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Enabling a Fully Interoperable GNSS Space Service Volume

James J. Miller, Deputy Director, Policy and Strategic Communications

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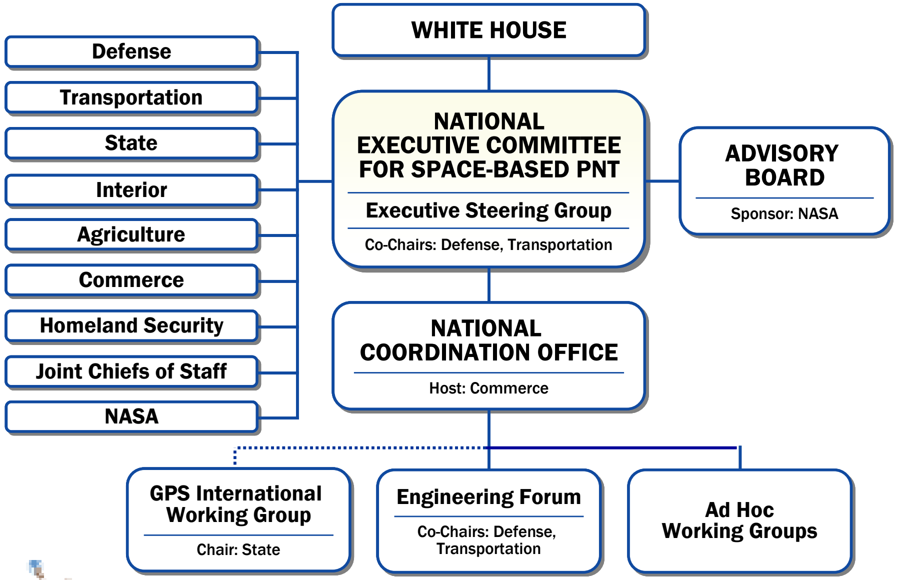
Briefing Overview

- Introduction
  - Why is NASA advocating for GPS services in space?
- Emerging Benefits of GNSS Service to Space Users
  - Planned NASA missions using GNSS services
  - Multi-GNSS receiver enhancements to support GPS SSV users
- Evolution of the GPS Space Service Volume (SSV) Concept
  - GPS SSV – From concept to reality
  - NASA experiment on AO-40 Mission
- GPS SSV Performance Characteristics for Space Applications
  - What is the GPS/GNSS Space Service Volume (SSV)?
  - Signal Availability (visibility & geometry)
  - Received Power (altitude)
  - Pseudorange Accuracy
- Closing Remarks
  - An integrated GNSS SSV will enhance performance and availability for all space users to better serve all Earth populations
  - "Enhanced Services" for GNSS constellations should include space services if all user groups are to be considered – ***This REQUIRES action by Administrations!***

U.S. PNT / Space Policy and NASA's Role

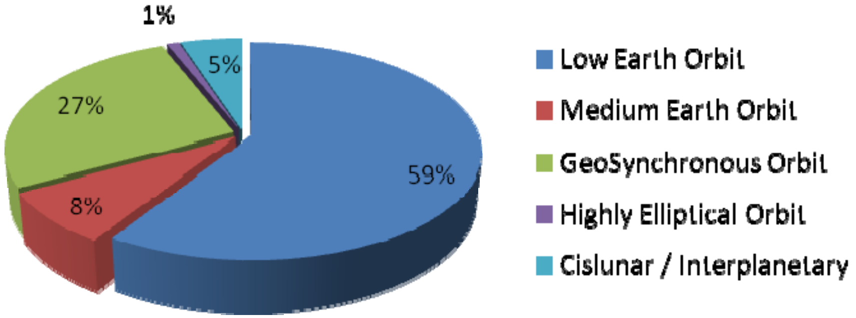
- The 2004 U.S. Space-Based Positioning, Navigation, and Timing (PNT) Policy tasks the NASA Administrator, in coordination with the Secretary of Commerce, to develop and provide requirements for the use of GPS and its augmentations to support civil space systems
- The 2010 National Space Policy reaffirms PNT Policy commitments to GPS service provisions, international cooperation, and interference mitigation, i.e., *"Foreign PNT may be used to strengthen resiliency"*
- GPS enables space users to maximize the "autonomy" of spacecraft and reduces the burden and costs of network operations. It also enables new methods of spaceflight such as precision formation flying, station-keeping, and unique science measurements
- NASA is engaging with other space agencies at venues such as the International Committee on GNSS (ICG) and the Interagency Operations Advisory Group (IOAG) to seek similar benefits from other PNT constellations to maximize performance, robustness, and interoperability for all



