Update on NASA GPS Applications for Space Operations and Science

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Policy and Strategic Communications (PSC)

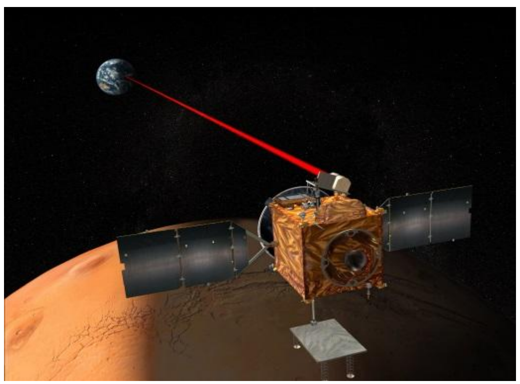
Space Communications and Navigation (SCaN)

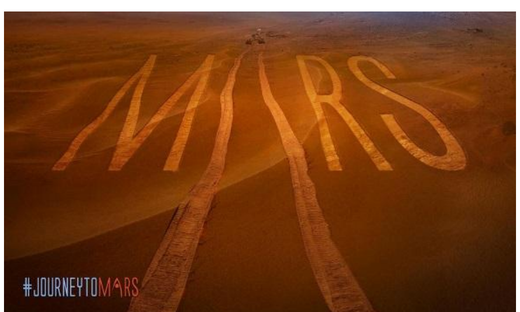
22nd Asia-Pacific Regional Space Agency Forum

Bali, Indonesia

2 December 2015

SCaN Oversees NASA Infrastructure for Space Communications and Navigation





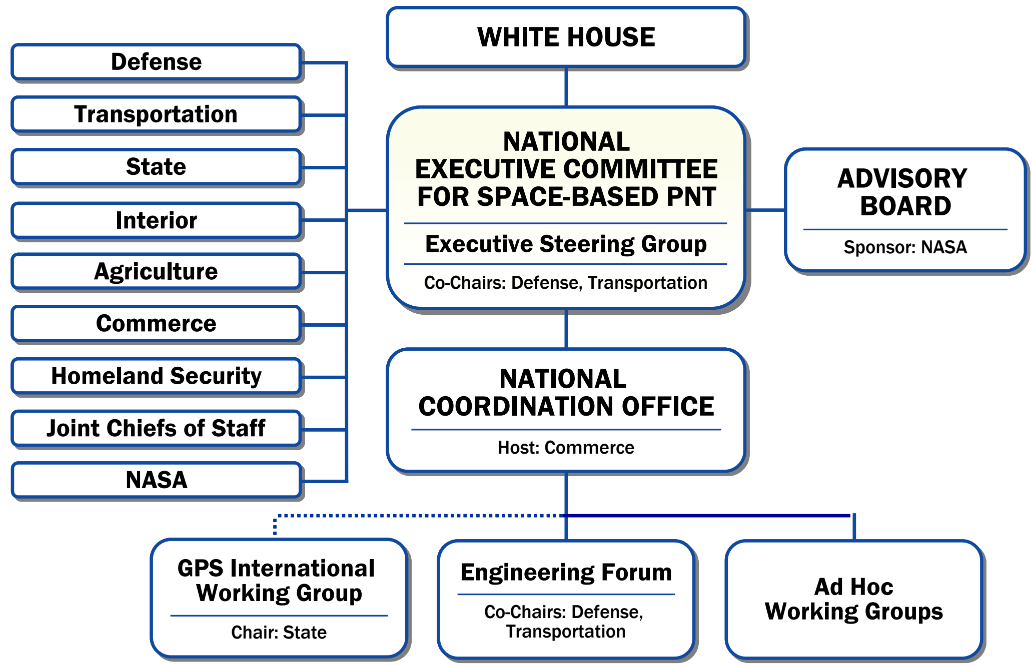
- SCaN is responsible for providing worldwide communications & navigation services to enable and enhance robotic and human exploration and science missions – acquires & operates DSN, TDRSS, and NEN
- SCaN leads in enabling NASA's overall comm & nav capabilities through:
  - standards development
  - 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 reduce burdens on network operations while maximizing spacecraft "autonomy" and enabling new science applications

NASA's Role: U.S. PNT & Space Policy
Assured Positioning, Navigation, & Timing Services

- The 2004 U.S. Space-Based Positioning, Navigation, and Timing (PNT) Policy **tasks the NASA Administrator to develop and provide requirements for the use of 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 positioning, navigation, and timing (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:
  - Interoperability Plenary (IOP)
  - **Interagency Operations Advisory Group (IOAG)**
  - Space Frequency Coordination Group (SFCG)
  - Consultative Committee for Space Data Systems (CCSDS)
  - International Telecommunications Union (ITU)
  - **International Committee on Global Navigation Satellite Systems (ICG)**



2015-2017 PNT Board Membership & Focus: Protect, Toughen, Augment “PTA” for Assured PNT

- **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)

U.S. PNT Advisory Board & International Committee for GNSS (ICG)

- The 16th U.S. Space-based Positioning, Navigation, and Timing (PNT) Advisory Board was held on Oct. 30-31, 2015
  - Sponsored by NASA on behalf of the U.S. National Space-based PNT Executive Committee
  - Held concurrently with ICG-10 to facilitate information exchanges with ICG delegates
  - Agenda/Briefings: http://www.gps.gov/governance/advisory/meetings/2015-10/
- The UN ICG-10 was hosted by the U.S. Dept. of State in Boulder, Colorado, 1-6 Nov. 2015
  - Agenda: http://www.unoosa.org/pdf/icg/2015/icg10/icg10agenda.pdf
  - Briefings: http://www.unoosa.org/oosa/en/ourwork/icg/meetings/ICG-2015.html
- ICG-11 to be held in Sochi, Russia, in 2016

ICG-10 Delegates

16th PNT Advisory Board

ICG-10 Joint Statements on GNSS SSV

GNSS Space Service Volume (SSV):

- Acknowledges that important progress has been made in establishing an interoperable GNSS SSV
- All service providers recognize the importance of GNSS for space missions
- Characteristics to establish an interoperable GNSS SSV were given by all six providers
- ICG appreciates the efforts conducted by all Service Providers to establish these characteristics
- Members of the Working Group will continue to develop a booklet on interoperable GNSS space service volume for presentation at the next Providers' Forum and conduct the necessary simulations as a joint effort

All Space Agencies Play a Role in Shaping GNSS Policies and Technologies

- **NASA's sponsorship of PNT Board and active engagement at fora such as IOAG and ICG secures policy leverage and supplements technical contributions to GPS**

