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GNSS Space Service Volume & Space User Data Update

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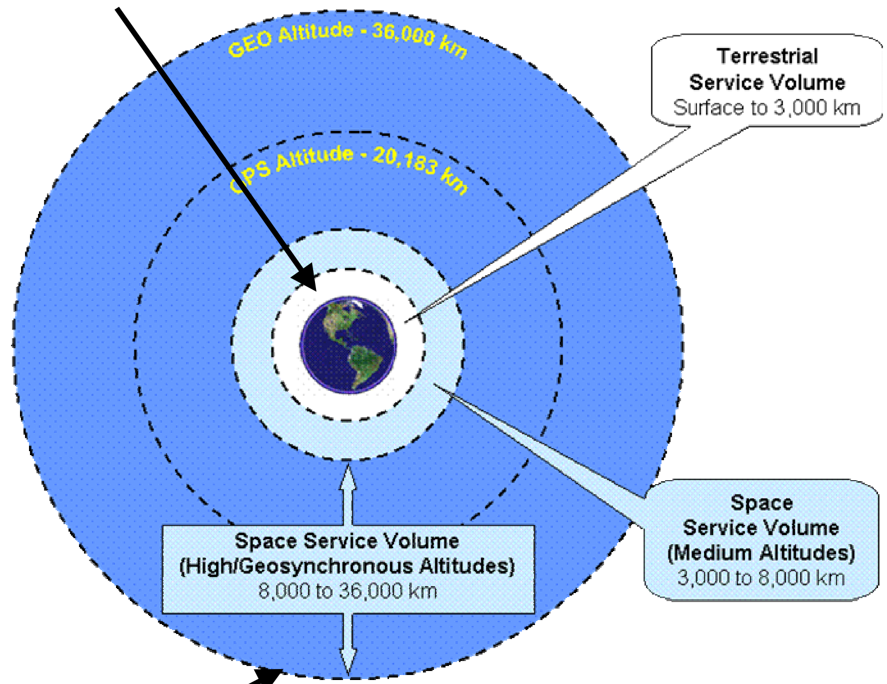
Expanding the GPS Space Service Volume (SSV) into a multi-GNSS SSV

- At least <u>four</u> GNSS satellites in line-of-sight are needed for on-board real-time position solutions
  - GPS currently provides this up to 3,000 km altitude
  - Enables better than 1-meter position accuracy in real-time
- At Geosynchronous altitude, 0-1 GPS satellites will be available using only GPS Main Antenna Lobe Signal.
  - **GPS-only** positioning still possible with on-board filtering, but only up to approx. 100-meter absolute position accuracy and long waits for navigation recovery from trajectory maneuvers.
  - **GPS** + **Galileo** combined would enable an average of approx 3 GNSS satellites in-view at all times, with infrequent 4 GNSS satellite availability (<30% of time).
  - **GPS** + **Galileo** + **GLONASS** would enable frequent 4 GNSS satellites in-view (68% of the time).
  - **GPS** + **Galileo** + **GLONASS** + **Beidou** would average 6 GNSS satellites in-view, with very frequent 4 GNSS satellite availability (91% of the time). This provides best accuracy and, also, on-board integrity.
- However, this requires:
  - Interoperability among these the GNSS constellations; <u>and</u>
  - Common definitions/specifications for use of GNSS signals within the Space Service Volume (3,000 km to Geosynchronous altitude)
- Further improvements can be realized by also specifying the Provider's side lobe signals

≥ 7 GPS satellites in line-of-sight here (surface to 3000 km)



Only average of 1.6 GPS satellites in line-of-sight at Geosynchronous orbit altitude

... but, <u>if</u> interoperable, then GPS + Galileo + GLONASS + Beidou provide > 4 GNSS sats in line-of-sight at Geosynchronous orbit altitude 91% of the time.

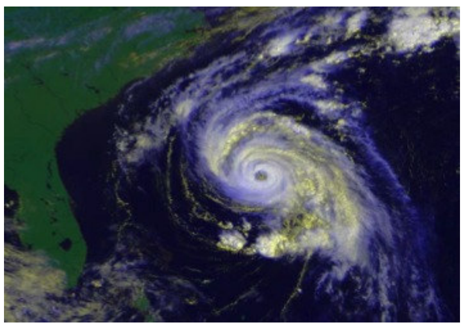
Space User/Space Service Volume Summary from ICG-8 (Dubai) Working Group-B

- **Discussions**
  - Significant progress has been made in establishing an interoperable Global Navigation Satellite System (GNSS) Space Service Volume (SSV) through pre-work, presentations, and additional robust contributions from the administrations of the Russian Federation and China.
  - Also recognize Europe, Japan and India for their long-term interest in a GNSS SSV and encourage SSV template completion and antenna characterization
  - The Working Group further discussed the benefits of an interoperable GNSS SSV
  - All WG-B participants believe that a fully interoperable GNSS SSV will result in significant benefits for future space users as it will allow for performance no single system can provide on its own
- **Recommendations from ICG-8**
  - **SSV Template Completion**: recommend all providers complete and formally submit SSV template. (Russia, China, Japan completed the templates, but not formally submitted)
  - **Definition Maturations**: Develop standard definitions of minimum number of satellites, constellation geometry, etc (this will help to perform unified GNSS SSV analysis)
  - **Spaceborne GNSS Receivers**: Build multi-frequency, and multi-constellation GNSS receivers to exploit the SSV
  - **Antenna / Electronics Characterization**: Measuring satellite transmit antenna patterns (pseudorange and phase vs. angle), and designing spacecraft electronics with strict requirements on phase and group delay coherence

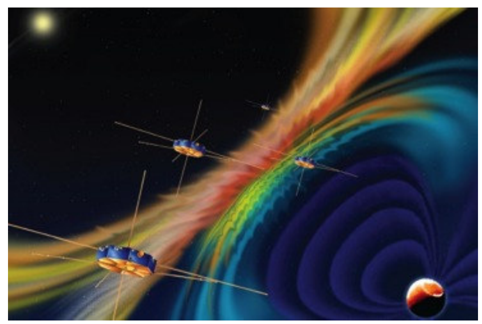
The Promise of using GNSS to Navigate in Cis-Lunar Space

SSV specifications are crucial for all space users, providing real-time navigation solutions in Low, Medium & High Earth Orbit & Beyond!

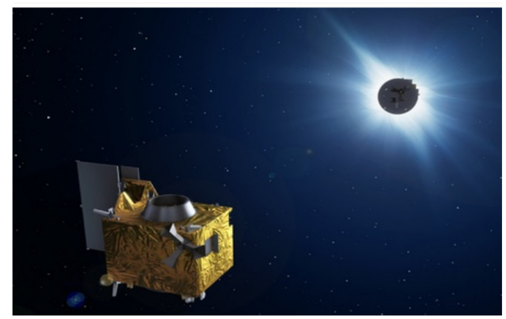
- **Supports increased satellite autonomy for missions, lowering mission operations costs**
- **Significantly improves vehicle navigation performance in these orbits**
- **Supports quick mission recovery after spacecraft trajectory maneuvers**
- **Enables new/enhanced capabilities and better performance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



Improved Weather Prediction using Advanced Weather Satellites

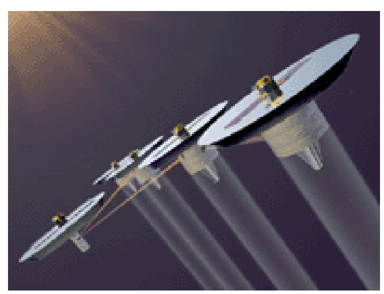


Space Weather Observations

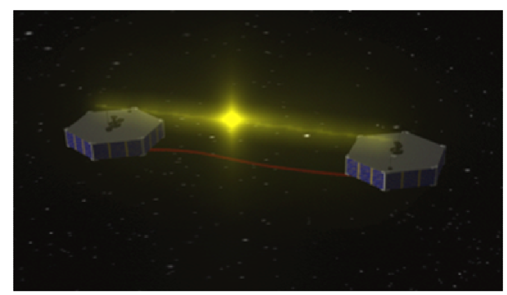


Solar Occultation Observations

En-route Lunar Navigation Support



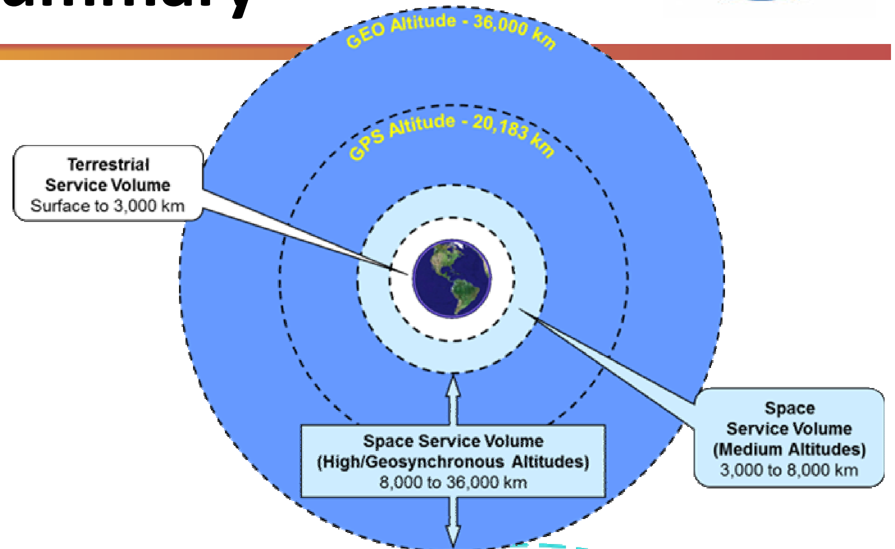
Formation Flying & Constellation Missions

