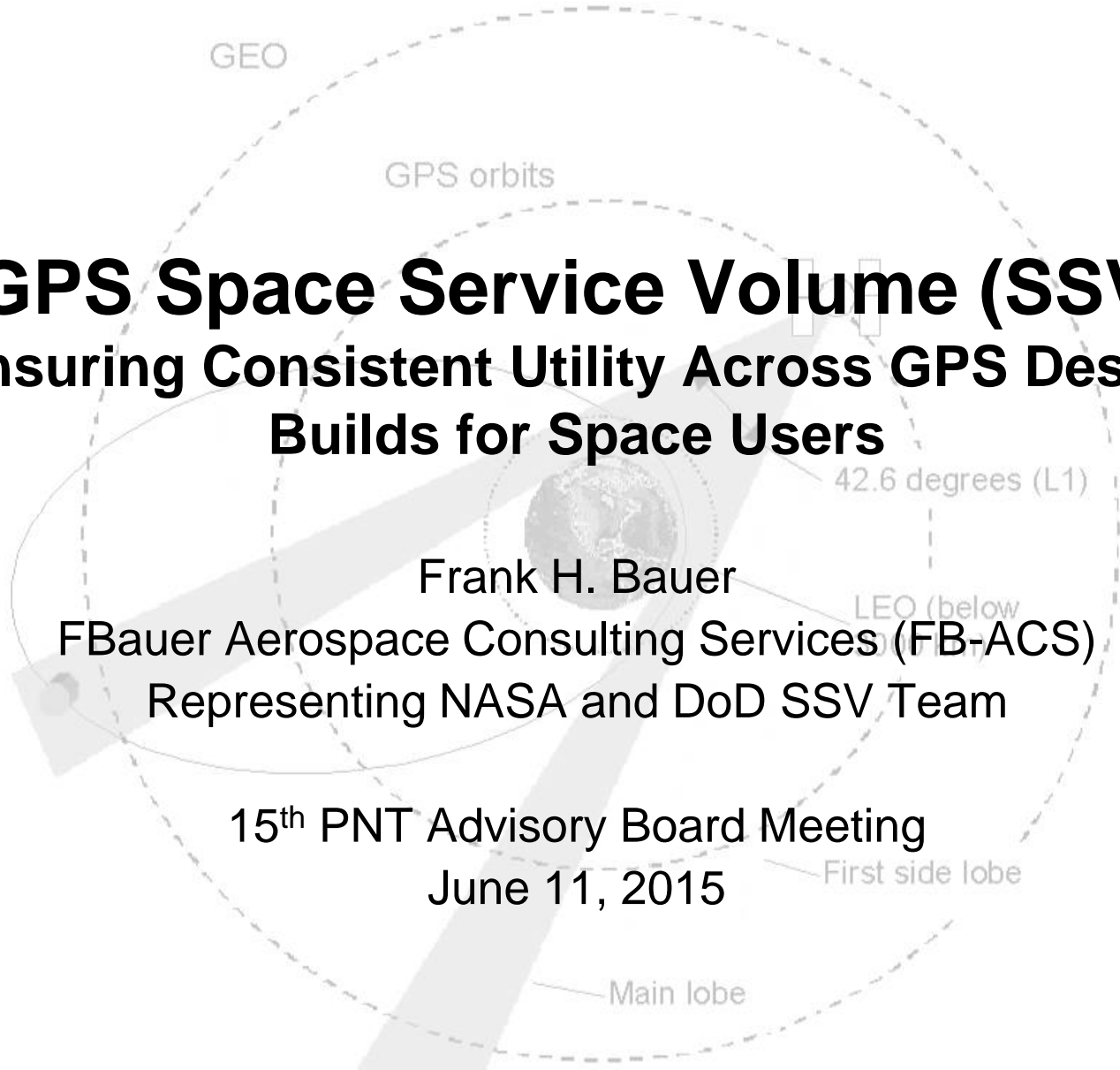


GPS Space Service Volume (SSV)

Ensuring Consistent Utility Across GPS Design Builds for Space Users



Frank H. Bauer

FBauer Aerospace Consulting Services (FB-ACS)

Representing NASA and DoD SSV Team

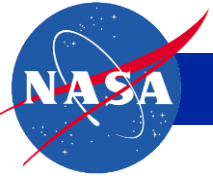
15th PNT Advisory Board Meeting

June 11, 2015



Agenda

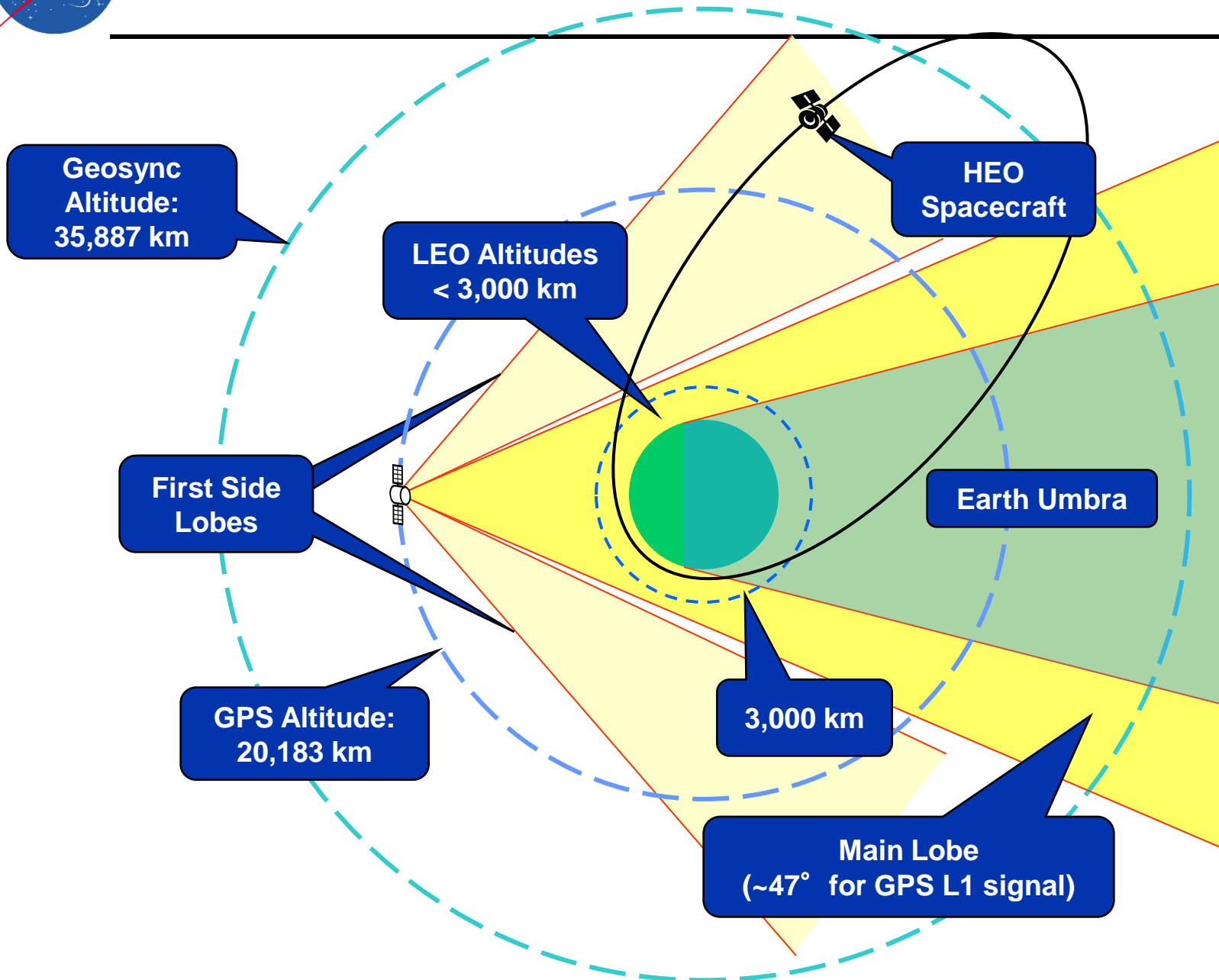
- **Background**
- **SSV Specification History**
- **SSV Revisit: Knowledge Gained & Lessons Learned**
- **Proposed SSV Specification Updates to Ensure Minimal Degradation in Signal Strength/Availability**
- **Summary and Closing Remarks**



