbit

- **Supports increased satellite autonomy for missions, lowering mission operations costs**
- **Significantly improves vehicle navigation performance in these orbits**
- **Enables new/enhanced capabilities and better performance for HEO and GEO/GSO future missions, such as:**



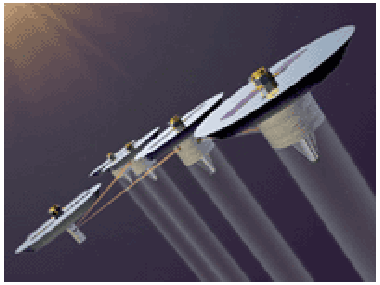
Improved Weather Prediction using Advanced Weather Satellites



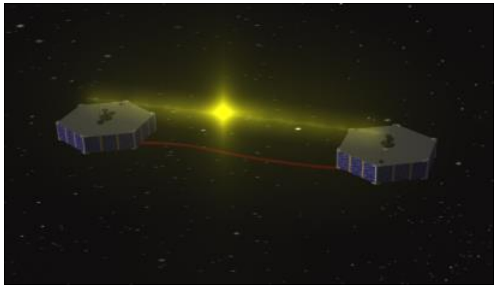
Space Weather Observations

Astrophysics Observations

En-route Lunar Navigation Support



Formation Flying & Constellation Missions



Closer Spacing of Satellites in Geostationary Arc

Use of GPS in the Space Service Volume (SSV)

- **GPS signals in High Earth Orbit and Geosynchronous Altitude utilized by multiple DOD, NASA & NOAA programs**
  - SBIRS, ANGELS, Classified Programs
  - GOES-R, MMS
- **Autonomous navigation enables new mission needs and significantly improves PNT performance over past methods**
  - GPS Ephemeris and timing data can be provided near real time with collected satellite products
  - Achievable accuracy is greatly improved over typical methods using ground based ephemeris processing via ranging and angle measurements
- **NASA activities have included:**
  - Conducting flight experiments to characterize GPS performance in SSV
  - Development of new weak signal GPS receivers for spacecraft in Geostationary or highly elliptical orbits
  - Working with the GPS Directorate and DoD community to formally document GPS requirements for space users
  - International coordination to encourage other GNSS constellations (e,g, Galileo, GLONASS, BeiDou) to specify interoperable SSV capabilities
  - Developing missions and systems to utilize GPS signals in the SSV

Civil Space Missions using GPS above the GPS Constellation

GOES-R Weather Satellite Series

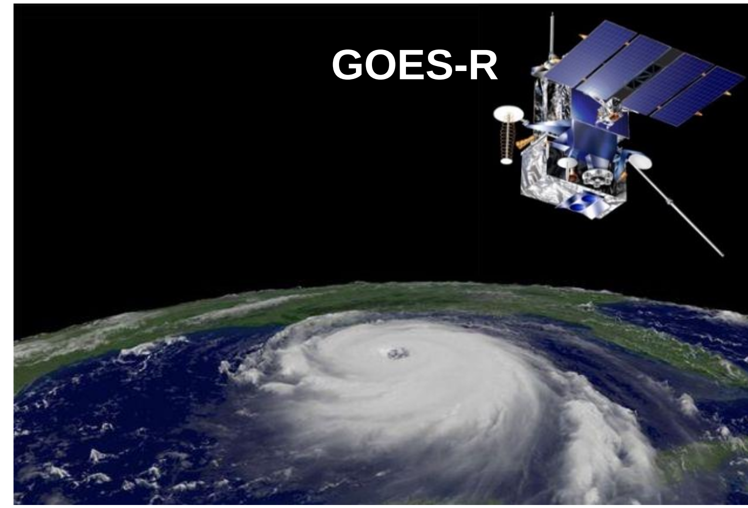
•First public safety use of GPS above the constellation

•Improves navigation performance for GOES-R

•Station-keeping operations on current GOES-N-Q constellation require relaxation of Image Navigation Registration for several hours

•GPS supports GOES-R breaking large station-keeping maneuvers into smaller, more frequent ones

- Quicker Recovery
- Minimal impact on Earth weather science



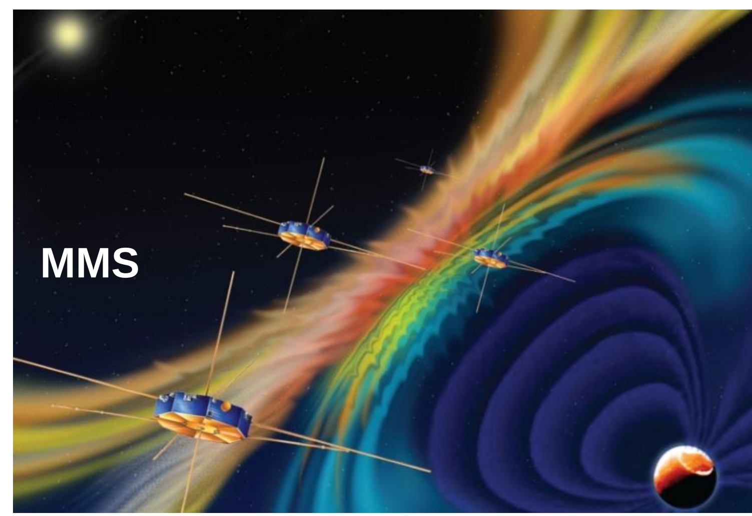
Magnetospheric Multi-Scale (MMS) Mission

•Launched March 12, 2015

•Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)

•Four spacecraft in highly eccentric orbits

- Starts in 1.2 x 12 Re-orbit (7,600 km x 76,000 km)
- Ultimately extends to 25 Re-orbit ~150,000 km)

