Update on NASA GPS Applications for Space Operations and Science

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Tampa, Florida

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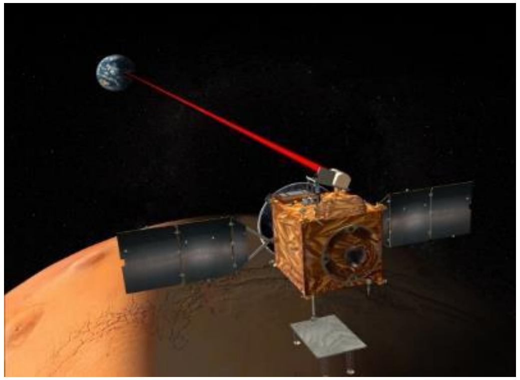
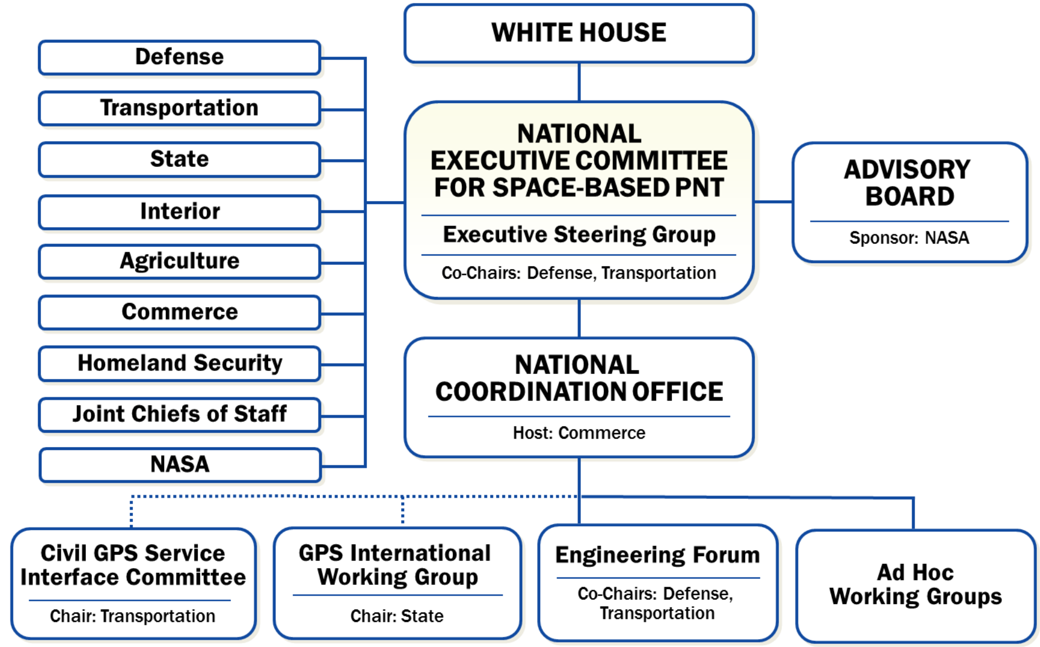
SCaN Oversees NASA Infrastructure for Space Communications and Navigation



- The Space Communications and Navigation (SCaN) program is responsible for providing worldwide communications & navigation services to enable and enhance robotic and human exploration and science missions
- SCaN leads in enabling NASA's overall navigation capabilities through:
  - standards development
  - systems engineering
  - architecture integration
  - technology R&D
  - spectrum coordination
  - international interoperability
  - national policy advocacy
- Use of GPS/GNSS as another position and time source allows NASA to maximize the "autonomy" of spacecraft while reducing the burden on network operations and enabling countless science applications

NASA’s Role: U.S. PNT & Space Policy

- The 2004 U.S. Space-Based Positioning, Navigation, and Timing (PNT) Policy tasks the NASA Administrator, in coordination with the Secretary of Commerce, to develop and provide requirements for the use of the Global Positioning System (GPS) and its augmentations to support civil space systems
- The 2010 National Space Policy reaffirms PNT Policy commitments to GPS service provisions, international cooperation, and interference mitigation
  - Foreign PNT services may be used to augment and strengthen the resiliency of GPS
- Besides direct collaboration with interagency partners & foreign space agencies, NASA international engagement is conducted at:
  - International Committee on Global Navigation Satellite Systems (ICG)
  - International Telecommunications Union (ITU)
  - Interoperability Plenary (IOP)
  - Interagency Operations Advisory Group (IOAG)
  - Space Frequency Coordination Group (SFCG)
  - Consultative Committee for Space Data Systems (CCSDS)



2015-2017 PNT Board Membership: Focus is on Assured PNT through "PTA" (Protect, Toughen, Augment)

- **John Stenbit (Chair)**, former DoD Chief Information Officer
- **Bradford Parkinson (Vice Chair)**, Stanford University original GPS Program Director
- **James E. Geringer (2nd Vice Chair)**, ESRI Former Governor of Wyoming
- **Thad Allen**, Booz Allen Hamilton retired Commandant of the Coast Guard
- **Penina Axelrad**, University of Colorado, Chair of Department of Aerospace Engineering
- **John Betz**, MITRE, Former Chair Air Force Scientific Advisory Board
- **Dean Brenner**, Vice President, Government Affairs Qualcomm
- **Scott Burgett**, Garmin International
- **Joseph D. Burns**, United Airlines, Former Chief Technical Pilot, United Airlines
- **Ann Ciganer**, VP Trimble Navigation, Director of GPS Innovation Alliance
- **Per K. Enge**, Stanford University, Head of Stanford Center for PNT
- **Martin C. Faga**, MITRE Retired CEO of Mitre
- **Dana A. Goward**, Resilient Navigation & Timing Foundation, Founder
- **Ronald R. Hatch**, consultant to John Deere, inventor of the GPS "Hatch" filter
- **Larry James**, Deputy Director, Jet Propulsion Laboratory
- **Peter Marquez**, Planetary Resources, Former White House National Security Space Policy
- **Terence J. McGurn**, private consultant, retired CIA analyst of Position, Navigation and Control
- **Timothy A. Murphy**, The Boeing Company, Technical Fellow with Boeing Commercial Airplane
- **Ruth Neilan**, Jet Propulsion Laboratory, vice chair, Global Geodetic Observing System
- **T. Russell Shields**, Ygomi, a founder of NavTeq

International Members:

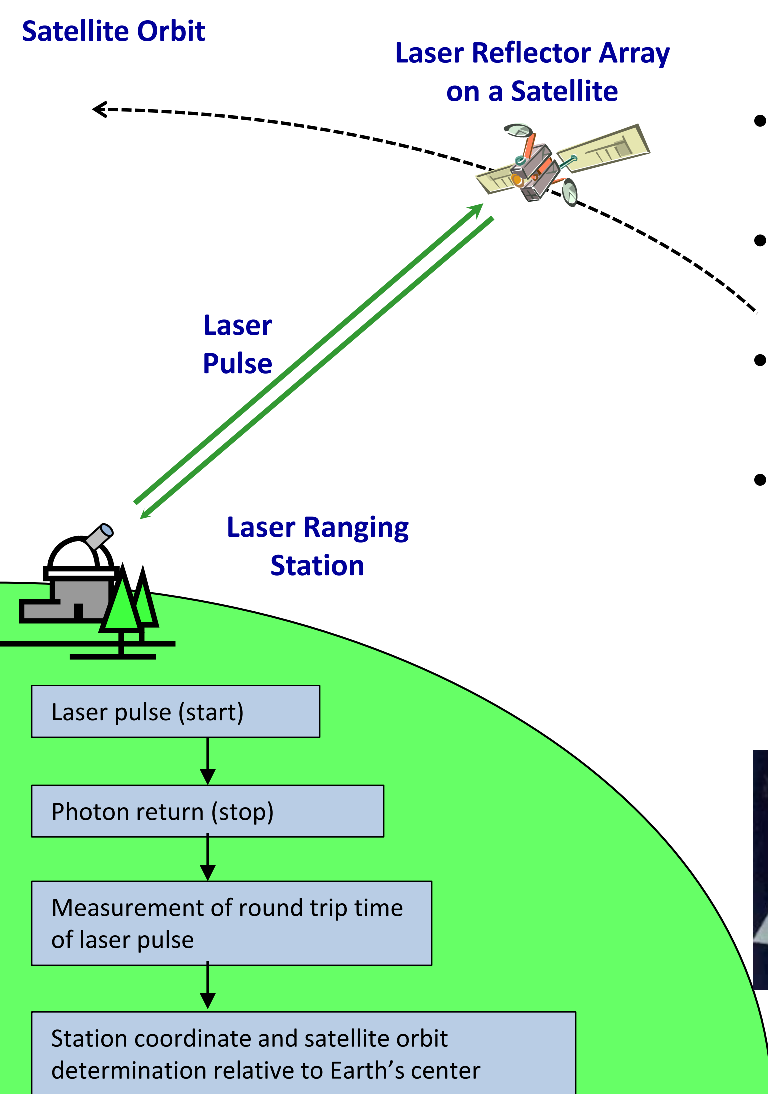
- **Gerhard Beutler**, Professor of Astronomy and Director of the Astronomical Institute, U. of Bern.
- **Sergio Camacho-Lara**, Regional Centre for Space Science and Technology Education for Latin America and the Caribbean, Mexico
- **Arve Dimmen**, Division Director Maritime Safety Norwegian Coastal Administration (Norway)
- **Matt Higgins**, President International GNSS Society (Australia)
- **Rafaat M. Rashad**, Chairman Arab Institute of Navigation (Egypt)