Background



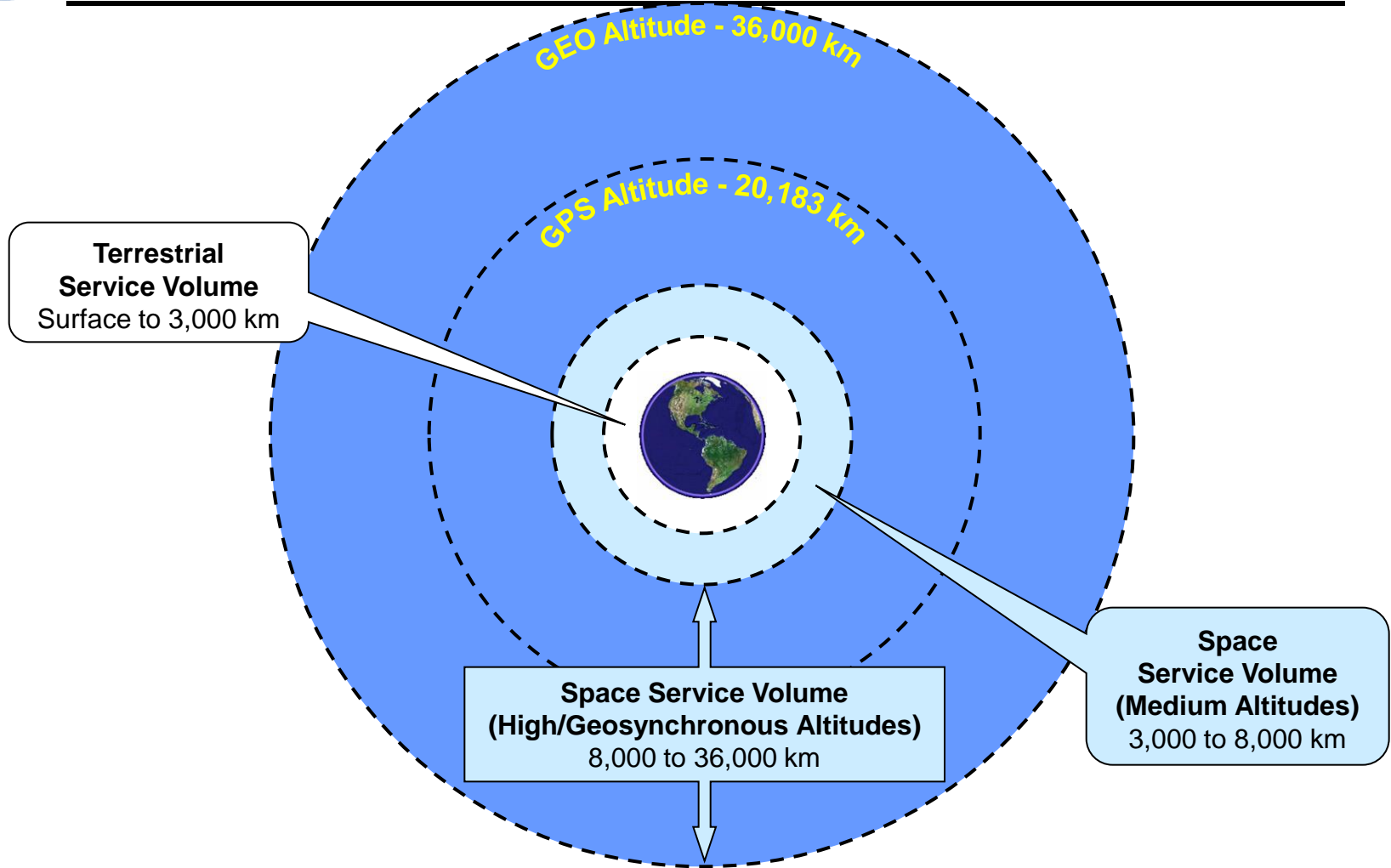
Reception Geometry for GPS Signals in Space



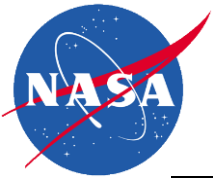


What is a Space Service Volume (SSV)?

Current SSV Specification

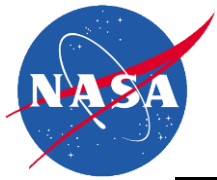


***Specification of SSV, Signal Strength and Availability
Crucial for Reliable Space User Mission Designs***



Space Service Volume Observations

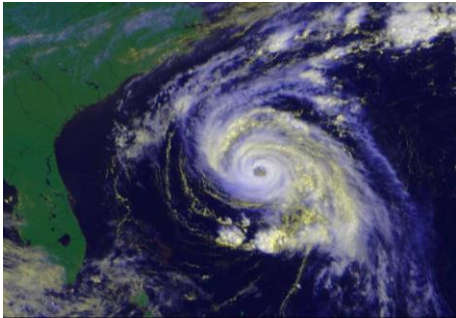
- **GPS availability and signal strength originally specified for users on or near surface of Earth with transmitted power levels specified at edge-of-Earth, 14.3 degrees**
- **Prior to the SSV specification, on-orbit performance of GPS varied from block build to block build (IIA, IIRM, IIF) due to main 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



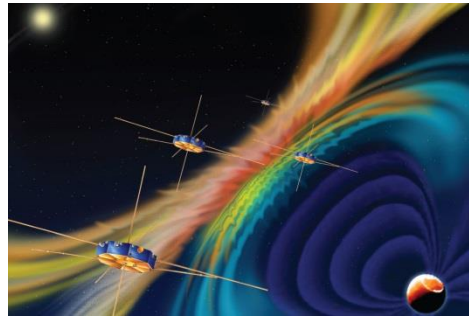
Why is the Space Service Volume Specification Important for Missions in High Earth Orbit?