GPS in Space – Space Ops & Science

- Projections show that over the next 20 years:
  - Approximately 60% of space missions will operate in LEO (< 3,000 km)
  - Approximately 35% of space missions will operate at higher altitudes up to GSO (36,000 km)

20-Year Worldwide Space Mission Projections by Orbit Type



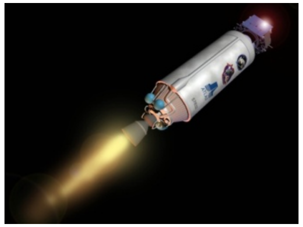
Low Earth Orbit:
Earth Observation, LEO communication constellations, etc.

Medium Earth Orbit:
GNSS Constellations

Geosynchronous:
Communication satellites, Regional Navigation Satellite Systems

Highly Elliptical Orbits*:
Examples: NASA MMS 4-satellite constellation, communication satellites, etc.

(*) Apogee above GEO/GSO



Orbital Transfers: LEO-to-GEO, Cislunar transfer orbit (figure), transplanetary injection, etc.

Source: Aerospace America, Jan 2008

Examples of Planned NASA Missions Using GNSS

Mission	GNSS	Application	Orbit	Receiver	Signals	Launch
LandSat-8	GPS	Orbit	LEO	GD Viceroy	L1	2012
CONNECT (ISS)	GPS	Occultation, precision orbit, time	LEO	Blackjack SDR	L1, L2, L5, option for Galileo & GLONASS	2012
COSMIC IIA	GPS, GLONASS, Galileo	Occultation	LEO	TriG	L1, L2, L5, Galileo, GLONASS	2013
Jason III	GPS, GLONASS, Galileo	Oceanography	LEO	TriG	L1, L2, L5, Galileo, GLONASS	2013
GPM	GPS	Orbit, time	GEO	Navigator	L1 C/A	2013
COSMIC IIB	GPS, GLONASS, Galileo	Occultation	LEO	TriG	L1, L2, L5, Galileo, GLONASS	2014
MMS	GPS	Rel. range, orbit, time	up to 30 Earth radii	Navigator	L1 C/A	2014
GOES-R	GPS	Orbit	GEO	GD Viceroy	L1 C/A	2015
GRACE FO	GPS	Occultation, precision orbit, time	LEO	TriG	L1, L2, L5, Galileo, GLONASS	2015

GPS/GNSS Receiver Development (1)

Jet Propulsion Laboratory R&D

- 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)
  - 18 BlackJack receivers launched

- IGOR: Commercial version from Broad Reach Engineering
- CoNNeCT Software Defined Radio
- TriG is under development: GPS L1, L2(C), L5, Galileo E1, E5a, GLONASS (CDMA and FDMA)
  - Features: open-loop tracking, beam-forming 2-8 antennas, 36 channels, RAD hard
  - Engineering models: 2011
  - Production schedule: 2013