NASA Contributions to GPS Enterprise

- **NASA's policy sponsorship of PNT Board supplements technical contributions to GPS**
  - Minutes, Recommendations, and Reports from taskings available at www.gps.gov
  - 15th meeting held Jun. 11-12, 2015, in Annapolis, MD
  - 16th meeting scheduled for Oct. 30-31, 2015 in Boulder, CO (in conjunction with the ICG 10th meeting)
- **NASA's technical contributions focus on improving space operations & science for all**
  - RNSS spectrum protection
  - GPS-based science applications (radio-occultation, geodesy, earthquake/tsunami warning, etc.,)
  - GPS/GNSS civil signal monitoring (operational performance)
  - GPS MEOSAR (search and rescue)
  - Laser Retro-reflector Arrays (LRAs) on GPS III
  - Multi-GNSS space receivers (GSFC "Navigator" & JPL "TriG" families)
  - Interoperable GNSS Space Service Volume (SSV)
- **NASA contributes towards fulfilling national policy goals through application of technology**

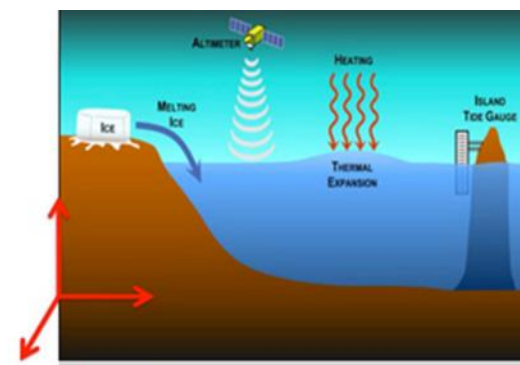
  "The U.S. maintains space-based PNT services that -- (1) provide uninterrupted availability of PNT services; (2) meet growing national, homeland, economic security, civil requirements, and scientific and commercial demands; (3) remain the pre-eminent military space-based PNT service; (4) continue to provide civil services that exceed or are competitive with foreign civil space-based PNT services; (5) remain essential components of internationally accepted PNT services; and (6) promote U.S. technological leadership in applications involving space-based PNT services."
- **Enhancing GPS precision and availability enables "cutting edge" science, which in turn allows science to be applied towards improving GPS performance -- *i.e., Satellite Laser Ranging (SLR)…***

Satellite Laser Ranging (SLR) on GPS III



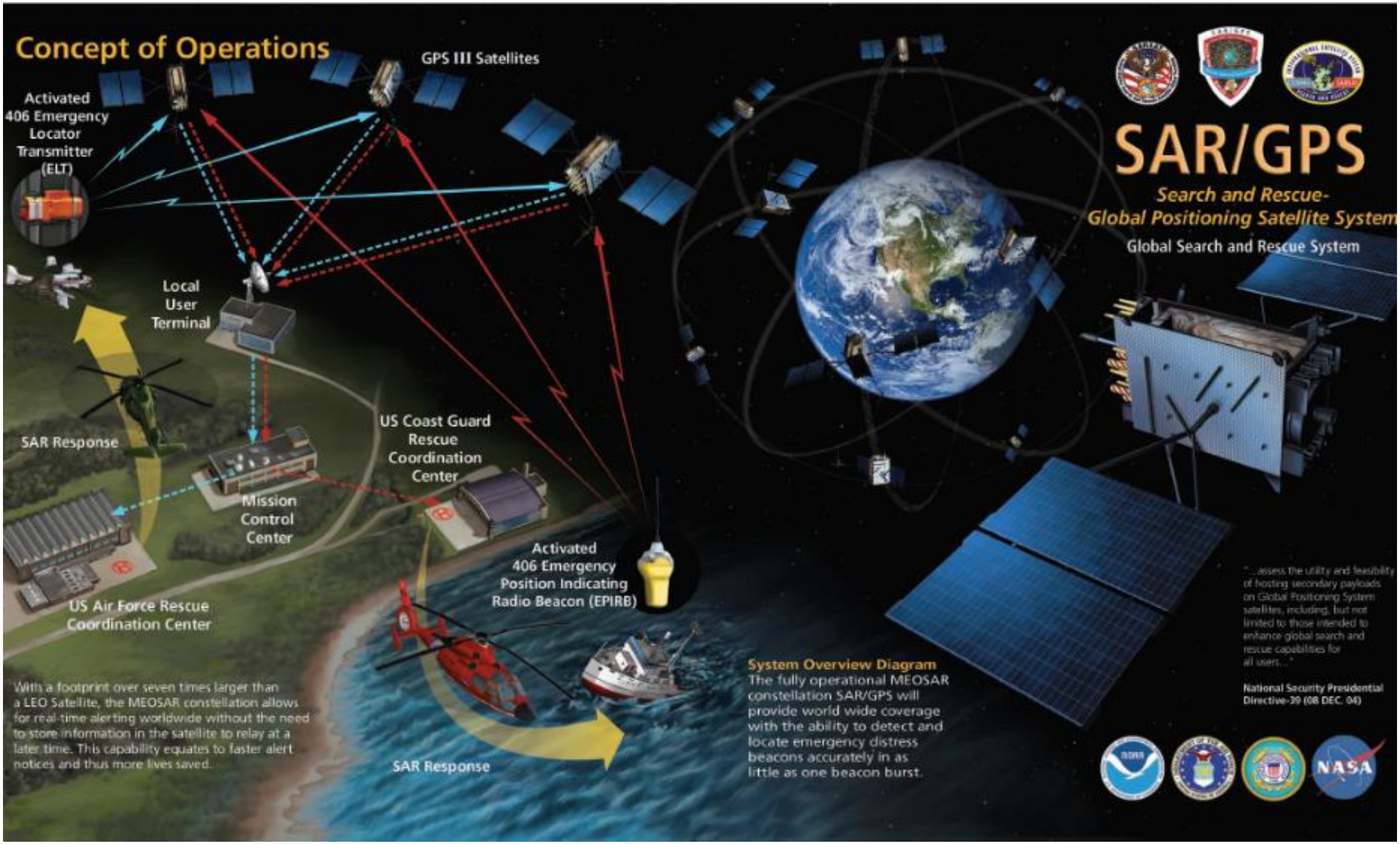
- Laser ranging to GNSS satellites enables the comparison of optical laser measurements with radiometric data, identifying systemic errors
- Post-processing this data allows for refining station coordinates, satellite orbits, and timing epochs
- The refined data enables improved models and reference frames
- This results in higher PNT accuracies for all users, while enhancing interoperability amongst constellations
- NASA Administrator Bolden collaborated with Air Force Gen Shelton & Gen Kehler to secure approval for Laser Reflector Arrays (LRAs) on GPS III

GPS Block II SVs 35 & 36



Space Geodesy provides positioning, navigation, and timing reference systems and Earth system observations

Search and Rescue from Space: Distress Alerting Satellite System evolves into SAR/GPS

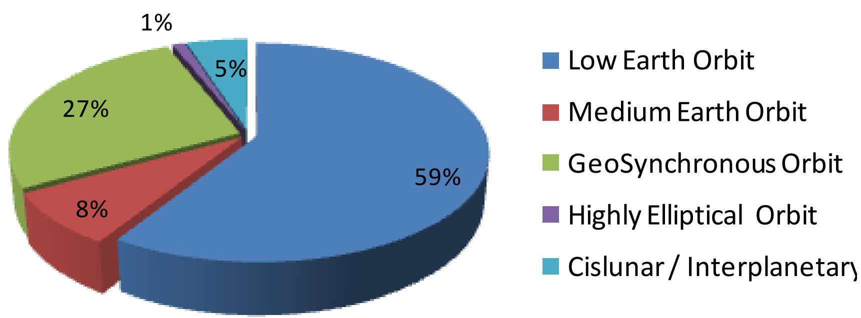


Growing GPS Uses in Space: Space Operations & Science

- NASA strategic navigation requirements for science and space ops continue to grow, especially as higher precisions are needed for more complex operations in all space domains
- **Nearly 60%**[*] of projected worldwide space missions over the next 20 years will operate in LEO
  - That is, inside the Terrestrial Service Volume (TSV)
- **An additional 35%**[*] of these space missions that will operate at higher altitudes will remain at or below GEO
  - That is, inside the GPS/GNSS Space Service Volume (SSV)
- In summary, approximately **95% of projected worldwide space missions over the next 20 years** will operate within the *GPS service envelope*

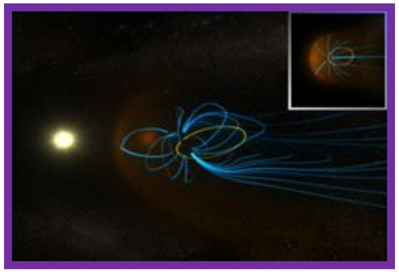
(*) Source: Aerospace America, American Institute of Aeronautics and Astronautics (AIAA), Dec. 2007

20-Year Worldwide Space Mission Projections by Orbit Type *



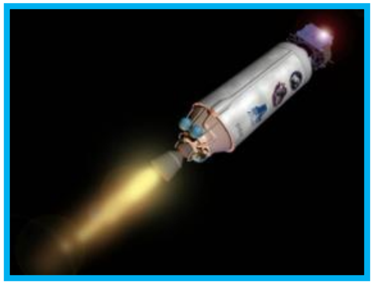
Highly Elliptical Orbits*: Example: NASA MMS 4-satellite constellation.

(*) Apogee above GEO/GSO



Medium Earth Orbit: GNSS Constellations, etc.,

GeoSynchronous: Communication Satellites, etc.,



Orbital Transfers: LEO-to-GSO, cislunar transfer orbit, transplanetary injection, etc.