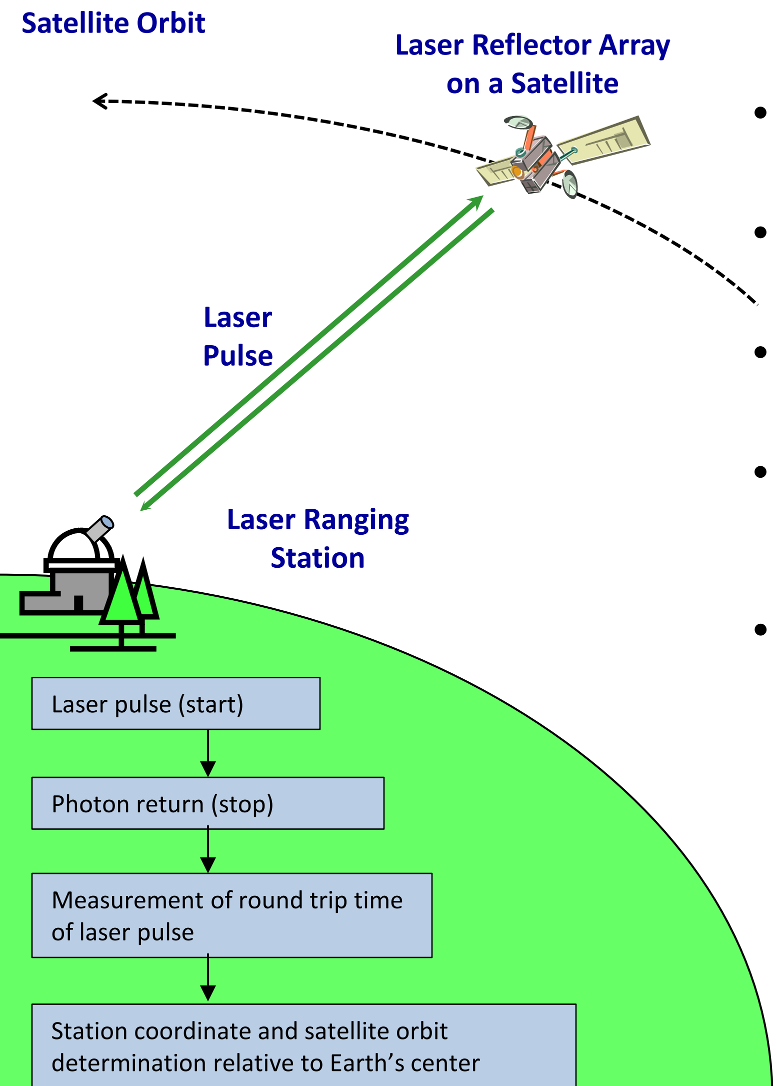
- **NASA seeks to contribute fulfilling governmental policy goals through technology application**

  "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."

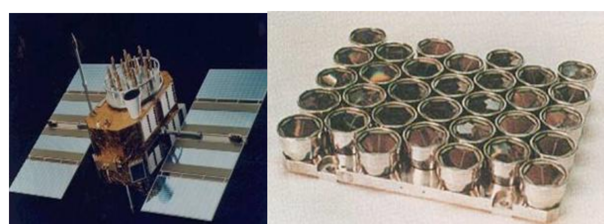
- **GPS technical contributions focus on improving space operations & science for societal benefit**
  - RNSS spectrum protection
  - GPS-based science applications (radio-occultation, geodesy, earthquake prediction, tsunami warning, etc.,)
  - GPS/GNSS civil signal monitoring (operational performance)
  - GPS MEO SAR (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)

- **Enhancing GPS precision and availability enables "cutting edge" science, which in turn allows science to be applied towards improving GPS performance -- win-win cycle that serves all!**

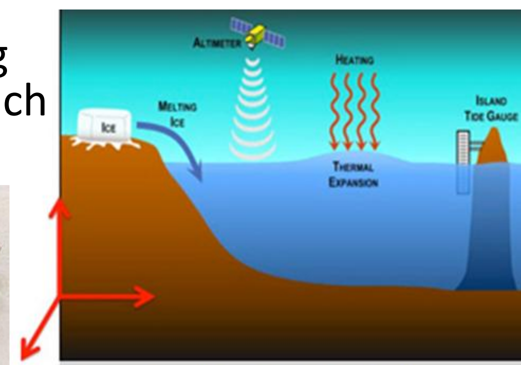
Satellite Laser Ranging (SLR) on GPS III



- 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 worked with U.S. Air Force leadership to approve Laser Reflector Arrays (LRAs) onboard GPS III
- Plans are now underway to deploy LRAs on GPS III starting with Space Vehicle 11 for launch in the 2020-2025 timeframe