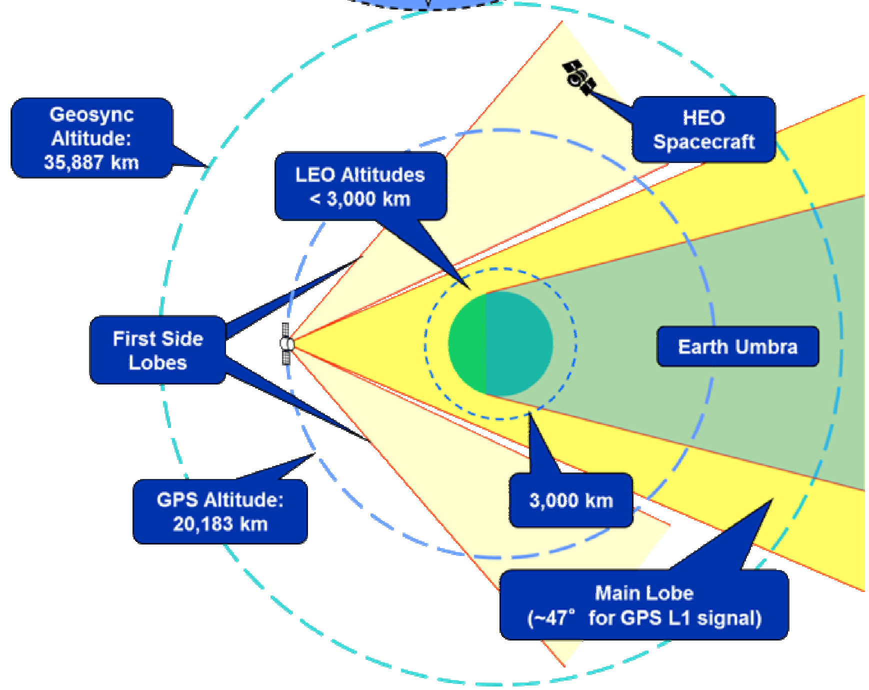


Closer Spacing of Satellites in Geostationary Arc

GPS SSV Status & Lessons Learned: Executive Summary

- Current SSV specifications, developed with limited on-orbit knowledge, employ only the GPS main lobe signal
- On-orbit data & lessons learned since spec development show significant PNT performance improvements when main lobe and side lobes are employed together
  - –Side lobe signals make significant contributions to PNT performance, enabled by modern weak signal tracking GPS receivers
- Numerous operational missions in High & Geosynchronous Earth Orbit (HEO/GEO) employ GPS side lobes to enhance vehicle PNT performance; many other missions in development
- Space user community is vulnerable to GPS constellation design changes if side lobe signal performance parameters not formally recognized
- Failure to protect GPS side lobe signals can result in significant loss of capability for space users in HEO/GEO orbits and should be preserved for on-board PNT in the 2025-2040 timeframe





U.S. Initiatives and Contributions to the International Community to Ensure an Interoperable, Sustained, Quantified GNSS Capability for Space Users

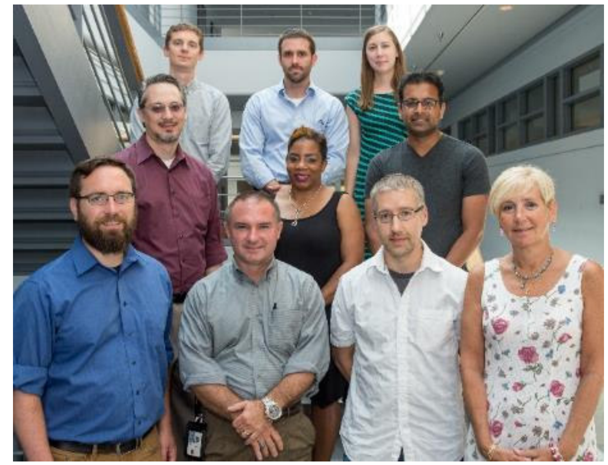
- Performing additional flight experiments above the constellation (e.g. ACE)
- Developing new weak signal GPS/GNSS receivers for spacecraft in cis-Lunar space (e.g. NASA Goddard Navigator and its commercial variants)
- Working with the GPS Directorate and DoD community to formally document GPS requirements and antenna patterns for space users
- Encouraging international coordination with other GNSS constellations (e,g, Galileo, GLONASS, BeiDou) to specify interoperable SSV capabilities
- Developing missions and systems to utilize GNSS signals in the SSV (e.g. MMS, GOES)

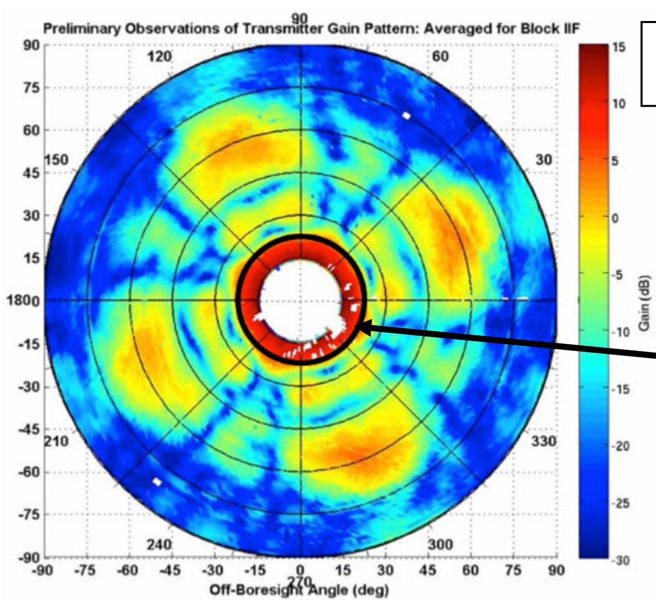
GPS Antenna Characterization Experiment (ACE)

GPS Antenna Characterization Experiment (ACE)

- GPS ACE project deployed advanced GPS receivers at the ground station of a Geostationary Earth Orbit (GEO) satellite
- Collection of side lobe data as seen at GEO in order to characterize the transmit antenna patterns
- On July 8, 2015 the GPS ACE NASA Team was awarded the Group Achievement Award by the NASA Administrator *for contributions to an unprecedented intergovernmental collaboration to perform the first comprehensive, on-orbit characterization of GPS satellite side-lobe transmissions*
- The project will contribute to the development of the GPS SSV

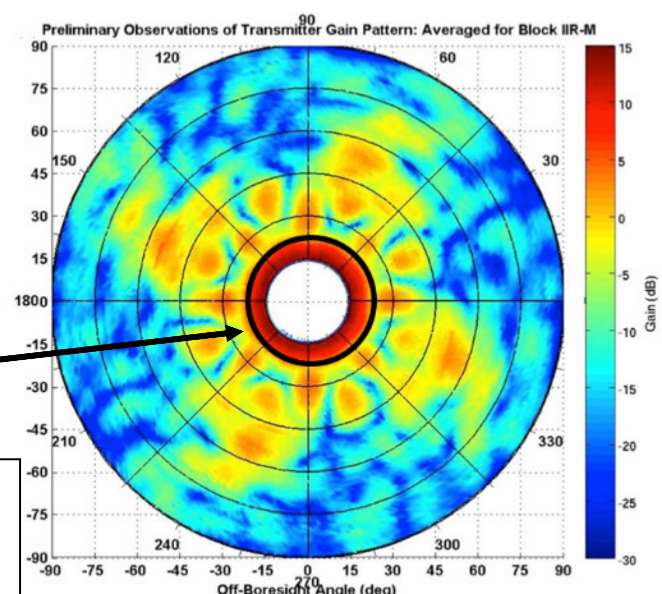
GPS ACE NASA Team





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

The current GPS spec only covers out to an angle of 23.5°



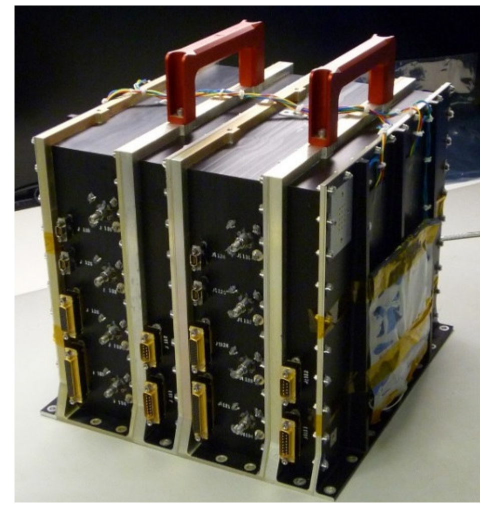
In-Flight Measurement Average from GPS **IIR-M** SVs