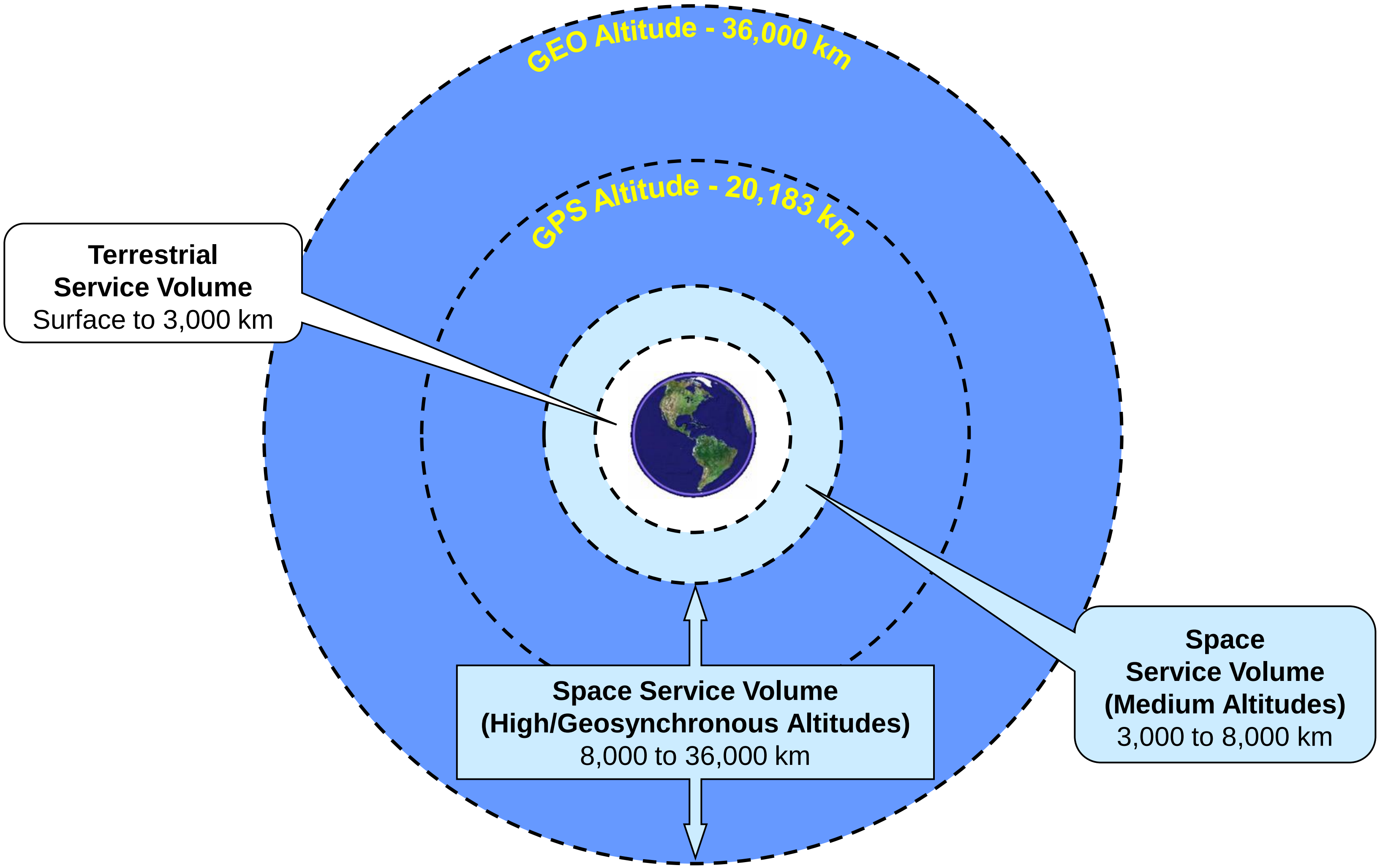


SSV Specification History

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**

GPS III SSV Specification: Terrestrial and Space Service Volume Definition



GPS III SSV Specification: Minimum Received Signal Power (dBW)

Signal	Terrestrial Minimum Power (dBW)	SSV Minimum Power (dBW)	Reference Half-beamwidth
L1 P(Y)	-161.5	-187.0	23.5
L1 C/A	-158.5	-184.0	23.5
L1 M	-158.0	-183.5	23.5
L1C	-157.0	-182.5	23.5
L1 composite	-151.2		
L2 P(Y)	-161.5	-186.0	26
L2 C/A or L2C	-158.5	-183.0	26
L2 M	-158.0	-182.5	26
L2 composite	-151.5		
L5 I5	-157.0	-182.0	26
L5 Q5	-157.0	-182.0	26
L5 composite	-154.0		

- **SSV minimum power levels were specified based on the worst-case (minimum) gain across the Block IIA, IIR, IIR-M, and IIF satellites**
- **Some signals have several dB margin with respect to these requirements at reference half-beamwidth point**

GPS III SSV Specification: Minimum Availability Requirement

- **Assuming a nominal, optimized GPS constellation and no GPS spacecraft failures, signal availability at 95% of the areas at a specific altitude within the specified SSV are planned as:**

	MEO SSV		HEO/GEO SSV	
	at least 1 signal	4 or more signals	at least 1 signal	4 or more signals
L1	100%	≥ 97%	≥ 80% [1]	≥ 1%
L2, L5	100%	100%	≥ 92% [2]	≥ 6.5%

1. With less than 108 minutes of continuous outage time.
2. With less than 84 minutes of continuous outage time.

- **Objective Requirements:**
  - MEO SSV: 4 GPS satellites always in view
  - HEO/GEO SSV: at least 1 GPS satellite always in view

SSV Revisit: Knowledge Gained & Lessons Learned

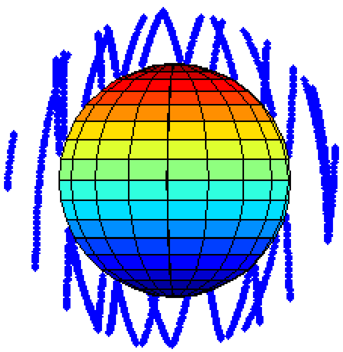
Knowledge Gained Since GPS IIIA SSV Specification

- **At last SSV specification update (2003-2005), GPS community had limited understanding of SSV signal strength/capabilities**
- **Data limited to brief flight experiments above the constellation**
  - Most comprehensive data from AMSAT-Oscar-40 flight experiment which spanned several weeks
- **Over the past decade, significant information gathered from:**
  - Additional flight experiments (e.g. GIOVE)
  - On-orbit missions in HEO (e.g. MMS and ACE)
  - Newly developed weak signal spaceborne receivers (e.g. Navigator)
  - Released GPS Antenna Pattern measurement data