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
1	ASI	CSK	GPS			Es	2007	4 satellites
2	ASI	CSG	GPS, Galileo Ready			Es	2016	2 satellites
3	ASI	AGILE	GPS			Ee	2007	
4	ASI	PRISMA	GPS			Es	2015	
5	ASI	OPSIS	GPS			Es	2017	
6	CNES	CALIPSO	GPS	L1 C/A	Orbit, Time	Es	2006	CNES controls the in flight satellite .
7	CNES	COROT	GPS	L1 C/A	Orbit, Time	Ep (90°)	2006	CNES controls the in flight satellite .
8	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)
9	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.
10	CNES	ELISA	GPS	L1 C/A	Orbit, Time	Es	2011	The system is with four satellites launched in Dec 2011. Receiver: MOSAIC
11	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)
12	CNES	MICROSCOPE	GPS, Galileo	L1 C/A, E1	Precise Orbit Determinatin (POD), Time	Es	2016	One satellite to be launched in 2016 Receiver: SKYLOC
13	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
14	CNES	MERLIN	GPS, Galileo	L1 C/A, E1	Orbit, Time	Es (TBC)	2018	Receiver : not yet decided
15	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
16	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.
17	DLR	TSX-1	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD, RO, precsie relative determination	Es	15-Jun-2007	
18	DLR	TDX-1	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD, RO, precsie relative determination	Es	21-Jun-2010	
19	DLR	TET	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support)	Ep	22-July-2012	
20	DLR	TET NOX experiment	GPS	GPS L1 C/A, L1/L2 P(Y)	Experiment (POD, RO)	Ep	22-July-2012	
21	DLR	BIROS	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support)	Ep	2015	
22	DLR	HAG-1	GPS	GPS L1 C/A	Experiment (navigation)	G	2014	GPS used for on-board experiment
23	DLR	Eu:CROPIS	GPS	GPS L1 C/A	navigation, flight dynamics	Ep	2016	
24	DLR	ENMAP	GPS			Ep	2017	
25	DLR/NASA	GRACE_FO	GPS GLO/GAL?)	GPS L1 C/A, L1/L2 P(Y), (others?)	Navigation, POD	Ep	2018	Joint mission with NASA.

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
26	DLR	DEOS	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support), relative navigation (formation flight/ rendezvous)	Ep	2017	
27	DLR	Electra	GPS		orbit determination	G	2018	
28	DLR	PAZ	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD	Ep	2014	Same as TSX
29	ESA	GOCE			POD	LEO	2009	
30	ESA	Swarm			POD	LEO	2013	
31	ESA	MetOp			Radio Occultaiton	LEO	2006	
32	ESA	EarthCare			Orbital GPB	LEO	2016	
33	ESA	BIOMASS				LEO	2018	
34	ESA	GMES S1			Orbit, POD	LEO	2013	
35	ESA	GMES S2			Orbit	LEO	2015	
36	ESA	GMES S3			Orbit, POD	LEO	2015	
37	ESA	MTG			Orbit, Time	GEO	2018	
38	ESA	NGGM			FF with MetOp	LEO		
39	ESA	STE-QUEST			Orbit, Time	LEO		
40	ESA	Proba 2			Orbit	LEO	2009	
41	ESA	Proba 3			FF with MetOp	HEO	2017	
42	ESA	ATV			Rendezvous	LEO	Began in 2009	
43	ESA	Small GEO			Orbit, Time	GEO	2014	
44	JAXA	GOSAT	GPS	L1	Orbit, time	LEO	2009-present	Remote Sensing
45	JAXA	GCOM-W1	GPS	L1	Orbit, time	LEO	2012-present	Remote Sensing
46	JAXA	GCOM-C1	GPS	L1	Orbit, time	LEO	2016	Remote Sensing
47	JAXA	ALOS-2	GPS	L1, L2	Precise orbit (3σ<1m), Orbit, time,	LEO	2013	Remote Sensing
48	JAXA	HTV-series	GPS	L1	Orbit(relative)	LEO	2009-present	Unmanned ISS transportation
49	JAXA	GOSAT-2	GPS	L1, L2 (TBD)	Orbit, time	LEO	2017	Remote Sensing
50	JAXA	ASTRO-H	GPS	L1, L2	Orbit, time	LEO	2015	Remote Sensing

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
51	NASA	ISS	GPS	L1 C/A	Attitude Dynamics	LEO	Since 1998	Honeywell SIGI receiver
52	NASA	COSMIC (6 satellites)	GPS	L1 C/A, L1/L2 semicodeless, L2C	Radio Occultation	LEO	2006	IGOR (BlackJack) receiver; spacecraft nearing end of life
53	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
54	NASA	IceSat	GPS	L1 C/A, L1/L2 semicodeless	Precise Orbit Determination	LEO	2003	BlackJack receiver; mission retired 14 August 2010
55	NASA	GRACE (2 satellites)	GPS	L1 C/A, L1/L2 semicodeless	Precise Orbit Determination, Occultation	LEO	2002	BlackJack receiver, joint mission with DLR
56	CNES/NASA	OSTM/Jason 2	GPS	L1 C/A, L1/L2 semicodeless	Precise Orbit Determination	LEO	2008	BlackJack receiver
57	NASA	Landsat-8	GPS	L1 C/A	Orbit	LEO	2013	GD Viceroy receiver
58	NASA	ISS Commercial Crew and Cargo Program - Dragon	GPS	L1 C/A	Orbit / ISS rendezvous	LEO	2013+	
59	NASA	ISS Commercial Crew and Cargo Program: Cygnus	GPS	L1 C/A	Orbit / ISS rendezvous	LEO	2013+	
60	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.
61	NASA	GPM	GPS	L1 C/A	Orbit, time	LEO	2014	Navigator receiver
62	NASA	Orion/MPCV	GPS	L1 C/A	Orbit / navigation	LEO	2014 - Earth Orbit, 2017 Cislunar	Honeywell Aerospace Electronic Systems 'GPSR' receiver
63	NSPO/USAF/NASA	COSMIC IIA (6 satellites)	GPS, GLONASS, Galileo	L1 C/A, L2C, L5, Galileo, GLONASS	Occultation	LEO	2015	TriG receiver
64	NASA	DSAC	GPS, GLONASS, Galileo	L1 C/A, L2C, L5, Galileo, GLONASS	Time transfer	LEO	2015	TriG receiver
65	CNES/NASA	Jason-3	GPS, GLONASS, Galileo	L1 C/A, L1/L2 semicodeless, L2C	Precise Orbit Determination, Oceanography	LEO	2015	IGOR+ (BlackJack) receiver
66	NASA	MMS	GPS	L1 C/A	Rel. range, orbit, time	up to 30 Earth radii	2015	Navigator receiver (8 receivers)
67	NASA	GOES-R	GPS	L1 C/A	Orbit	GEO	2016	General Dynamics Viceroy-4
68	NASA	ICESat-2	GPS	-	-	LEO	2016	RUAG Space receiver
69	NASA	CYGNSS (8 sats)	GPS	-	GPS bi-scatterometry	LEO	2016	Delay Mapping Receiver (DMR)
70	NSPO/USAF/NASA	COSMIC IIB (6 satellites)	GPS, GLONASS, Galileo	L1 C/A, L2C, L5, Galileo, GLONASS, BeiDou	Occultation	LEO	2017	TriG receiver
71	NASA/DLR	GRACE FO	GPS, GLONASS, Galileo	L1 C/A, L2C, L5, Galileo, GLONASS	Occultation, precision orbit, time	LEO	2018	TriG receiver, joint mission with DLR
72	NASA	Jason-4	GPS, GLONASS, Galileo	L1 C/A, L2C, L5, Galileo, GLONASS	Precise Orbit Determination	LEO	2018	Trig receiver (proposed)
73	NASA	GRASP	GPS, GLONASS, Galileo	L1 C/A, L2C, L5, Galileo, GLONASS	Precise Orbit Determination	LEO	2017	Trig receiver (proposed)
74	NASA	GRACE II	GPS, GLONASS, Galileo	L1 C/A, L2C, L5, Galileo, GLONASS	Science	LEO	2020	Trig receiver (proposed)
75	NASA	NICER (ISS)	GPS	L1 C/A	Orbit	LEO	2016	Moog/Navigator receiver

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
76	NASA	Pegasus Launcher	GPS	L1 C/A	Navigation	Surface to LEO	Since 1990	Trimble receiver
77	NASA	Antares (formerly Taurus II) Launcher	GPS	L1 C/A	Integrated Inertial Navigation System (INS) & GPS	Surface to LEO	Since 2010	Orbital GPB receiver
78	NASA	Falcon-9 Launcher	GPS	L1 C/A	Overlay to INS for additional orbit insertion accuracy	Surface to LEO	Since 2013	
79	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.
80	NASA	NI-SAR (was Desdyni)	GPS, GLONASS, Galileo	L1 C/A, L2C, L5, Galileo, GLONASS	Precise Orbit Determination, timing	LEO	2020	TriG receiver

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 initially prepared for the Interagency Operations Advisory Group (IOAG), and then updated for the International Committee on GNSS (IGS)
- The objective is to ensure the scope and needs of the emerging space user community are documented and to enable space agencies to collectively analyze potential requirements for space applications using GNSS
- Space agencies are positioned to help GNSS service providers plan for provision of PNT signals to support space users out to GeoSynchronous Orbit altitudes
- Space agency stakeholders will provide user requirements to GNSS/PNT service providers as knowledge is gained – as Performance Standards and Interface Specifications are updated
- Space agencies have been defining their space user performance needs for their respective GNSS constellations, and strengthening 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) includes language on the GNSS Space Service Volume:

UNOOSA United Nations Office for Outer Space Affairs

ICG International Committee on Global Navigation Satellite Systems

(http://www.unoosa.org/pdf/icg/2013/icg-8/ICG-8_JointStatement.pdf)