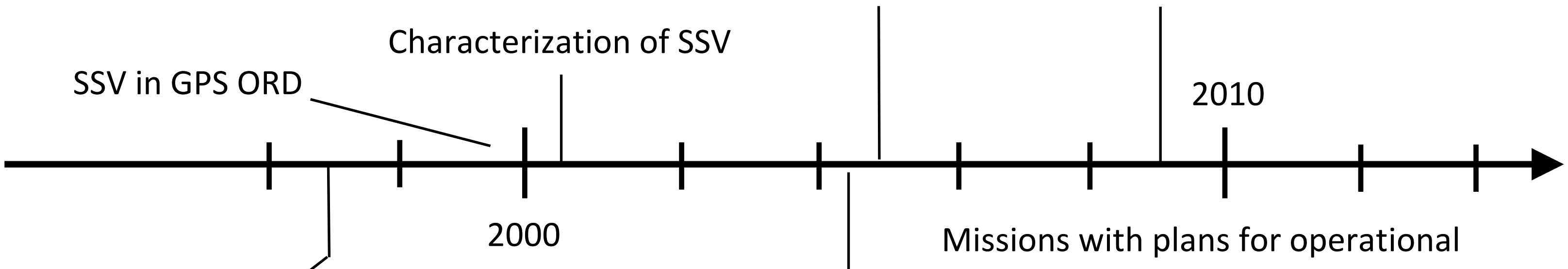
GPS/GNSS Receiver Development (2)

Goddard Space Flight Center R&D

- Navigator GPS Receiver:
  - Tracks GPS L1 C/A
  - Flew on Hubble Space Telescope Service Mission 4 (May 2009);
    planned for MMS, GPM
  - Onboard Kalman filter for orbit/trajectory estimation, fast acquisition, RAD hard, unaided acquisition at 25 dB-Hz
  - Navigator receiver design commercialized by Broad Reach Engineering in their Pyxis GEO receiver
  - Honeywell is developing commercial version for the Orion Crew Exploration Vehicle

- Potential future developments:
  - 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 SSV Development Timeline


SSV characteristics to include *Medium Altitudes* and users outside equatorial plane

GPS III Capability Development Document includes SSV specifications

Characterization of SSV

SSV in GPS ORD

2010

2000

Missions with plans for operational use of GPS in high altitude orbits

EQUATOR-S, TEAMSAT, & **Falcon Gold** flight experiments

EQUATOR-S: German Space Agency mission that studied the Earth's equatorial magnetosphere out to distances of 67000 km http://www.mpe.mpg.de/EQS/

TEAMSAT: ESA minisatellite embedded in Maqsat-H, dummy telecom satellite on 2^{nd} Ariane-5 qualification flight http://www.esa.int/esapub/bulletin/bullet95/BANDECCHI.pdf

FALCON-GOLD: USAF academy mission to investigate the feasibility of performing GPS-aided navigation by high-altitude satellites http://www.usafa.af.mil/information/factsheets/factsheet_print.asp?fsID=14314&page=1

AMSAT AO-40: Amateur radio satellite with NASA experiment*

(*) Reference: Michael C. Moreau, Frank H. Bauer, J. Russell Carpenter, Edward P. Davis, George W. Davis, and Larry A. Jackson, *Preliminary Results of the GPS Flight Experiment on the High Earth Orbit AMSAT-OSCAR 40 Spacecraft,* 25th Annual AAS Guidance and Control Conference, Feb. 6-10, 2002, Breckenridge, CO. http://www-ccar.colorado.edu/~moreau/pubs/ao40aasgnc_fin.pdf