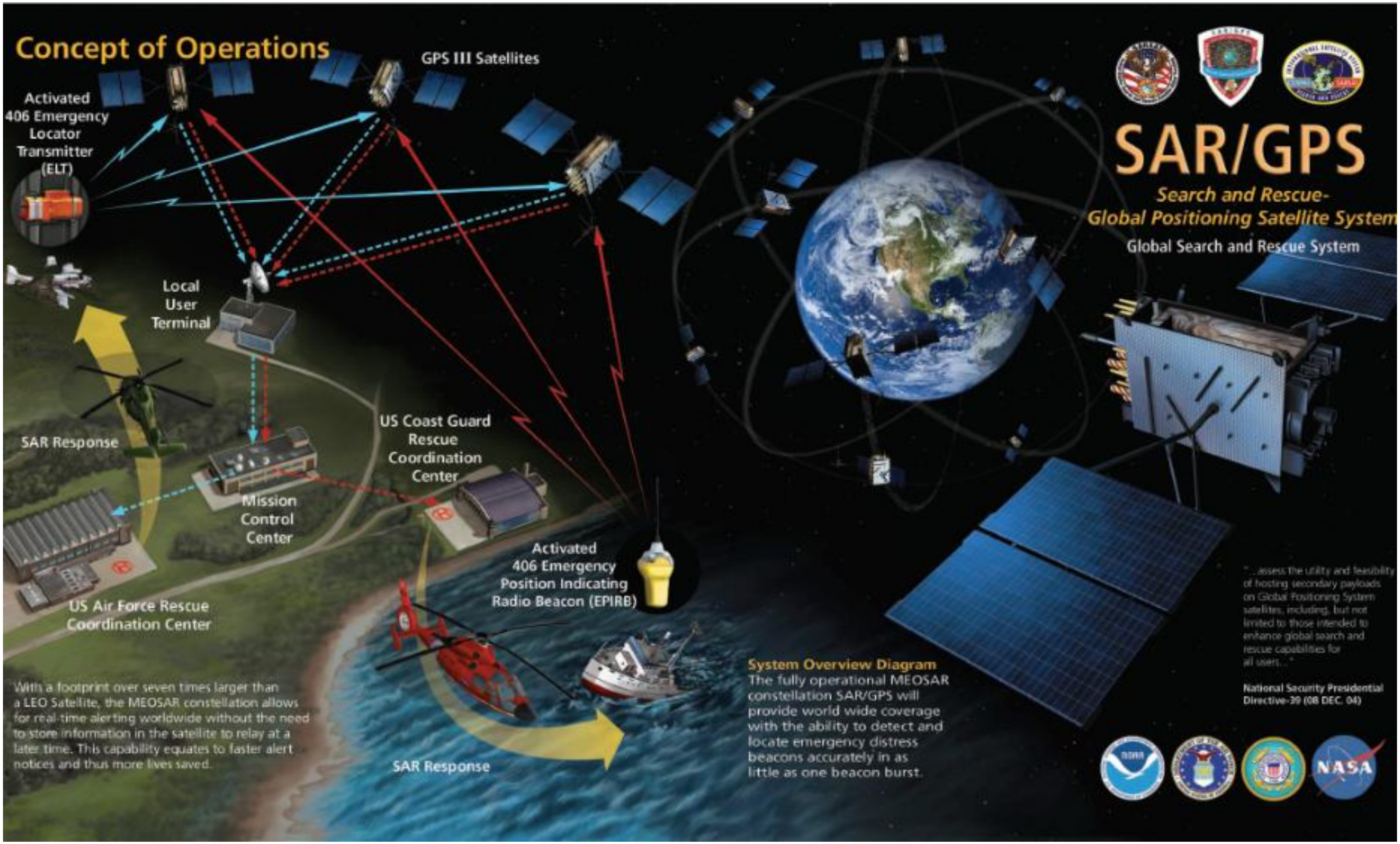


GPS 35/36 (US Air Force)



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

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

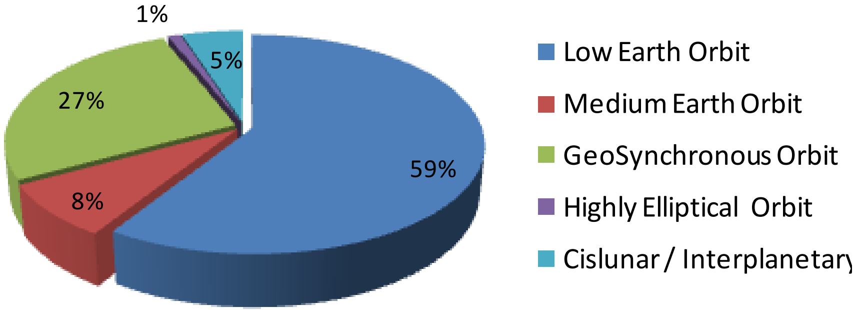


Growing GPS Uses in Space: Space Operations & Science

- 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*

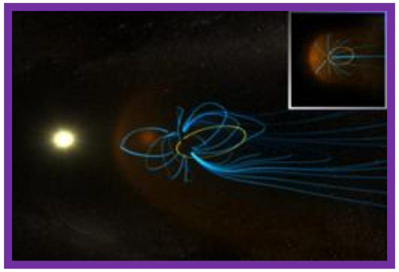
(*) Source: Aerospace America, American Institute of Aeronautics and Astronautics (AIAA), Dec. 2007

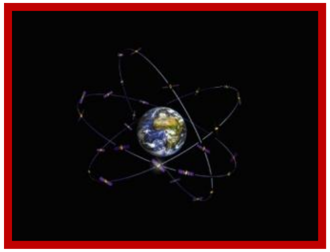
20-Year Worldwide Space Mission Projections by Orbit Type *



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

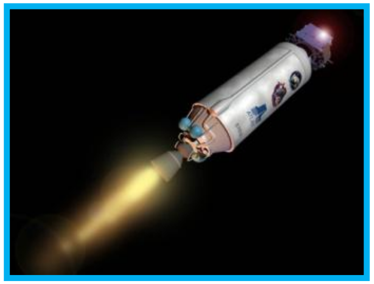
(*) Apogee above GEO/GSO





Medium Earth Orbit: GNSS Constellations, etc.,

GeoSynchronous: Communication Satellites, etc.,



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

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

- Since IOAG-19a (Sep. 10, 2015) the IOAG reference tables of missions relying on GNSS has been updated (previous table was last updated on May 13, 2014)
- The updated tables were presented at the ICG-10 meeting to emphasize the importance of continuing to develop interoperable GNSS-based capabilities to support the space users

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

GNSS Mission Areas Updated for IOAG & ICG (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
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
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

GNSS Mission Areas Updated for IOAG & ICG (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
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
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	

GNSS Mission Areas Updated for IOAG & ICG (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
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
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