Challenges for GPS use in Space

- GPS availability and signal strength requirements for PNT services originally specified for users on or near surface of Earth
  - Primarily land, air, and maritime users
- Many emerging space users of GPS beyond Low Earth Orbit
  - Not just Geostationary Orbit
- Space users above the terrestrial service volume (>3,000 km altitude) share unique GPS signal challenges
- GPS space flight experiments in high orbits have shown that existing signal availability becomes more limited due to:
  - Geometry between the SV and the space user
  - Vast signal strength changes due to signal path length variations (near/far problem)
- To formally stabilize GPS signals for high altitude space users, NASA worked with U.S. Air Force to create a new Space Service Volume (SSV) definition and specifications

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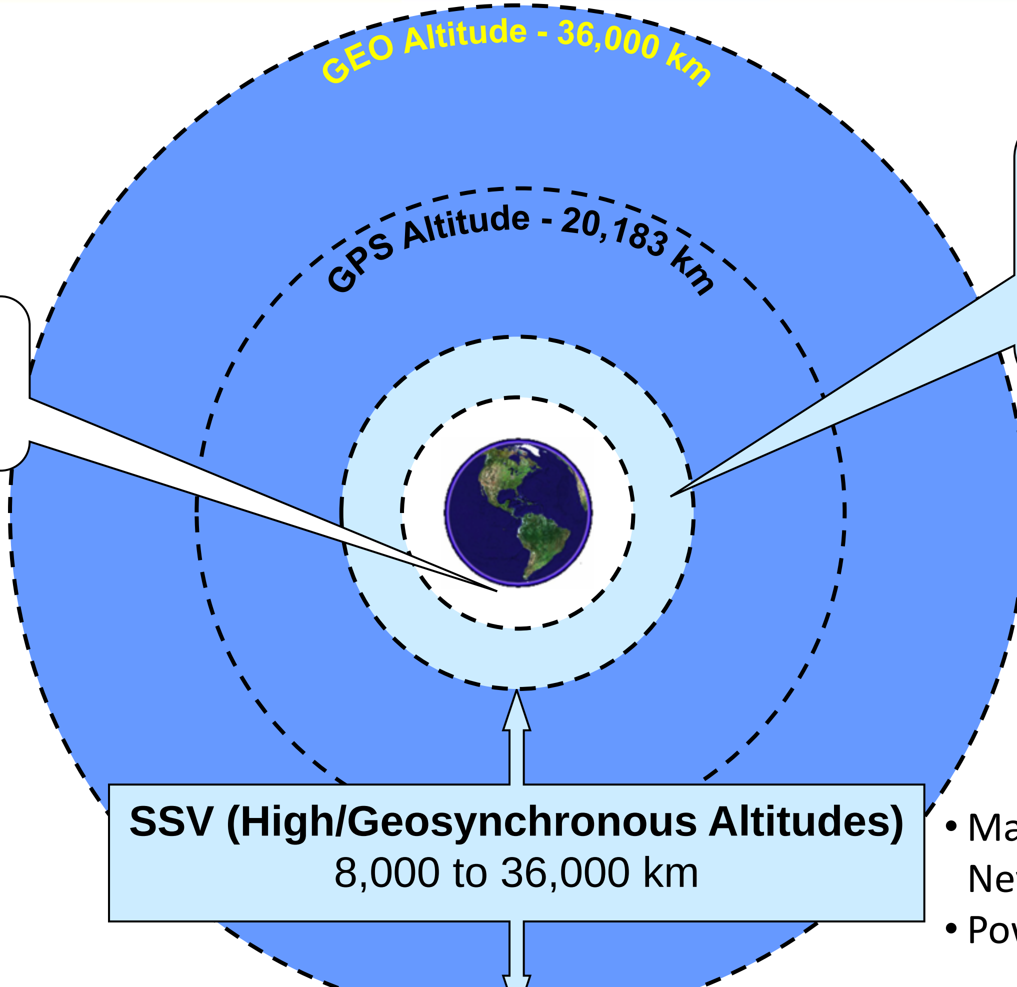
What is a Space Service Volume (SSV)?
Current SSV Geometry Definitions

Terrestrial Service Volume
Surface to 3,000 km

- Missions <3000 km
- Main Lobe Availability: 4+ sats



Space Service Volume (Medium Altitudes)
3,000 to 8,000 km

- Main Lobe Availability: nearly continuous 4+ sats
- Power: Some reduced levels

SSV (High/Geosynchronous Altitudes)
8,000 to 36,000 km

- Main Lobe Availability: Never 4+ sats
- Power: Weak signal levels

Specification of SSV Availability & Signal Strength is Crucial for Reliable Space User Mission Designs

GPS Space Service Volume Requirements / Performance Parameters

- Users in the SSV cannot always rely on conventional, instantaneous GPS solutions

- Thus, GPS III performance requirements for the SSV are established via three parameters:
  - **Signal Availability**
  - **Received Power**
  - **Pseudorange Accuracy** (also known as User Range Error, or URE): GPS III requirement ≤ 0.8 meter (rms)

GPS III Minimum Received Civilian Signal Power (dBW) Requirement

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
L2 C/A or L2C	-158.5	-183.0	26
L5	-157.0	-182.0	26

GPS III Availability*

	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.

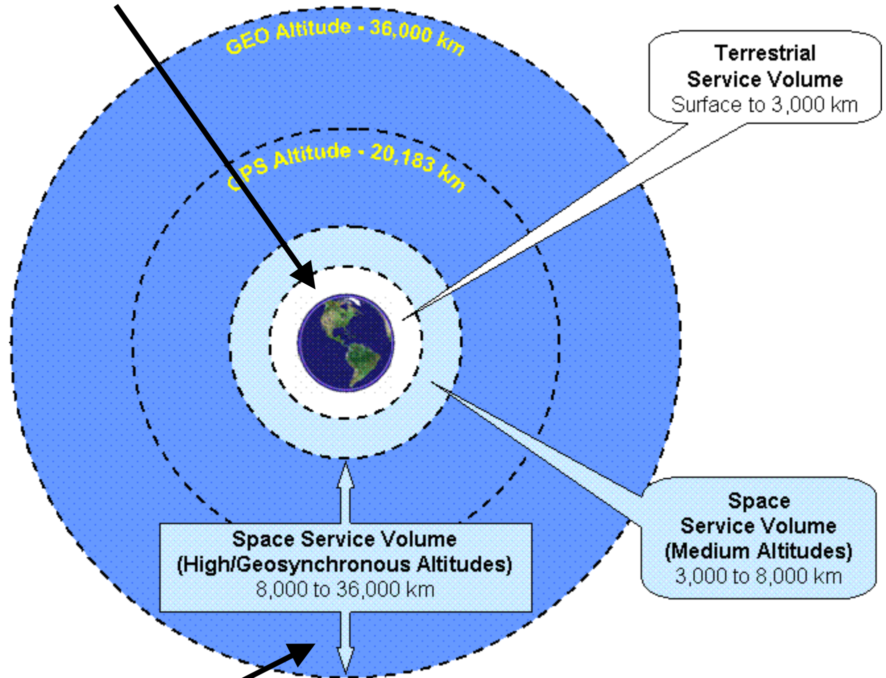
(*) Assumes a nominal, optimized GPS III constellation and no GPS spacecraft failures. Signal availability at 95% of the areas within the specific altitude.

- Benefits of defining SSV requirements for other Global Navigation Satellite Systems (GNSS):
  - Provide additional GNSS signals in space for much greater signal availability at higher altitudes
  - Enable new interoperable capabilities as new PNT systems emerge
  - Protect legacy applications and RNSS radio frequency (RF) spectrum as GNSS services evolve
  - Secure mission economies of scale that extend network capabilities for all participating space users
  - Increase onboard and safety for spacecraft operations while reducing burdens on network tracking and communications for all participating space users

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 autonomous navigation
  - GPS currently provides this up to 3,000 km altitude
  - Enables better than 1-meter position accuracy in real-time
- At GSO altitude, only <u>one</u> GPS satellite will be available at any given time.
  - **GPS-only** positioning at GSO is still possible with on-board processing, but only up to approx. 100-meter absolute position accuracy.
  - **GPS** + **Galileo** combined would enable 2-3 GNSS sats in-view at all times.
  - **GPS** + **Galileo** + **GLONASS** would enable at least 4 GNSS sats in-view at all times.
  - **GPS** + **Galileo** + **GLONASS** + **Beidou** would enable > 4 GNSS sats in view at all times. 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 the Space Service Volume (3,000 km to GSO altitude)

≥ 4 GPS satellites in line-of-sight here (surface to 3000 km)



Only 1-2 GPS satellites in line-of-sight here (GSO)

... but, <u>if</u> interoperable, then GPS + Galileo + GLONASS + Beidou provide > 4 GNSS sats in line-of-sight at GSO.