HEO & GEO Space Mission Navigation Significantly Enhanced when GPS Side Lobes Included

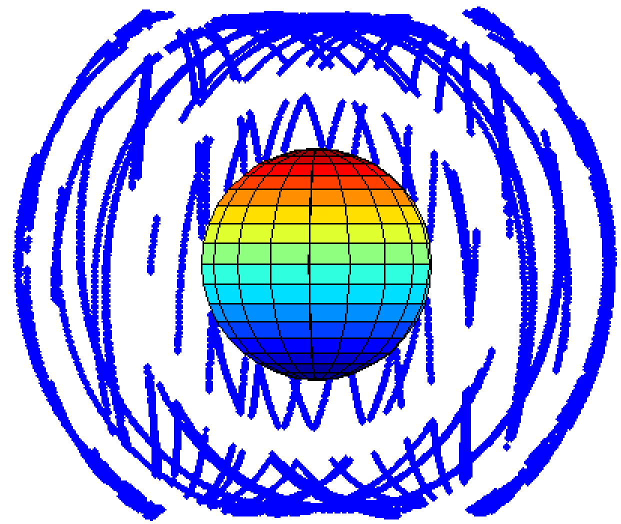
Signal Availability Results from AO-40 Flight Experiment

Main Lobe Only



4 or more SVs visible: never
1 or more SVs visible: 59%
no SVs visible: 41%

Main and Side Lobes



4 or more SVs visible: 99%
1 or more SVs visible: always
no SVs visible: : never

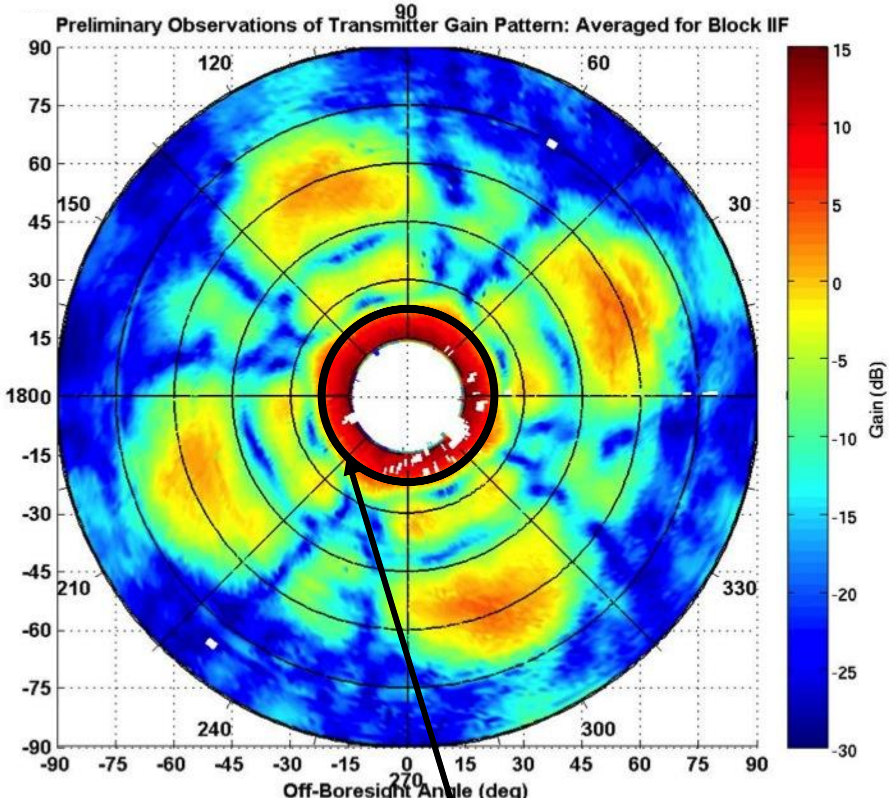
- Side lobe signals afford HEO/GEO missions:
  - Significantly improved signal availability
  - Improved Dilution of Precision (DOP)
- However, side lobe signals are not specified in the current SSV specifications

Protection of Side Lobe Information Critically Important to Ensure Robust Signals in the SSV and to "Do No Harm" to Current & Future Space Users

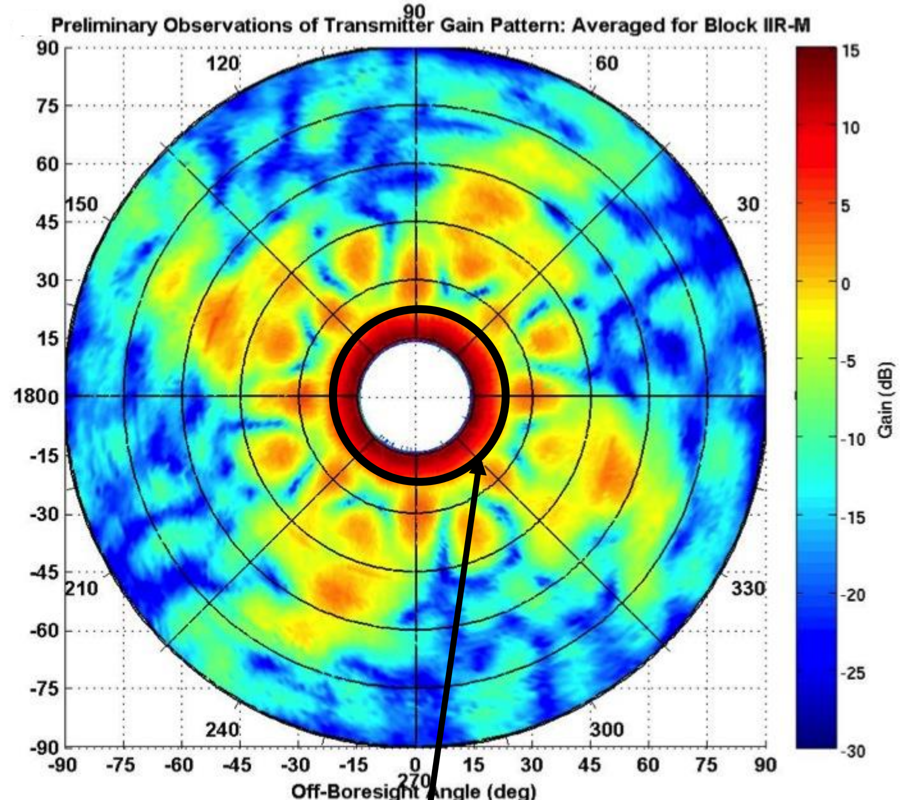
GPS ACE Flight Data for Block IIR-M and IIF