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

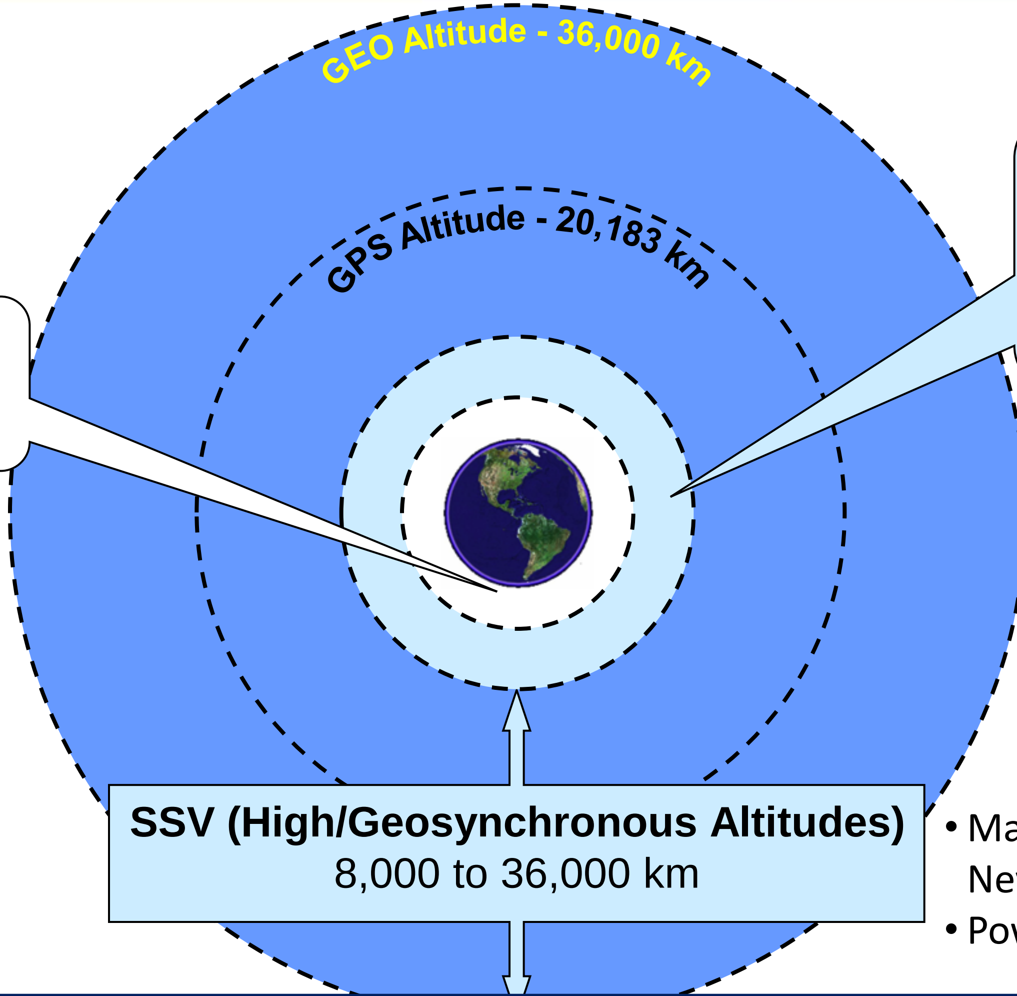
N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes	Last Updated	Updated By
63	NASA	DSAC	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Time transfer	LEO	2015	TriG lite receiver	2015-Oct-6	JJ Miller
64	CNES/NASA	Jason-3	GPS, GLONASS FDMA	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
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)

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

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

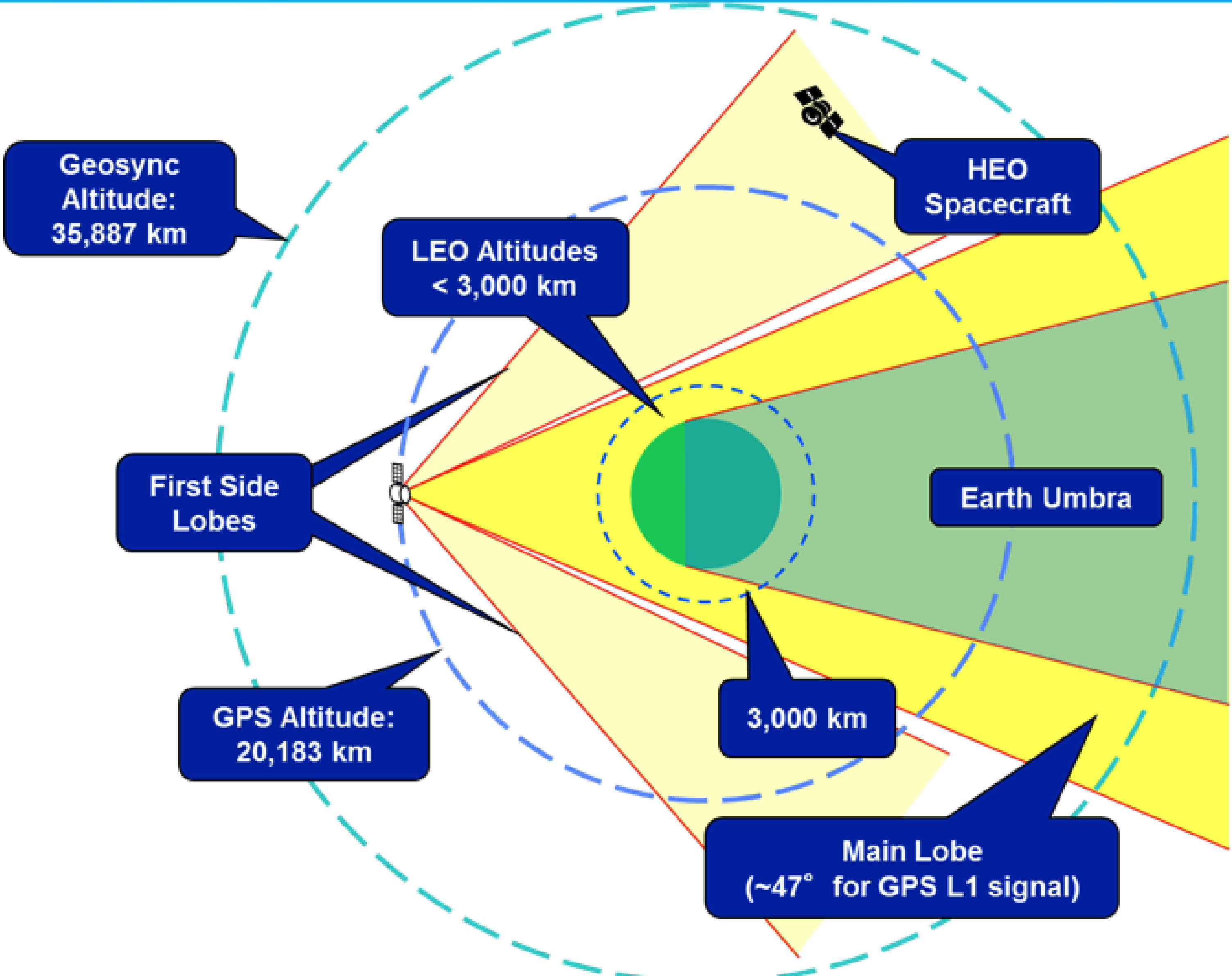
- Main Lobe Availability: nearly continuous 4+ sats
- Power: Some reduced levels

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

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

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

Reception Geometry for GPS Signals in Space



GPS Space Service Volume Requirements / Performance Parameters

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

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

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.