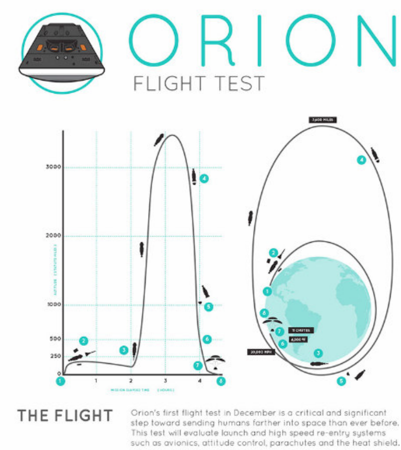
Navigator GPS Receiver for HEO/GEO Ops

- 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
- Multi-frequency receiver in development

<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)

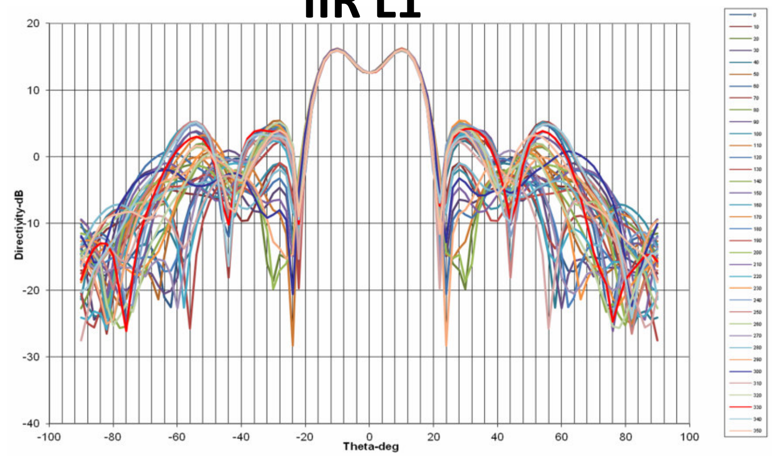




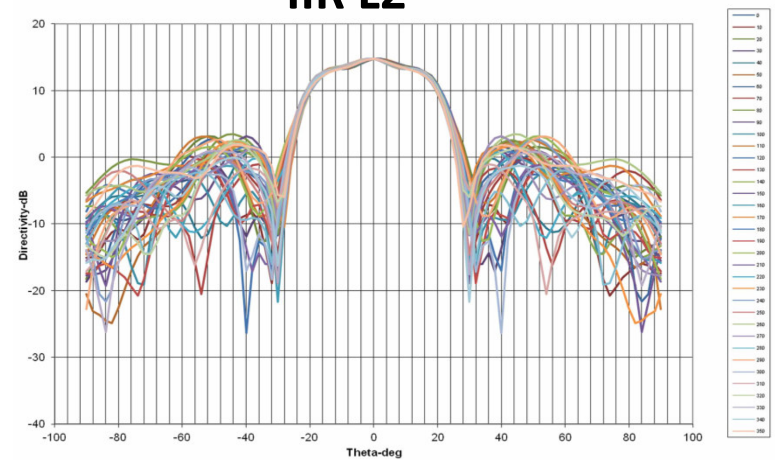
U.S. Publication of GPS Block IIR & IIR(M) Antenna Patterns

- 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 capabilities of current missions & enables development of enhanced GPS SSV specification, including sidelobe information

IIR L1



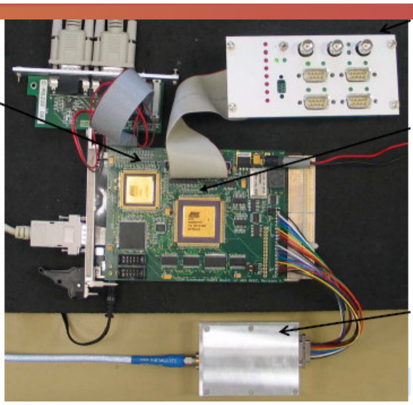
IIR L2



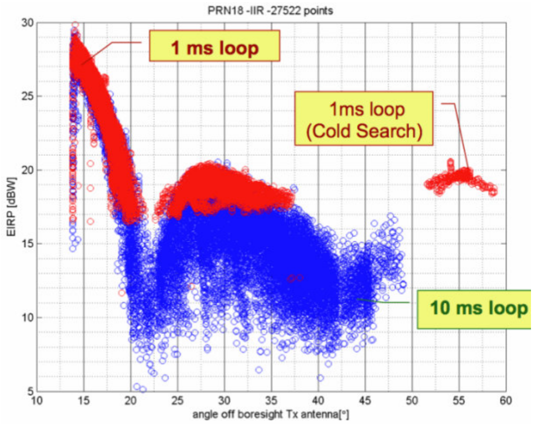
Special thanks to Willard Marquis/Lockheed Martin & Air Force GPS Program for publicly releasing this information!!

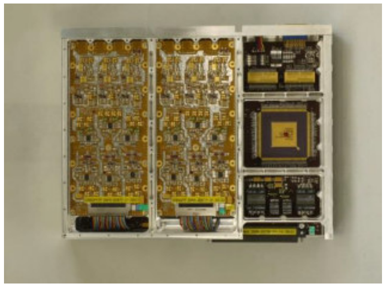
International SSV Coordination Example Initiatives

- **ICG/IOAG Forward Work**
  - Highly encourage GNSS, and regional navigation systems, partners to participate
    - Complete SSV templates
    - Develop SSV specification for your constellation
    - Publish your constellation antenna data
- **Airbus/Astrium**
  - LION Navigator HEO/GEO GNSS receiver development
  - Performed 2011 study on Galileo SSV
  - Paper presented at AAS GN&C conference on Lion Navigator receiver & interest in Galileo SSV specification
- **SSTL**
  - GIOVE-A SGR-GEO experiment (2013) which operated in circular orbit at 23,200 km (3,200 km above GPS)
  - 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)



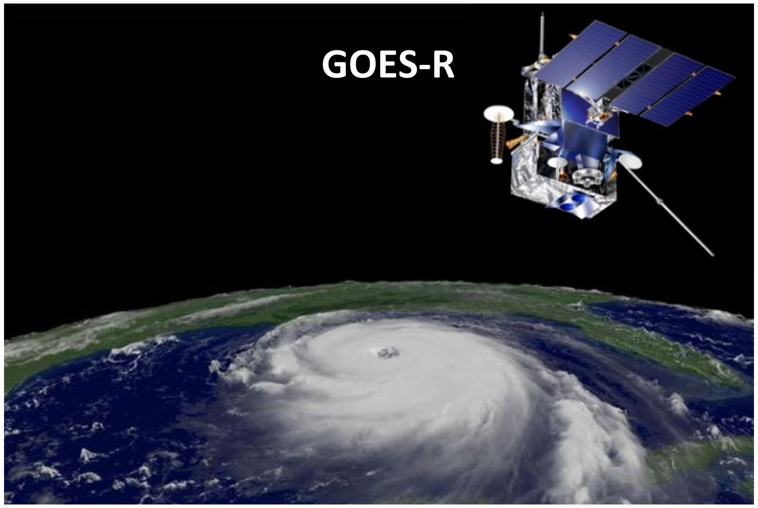
Lion Navigator Breadboard





Using GPS above the GPS Constellation: NASA/NOAA GOES Weather Satellites

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**

GOES-R provides conservative example of performance achievable using side lobe signals (based on ground based receiver testing).