- GPS ACE project deployed advanced GPS receivers at the ground station of a GEO satellite
- Comprehensive collection of side lobe data as seen at GEO in order to characterize the transmit antenna patterns

In-Flight Measurement Average from **IIF** SVs



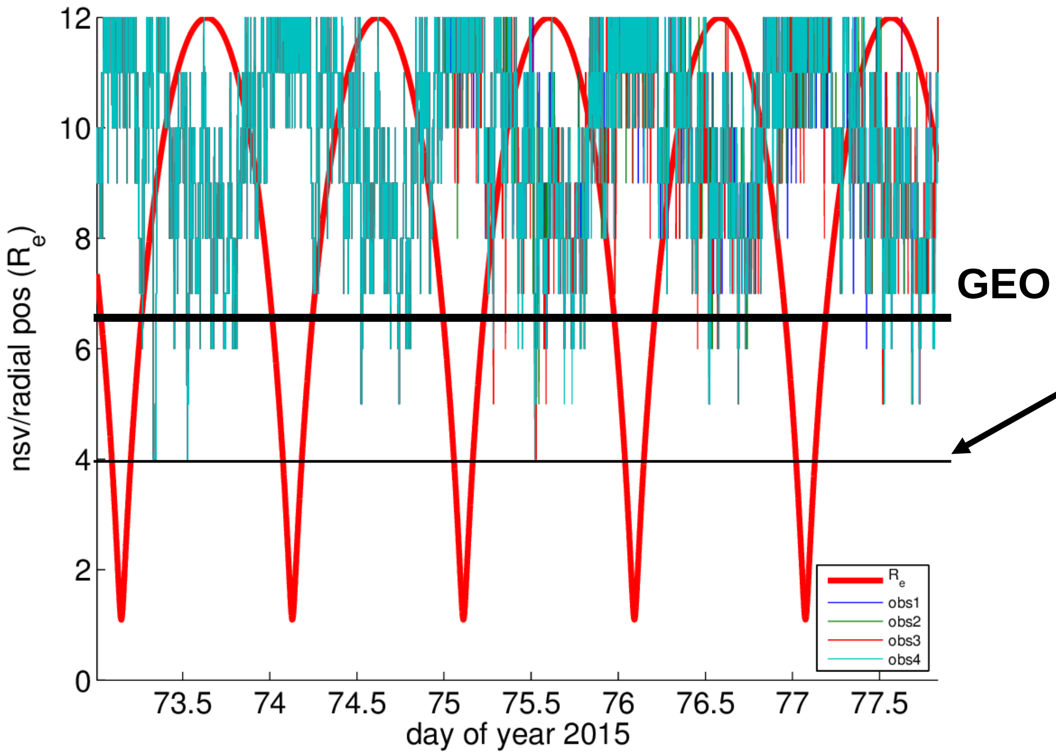
In-Flight Measurement Average from **IIR-M** SVs



Current spec only covers out to 23.5°

Recent Flight Data: MMS

- **Magnetospheric Multi-Scale (MMS) mission**
  - Launched March 12, 2015
  - 1.2 × 12 Re orbit (7,600 km × 76,000 km)
- **NASA-developed Navigator receiver**
- **Below: On-orbit number of SVs tracked vs. orbit radius**



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

MMS is seeing **100%.**

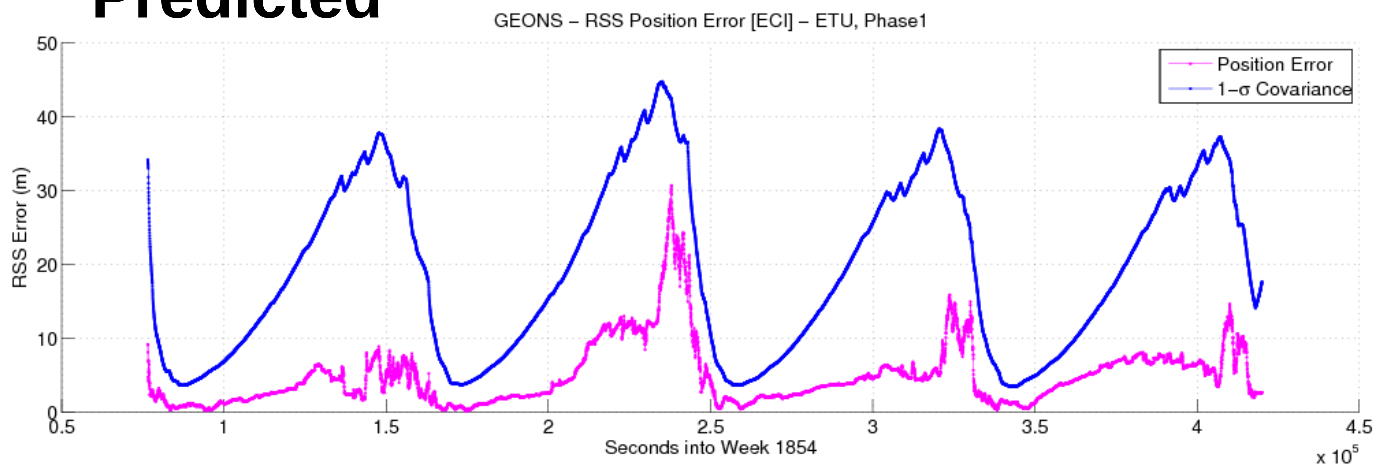
Recent Flight Data: MMS

Position error:

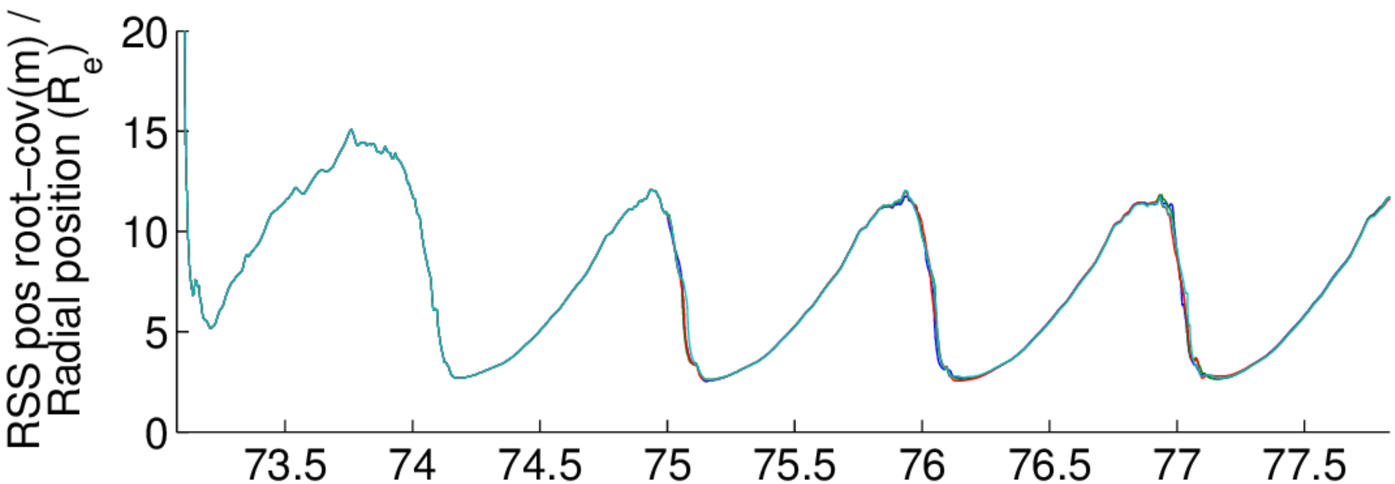
Achieved covariance is >50% improved over prediction.

Primary differentiator: availability of extra side-lobe signals in the SSV.

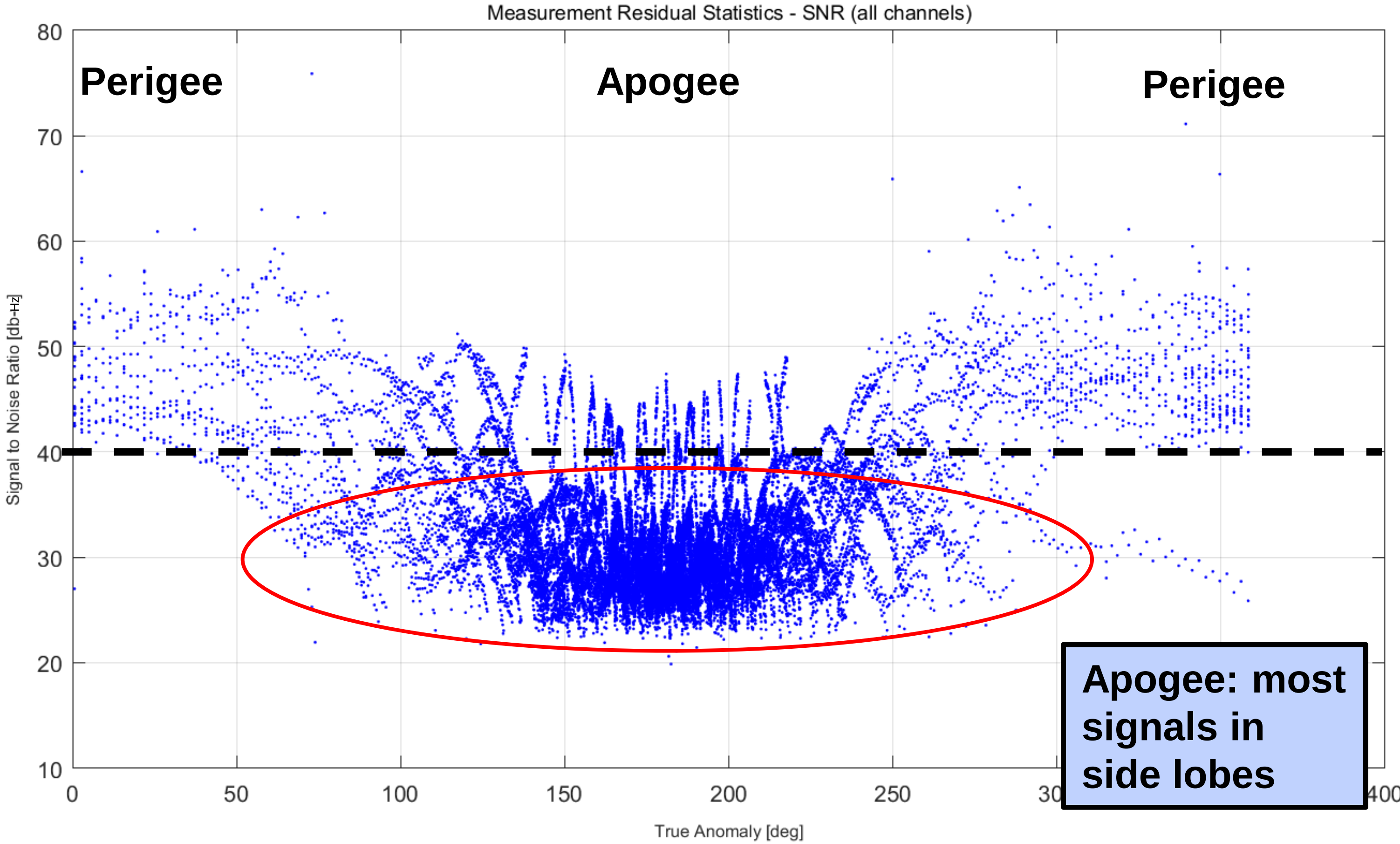
Predicted



Achieved



Recent Flight Data: MMS



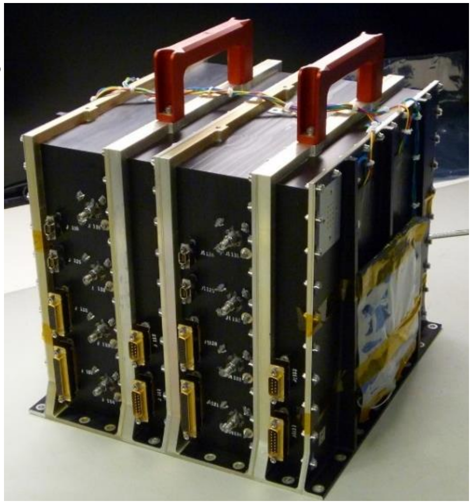
Strong (main lobe) signals

Weak (side lobe) signals

Signal strength (C/N0) vs. position in orbit

Navigator GPS Receiver for HEO/GEO Ops

- **Single frequency C/A code Rx ~10m level onboard accuracy for LEO/GEO/HEO**
- **Performance for high altitude applications enabled by**
  - Weak signal acquisition and tracking (25 dB-Hz)
  - Integrated on-board navigation filter (GEONS)
  - Radiation hardness
- **Navigator innovations incorporated in commercial HEO/GEO ops receivers developed by Moog Broad Reach, Honeywell and General Dynamics**