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



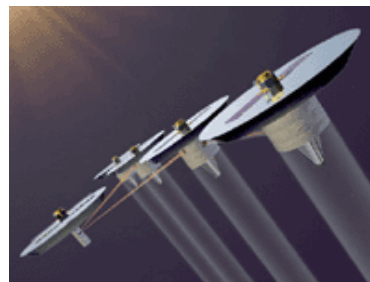
Space Weather Observations



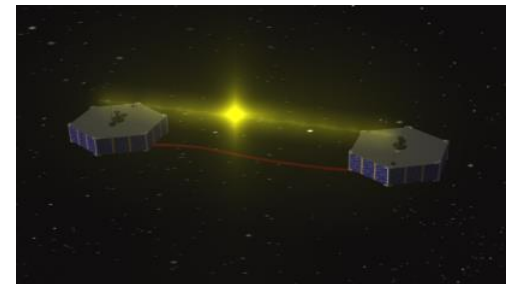
Astrophysics Observations



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)

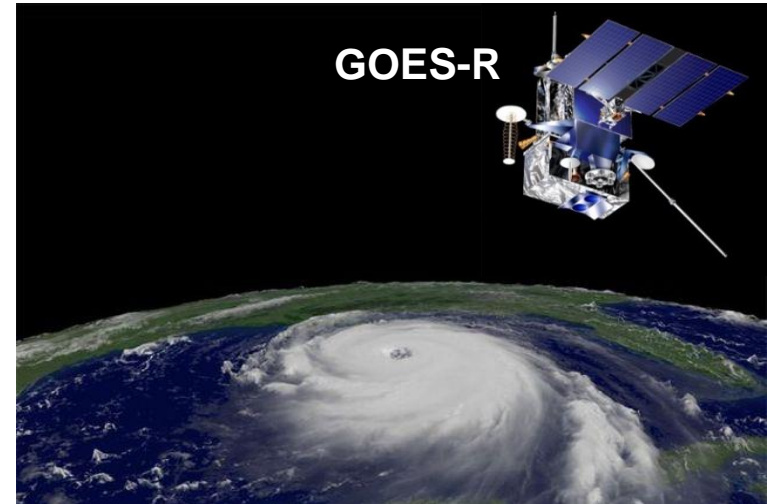
- **GPS signals in High Earth Orbit and Geosynchronous Altitude utilized by multiple DOD, NASA & NOAA programs**
 - SBIRS, ANGELS, Classified Programs
 - GOES-R, MMS
- **Autonomous navigation enables new mission needs and significantly improves PNT performance over past methods**
 - GPS Ephemeris and 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

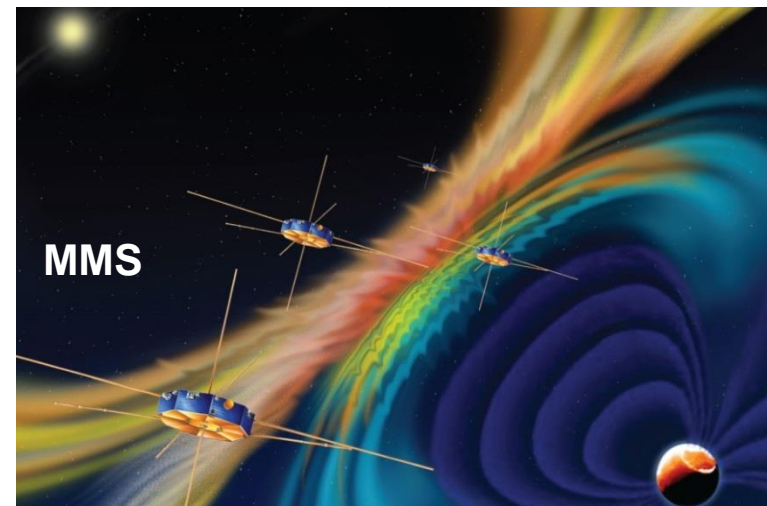
GOES-R Weather Satellite Series

- 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)



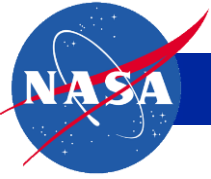


HEO/GEO Missions Operational and on the Horizon

SATELLITE	LAUNCH DATE OR OPERATIONAL PERIOD	ORBIT	RECEIVER/VENDOR	GPS APPLICATION	RECEIVER
Restricted	2014**	GEO	General Dynamics Viceroy	OPERATIONAL	HEO Receiver
Restricted	2014**	GEO	General Dynamics Viceroy	OPERATIONAL	HEO Receiver
Restricted	2014**	GEO	General Dynamics Viceroy	OPERATIONAL	HEO Receiver
MMS	2015	HEO	NASA Goddard Navigator	OPERATIONAL	HEO Receiver
SBIRS GEO 3	2015	GEO	General Dynamics Monarch	OPERATIONAL	Modified Legacy Receiver
GOES-R	2016	GEO	General Dynamics Viceroy	OPERATIONAL	HEO Receiver
SBIRS GEO 4	2016	GEO	General Dynamics Monarch	OPERATIONAL	Modified Legacy Receiver
EAGLE	2017	GEO	Moog NavSBR	OPERATIONAL	HEO, Navigator Heritage
GOES-S	2017	GEO	General Dynamics Viceroy	OPERATIONAL	HEO Receiver
Restricted	2017**	GEO	General Dynamics Monarch	OPERATIONAL	Modified Legacy Receiver
Orion Exploration Mission 1	2018	Trans-lunar	Honeywell	EXPERIMENT	Modified Legacy Receiver
Proba-3	2018	HEO	Ruag PODRIX	OPERATIONAL	HEO Receiver

** Date of delivery of receiver to customer

And many more coming...