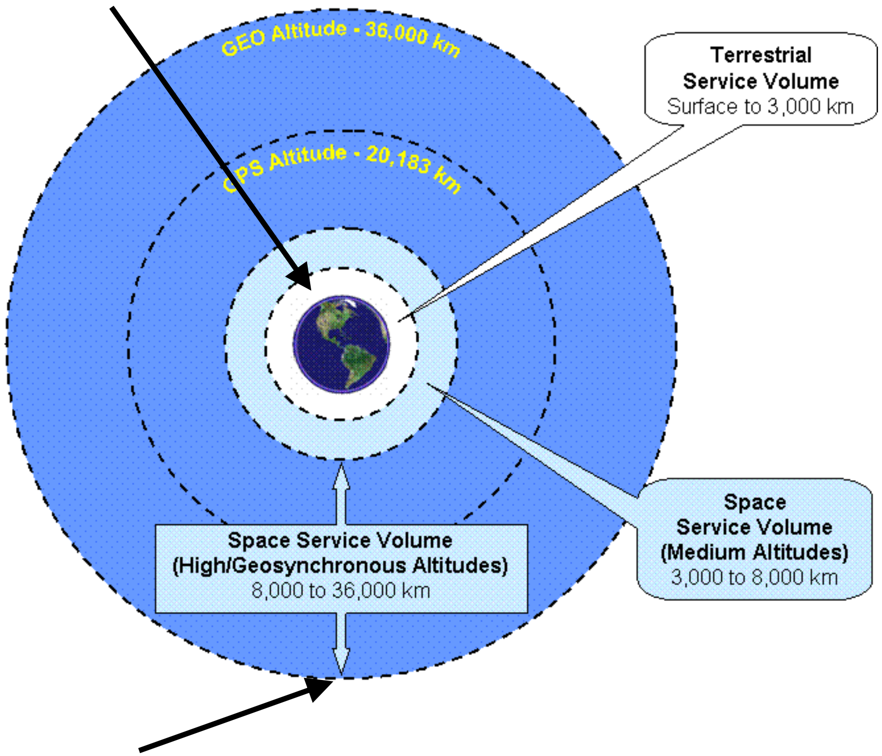
(*) Assumes a nominal, optimized GPS III constellation and no GPS spacecraft failures. Signal availability at 95% of the areas within the specific altitude.

- 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 four 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 Geosynchronous altitude, 1-2 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; and
  - 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)



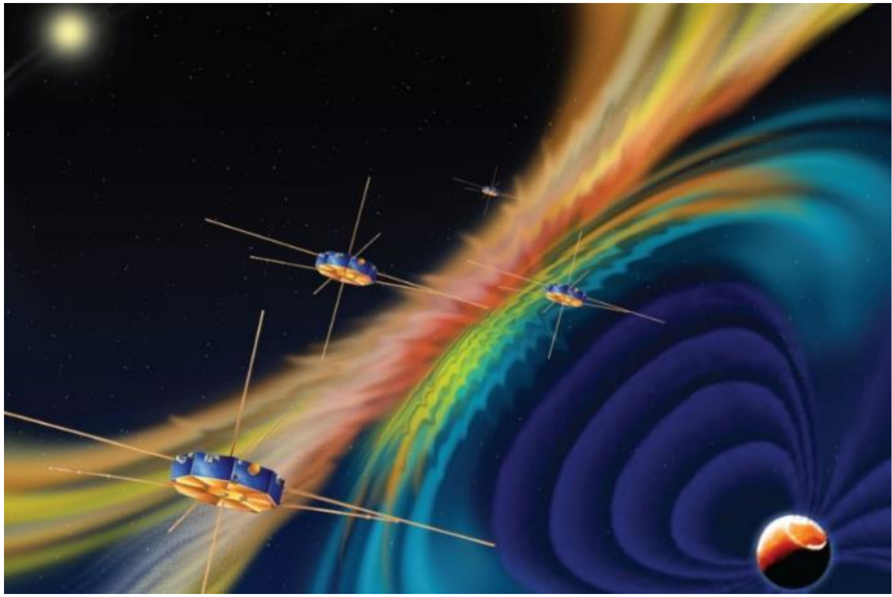
Only average of 1.6 GPS satellites in line-of-sight at GEO orbit altitude

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

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

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
  - 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

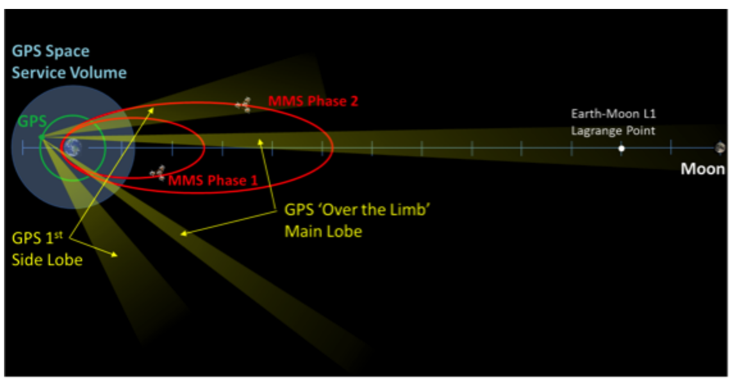
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping
- The MMS Navigator system exceeded all of the team's expectations, it has set the record for the highest GPS use in space
- At the highest point of the MMS orbit Navigator set a record for the highest-ever reception 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

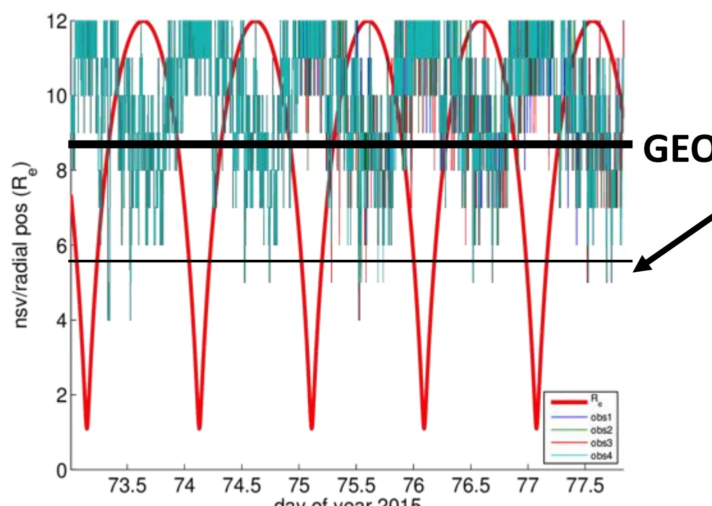
Signal Availability Contributed by Side Lobes (Assumes 24 Satellite Constellation)		
L1 Signal Availability	**Main Lobe Only**	**Main and Side Lobes**
4 or More SVs Visible	**Never**	**99%**
1 or More SVs Visible	59%	Always
No SVs Visible	41%	Never