<u>Missions</u>

- **Early demonstration on Hubble Space Telescope Servicing Mission 4 STS-125 RNS (May 2009)**
  - Captured unique reflected GPS dataset
- **Global Precipitation Measurement (GPM) Mission (2014) Launch)→First operational use of Navigator**
- **Orion EFT-1 (2014)**
  - Navigator technology integrated into the Honeywell GPS receiver
  - ***Fast acquisition of GPS signals*** benefits navigation recovery after re-entry radio blackout without relying on IMU, stored states.
- **Magnetospheric Multi-Scale (MMS) Mission (2015)**
  - Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
  - Four spacecraft in highly eccentric orbits
    - Starts in 1.2 x 12 Re-orbit (7,600 km x 76,000 km)
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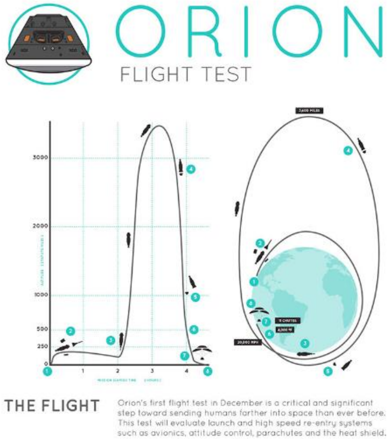
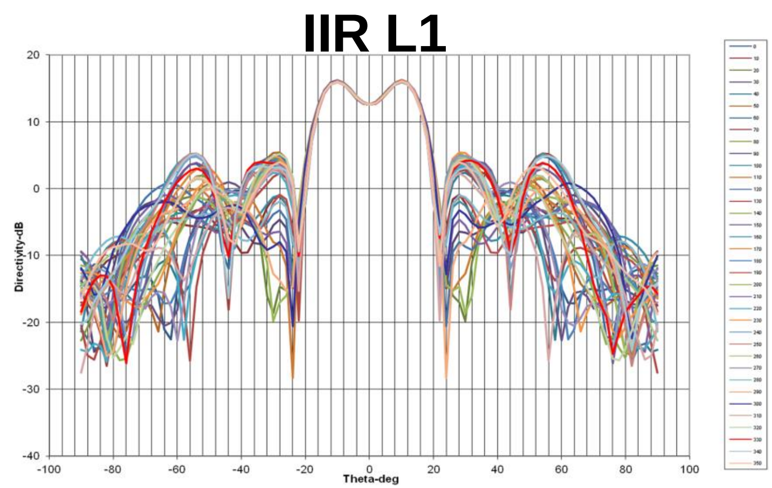
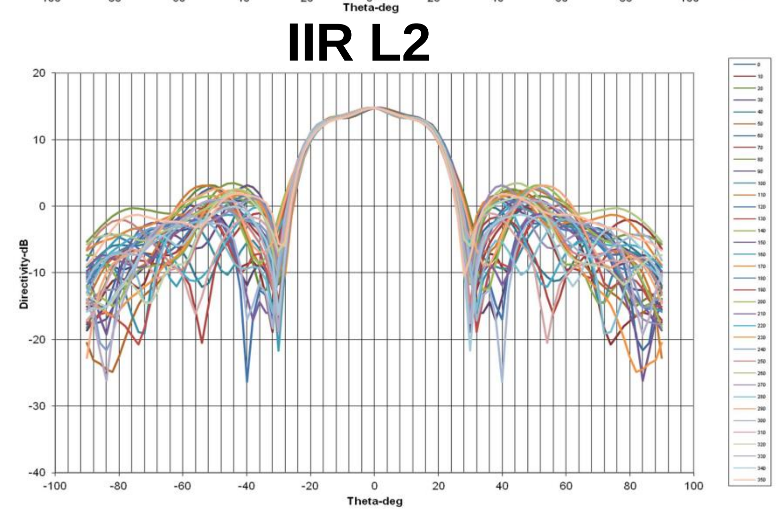


U.S. Publication of GPS Block IIR & IIR(M) Antenna Patterns

- Substantial pre-flight ground measurement of IIR & IIR(M) antenna patterns performed by Lockheed Martin for each GPS spacecraft
- Data now publically released. To access: www.gps.gov & click on support, technical documentation, GPS antenna patterns
- Hemispherical gain patterns for each GPS satellite can be developed by combining data along (+/- 90 degrees) and around (0-360 degrees) antenna boresight
- Enables high fidelity analyses and simulations for HEO/GEO missions
- Information bolsters confidence in developing new mission types, enhances navigation performance predictions and **enables development of enhanced GPS SSV specification, including sidelobe information**

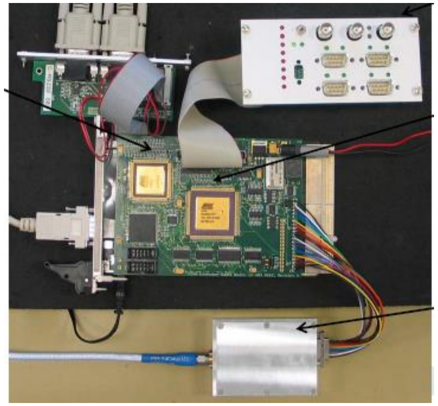




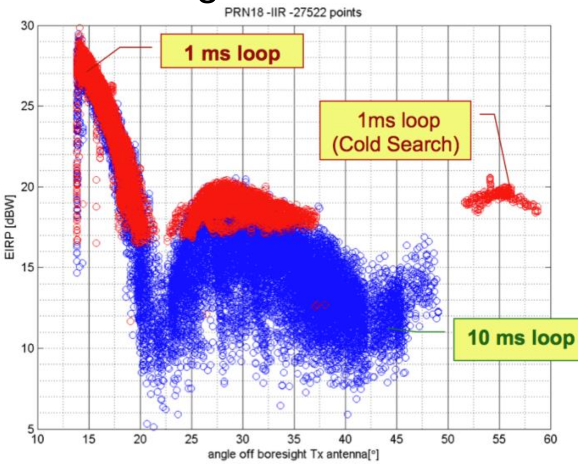
Special thanks to Willard Marquis/Lockheed Martin & Air Force GPS Program for publicly releasing this information!!