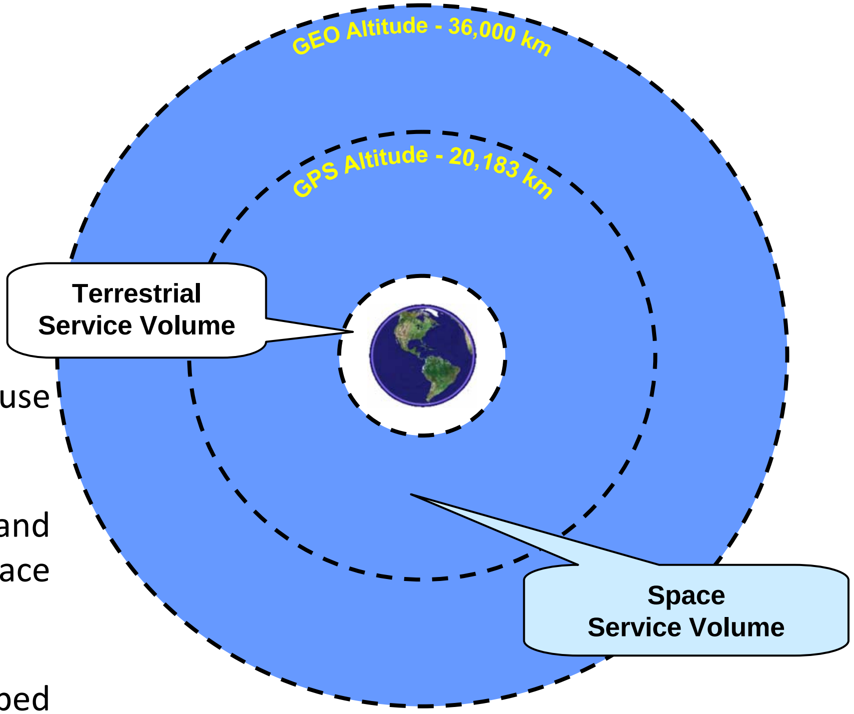
SSV Meant to Overcome "Traditional" GPS Constraints in Space Environment

- GPS availability and signal strength for Positioning, Navigation, and Timing (PNT) services originally specified for users on or near the Earth's surface
  - Primarily developed for land, air, and maritime users, however most LEO space users up to 3,000 km share similar operational benefits as more "traditional" Earth users
- Space users increasingly rely on GPS/GNSS for spacecraft navigation and science, however space remains a challenging operational environment at higher altitudes:
  - Rapidly changing geometry affects acquisition, tracking, time-tagging, navigation
  - Large dynamic ranges – "weak" and "strong" satellites with wide signal gain variability
  - High Doppler & Doppler Rates
  - Fewer satellite signals available
  - Mission antenna placement – visibility, multipath, radiation on very dynamic platforms
- To overcome these constraints, NASA has invested in:
  - Conducting flight experiments to characterize GPS signal performance beyond LEO
  - Developing new GPS/GNSS space-qualified receivers to support missions in geosynchronous orbit and highly elliptical orbits with apogees beyond GEO

Defining the Space Service Volume: GPS Services in Space

- **Terrestrial Service Volume (TSV)**
  - The volume of space between the surface, and an altitude of 3,000 km (which includes much of LEO) is referred to as the *Terrestrial Service Volume*, or TSV
  - The performance characteristics of GPS within the Terrestrial Service Volume are described in the *GPS Standard Positioning Service (SPS) Performance Standard:* http://www.gps.gov/technical/ps/
- **Space Service Volume (SSV)**
  - Space user community was vulnerable to design changes because requirements were not explicitly stated
  - The volume of space between 3,000 km altitude and geosynchronous altitude (36,000 km) was defined as the Space Service Volume in GPS technical documents
  - Performance requirements for the GPS SSV were then developed to include satellite antenna patterns (side lobes) and group/phase delay variations
  - SSV therefore reflects a guaranteed level of performance within a service volume or sphere expanding out from the TSV to GEO

The volume of space where GPS provides PNT services is referred to as a *Service Volume*