GPS SSV Limitations & Knowledge Gained Since

- **2003-2006 CDD update performed despite limited understanding of GPS signal strength & availability in SSV**
- **At the time, on-orbit 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 SSV-relevant knowledge gained from:**
  - Performance and capabilities of newly developed weak signal spaceborne receivers (e.g. Navigator)
  - Additional flight experiments (e.g. GIOVE)
  - Released GPS Antenna Pattern measurement data
  - On-orbit mission performance in HEO (e.g. GPS ACE & MMS)

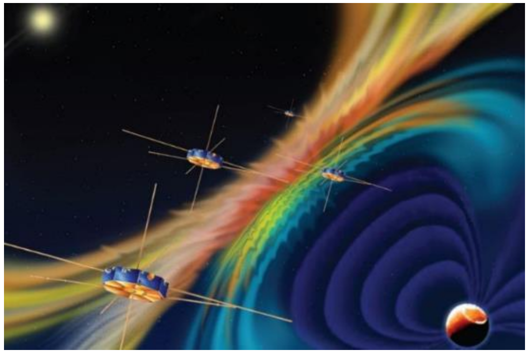
Using GPS above the GPS Constellation: NASA MMS Mission – GSFC Team Info

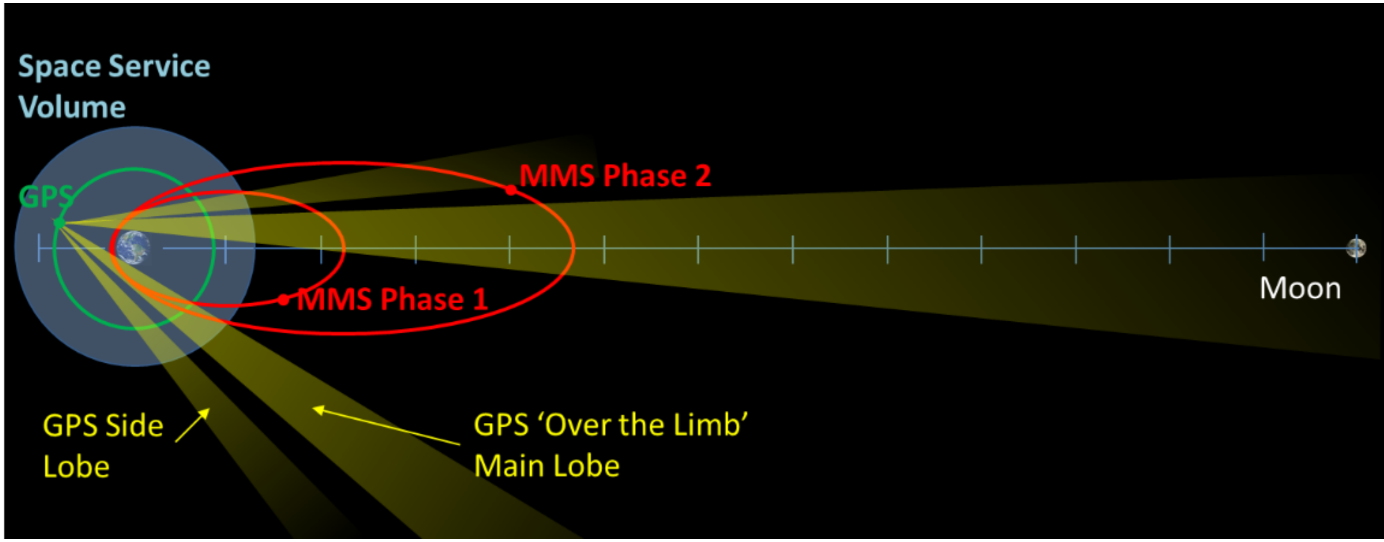
Magnetospheric Multi-Scale (MMS)

- 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 **set a record as the fastest operational GPS receiver** in space, at velocities over 35,000 km/h



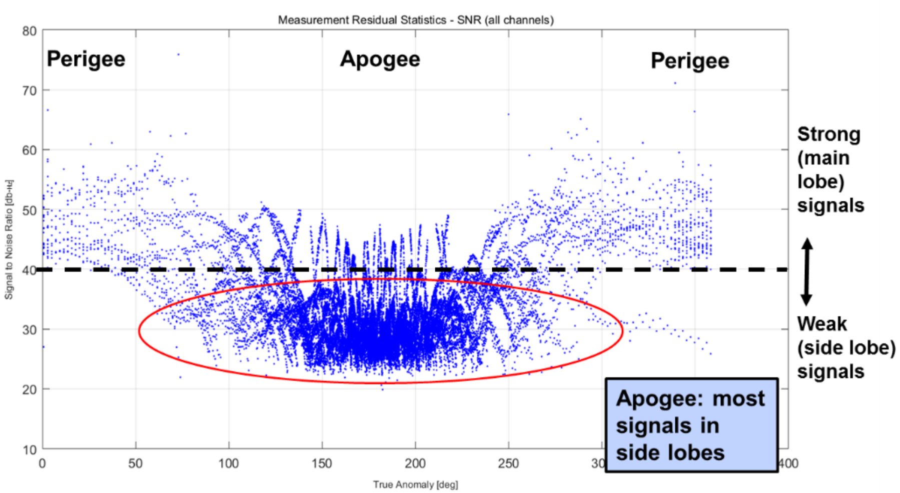


Measured Performance with Side Lobe Signal Availability

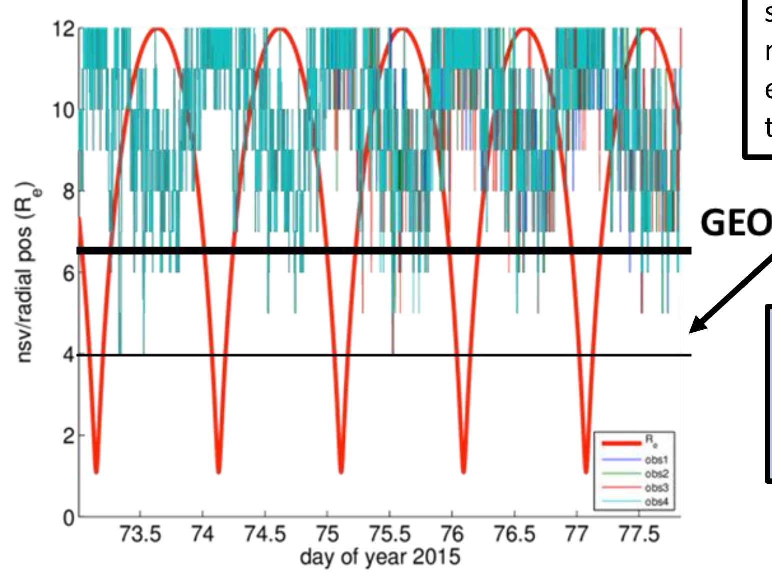
Signal Availability Contributed by Side Lobes (Assumes 24 Satellite Constellation)		
L1 Signal Availability	**Main Lobe Only**	**Main and Side Lobes**
4 or More SVs Visible	**Never**	**99%**
1 or More SVs Visible	59%	Always
No SVs Visible	41%	Never

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

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



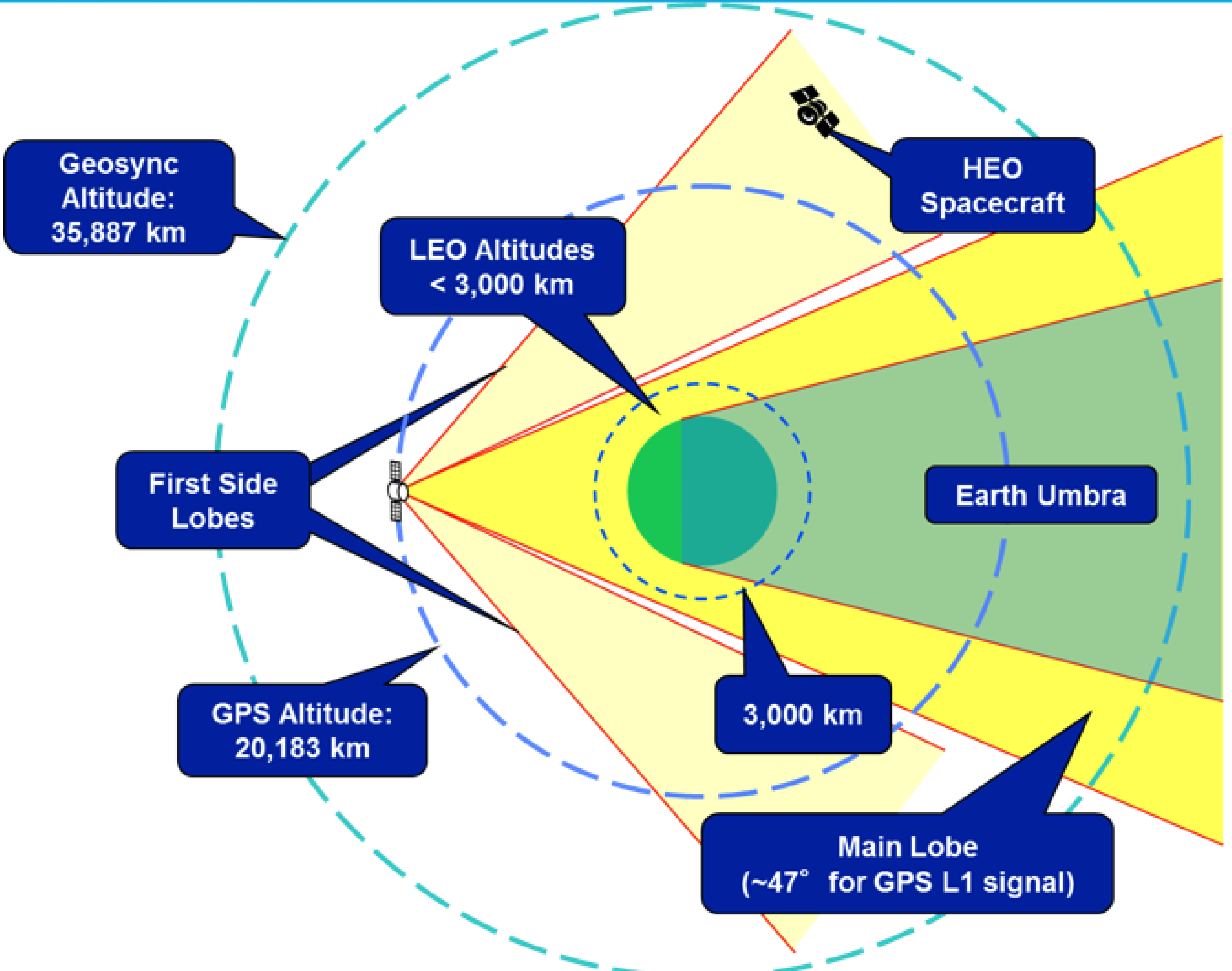
Signal strength (C/N0) vs. position in orbit