SSV Specification History

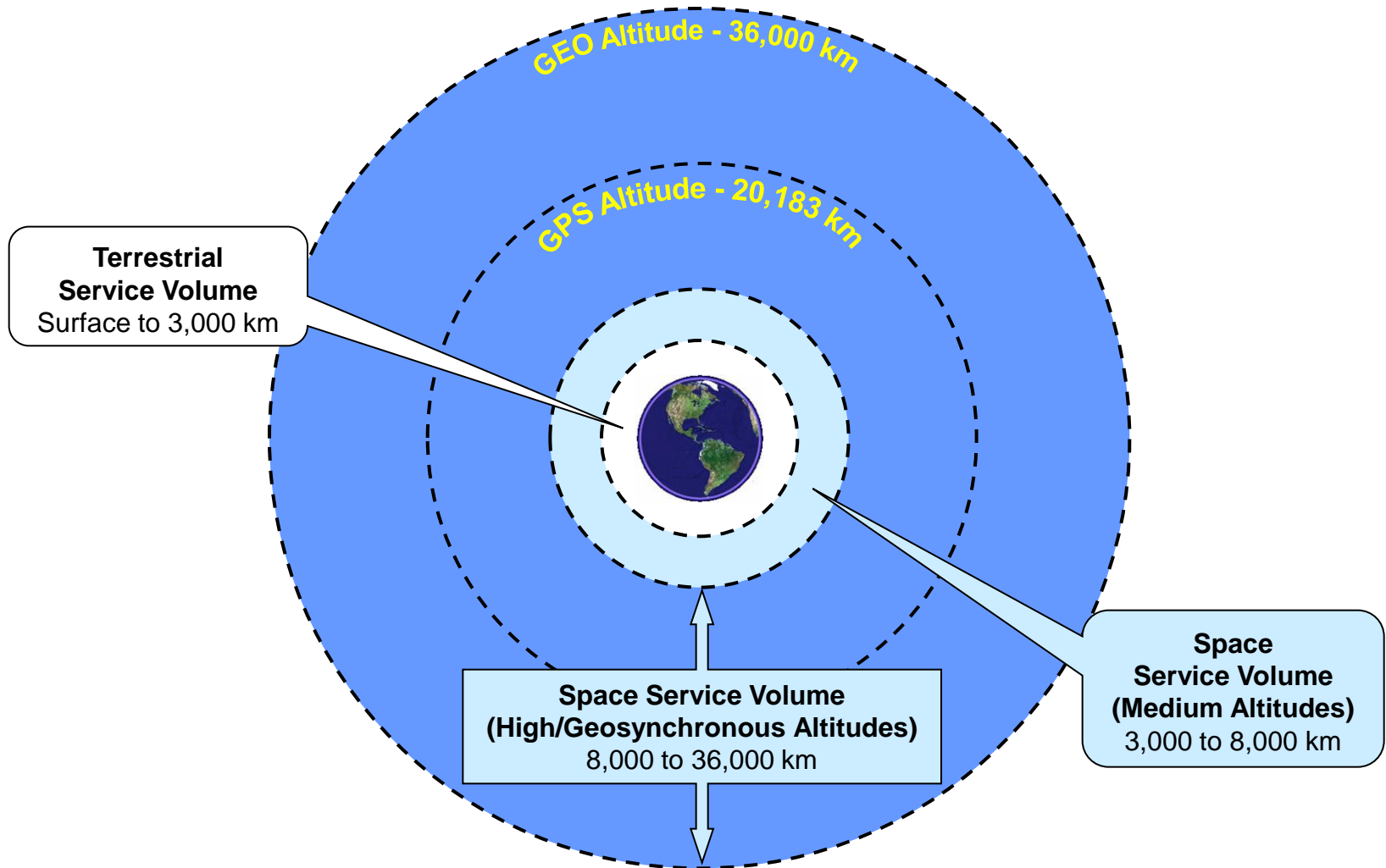


GPS Space Service Volume Specification History

- **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**

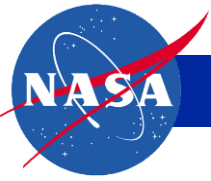


GPS III SSV Specification: Minimum Availability Requirement

- 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%	$\geq 97\%$	$\geq 80\%$ ₁	$\geq 1\%$
L2, L5	100%	100%	$\geq 92\%$ ₂	$\geq 6.5\%$
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

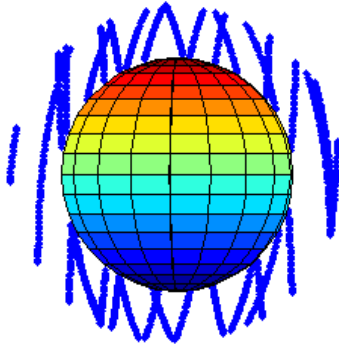
- **At last SSV specification update (2003-2005), GPS community had limited understanding of SSV signal strength/capabilities**
- **Data limited to brief flight experiments above the constellation**
 - Most comprehensive data from AMSAT-Oscar-40 flight experiment which spanned several weeks
- **Over 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

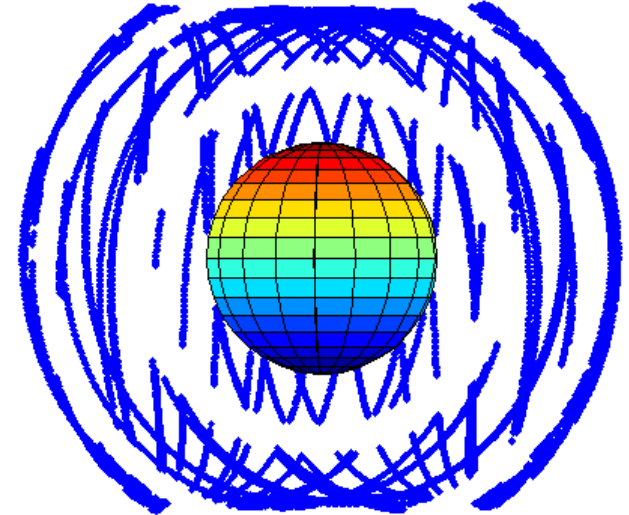
Main Lobe Only



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

- 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

Main and Side Lobes



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

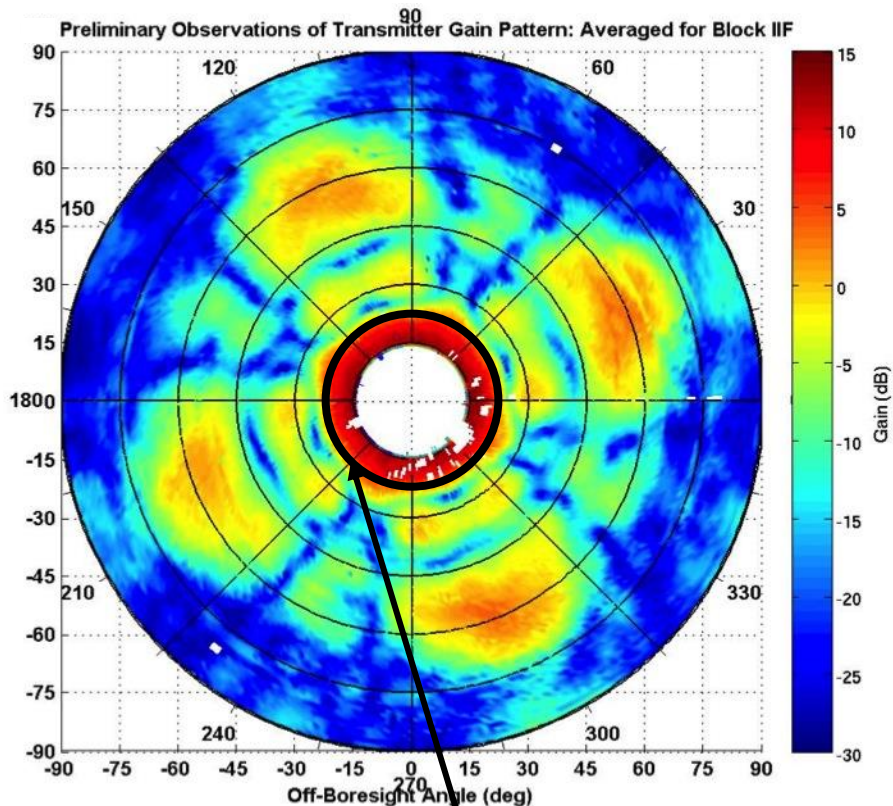
Protection of Side Lobe Information Critically Important to Ensure Robust Signals in the SSV and to “Do No Harm” to Current & Future Space Users