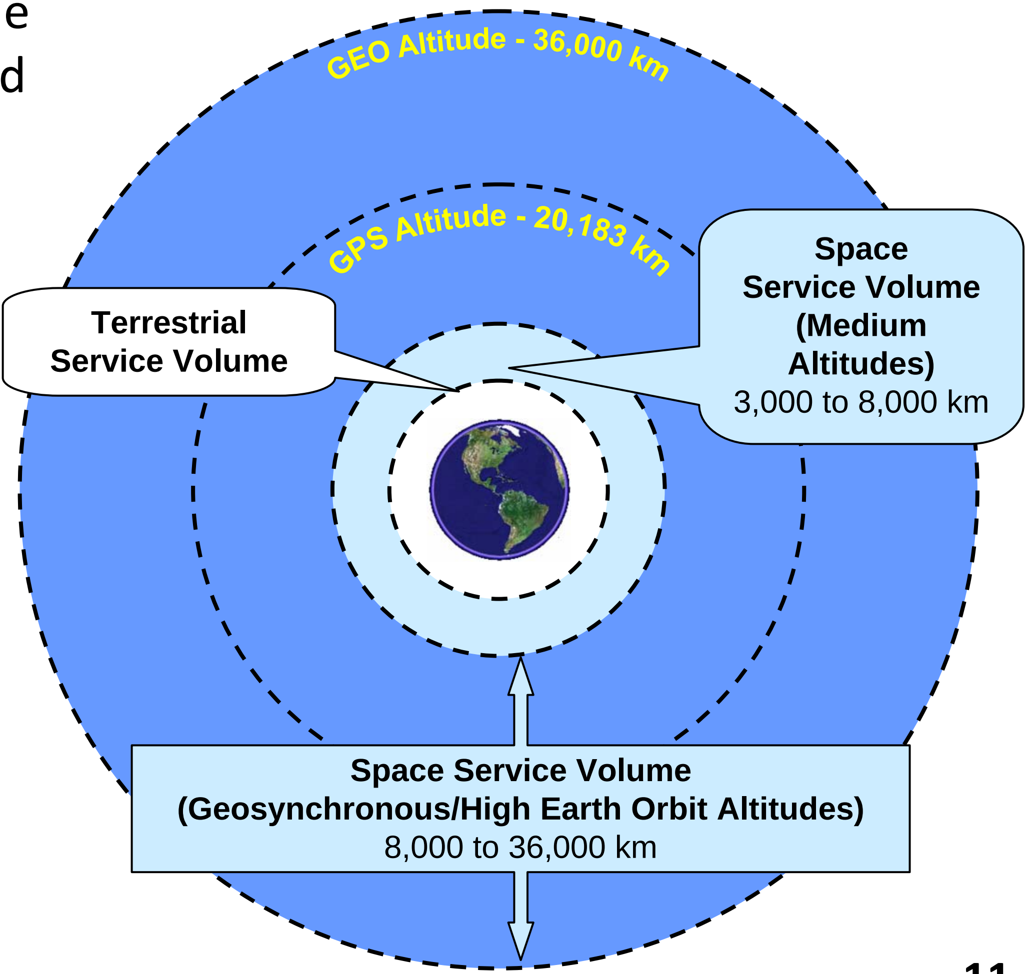
"To scale" visualization of the terrestrial and space service volumes defined to specify space use of GPS

Defining the Space Service Volume Above LEO

- Due to GPS performance variations based on altitude and geometry, the overall GPS SSV is in turn subdivided into two separate service domains:

- SSV for Medium Altitudes:
  - 3,000 to 8,000 km altitude
  - Visible GPS satellites can be present both above and below the user

- SSV for GSO/HEO Altitudes:
  - 8,000 to 36,000 km altitude
  - Visible GPS satellites are predominantly below the user