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

MMS is seeing **100%**

Reception Geometry for GPS Signals in Space



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

- Would give "green light" for space Project Managers / Mission Planners to consider GPS for future space missions beyond LEO
- Would substantially enhance 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, supporting…
    - Agile, maneuvering space vehicles
    - Improved science return
    - Formation/Cluster flight

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

SSV Development Acknowledgements

- Sincere thanks to all in the U.S. that have helped realize the Space Service Volume vision and continue working towards improving it:
  - USAF SMC GPS-Directorate
  - GSFC Antenna Characterization Experiment (ACE) Team
  - GSFC Magnetospheric Multi-Scale (MMS) Mission Team
  - Frank Bauer
  - E. Blair Carter
  - Stephan Esterhuizen
  - Dale Force
  - Arthur Hutchinson
  - Jim Johansen
  - Thomas Johnson
  - Jules McNeff
  - James Miller
  - Mike Moreau
  - A. J. Oria
  - Scott Pace
  - John Rush
  - Joel Parker
  - Park Temple
  - Jennifer Valdez
  - Larry Young
- Also acknowledging, in advance, all outside the U.S. that recognize the in-space advantages of the Space Service Volume specification and provide leadership in developing a Space Service Volume specification for their GNSS constellation

Closing Remarks

- NASA and other space users increasingly rely on GPS/GNSS over an expanding range of orbital applications to serve Earth populations in countless ways
- The United States will continue to work towards maintaining GPS as the “gold standard” as other international PNT constellations come online
- NASA is proud to work with the USAF to contribute making GPS services more accessible, interoperable, robust, and precise for all appropriate users
- GPS precision enables incredible science, which in turn allows NASA to use this science to improve GPS performance

“On Target with GPS Video”
www.youtube.com/watch?v=_zM79vSnD2M

Backup

GPS-III LRA Implementation Update

- Systematic co-location in space through the precision orbit determination of GPS satellites via satellite laser ranging will contribute significantly towards improving the accuracy and stability of the International and WGS 84 Terrestrial Reference Frames
- NASA-DoD partnership to support laser ranging of next generation GPS satellites
  - Naval Research Lab supporting the development and testing of the flight arrays
  - National Geospatial-Intelligence Agency supporting the integration of the arrays with the satellite vehicles
- AFSPC-NASA-STRATCOM Memorandum of Understanding signed on August 22, 2013
- NASA has planned for the delivery of at least 27 arrays

✓ Successful LRA Preliminary Design Review (PDR) on April 25, 2013

✓ Sub-array successfully demonstrated spacecraft compatibility in September 2013

✓ Interface Control Document (ICD-GPS-824) approved by GPS Change Configuration Board on Jan 23, 2014

✓ Completed Engineering Qualification Model (EQM) assembly on Nov 7, 2014

- Draft joint NASA-DoD Concept of Operations developed and going through DoD approval cycle
- Development and Implementation is a collaboration between Goddard Space Flight Center, NGA, and NRL

LRA Engineering Qualification Model

7-Aperture Sub-Array

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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.

M.Moreau, E.Davis, J.R.Carpenter, G.Davis, L.Jackson, P.Axelrad "Results from the GPS Flight Experiment on the High Earth Orbit AMSAT AO-40 Spacecraft," Proceedings of the ION GPS 2002 Conference, Portland, OR, 2002.

Kronman, J.D., "Experience Using GPS For Orbit Determination of a Geosynchronous Satellite," Proceedings of the Institute of Navigation GPS 2000 Conference, Salt Lake City, UT, September 2000.

Chuck H. Frey, et al., "GPS III Space Service Volume Improvements," Joint Navigation Conference, June 19, 2014.

These and other NASA References:

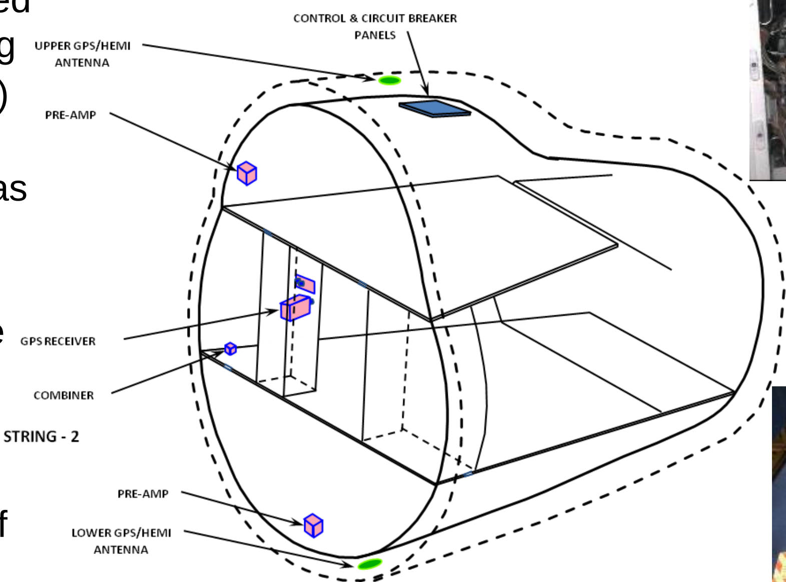
http://www.emergentspace.com/related_works.html

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 & AFSPC to assess impacts of proposed requirements to GPS-III
  - – Government System Spec (SS-SYS-800) includes threshold 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 and Human Space Flight: Past, Present, and Future

- **Space Shuttle Program**
  - Specialized MAGR GPS receivers were designed to accept Inertial Navigation System (INS) aiding
  - One GPS receiver (retaining TACAN as backup) was installed on Discovery and Atlantis
  - Three GPS receivers on Endeavour (TACAN was removed)
- **International Space Station (ISS)**
  - Combined GPS + INS receiver tested on shuttle flights in April 2002 (STS-110 / Atlantis)
  - Four GPS antennas on the ISS truss assembly
  - Used for attitude determination
  - Relative GPS navigation used for rendezvous of ISS unmanned resupply

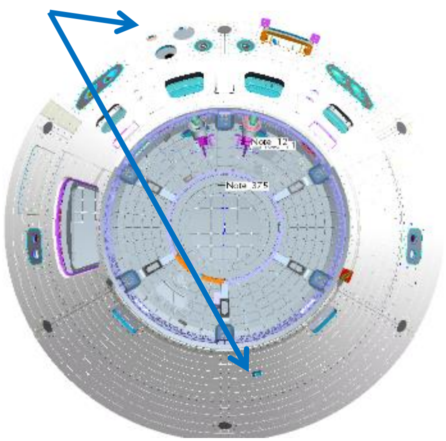


A MAGR installed in Av Bay 3B

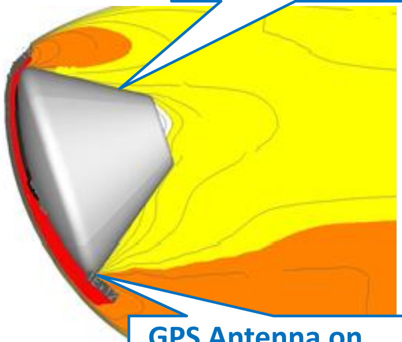
The DFT Collins 3M Receiver today

- **Orion**
  - Two Honeywell GPS receivers integrated with INS
  - Highly sensitive RF radio can track weak signals from the GPS constellation half way to the moon
  - Orion Exploration Flight Test-1 (1st unmanned flight) launched on Delta-IV in Dec. 2014

GPS Antennae (2)



GPS Antenna on Winward Side

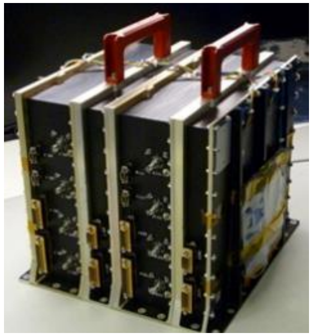


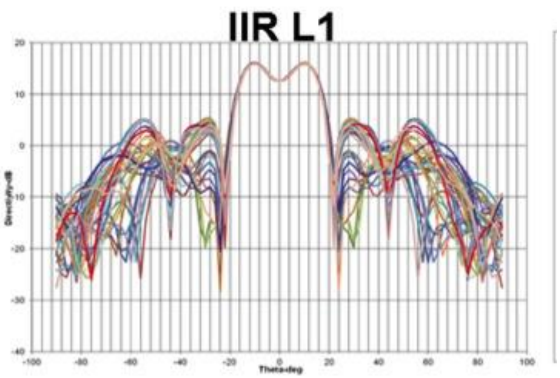
GPS Antenna on LeewardSide

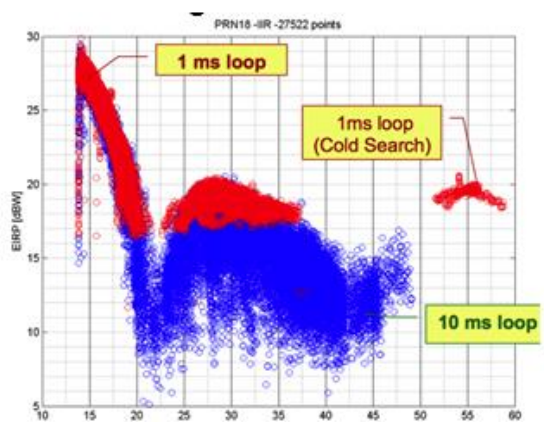
Honeywell GPS Receiver

Additional HEO/GEO GPS Enablers

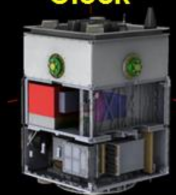
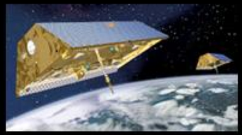
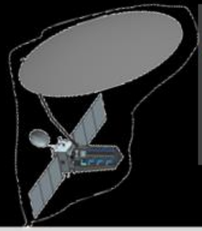
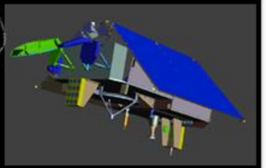
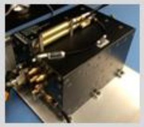
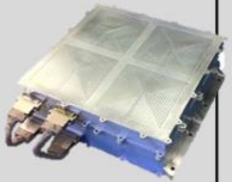
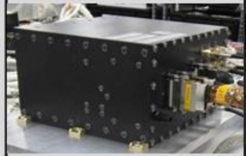
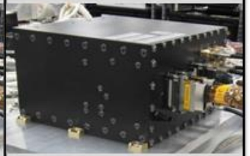
- **Weak signal spaceborne receivers, including NASA GSFC's Navigator**
  - HEO/GEO performance enabled through:
    - Weak signal acquisition and tracking (25 dB-Hz)
    - Integrated on-board navigation filter (GEONS)
    - Radiation hardness
  - Navigator innovations incorporated in commercial HEO/GEO receivers developed by Moog Broad Reach, Honeywell and General Dynamics
- **U.S. Publication of GPS Block IIR & IIR(M) Antenna Patterns**
- **International Engagement in HEO/GEO GNSS Operations**
  - GIOVE on-orbit antenna measurement experiment
  - HEO/GEO receiver development