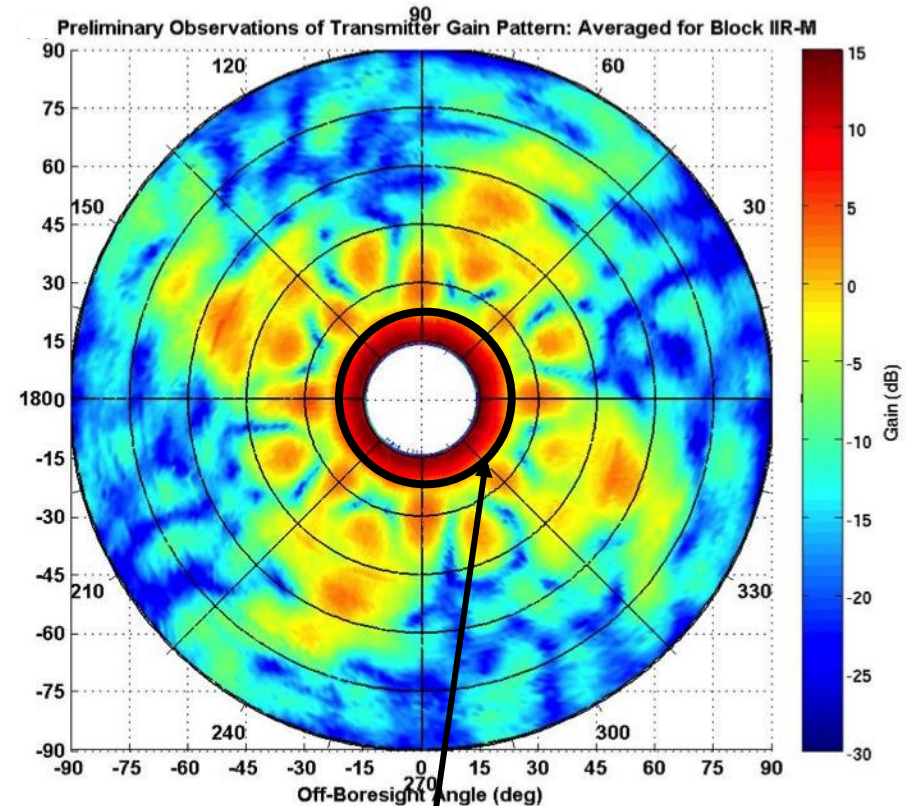
GPS ACE Flight Data for Block IIR-M and IIF

- 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

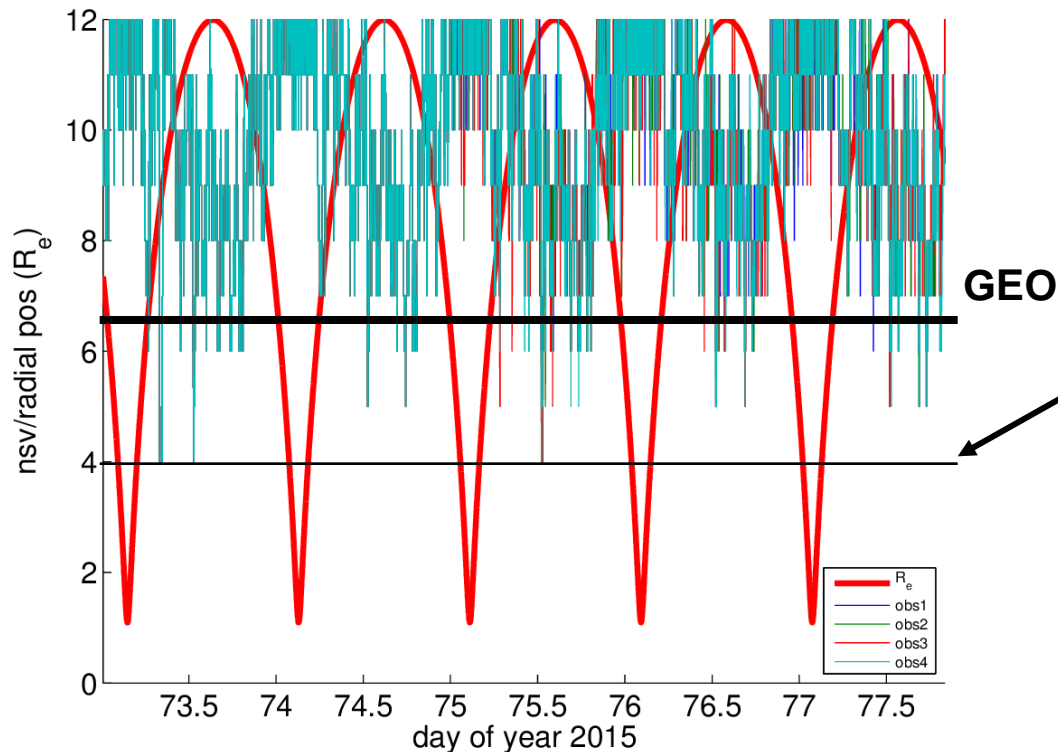


Current spec only covers out to 23.5°



Recent Flight Data: MMS

- **Magnetospheric Multi-Scale (MMS) mission**
 - Launched March 12, 2015
 - $1.2 \times 12 R_e$ orbit (7,600 km \times 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%**.



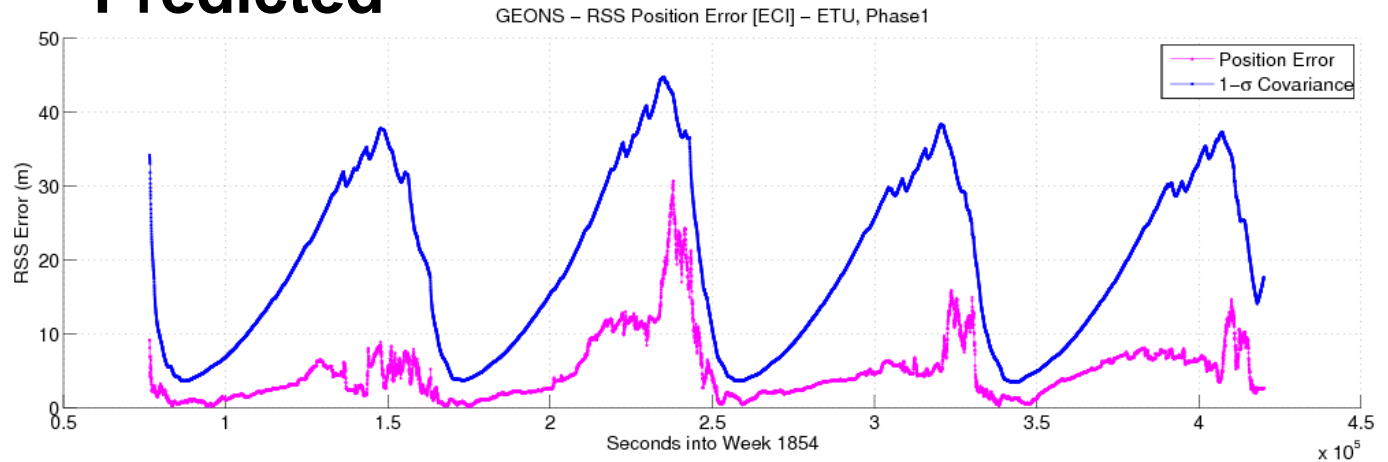
Recent Flight Data: MMS

Position error:

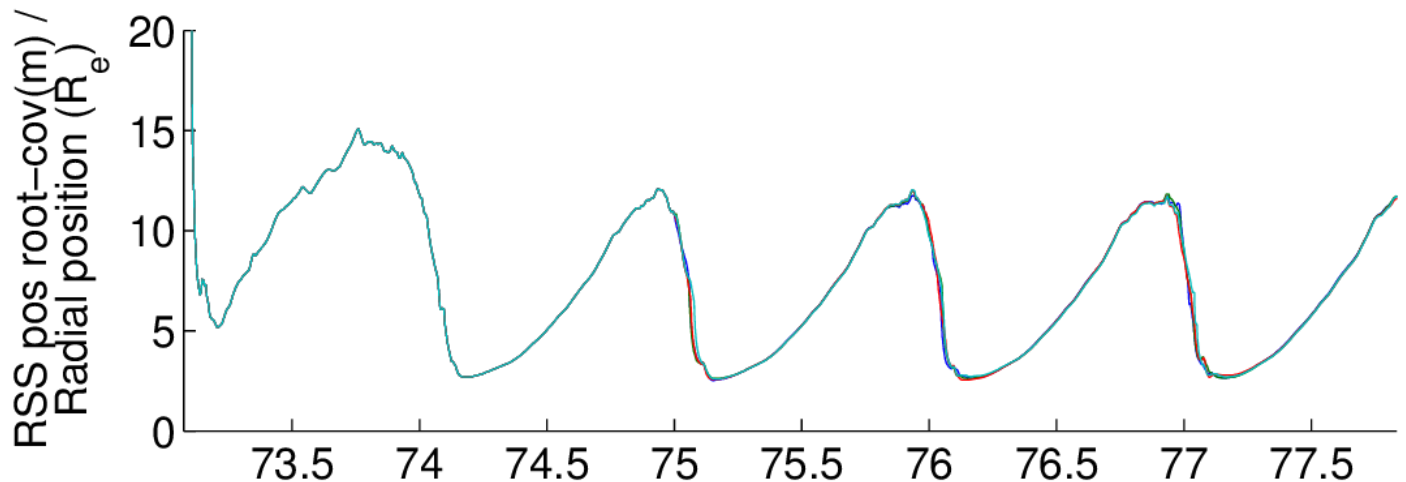
Achieved covariance is >50% improved over prediction.

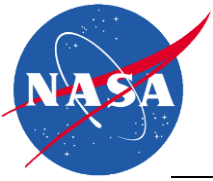
Primary differentiator: availability of extra side-lobe signals in the SSV.

Predicted

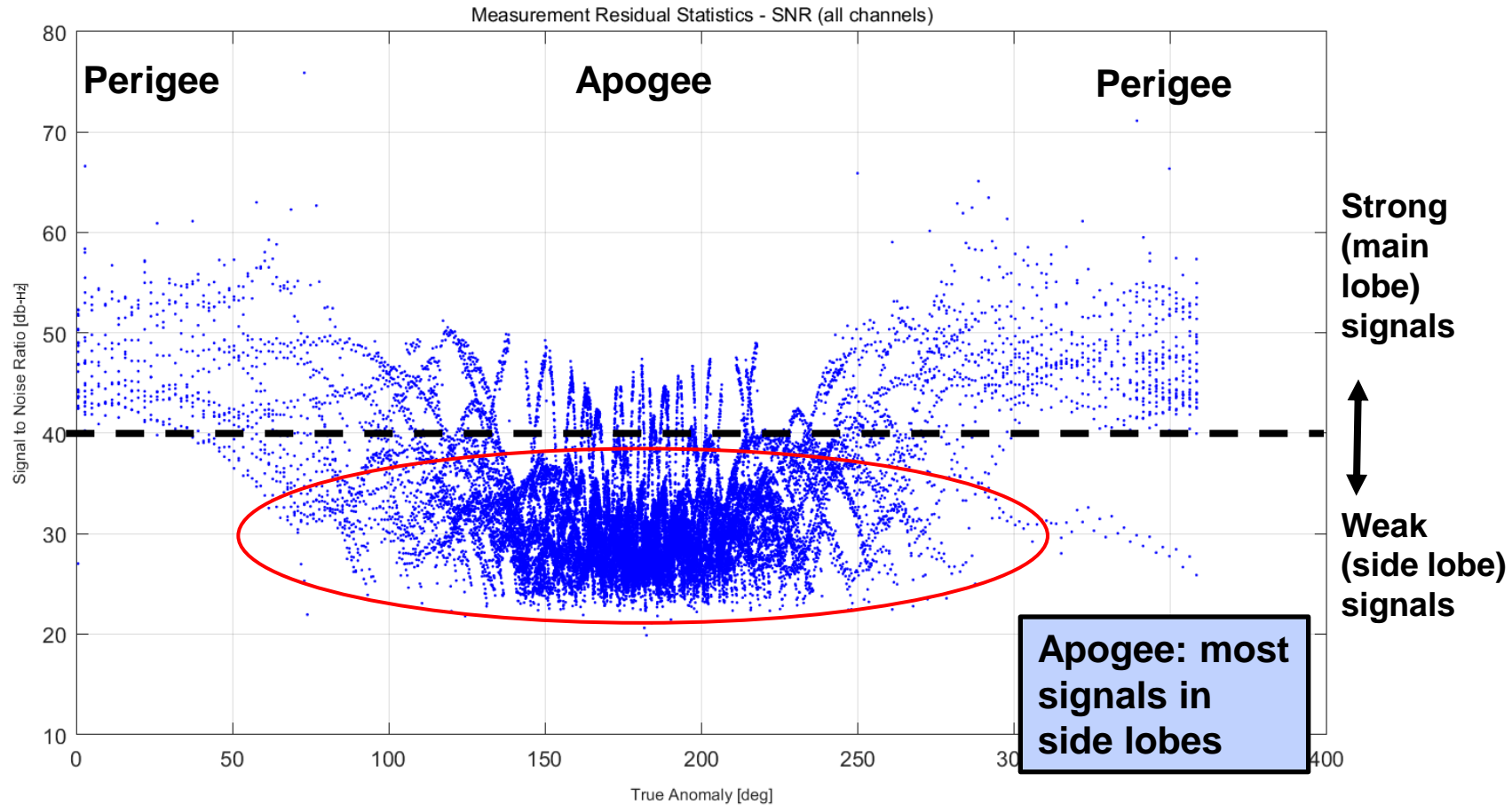


Achieved





Recent Flight Data: MMS



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



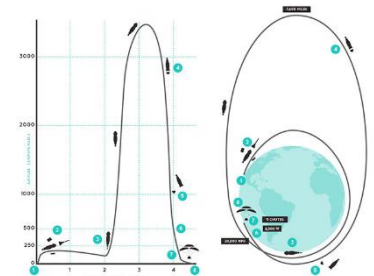
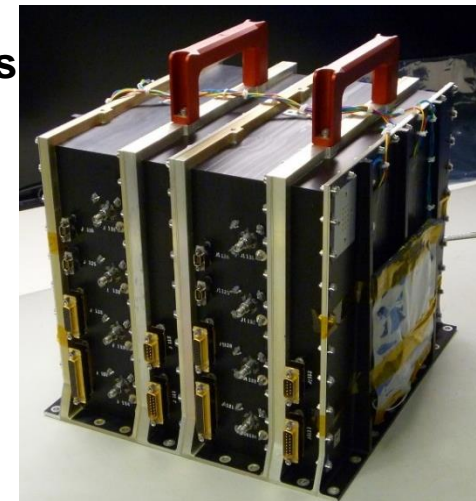
Navigator GPS Receiver for HEO/GEO Ops