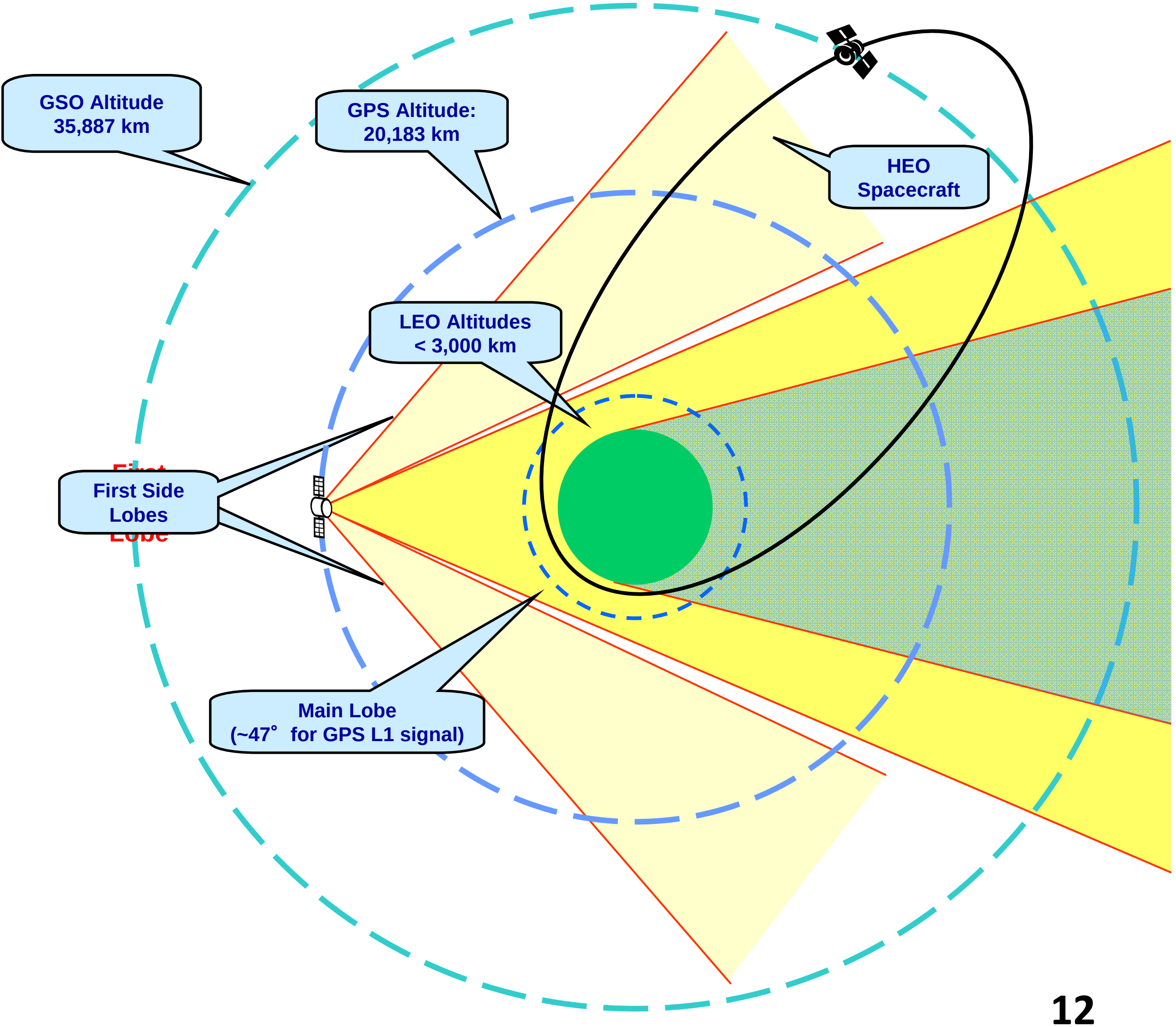
Terrestrial Service Volume

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

Space Service Volume (Geosynchronous/High Earth Orbit Altitudes)
8,000 to 36,000 km

Using GPS Beyond LEO: Reception Geometry for GPS Signals

- When operating at higher orbits we are tracking the GPS signals broadcast "over the limb" of the Earth
- This is sometimes referred as 'above the GPS constellation' navigation
- Earth is blocking most of the GPS signals, so the availability is much smaller
- This is why the GPS transmitter 'side lobes' become vital to space users



Space Service Volume Characteristics

- The characteristics that differentiate the SSV for Medium Altitudes & SSV for GSO/HEO Altitudes are as follows,

- **Medium Altitudes (3,000 – 8,000 km)**
  - Four GPS signals available simultaneously a majority of the time
  - Conventional space GPS receivers will have difficulty:
  - GPS signals over the limb of the Earth become increasingly important
  - Wide range of received GPS signal strength
  - One-meter orbit accuracies feasible