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

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



MMS Phase 1: 1.2 × 12 Re orbit (7,600 km × 76,000 km)



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

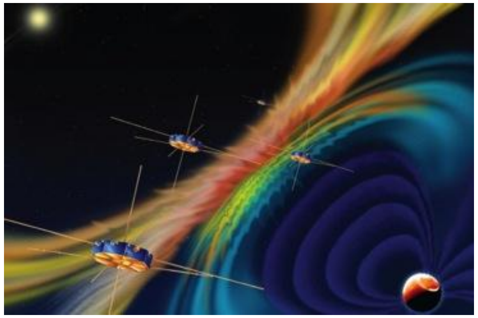
MMS is seeing **100%**

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

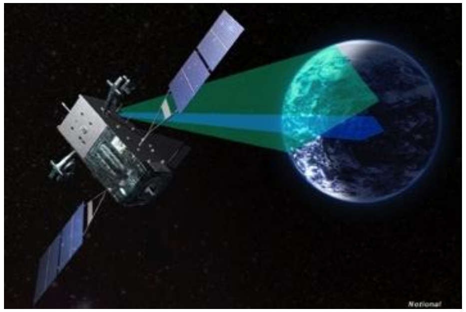
SSV specifications are crucial for space users, providing real-time GPS navigation solutions in High Earth Orbit

- **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

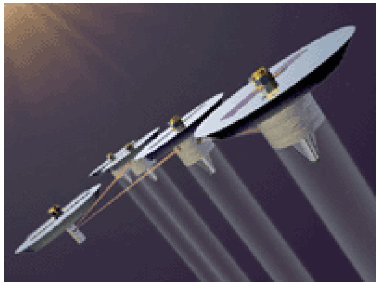


Space Weather Observations

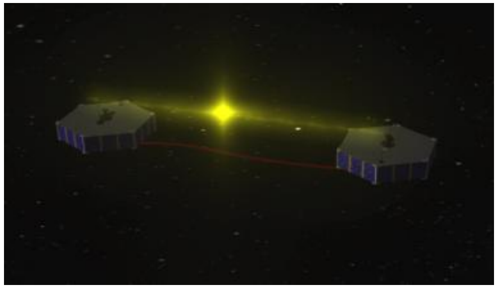


Military Applications

En-route Lunar Navigation Support



Formation Flying & Constellation Missions



Closer Spacing of Satellites in Geostationary Arc

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

- Gives green light for space 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, 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 Signals in Space

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
- All Space Agencies have a role to play in shaping their operating environment to ensure GNSS constellations serve our fast growing space user base

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

Backup

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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:

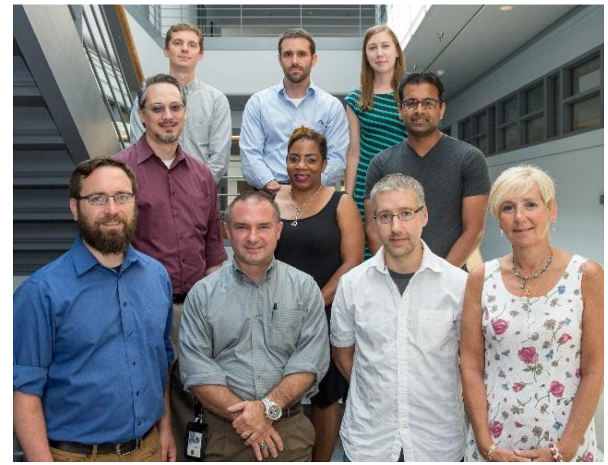
http://www.emergentspace.com/related_works.html

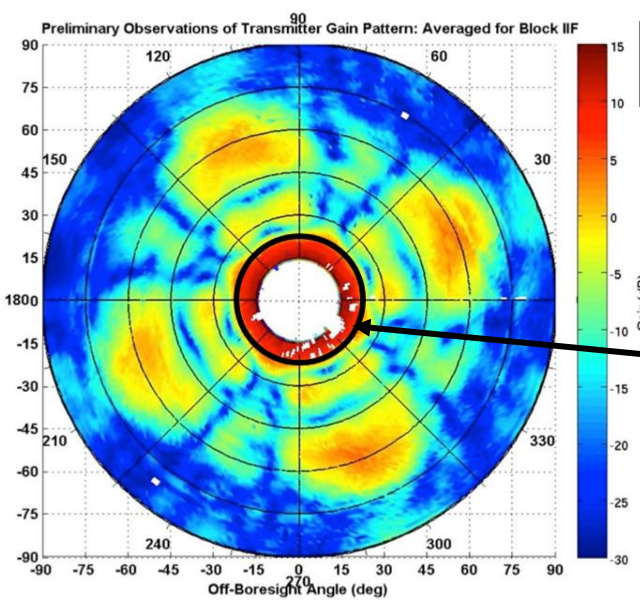
GPS
Antenna Characterization Experiment (ACE)

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

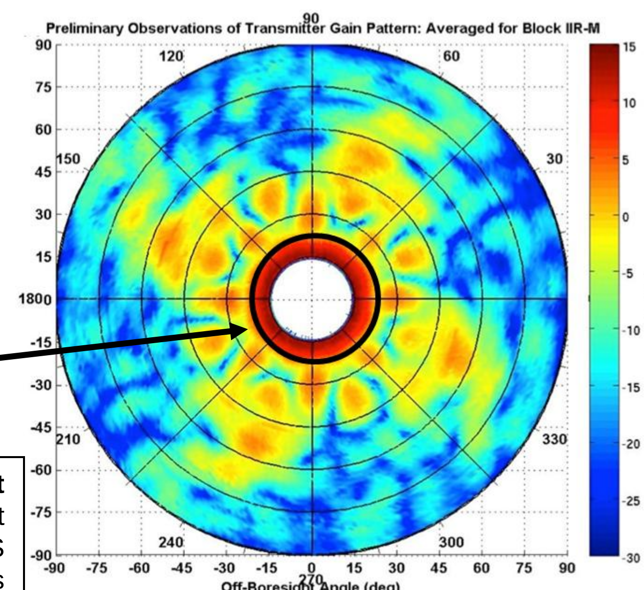
GPS ACE NASA Team





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

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



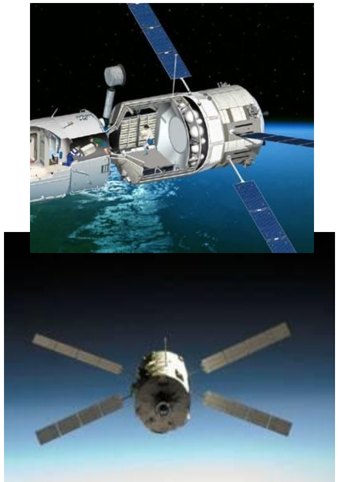
In-Flight Measurement
Average from GPS **IIR-M** SVs