- 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



Missions

- 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)
 - Ultimately extends to 25 Re-orbit ~150,000 km)

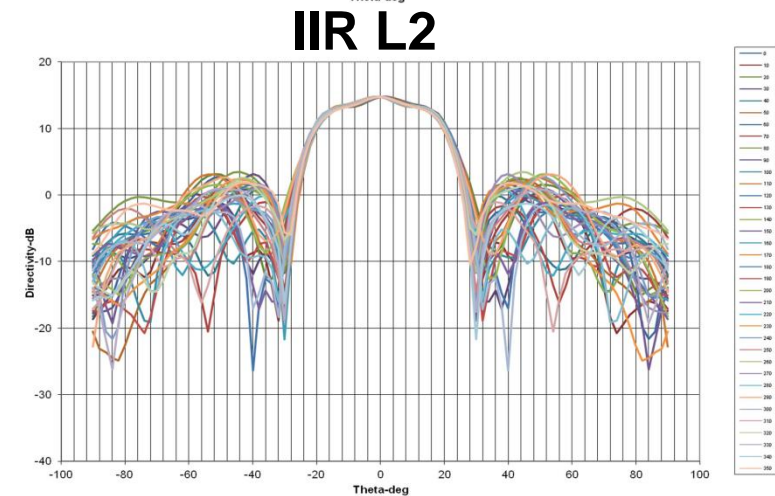
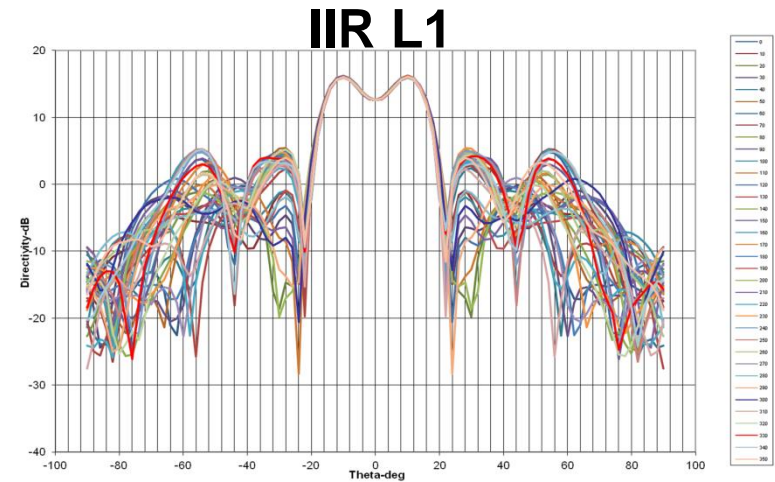


THE FLIGHT Orion's first flight test in December is a critical and significant step toward sending humans further into space than ever before. This test will evaluate launch and high speed re-entry systems such as avionics, attitude control, parachutes and the heat shield.



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

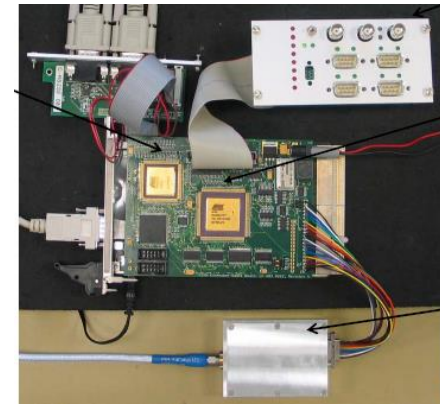
- Development of LION Navigator GNSS receiver for operations in HEO/GEO
- Performed 2011 study on Galileo SSV
- Paper presented at AAS GN&C conference on Lion Navigator receiver and interest in SSV specification for Galileo

• SSTL

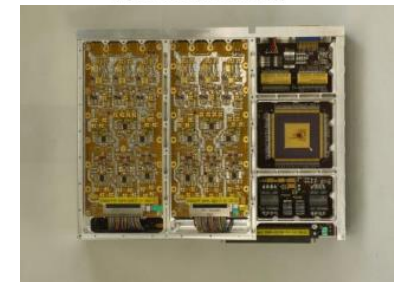
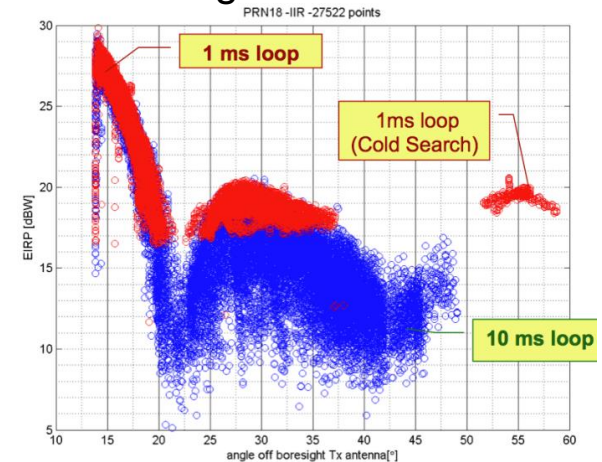
- GIOVE-A SGR-GEO experiment (2013) which carried 12 channel L1 C/A code GPS Receiver and operated in circular orbit at 23,200 km (3,200 km above GPS)
- Successfully tracked some 2nd side lobe signals & characterized antenna patterns for GPS IIA, IIR, IIR(M) and IIF satellites
- New GNSS receiver for 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