TriG Future Missions and Configurations

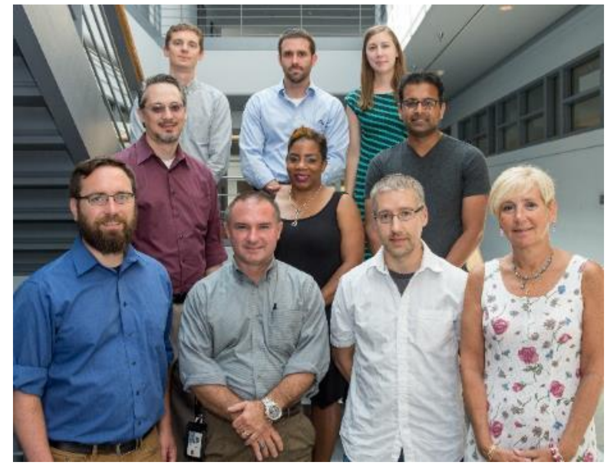
	Deep Space Atomic Clock	COSMIC 2 Equatorial	Grace FO IPU	COSMIC 2 Polar	SWOT	Ni-SAR	JASON CS
							
TriG Payload Type							
Description	Precise Clock Validation Timing using Precise Orbit Determination	Radio Occultation and Space Weather Observations.	Micron Ranging and Precise Orbit Determination Some RO	Radio Occultation and Space Weather Observations	Precise Orbit Determination 1553 comm card	Precise Orbit Determination Cold Spare	Precise Orbit Determination Radio Occultation 1553 comm card
Mission Phase	Phase C/D	Phase C/D	Phase C/D	Phase A	Phase A	Phase A	Pre Phase A
Launch	Mid 2016	Mid 2016	August, 2017	Mid 2018	2020	2021	2020
System Mass (kg) CBE	6	12	6	12	6	6	22
Power Est (W)	25	65	25	65	35	30	65

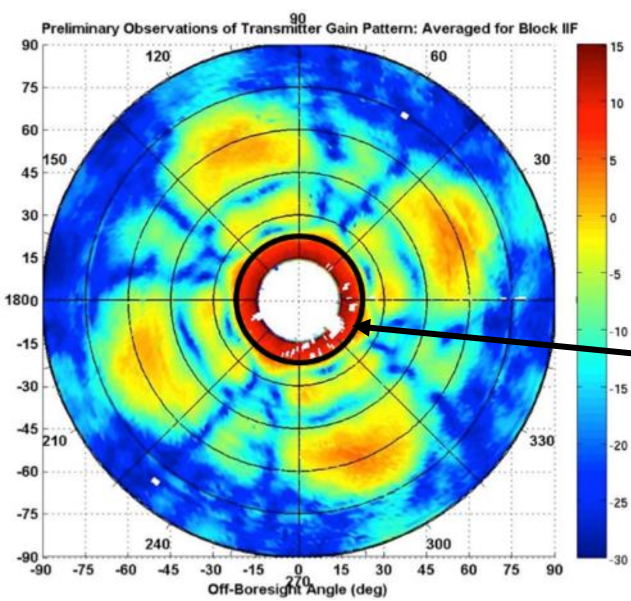
GPS Antenna Characterization Experiment (ACE)

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

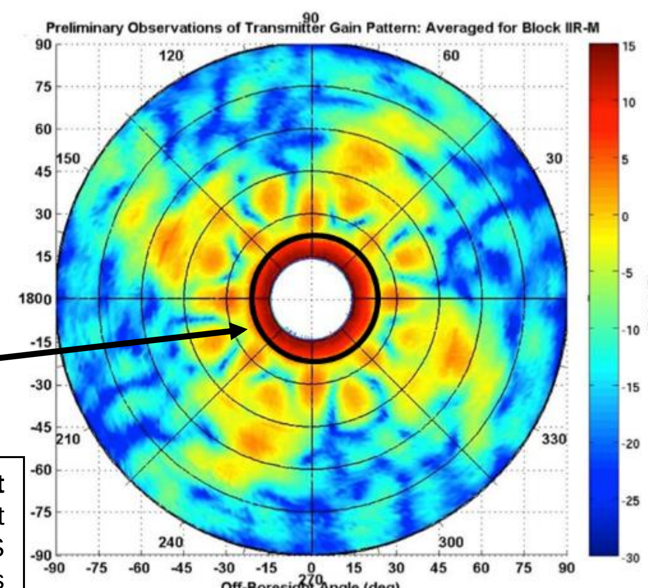
GPS ACE NASA Team





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

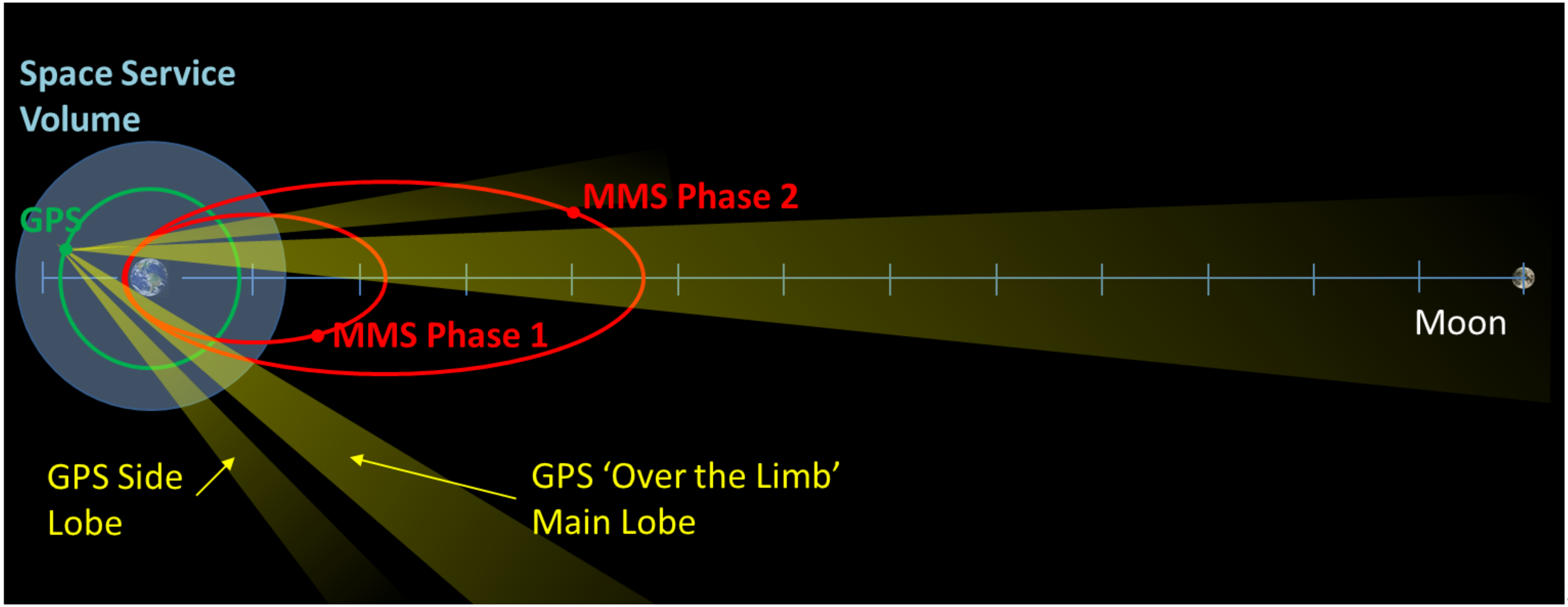
The current GPS spec only covers out to an angle of 23.5°



In-Flight
Measurement
Average from GPS
IIR-M SVs

MMS Navigator System: Initial Observations

- In the first month after launch, the MMS team began turning on and testing each instrument and deploying booms and antennas.
  - During this time, the team compared the Navigator system with ground tracking systems and found it to be even more accurate than expected
  - At the farthest point in its orbit, some 76,000 km from Earth, Navigator can determine the position of each spacecraft with an uncertainty of better than 15 meters
  - The receivers on MMS have turned out to be strong enough that they consistently track transmissions from eight to 12 GPS satellites – excellent performance when compared to pre-flight predictions of frequent drop outs during each orbit

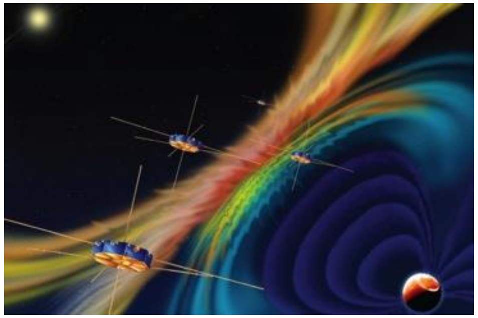


Why is the Space Service Volume Specification Important for Missions in High Earth Orbit?