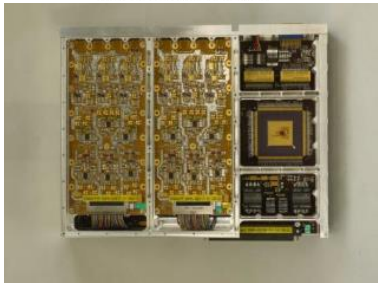
International Engagement in HEO/GEO GNSS Operations

- **Airbus/Astrium**
  - Development of LION Navigator GNSS receiver for operations in HEO/GEO
  - Performed 2011 study on Galileo SSV
  - Paper presented at AAS GN&C conference on Lion Navigator receiver and interest in SSV specification for Galileo
- **SSTL**
  - GIOVE-A SGR-GEO experiment (2013) which carried 12 channel L1 C/A code GPS Receiver and operated in circular orbit at 23,200 km (3,200 km above GPS)
  - Successfully tracked some 2nd side lobe signals & characterized antenna patterns for GPS IIA, IIR, IIR(M) and IIF satellites
  - New GNSS receiver for HEO/GEO: SGR-Axio
  - Future pattern characterization of Galileo, Glonass & Beidou
- **RUAG PODRIX HEO GPS/Galileo Receiver**
  - Planned operational use on ESA Proba-3 HEO (600 km x 60,000 km)



Lion Navigator Breadboard





Lessons Learned Summary

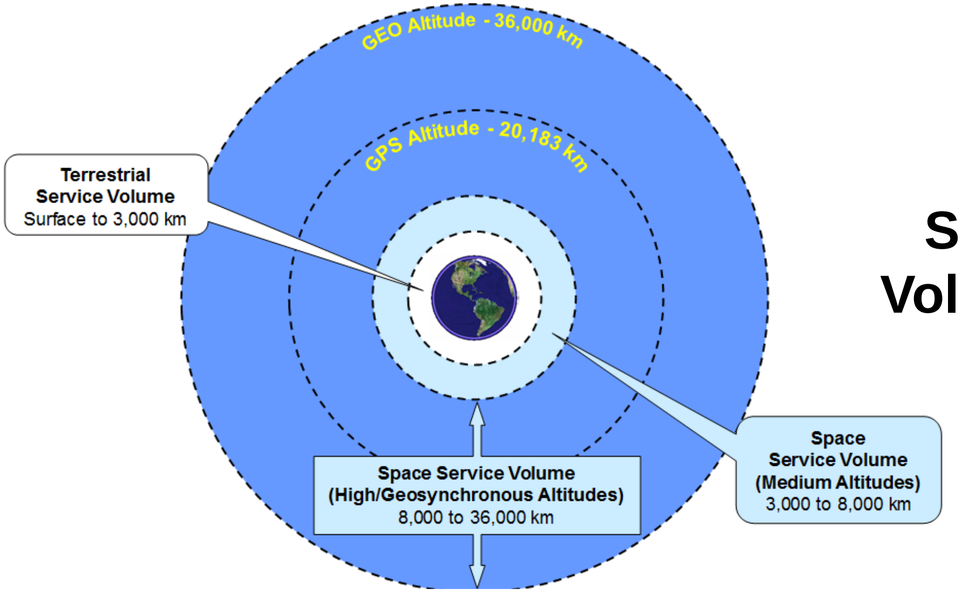
SSV Lessons Learned Over Past Decade:

- **GPS side lobe signals critically important for civil and military space users in HEO/GEO orbits**
  - Current and future civil and military space missions rely on side lobe signals to augment and enhance on-board PNT performance, improving vehicle resiliency
  - Side Lobe signals enhance Space and Earth weather prediction through improved navigation performance; strategically important for civil and military operations
- **Protection of side lobe signals ensures consistent GPS signal availability to U.S. civil & military missions at HEO/GEO**
  - No other GNSS constellation specifies SSV and side lobe signals

Protection of GPS Side Lobe Signals through Specification is Critically Important to "Do No Harm" to Current and Future Users of the SSV

Proposed SSV Specification Updates to Ensure Minimal Degradation in Signal Strength/Availability