GPS Extends the Reach of NASA Networks to Enable New Space Ops, Science, and Exploration Apps

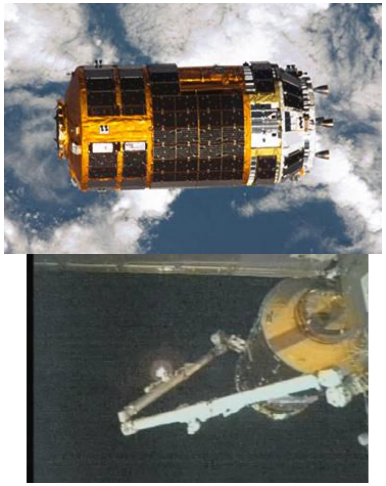
GPS PNT Services Enable:

- **Real-time On-Board Navigation:** Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, GEO satellite servicing
- **Attitude Determination:** Use of GPS enables some missions to meet their attitude determination requirements, such as ISS
- **Earth Sciences:** GPS used as a remote sensing tool supports atmospheric and ionospheric sciences, geodesy, and geodynamics -- from monitoring sea levels & ice melt to measuring the gravity field
- **NASA is investing over $130M** over the next 5 years on GPS R&D and its implementation in support of space operations and science applications

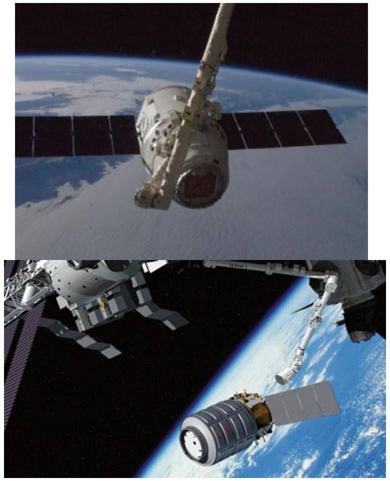
GPS Relative Navigation is used for Rendezvous to ISS



ESA ATV 1st mission to ISS in 2008



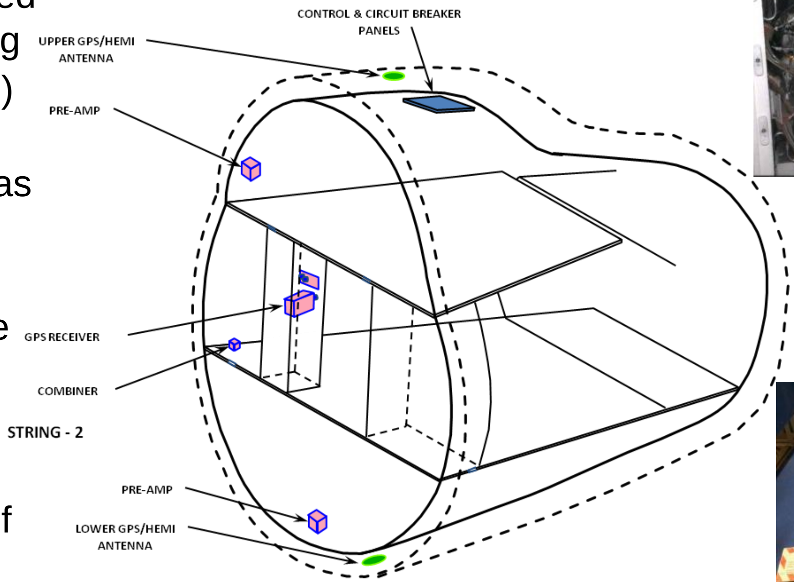
JAXA's HTV 1st mission to ISS in 2009



Commercial Cargo Resupply (Space-X & Cygnus), 2012+

GPS and Human Space Flight: Past, Present, and Future

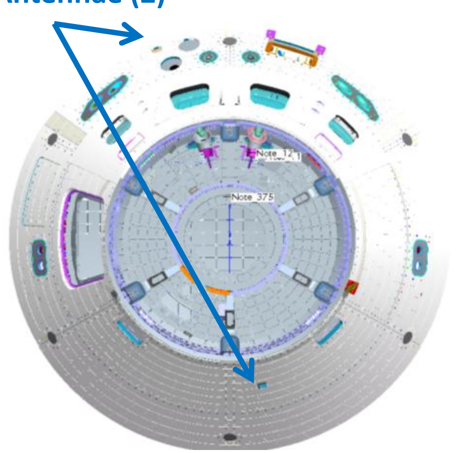
- **Space Shuttle Program**
  - Specialized MAGR GPS receivers were designed to accept Inertial Navigation System (INS) aiding
  - One GPS receiver (retaining TACAN as backup) was installed on Discovery and Atlantis
  - Three GPS receivers on Endeavour (TACAN was removed)
- **International Space Station (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

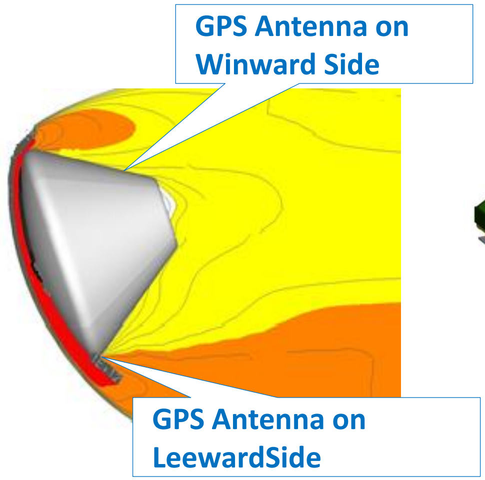


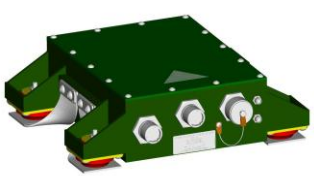
A MAGR installed in Av Bay 3B

The DFT Collins 3M Receiver today

GPS Antennae (2)