- **GSO/HEO Altitudes (8,000 – 36,000 km)**
  - Nearly all GPS signals received over the limb of the Earth
  - Users will experience periods when no GPS satellites are available
  - Received power levels will be weaker than those in TSV or Medium Altitudes SSV
  - A properly designed receiver should be capable of accuracies ranging between 10 and 100 meters depending on receiver sensitivity and local oscillator stability

Specifications to Support SSV Users

- Three parameters are used to determine the characteristics of GPS signals to support positioning, navigation, and timing (PNT) in the SSV
  - **Signal Availability:** the number of GPS/GNSS satellites in direct line-of-sight with the receiver at any given time
  - **Received Power:** the minimum power level required at the GPS/GNSS receiver at altitude
  - **Pseudorange Accuracy:** contribution of the GPS/GNSS system to the measurement of the distance between a GPS/GNSS satellite and a GPS/GNSS receiver

Specifications (1): 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/GEO SSV: at least 1 GPS satellite always in view

Specifications (2): 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 dBi 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 half-beamwidth point

Specifications (3): Pseudorange Accuracy

- In the Terrestrial Service Volume, a ***position accuracy*** is specified
- In the Space Service Volume, ***pseudorange accuracy*** is specified
- Also known as User Range Error (URE) - Error bound on GPS range measurement
- Function of
  - Accuracy of GPS orbit and clock solutions from Operational Control Segment
  - Age of Data
  - Uncertainty in GPS physical and modeling parameters
    - Antenna group delay and phase errors vary as a function of off-nadir angle
    - The group delay differential parameters for the radiated L1 signal with respect to the Earth Coverage signal for users of the Space Service Volume will be provided at http://www.igs.org/products/ssv
- Specification: The space service volume pseudorange accuracy shall be ≤ 0.8 m (rms) (**Threshold**); and ≤ 0.2 m (rms) (**Objective**)
- Position accuracy within the space service volume remains dependent on many mission specific factors, which are unique to this class of user, such as user spacecraft orbit, CONOPS, navigation algorithms and User Equipment

Credits / References

Evolution of the GPS Space Service Volume (GPS SSV) concept was made possible by the contributions of NASA representatives Mr. John Rush, Mr. Frank Bauer, Dr. Mike Moreau, Dr. Russell Carpenter, Dr. Larry Young, and other interagency team members, especially from within the U.S. Department of Defense (DoD) and U.S. Air Force. For more specific background information with additional source material, please see citations below:

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

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M. Moreau, *GPS Space Service Volume: Increasing the Utility of GPS for Space Users*, Briefing to the PNT Advisory Board, October 16, 2008.

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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
- "Enhanced Services" for GNSS constellations should include space services if all user groups are to be considered
- Without a formal definition of GPS/GNSS space service
  - Power supplied past edges of Earth could vary to unusable levels
  - Number of satellite signals may be inadequate
  - Quality of range and phase observations may be inadequate
- The opportunity now exists to expand the GPS SSV concept so that all PNT constellations are made more robust and interoperable, i.e., GNSS SSV
- Reaching the full performance potential of interoperable GNSS
  - Will require defined performance specifications by stakeholders
  - Transmittal of requirements and vigilant advocacy with policy makers and satellite builders
- It is recommended that GNSS providers develop docs/templates (ICDs, ISs, etc.,) that:
  - Contains an acknowledgement of service provision for space users (specify a SSV domain)
  - Details the operational performance characteristics to support a SSV domain