Main lobe + side lobes

GOES-R Requirement vs Ground Test Results

Parameter	Reqt. (m, 3 sigma)	Performance (m, 3 sigma)
Radial	100	55.1
In-track	75	4.9
Cross-track	75	5.2

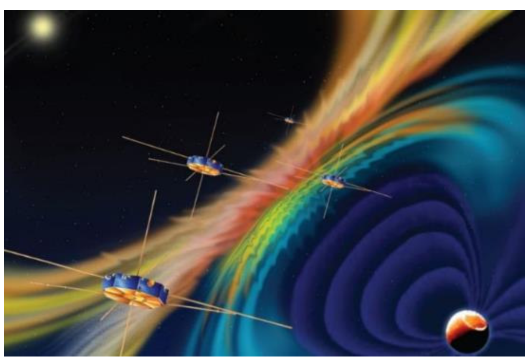
Using GPS above the GPS Constellation: NASA GSFC MMS Mission

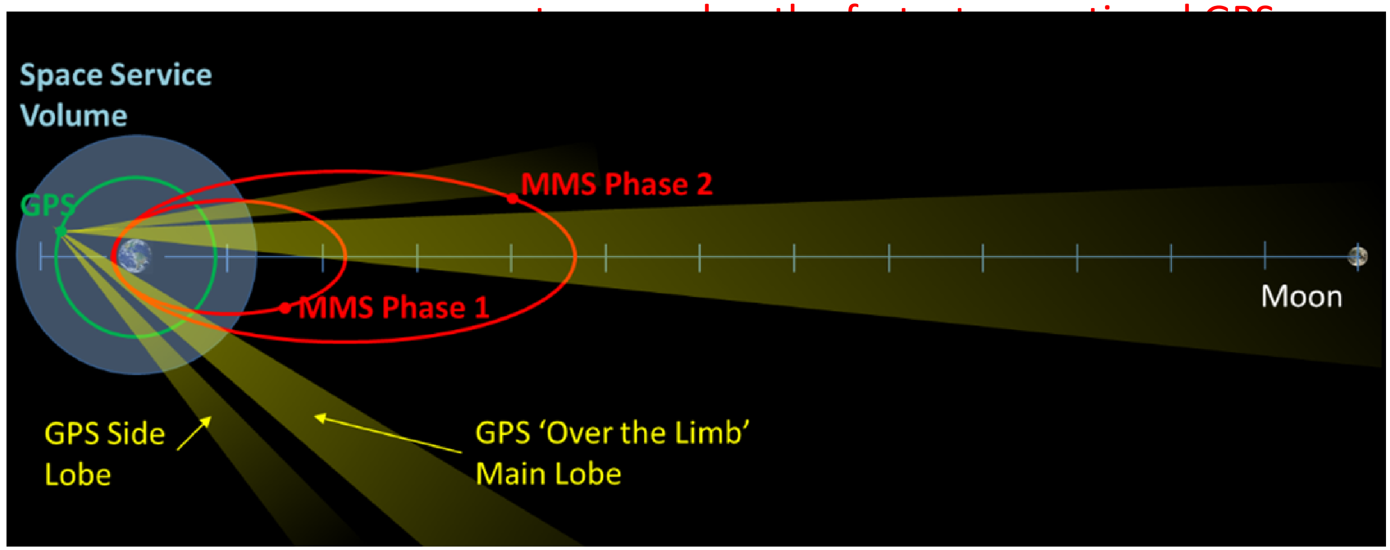
Magnetospheric Multi-Scale (MMS)

- 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)

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 a 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



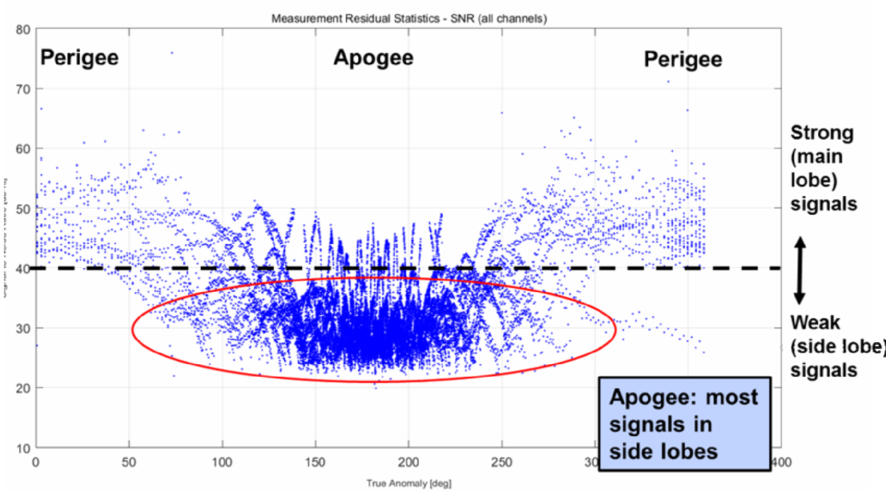


Measured Performance of MMS with Side Lobe Signal Availability

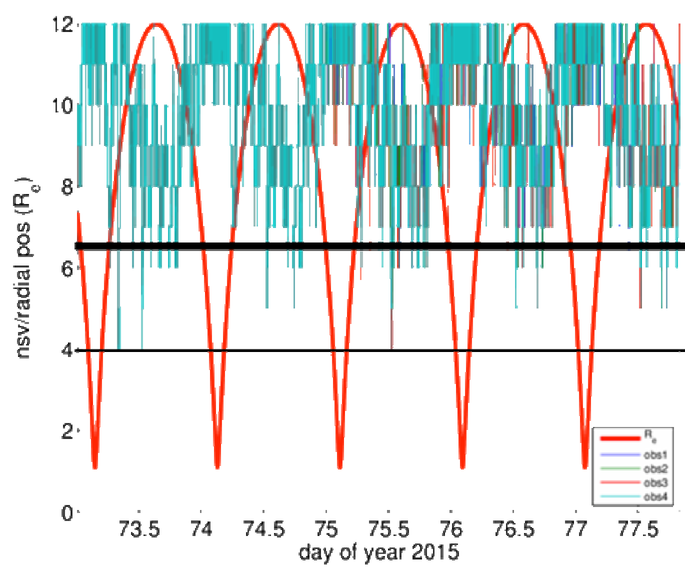
Signal Availability Contributed by Side Lobes (Assumes 24 Satellite Constellation)		
L1 Signal Availability	**Main Lobe Only**	**Main and Side Lobes**
4 or More SVs Visible	**Never**	**99%**
1 or More SVs Visible	59%	Always
No SVs Visible	41%	Never

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

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



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



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

MMS is seeing **100%**

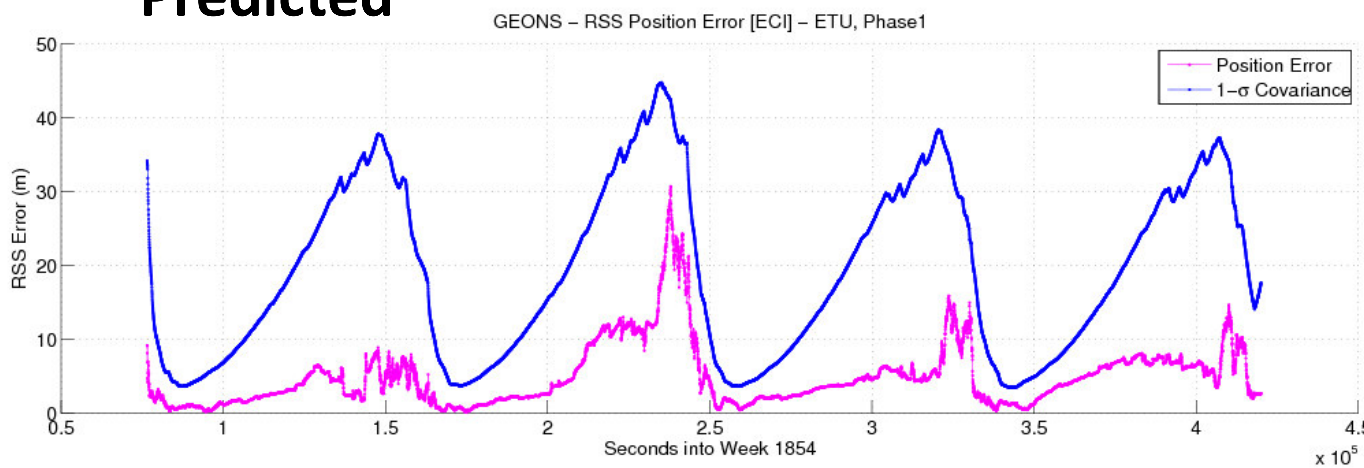
Navigation Performance: MMS Flight Data

Position error:

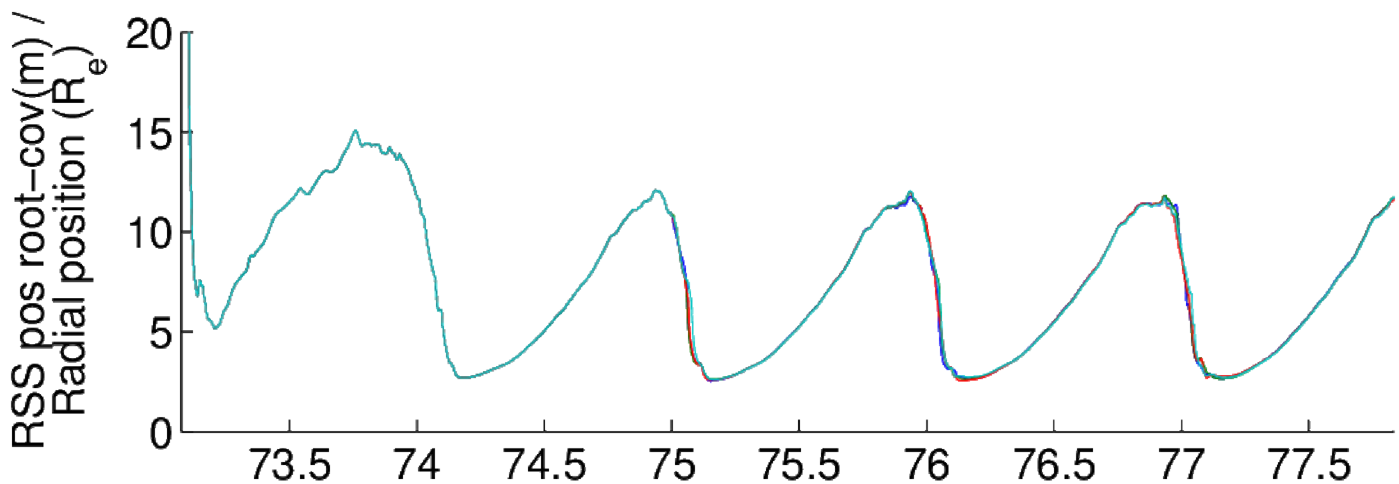
Achieved covariance is >50% improved over prediction.

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

Predicted



Achieved



Space User Vulnerability—Past and Present

- Circa 2003, GPS SSV vulnerability identified: signal availability & signal strength varied across block builds (IIA, IIRM, IIF) due to variances in main lobe antenna gain and beamwidth
  - Main lobe vulnerability resolved via 2006 SSV specifications for GPS IIIA
- Recent experience: performance significantly exceeds the current SSV specification (main lobe) and side lobe signals vary across block builds
  - On-orbit mission performance in HEO (MMS, GPS ACE, others) has demonstrated high signal quality of the side lobe signals→**Navigation Grade**
  - Side lobes currently have no specification
- Implication: Significant reductions in current performance could occur with future blocks of GPS Satellites (GPS-III SV9+) while still meeting all existing requirements
  - Side lobe signals already play crucial role in HEO/GEO signal availability & mission performance for a number of current/future missions

Coordinated Effort Underway through GPS IFOR Process to Protect Main Lobe and Side Lobe Signals

U.S. Delegation Experience attaining a GPS Space Service Volume Specification

- Mid-1990s—efforts started to develop a formal Space Service Volume
- February 2000—GPS Operational Requirements Document (ORD), released with first space user requirements and description of SSV
- 1997-Present—Several space flight experiments, particularly the AMSAT-OSCAR-40 experiment demonstrated critical need to enhance space user requirements and SSV
- 2000-2010—NASA/DoD team coordinated set of updated Space User requirements to meet existing and future PNT needs
  - Team worked with SMC/GPE, Aerospace support staff and AFSPACE to assess impacts of proposed requirements to GPS-III and to incorporate appropriate language into GPS-III Capabilities Description Document (CDD)
  - Threshold requirements correspond to performance from current constellation (do no harm to space users)
  - Future space user needs included as Objective requirements
  - Continual Joint Program Office “zero impact” push back on CDD levels to GPS-III baseline (Objective requirements)
  - Government System Spec (SS-SYS-800) includes CDD threshold & objective performance
  - 2015 and beyond—Working within US government processes (IFOR) to specify aggregate signal (main and sidelobes) to ensure signal availability for HEO/GEO space users

HEO/GEO SSV
Signal Protection Requirement Concepts

Primary goals

1) Protect current signals so new constellation builds maintain current PNT performance for HEO/GEO users

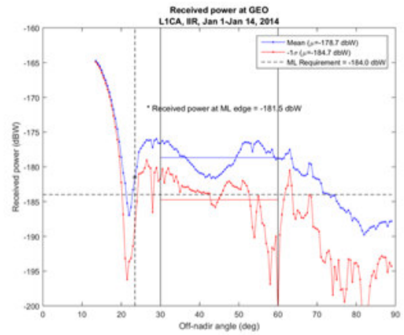
2) Specify smartly to not drive design

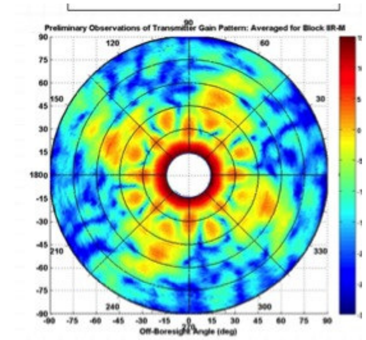
3) Similar to or minor changes to current SSV specification

4) No better than current system

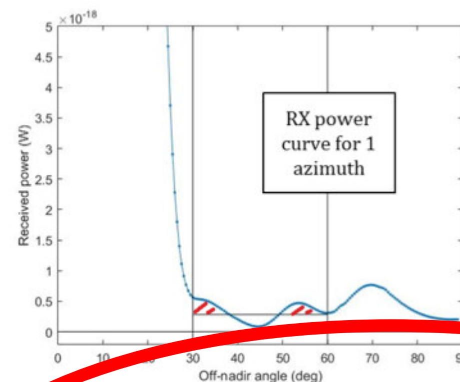
- Assumes 24 satellite constellation
- Analyses use constellation build with worst case signals in space

3 Concepts Currently Considered





Mean Received Side Lobe Power



Total Received Signal Power

	MEO SSV (unchanged from current requirement)		HEO/GEO SSV	
	at least 1 signal	4 or more signals	at least 1 signal	4 or more signals
L1	100%	≥ 97%	100%	≥ 99%
L2, L5	100%	100%	100%	≥ 77%

Signal Availability above Threshold Power

Work in Progress/Tentative Ideas

Benefits of Aggregate (Main & Side Lobe) GPS Signal Protection

- Gives green light for Project Managers to consider GPS in future space missions beyond LEO
- Substantially enhanced HEO/GEO missions and new mission types through:
  - Significantly improved signal availability
  - Improved navigation performance
  - Improved Position Dilution of Precision (PDOP)
  - Faster mission restoration after trajectory maneuvers

Protection of Aggregate GPS Signals Minimizes Risk to Future HEO/GEO Missions and Allows Project Managers to Exploit Signals in Space

GNSS Mission Areas (1):
Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes	Last Updated	Updated By
1	ASI	COSMO SKYMED (CSK)	GPS	L1/L2 C/A, P(Y)	Precise Orbit Determinatin (POD), Time	Es	2007, 2008, 2010	4 satellites	2015-Oct-08	F.D'AMICO
2	ASI	COSMO SKYMED SECOND GENERATION (CSG)	GPS, Galileo Ready	L1/L2/L2C (GPS) ready for E1 (Galileo)	Precise Orbit Determinatin (POD), Time	Es	2018 1st SAT, 2019 2nd SAT	2 satellites	2015-Oct-08	F.D'AMICO
3	ASI	AGILE	GPS	L1 C/A	Orbit, Time	Ee	2007		2015-Oct-08	F.D'AMICO
4	ASI	PRISMA	GPS		Orbit, Time	Es	2018		2015-Oct-08	F.D'AMICO
5	CNES	CALIPSO	GPS	L1 C/A	Orbit, Time	Es	2006	CNES controls the in flight satellite .	2014-Apr-23	JMS
6	CNES	COROT	GPS	L1 C/A	Orbit, Time	Ep (90°)	2006	CNES controls the in flight satellite .	2014-Apr-23	JMS
7	CNES	JASON-2	GPS*	L1 C/A	Orbit, Time	Ei (66°)	2008	CNES controls the in flight satellite in case of emergencey on behalf of NASA/NOAA or EUMETSAT.* GPS on Bus + GPSP on Payload (NASA)	2014-Apr-23	JMS
8	CNES	SMOS	GPS	L1 C/A	Orbit, Time	Es	2009	Launch was Nov 02, 2009. CNES controls the satellite in routine operations ; ESA operates the mission.	2014-Apr-23	JMS
9	CNES	ELISA	GPS	L1 C/A	Orbit, Time	Es	2011	The system is with four satellites launched in Dec 2011. Receiver: MOSAIC	2014-Mar-10	JMS
10	CNES	JASON-3	GPS*	L1 C/A	Orbit, Time	Ei (66°)	2015	CNES controls the in flight satellites in case of emergencey on behalf of NASA/NOAA or EUMETSAT.* GPS on Bus + GPSP on Payload (NASA)	2014-Apr-23	JMS
11	CNES	MICROSCOPE	GPS, Galileo	L1 C/A, E1	Precise Orbit Determinatin (POD), Time	Es	2016	One satellite to be launched in 2016 Receiver: SKYLOC	2014-Mar-10	JMS
12	CNES	CSO-MUSIS	GPS, Galileo	L1 C/A, L2C, L5 E1, E5a	Orbit, Time	Es	2017	The system is with three satellites to be launched from 2017. Receiver : LION	2014-Mar-10	JMS
13	CNES	MERLIN	GPS, Galileo	L1 C/A, E1	Orbit, Time	Es (TBC)	2018	Receiver : not yet decided	2014-Mar-10	JMS
14	CNES	SWOT	GPS, Galileo (to be decided)	GPS L1 C/A, other (to be decided)	Orbit, Time	Ep (77,6°)	2020	Receiver : not yet decided	2014-Apr-23	JMS
15	DLR/NASA	GR1 / GR2 (GRACE)	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD, RO	Ep	17-Mar-2002	Joint mission with NASA.	2014-Mar-17	MP
16	DLR	TSX-1	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD, RO, precsie relative determination	Es	15-Jun-2007		2014-Mar-17	MP
17	DLR	TDX-1	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD, RO, precsie relative determination	Es	21-Jun-2010		2014-Mar-17	MP
18	DLR	TET	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support)	Ep	22-July-2012		2014-Mar-17	MP