Honeywell GPS Receiver

- **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

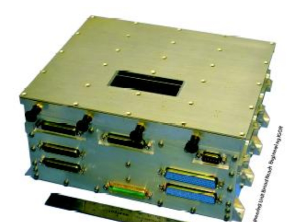
NASA GPS/GNSS Receiver Developments: Navigator & BlackJack "Family"

Goddard Space Flight Center

- Navigator GPS Receiver: GPS L1 C/A
  - Flew on Hubble Space Telescope SM4 (May 2009), planned for MMS, GOES, GPM, Orion (commercial version developed by Honeywell)
  - Onboard Kalman filter for orbit/trajectory estimation, fast acquisition, RAD hard, unaided acquisition at 25 dB-Hz
- Possible Future Capabilities
  - High-sensitivity Signal Acquisition and Tracking:
    - Acquisition thresholds down to 10-12 dB-Hz
    - Applicable to HEO, lunar, and cislunar orbits
  - Reception of New GPS Signals: L2C and L5
  - GPS-derived Ranging Crosslink Communications
    - Developed for MMS Interspacecraft Ranging and Alarm System (IRAS) to support formation flying
    - Features S-band communications link with code phase ranging, used in formation flying

Jet Propulsion Laboratory

- BlackJack Flight GPS Receiver: GPS L1 C/A, P(Y) and L2 P(Y)
  - Precise orbit determination (JASON, ICESat, SRTM missions)
  - Occultation science (CHAMP, SAC-C, FedSat, 2 GRACE , 6 COSMIC)
  - Gravity field (CHAMP, GRACE)
  - Surface reflections (SAC-C, CHAMP)
  - Over 18 BlackJack receivers launched to-date
- IGOR GPS receiver (commercial version from Broad Reach Engineering)
- CoNNeCT Software Defined Radio: GPS L1 C/A, L2C, L5
- Tri GNSS Receiver (TriG) is under development: GPS L1, L2(C), L5, Galileo E1, E5a, GLONASS (CDMA)
  - Features: open-loop tracking, beam-forming 2-8 antennas, 36 channels, RAD hard
  - Engineering models: 2011, production: 2013



GPS Space Service Volume Specification History

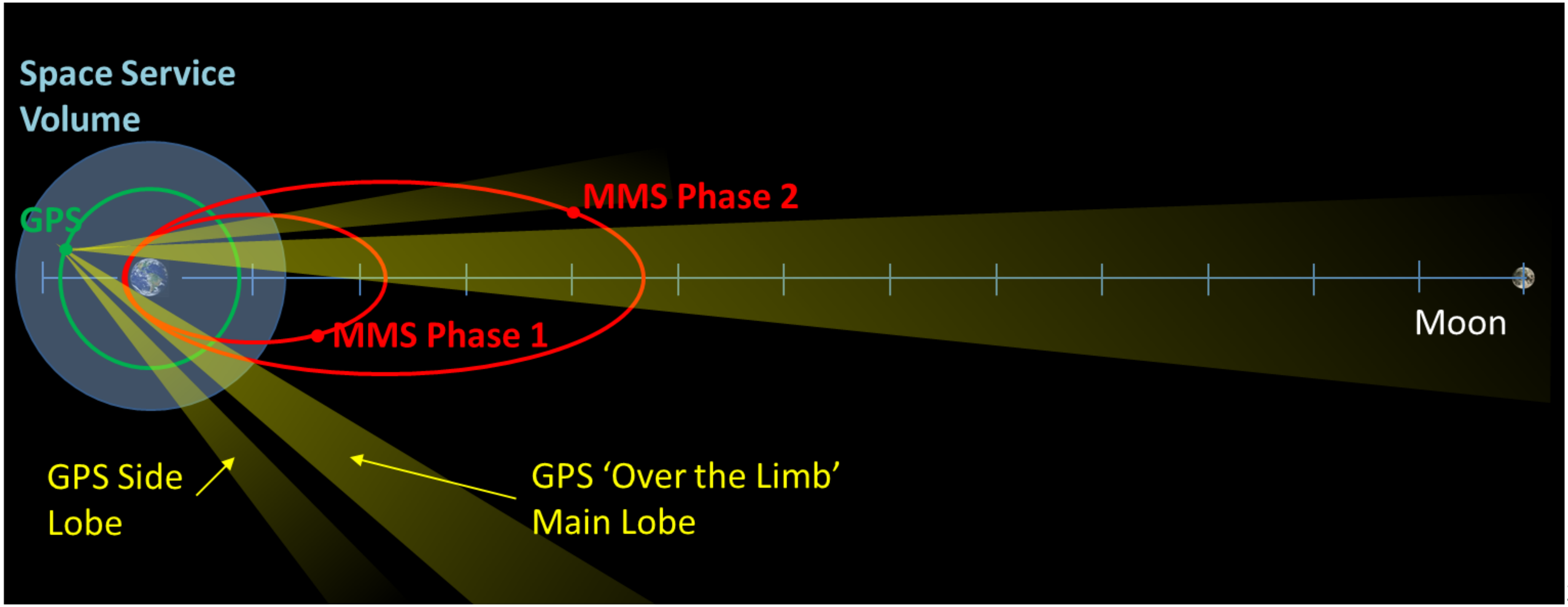
- **Mid-1990s**—efforts started to develop a formal Space Service Volume
  - –Discussion/debate about requiring "backside" antennas for space users
  - –Use of main lobe/side-lobe signals entertained as a no cost alternative
- **1997-Present**—Several space flight experiments, particularly the AMSAT-OSCAR-40 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 IIIA SSV Limitations & Knowledge Gained

- **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:**
  - On-orbit mission performance in HEO (e.g. MMS and ACE)
  - Performance and capabilities of newly developed weak signal spaceborne receivers (e.g. Navigator)
  - Released GPS Antenna Pattern measurement data
  - Additional flight experiments (e.g. GIOVE)

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



GPS-III Laser Retro-reflector Arrays (LRAs)

- 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
- NASA-Air Force Memorandum of Understanding signed on August 22, 2013 stating LRAs will fly on all GPS III vehicles starting with SV9 (now SV11)
- 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

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

LRA Engineering Qualification Model

7-Aperture Sub-Array

Augmenting GPS in Space with TASS

TDRSS Augmentation Satellite Service (TASS)