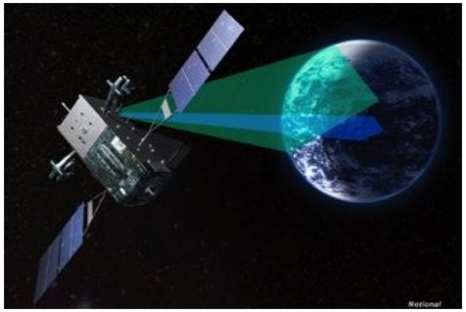
SSV specifications are crucial for space users, providing real-time GPS navigation solutions in High Earth Orbit

- **Supports increased satellite autonomy for missions, lowering mission operations costs**
- **Significantly improves vehicle navigation performance in these orbits**
- **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

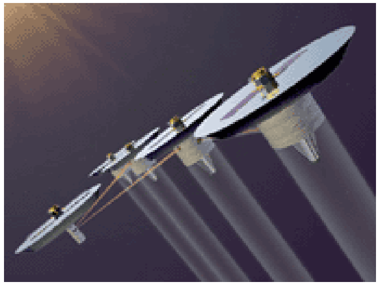


Space Weather Observations

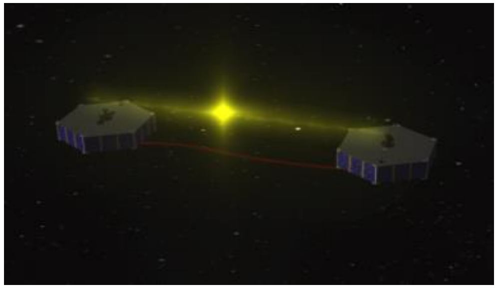


Military Applications

En-route Lunar Navigation Support



Formation Flying & Constellation Missions



Closer Spacing of Satellites in Geostationary Arc

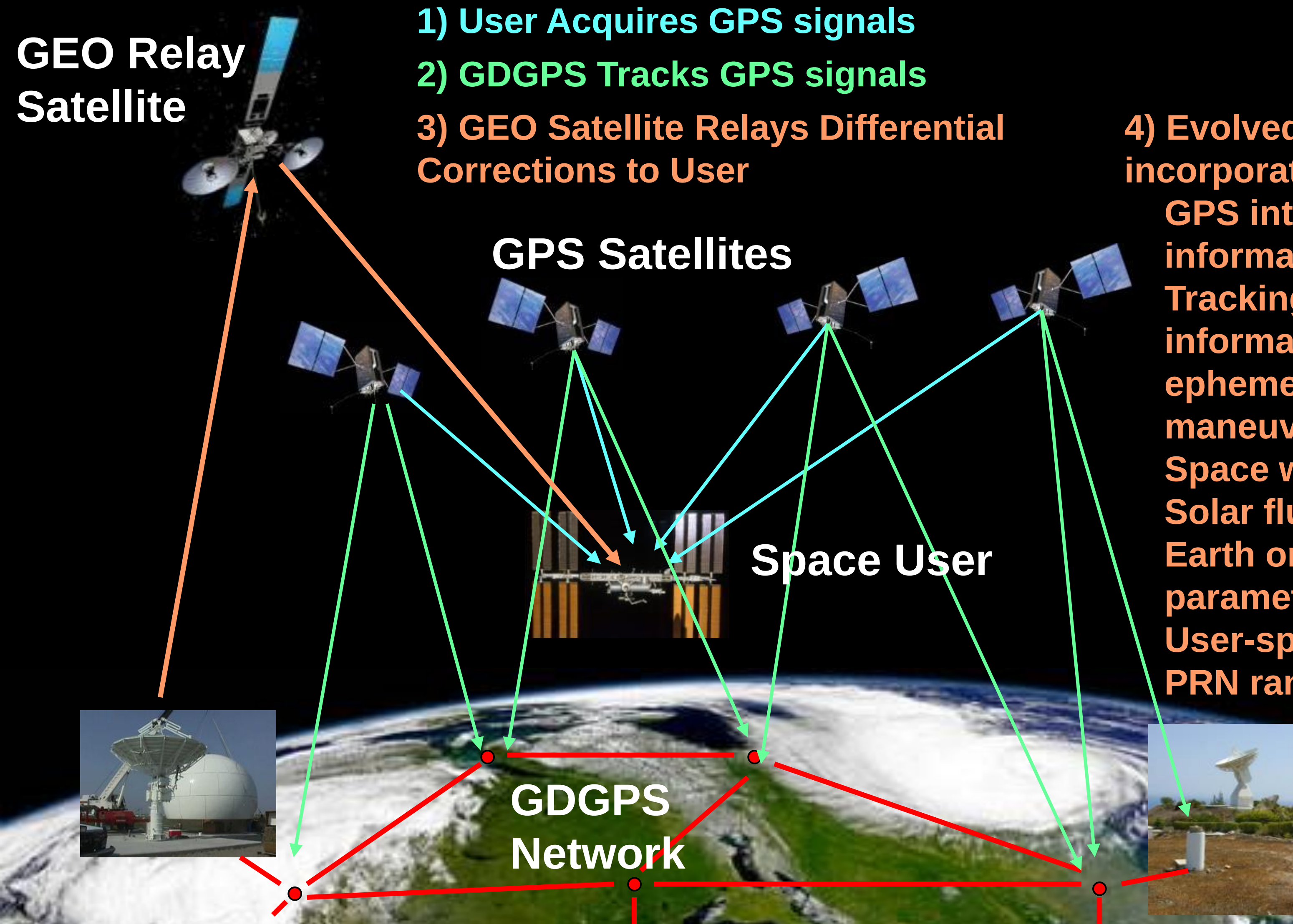
Augmenting GPS in Space with TASS

TDRSS Augmentation Satellite Service (TASS)

1) User Acquires GPS signals

2) GDGPS Tracks GPS signals

3) GEO Satellite Relays Differential Corrections to User

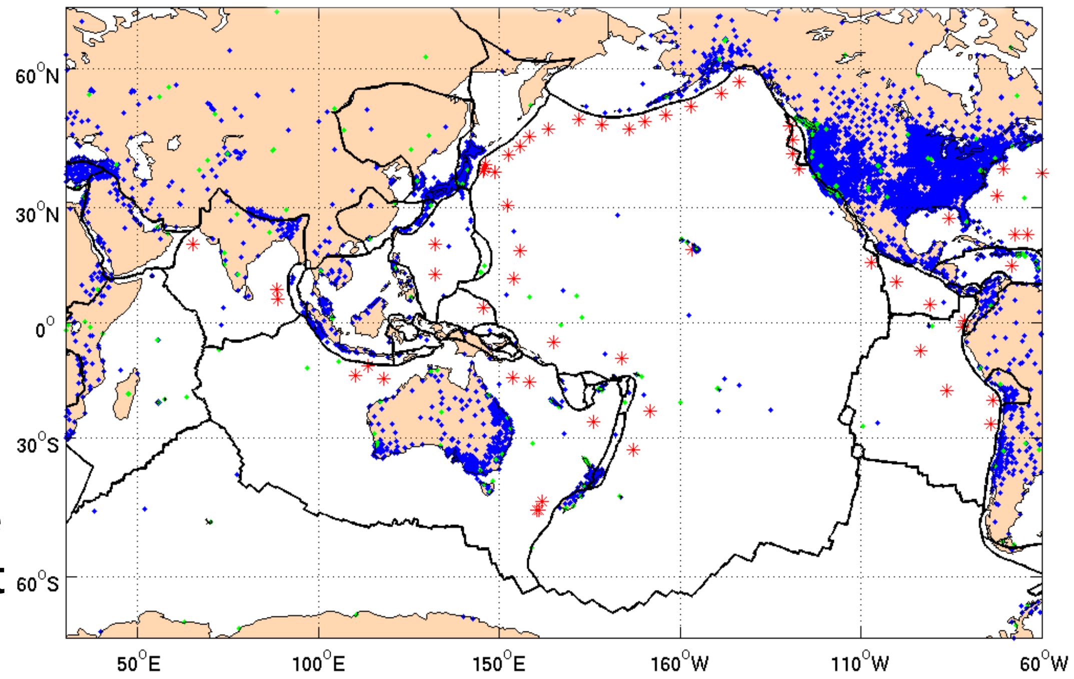


4) Evolved TASS could incorporate:
- GPS integrity information
- Tracking satellite information (health, ephemerides, maneuvers)
- Space weather data
- Solar flux data
- Earth orientation parameters
- User-specific commands
- PRN ranging code

Development of an Indo-Pacific GNSS Augmentation to the Tsunami Early Warning Network

A GNSS Augmentation to the Tsunami Early Warning System Requires International Cooperation and Data Sharing

- **The Pacific Region is well populated with GNSS CORS Networks - many that stream data in real-time**
- **Several research groups have worked to advance GNSS-aided rapid earthquake magnitude assessment and tsunami wave prediction**
- **Several international teams have recommended the establishment of a GNSS-aided tsunami warning network.**
- **The UN General Assembly, IUGG, IGS have issued resolutions for the sharing of geodetic data to mitigate Natural Hazards.**



Existing GNSS stations if streamed and analyzed in real-time will provide:
- **Rapid and more accurate tsunami warnings**
- **Basin wide tracking of propagating tsunamis**