Unchanged SSV Specifications



Space Service Volume Definition

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L1 P(Y)	-161.5	-187.0	23.5
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L5 I5	-157.0	-182.0	26
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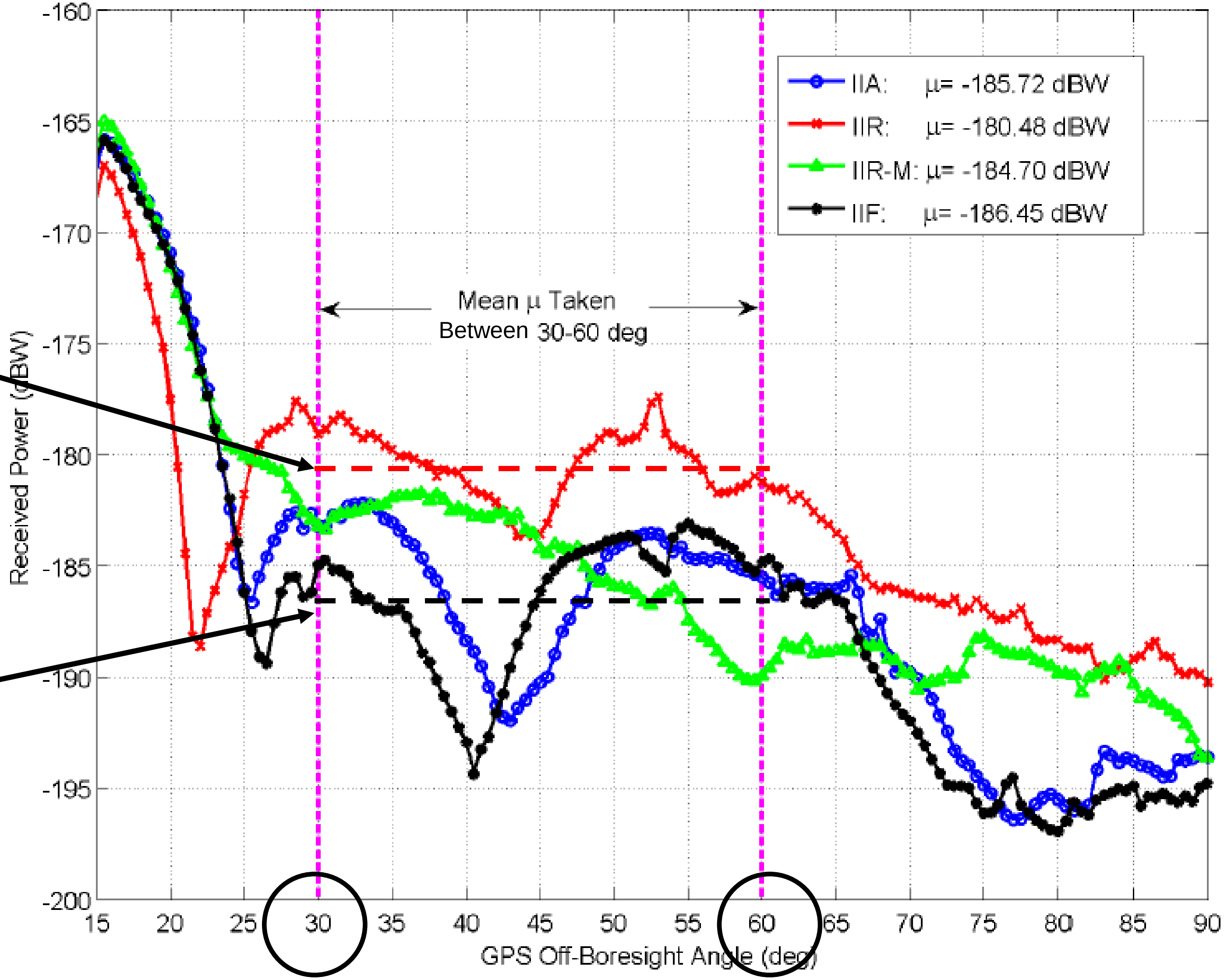
Main Lobe Signal Strength

Augmented SSV Requirement: Side Lobe Received Signal Power



Block IIR mean

Block IIF mean

GPS III Minimum Side Lobe Received Signal Power (dBW) Requirement

- **50% of SSV signals within the off-Nadir angle beamwidth shall be above the mean power**
- **84% of SSV signals within the off-Nadir angle beamwidth shall be above the mean power minus standard deviation power**
- **Assumes 24 satellite constellation & no GPS spacecraft failures**

Signal	Mean Power (dBW)	Mean Power Minus Standard Deviation Power (dBW)	Off-Nadir Angle (degrees)
L1 P(Y)	TBD	TBD	30 to 60 (TBR)
L1 C/A (TBR)	-186.0	-190.0	30 to 60 (TBR)
L1 M	TBD	TBD	30 to 60 (TBR)
L1C	TBD	TBD	30 to 60 (TBR)
L1 composite			
L2 P(Y)	TBD	TBD	30 to 60 (TBR)
L2 C/A or L2C	TBD	TBD	30 to 60 (TBR)
L2 M	TBD	TBD	30 to 60 (TBR)
L2 composite			
L5 I5	TBD	TBD	30 to 60 (TBR)
L5 Q5	TBD	TBD	30 to 60 (TBR)
L5 composite			

GPS III Minimum Availability Requirement

- **Assuming a nominal, optimized GPS constellation (24 satellites) and no GPS spacecraft failures, signal availability at 95% of the areas at a specific altitude within the specified SSV are planned as:**

	MEO SSV		HEO/GEO SSV	
	at least 1 signal	4 or more signals	at least 1 signal	4 or more signals
L1	100%	≥ 97%	100% 1	≥ 97% (TBR)
L2, L5	100%	100%	100% 2	≥ 97% (TBR)

1. With less than 108 minutes of continuous outage time.
2. With less than 84 minutes of continuous outage time.

- **Objective Requirements:**
  - MEO SSV: 4 GPS satellites always in view
  - HEO/GEO SSV: at least 4 GPS satellite always in view

Red: Specification Changes

DRAFT

Summary and Closing Remarks

Closing Remarks

- **NASA, NOAA, DoD and other space GPS users rely on GPS as critical component of space navigation infrastructure over an expanding range of orbital applications**
- **Space user community is still vulnerable to GPS constellation design changes because requirements not explicitly stated; specifically the side lobe signals**
- **Proposed SSV requirements update:**
  - Maintains backward compatibility with current constellation
  - Identifies potential areas for improved performance through objective requirements
  - Provides a green-light for civil and military space missions considering future operational use of GPS beyond LEO
- **Interoperability for all space users will be enhanced if other PNT service providers such as Galileo also implement similar requirements/operational capabilities.**
  - This issue has been actively worked as part of ICG meetings since 2011

Protection of GPS Side Lobe Signals through Specification is Critically Important to "Do No Harm" to Current and Future Users of the SSV

Way Ahead

- **Flesh out side lobe requirement TBDs via flight data and analysis**
- **Socialize SSV requirement changes through Civil and DoD communities**
- **Work with GPS Directorate, AF and DoD leadership to incorporate SSV specification modification in updated GPS system specification**

References

F.H. Bauer, M.C. Moreau, M.E. Dahle-Melsaether, W.P. Petrofski, B.J. Stanton, S. Thomason, G.A Harris, R.P. Sena, L. Parker Temple III, The GPS Space Service Volume, ION GNSS, September 2006.

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These and other NASA References:

http://www.emergentspace.com/related_works.html