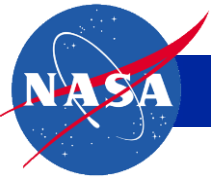


Lessons Learned Summary

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

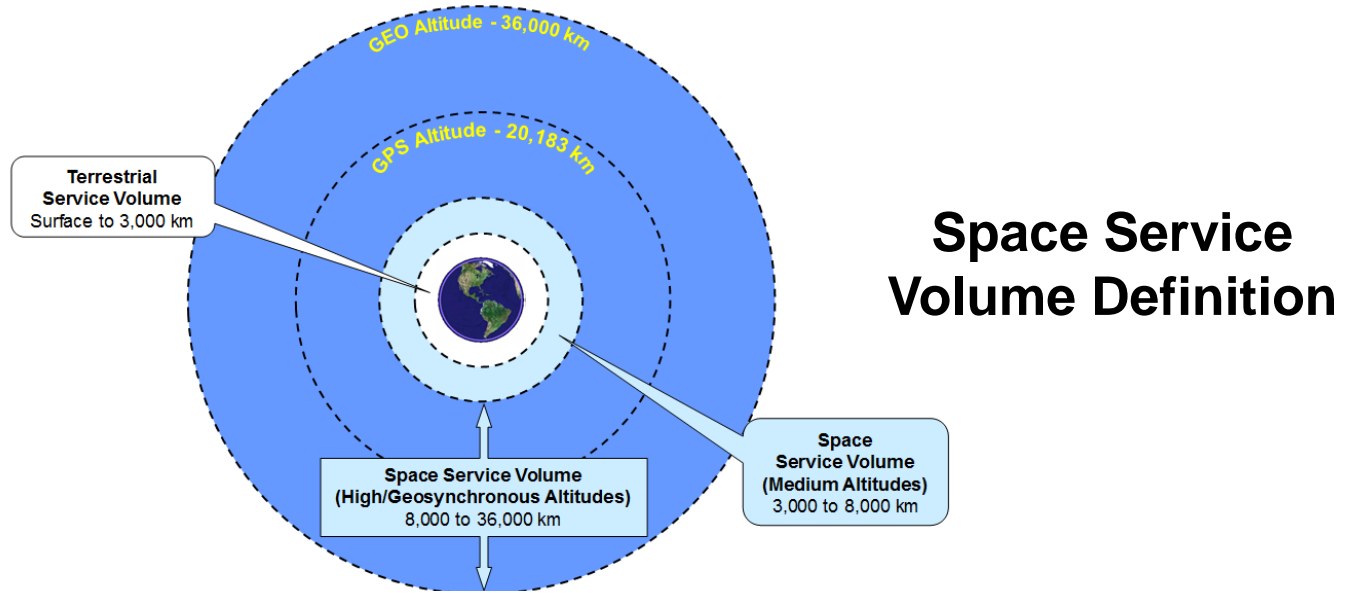
Protection of GPS Side Lobe Signals through Specification is Critically Important to “Do No Harm” to Current and Future Users of the SSV



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

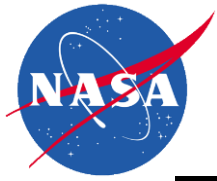


Unchanged SSV Specifications

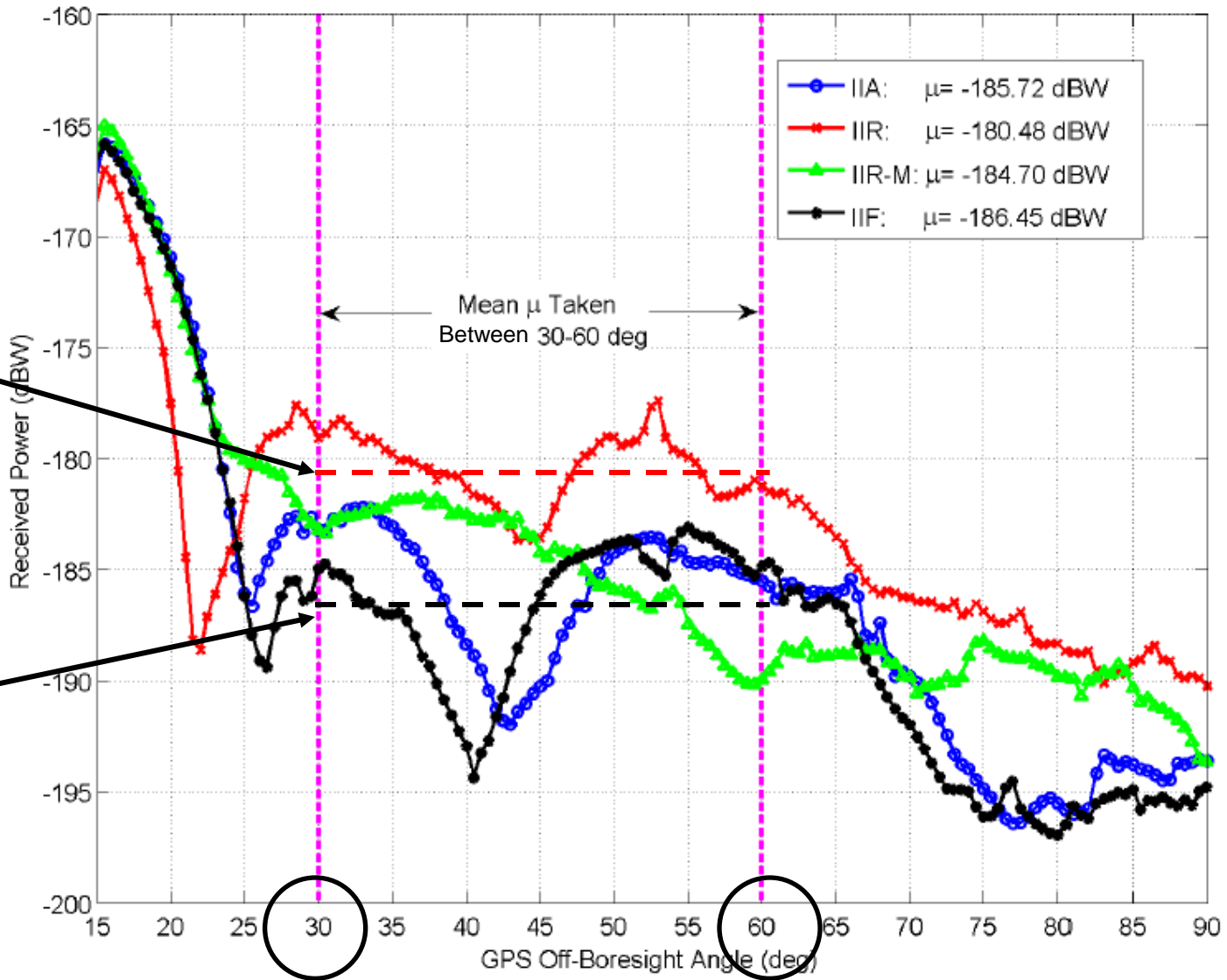


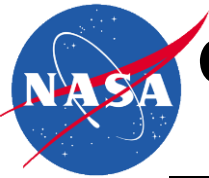
Signal	Terrestrial Minimum Power (dBW)	SSV Minimum Power (dBW)	Reference Half-beamwidth
L1 P(Y)	-161.5	-187.0	23.5
L1 C/A	-158.5	-184.0	23.5
L1 M	-158.0	-183.5	23.5
L1C	-157.0	-182.5	23.5
L1 composite	-151.2		
L2 P(Y)	-161.5	-186.0	26
L2 C/A or L2C	-158.5	-183.0	26
L2 M	-158.0	-182.5	26
L2 composite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

Main Lobe Signal Strength



Augmented SSV Requirement: Side Lobe Received Signal Power





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

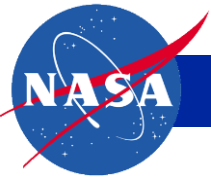
- Assuming a nominal, optimized GPS constellation (**24 satellites**) and no GPS spacecraft failures, signal availability at 95% of the areas at a specific altitude within the specified SSV are planned as:

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



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