GNSS Mission Areas (2):
Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes	Last Updated	Updated By
19	DLR	TET NOX experiment	GPS	GPS L1 C/A, L1/L2 P(Y)	Experiment (POD, RO)	Ep	22-July-2012		2014-Mar-17	MP
20	DLR	BIROS	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support)	Ep	2015		2014-Mar-17	MP
21	DLR	HAG-1	GPS	GPS L1 C/A	Experiment (navigation)	G	2014	GPS used for on-board experiment	2014-Mar-17	MP
22	DLR	Eu:CROPIS	GPS	GPS L1 C/A	navigation, flight dynamics	Ep	2016		2014-Mar-17	MP
23	DLR	ENMAP	GPS			Ep	2017		2013-May 27	MP
24	DLR/NASA	GRACE_FO	GPS GLO/GAL?)	GPS L1 C/A, L1/L2 P(Y), (others?)	Navigation, POD	Ep	2018	Joint mission with NASA.	2014-Mar-17	MP
25	DLR	DEOS	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support), relative navigation (formation flight/ rendezvous)	Ep	2017		2014-Mar-17	MP
26	DLR	Electra	GPS		orbit determination	G	2018		2013-May 27	MP
27	DLR	PAZ	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD	Ep	2014	Same as TSX	2014-Mar-17	MP
28	ESA	SWARM			POD	LEO	2013	Magnetosphere, 3 spacecraft	2015-Oct-02	MS
29	ESA	Earth Care			Orbit	LEO	2018		2015-Oct-02	MS
30	ESA	BIOMASS					2020	SAR	2015-Oct-02	MS
31	ESA	Sentinel S1			Orbit, POD	LEO	2014 / 16	SAR, 2 spacecraft	2015-Oct-02	MS
32	ESA	Sentinel S2			Orbit	LEO	2015	Imager, 2 spacecraft	2015-Oct-02	MS
33	ESA	Sentinel S3			Orbit, POD	LEO	2015	Altimetry & Imager, 2 spacecraft	2015-Oct-02	MS
34	ESA	Sentinel S4				LEO		UV Spectrometry	2015-Oct-02	MS
35	ESA	Proba 2			Orbit	LEO	2009	Tech Demo	2015-Oct-02	MS
36	ESA	Proba 3			FF	HEO	2019	FF Demo, 2 spacecraft	2015-Oct-02	MS

GNSS Mission Areas (3):
Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes	Last Updated	Updated By
37	ESA	Small GEO			Orbit, Time	GEO	2015	Telecom	2015-Oct-02	MS
38	ESA	FLEX				LEO	2022	Florescence Explorer	2015-Oct-02	MS
39	ESA	JASON-CS				LEO	2017	Altimetry	2015-Oct-02	MS
40	ESA	METOP			Radio Occultation	LEO	2012 / 18	Atmospheric Sounder, 2 spacecraft	2015-Oct-02	MS
41	ESA	MTG			Orbit, Time	GEO	2018 / 19	IR Sounder & Imager, 2 spacecraft	2015-Oct-02	MS
42	ESA	Post EPS					2021/27/33	3 spacecraft	2015-Oct-02	MS
43	JAXA	GOSAT	GPS	L1	Orbit, time	LEO	2009-present	Remote Sensing	2013-May-27	
44	JAXA	GCOM-W1	GPS	L1	Orbit, time	LEO	2012-present	Remote Sensing	2013-May-27	
45	JAXA	GCOM-C1	GPS	L1	Orbit, time	LEO	2016	Remote Sensing	2013-May-27	
46	JAXA	ALOS-2	GPS	L1, L2	Precise orbit (3σ<1m), Orbit, time,	LEO	2013	Remote Sensing	2013-May-27	
47	JAXA	HTV-series	GPS	L1	Orbit(relative)	LEO	2009-present	Unmanned ISS transportation	2013-May-27	
48	JAXA	GOSAT-2	GPS	L1, L2 (TBD)	Orbit, time	LEO	2017	Remote Sensing	2013-May-27	
49	JAXA	ASTRO-H	GPS	L1, L2	Orbit, time	LEO	2015	Remote Sensing	2013-May-27	
50	NASA	ISS	GPS	L1 C/A	Attitude Dynamics	LEO	Since 1998	Honeywell SIGI receiver	2014-Feb-4	JJ Miller
51	NASA	COSMIC (6 satellites)	GPS	L1 C/A, L1/L2 semicodeless, L2C	Radio Occultation	LEO	2006	IGOR (BlackJack) receiver; spacecraft nearing end of life	2014-Apr-28	JJ Miller
52	NASA	SAC-C	GPS	L1 C/A, L1/L2 semicodeless, L2C	Precise Orbit Determination, Occultation, surface reflections	LEO	2000	BlackJack receiver; mission retired 15 August 2013	2014-Feb-4	JJ Miller
53	NASA	IceSat	GPS	L1 C/A, L1/L2 semicodeless	Precise Orbit Determination	LEO	2003	BlackJack receiver; mission retired 14 August 2010	2014-Apr-28	JJ Miller
54	NASA	GRACE (2 satellites)	GPS	L1 C/A, L1/L2 semicodeless	Precise Orbit Determination, Occultation	LEO	2002	BlackJack receiver, joint mission with DLR	2014-Feb-4	JJ Miller

GNSS Mission Areas (4): Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes	Last Updated	Updated By
55	CNES/NASA	OSTM/Jason 2	GPS	L1 C/A, L1/L2 semicodeless	Precise Orbit Determination	LEO	2008	BlackJack receiver	2014-May-13	JJ Miller
56	NASA	Landsat-8	GPS	L1 C/A	Orbit	LEO	2013	GD Viceroy receiver	2014-Feb-4	JJ Miller
57	NASA	ISS Commercial Crew and Cargo Program - Dragon	GPS	L1 C/A	Orbit / ISS rendezvous	LEO	2013+		2014-Feb-4	JJ Miller
58	NASA	ISS Commercial Crew and Cargo Program: Cygnus	GPS	L1 C/A	Orbit / ISS rendezvous	LEO	2013+		2014-Feb-4	JJ Miller
59	NASA	CONNECT / SCaN Test-Bed (ISS)	GPS	L1 C/A, L1/L2 semicodeless, L2C, L5, + option for Galileo & GLONASS	Radio occultation, precision orbit, time	LEO	2013	Blackjack-based SDR. Monitoring of GPS CNAV testing began in June 2013.	April 28 2014	JJ Miller
60	NASA	GPM	GPS	L1 C/A	Orbit, time	LEO	2014	Navigator receiver	2014-Feb-4	JJ Miller
61	NASA	Orion/MPCV	GPS	L1 C/A	Orbit / navigation	LEO	2014 - Earth Orbit, 2017 Cislunar	Honeywell Aerospace Electronic Systems 'GPSR' receiver	2014-Feb-4	JJ Miller
62	NSPO/USAF/NASA	COSMIC IIA (6 satellites)	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Occultation	LEO	2015	TriG receiver, 8 RF inputs, hardware all-GNSS capable, will track GPS + GLONASS at launch	2015-Oct-6	JJ Miller
63	NASA	DSAC	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Time transfer	LEO	2015	TriG lite receiver	2015-Oct-6	JJ Miller
64	CNES/NASA	Jason-3	GPS, GLONASS FDMA	L1 C/A, L1/L2 semicodeless, L2C	Precise Orbit Determination, Oceanography	LEO	2015	IGOR+ (BlackJack) receiver	2015-Oct-6	JJ Miller
65	NASA	MMS	GPS	L1 C/A	Rel. range, orbit, time	up to 30 Earth radii	2015	Navigator receiver (8 receivers)	2014-Apr-28	JJ Miller
66	NASA	GOES-R	GPS	L1 C/A	Orbit	GEO	2016	General Dynamics Viceroy-4	2014-Apr-28	JJ Miller
67	NASA	ICESat-2	GPS	-	-	LEO	2016	RUAG Space receiver	2014-Feb-4	JJ Miller
68	NASA	CYGNSS (8 sats)	GPS	-	GPS bi-scatterometry	LEO	2016	Delay Mapping Receiver (DMR), SSTL UK	2015-Oct-6	JJ Miller
69	NSPO/USAF/NASA	COSMIC IIB (6 satellites)	GPS, GLONASS FDMA, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Occultation	LEO	2017	TriG receiver	2014-Feb-4	JJ Miller
70	NASA/DLR	GRACE FO	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Occultation, precision orbit, time	LEO	2018	TriG receiver with microwave ranging, joint mission with DLR	2015-Oct-6	JJ Miller
71	NASA	Jason-CS	GPS, GLONASS FDMA, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Precise Orbit Determination	LEO	2020	TriG receiver with 1553	2015-Oct-6	JJ Miller
72	NASA	GRASP	GPS, GLONASS FDMA, Beudou, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Precise Orbit Determination	LEO	2017	Trig receiver (proposed)	2015-Oct-6	JJ Miller

GNSS Mission Areas (5): Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes	Last Updated	Updated By
73	NASA	GRACE II	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Science	LEO	2020	Trig receiver (proposed)	2015-Oct-6	JJ Miller
74	NASA	NICER (ISS)	GPS	L1 C/A	Orbit	LEO	2016	Moog/Navigator receiver	2014-Apr-28	JJ Miller
75	NASA	Pegasus Launcher	GPS	L1 C/A	Navigation	Surface to LEO	Since 1990	Trimble receiver	2014-Feb-4	JJ Miller
76	NASA	Antares (formerly Taurus II) Launcher	GPS	L1 C/A	Integrated Inertial Navigation System (INS) & GPS	Surface to LEO	Since 2010	Orbital GPB receiver	2014-Feb-4	JJ Miller
77	NASA	Falcon-9 Launcher	GPS	L1 C/A	Overlay to INS for additional orbit insertion accuracy	Surface to LEO	Since 2013		2014-Feb-4	JJ Miller
78	NASA	Launchers* at the Eastern and Western Ranges	GPS	L1 C/A	Autonomous Flight Safety System	Range Safety	2016*	(*) Including ULA Atlas V and Delta IV (GPS system: Space Vector SIL, uses a Javad receiver). (**) Estimated initional operational test.	2014-Feb-4	JJ Miller
79	NASA	NISAR	GPS, GLONASS, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Precise Orbit Determination, timing	LEO	2020	TriG Lite receiver	2015-Oct-6	JJ Miller
80	NASA	SWOT	GPS, GLONASS FDMA	L1 C/A, L2C, L5, Galileo, GLONASS FDMA	Precise Orbit Determination - Real Time	LEO	2020	TriG Lite receiver with 1553	2015-Oct-6	JJ Miller

Notes: (1) Orbit Type: Ee = Equatorial Earth Orbiter; Ei = Inclined Earth Orbiter; Ep = Polar Earth Orbiter; Es = Sun Synchronous Earth Orbiter; G = Geostationary; H = High Elliptical Earth Orbit; R = Earth orbiter Relay; O = Other orbit type (specify in remarks)

- These reference tables were prepared for the Interagency Operations Advisory Group (IOAG), and then updated for the International Committee on GNSS (ICG)
- The objective is to ensure the space user community does not remain vulnerable when using other GNSS constellations
- Space agency stakeholders need 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 has been recommending that space agencies define their space user performance needs for their respective GNSS constellations, and strengthen collaboration with other international bodies such as ICG to ensure implementation of such capabilities
- As a result of these efforts, the *Joint Statement* issued at the 8th meeting of the ICG (ICG-8) included language on the GNSS Space Service Volume: (http://www.unoosa.org/pdf/icg/2013/icg-8/ICG-8_JointStatement.pdf)

Conclusions
(Chart 1 of 2)

- For the commercial and space science community to exploit the full potential of GNSS in space, it is crucial for the international GNSS to develop an interoperable, sustained, and quantified GNSS Capability that provides robust PNT support to users throughout the SSV
- The U.S. GPS partners have made significant steps in accomplishing this through the specification of the SSV, publication of GPS antenna patterns and open discussions on on-orbit experiment and flight mission results
- Based on lessons learned from recent space missions, U.S. GPS partners are developing new SSV sidelobe signal specifications to maintain current signal availability for users in HEO/GEO
  - International partners should consider an SSV specification which includes main and side lobe elements

Conclusions
(Chart 2 of 2)

- Others are starting to follow the U.S. lead, but formal documentation and GNSS specifications are still forthcoming
- Partners should work aggressively to complete the ICG-8 WG-B recommendations:
  - **SSV Template Completion**: recommend all providers complete and formally submit SSV template (Russia, China, Japan completed, but not formally submitted, the templates)
  - **Definition Maturations**: Develop standard definitions of minimum number of satellites, constellation geometry, etc (this will help to perform unified GNSS SSV analysis)
  - **Spaceborne GNSS Receivers**: Build multi-frequency, and multi-constellation GNSS receivers to exploit the SSV
  - **Antenna/Electronics Characterization**: Measuring satellite transmit antenna patterns (pseudorange and phase vs. angle), and designing spacecraft electronics with strict requirements on phase and group delay coherence

NASA GNSS Spaceborne Receiver Request for Information (RFI)

- Encompasses GNSS spaceborne receiver systems in industry, government, and academic institutions (US & international)
- Will help NASA understand receiver technology status currently available & will be available in 2-3 years
- Data specified as public is planned to be published in a public database
- Organizations with multiple receivers can provide multiple RFI inputs—1 per receiver
- To review the RFI & submit inputs
  - https://www.fbo.gov/spg/NASA/LaRC/OPDC20220/RFI-GNSS2015/listing.html
  - Easier Approach through Google Keyword Search: NASA RFI GNSS 2015
  - RFI planned to be open until December 11
- All are encouraged to submit; Please spread the word!

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- Sincere thanks to those in the U.S. for their leadership in realizing the Space Service Volume vision:
  - USAF SMC GPS Directorate
  - GSFC Antenna Characterization Experiment (ACE) Team
  - GSFC Magnetospheric Multi-Scale (MMS) Mission Team
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- Acknowledging, in advance, all outside the U.S. that recognize the in-space advantages of the GPS SSV specification and provide leadership in developing a SSV specification for their GNSS constellation

Backups

Specifications (1): Received Signal Power

Signal	Terrestrial Minimum Power (dBW)	SSV Minimum Power (dBW)*	Reference Half-beamwidth
L1 C/A	-158.5	-184.0	23.5
L1C	-157.0	-182.5	23.5
L2C	-158.5	-183.0	26
L5	-157.0	-182.0	26

(*) SSV Minimum power from a 0 dBiC antenna at GEO

- 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 specifications at reference off-nadir point

Specifications (2): Pseudorange Accuracy

- In the Terrestrial Service Volume, a position accuracy is specified. In the Space Service Volume, pseudorange accuracy is specified.
- Position accuracy within the space service volume is dependent on many mission specific factors, which are unique to this class of user, such as user spacecraft orbit, CONOPS, navigation algorithm, and User Equipment
- Specification: The space service volume pseudorange accuracy shall be ≤ 0.8 m (rms) (**Threshold**); and ≤ 0.2 m (rms) (**Objective**)
- In order for GPS to meet the SSV accuracy requirement, additional data must be provided to users:
  - The group delay differential parameters for the radiated signal with respect to the Earth Coverage
- To better clarify the pseudorange accuracy specification, it is suggested that partners consider the following in lieu of the above pseudorange accuracy specification:
  - Pseudorange specification: The space service volume maximum systematic error in pseudorange shall be ≤ 0.8 m (rms) (**Threshold**); and ≤ 0.2 m (rms) (**Objective**)
- Also, the following Carrier Phase specification is suggested:
  - Carrier Phase specification: The space service volume maximum systematic error in carrier phase shall be ≤ 8 mm (rms) (**Threshold**); and ≤ 2 mm (rms) (**Objective**)

Specifications (3): Signal Availability

- 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 should be as follows:

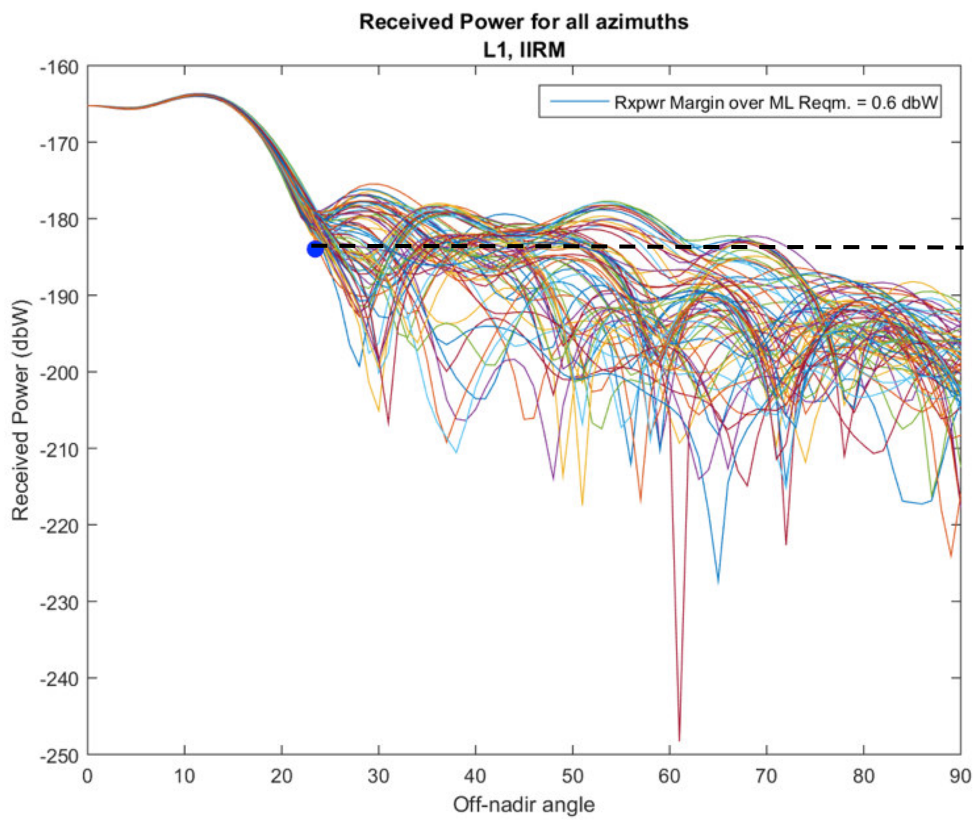
	MEO SSV		HEO/GEO SSV	
	at least 1 signal	4 or more signals	at least 1 signal	4 or more signals
L1	100%	≥ 97%	≥ 80% [1]	≥ 1%
L2, L5	100%	100%	≥ 92% [2]	≥ 6.5%

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

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

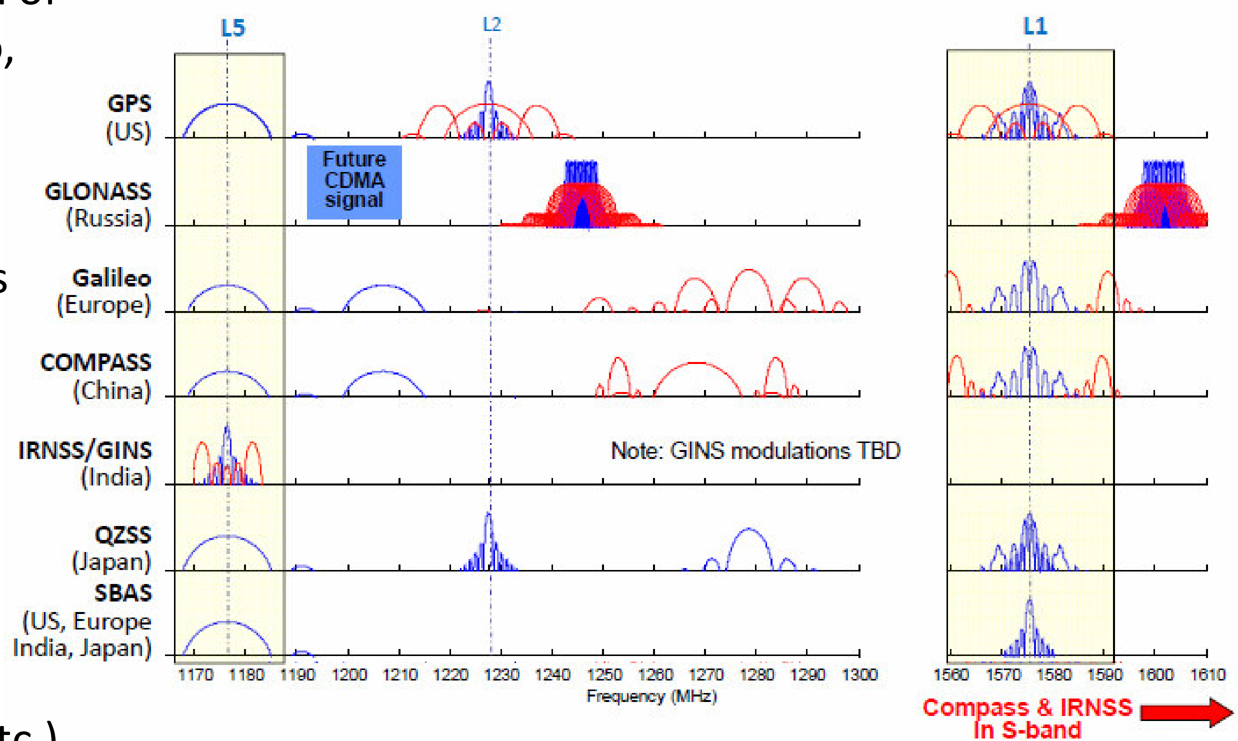
Example Transmitted Power Levels vs SSV Requirement: L1 C/A Signal

- Current requirements limited to main lobe signals only:
  - 23.5 degrees off nadir for L1
- Specification has significant margin against current signal in space (particularly for L2 and L5 signals)
- Many side lobe signals exceed main lobe specification



Current Global and Regional International Navigation Signal Plans

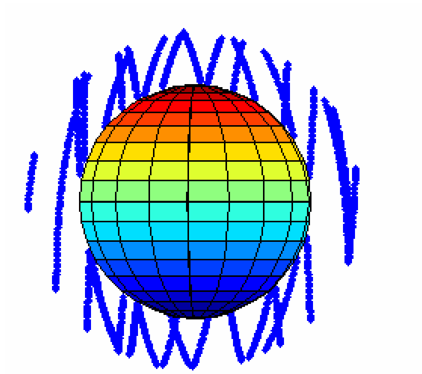
- There is an ongoing expansion of global (GPS, GLONASS, Galileo, Beidou) and regional (IRNSS, QZSS, SBAS) space systems to support PNT
- More than 100 GNSS satellites could be available in the near future
- The Radio Navigation Satellite Service (RNSS) spectrum is increasingly being populated with new signals to support various user communities (navigation, science, timing, etc.)



- Interoperability is the ability of global and regional navigation satellite systems and augmentations and the services they provide to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system

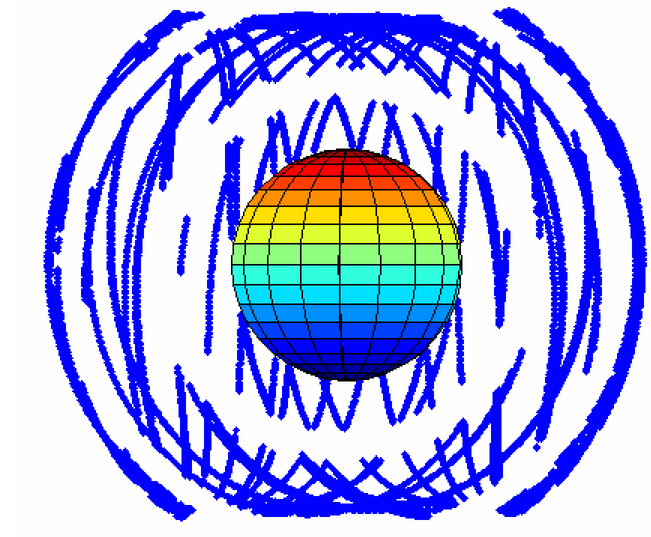
HEO & GEO Space Mission Navigation Significantly Enhanced when GPS Side Lobes Included

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
- HEO/GEO missions relying on unspecified GPS signals in the SSV for success
- Future specification of SSV side lobe signals?