Contact Information

James J. Miller

Deputy Director / Sr. GPS Technologist

Space Communications and Navigation

Space Operations Mission Directorate

National Aeronautics and Space Administration

(202) 358-4417

jj.miller@nasa.gov

www.nasa.gov

Back Up

GNSS Transmit Antenna Requirements for SSV Use

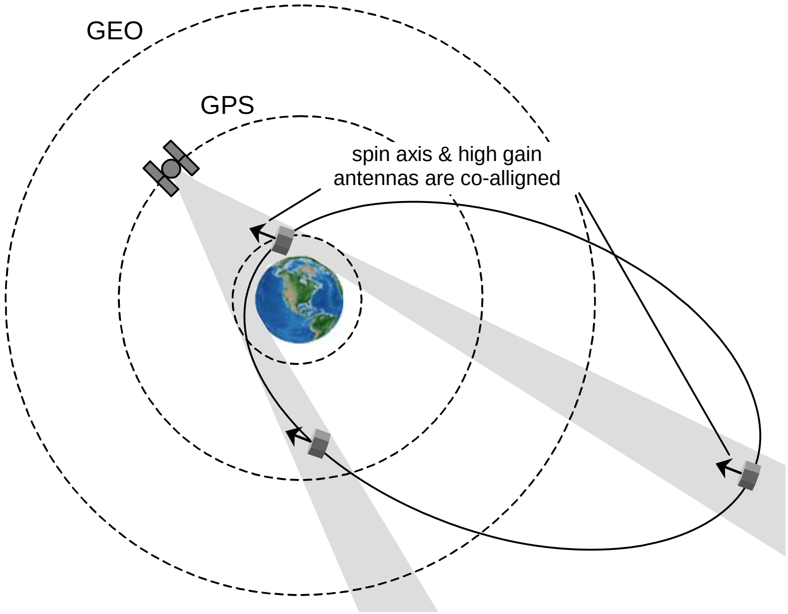
- The antenna specifications are also critical for GNSS SSV Use:
  - Antenna design should minimize phase and delay variations in the far field
  - The antenna best-fit phase center should be accurately provided to system users
  - A table of phase and delay variations vs angle should be provided to system users
  - Signal availability needs to be consistent with current performance if side-lobe signals are considered

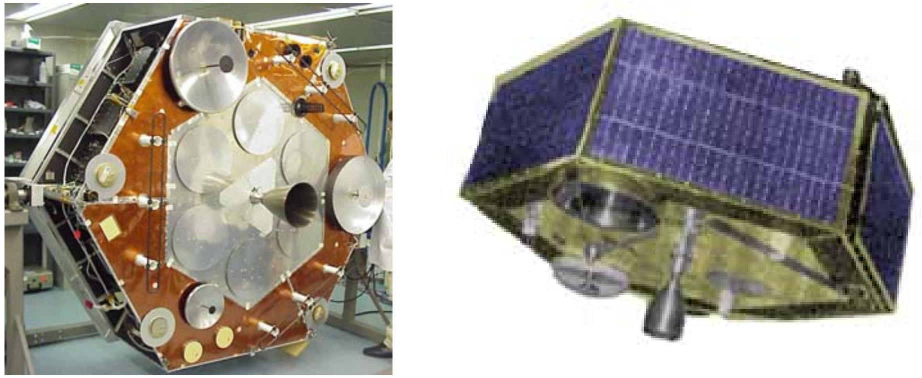
GPS/GNSS Antenna Requirements for High Accuracy Space Users

- Space science applications require accurate calibration/stability among carrier phases and ranging codes
  - Measurement of global sea level change requires sub-mm accuracy
  - Gravity field missions require 0.15 ns time transfer and cm-level formation flying
- Science users of GNSS require
  - Transmit antenna knowledge and stability
    - Antenna phase and delay center
    - Variations of phase and delay with angle
  - Signal monitoring and precision
    - Inter signal range biases
    - Commensurability among carriers

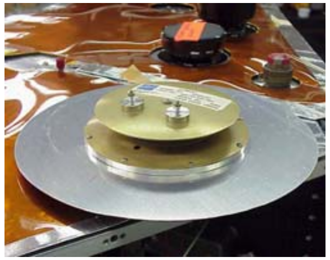
GPS Visibility in a Highly Elliptical Orbit (AO-40 Mission)

- AMSAT (amateur radio satellite) AO-40 spacecraft
- Included a NASA experiment to measure GPS L1 *main* and *side lobe* signals
- High apogee, high inclination, Molniya- type orbit



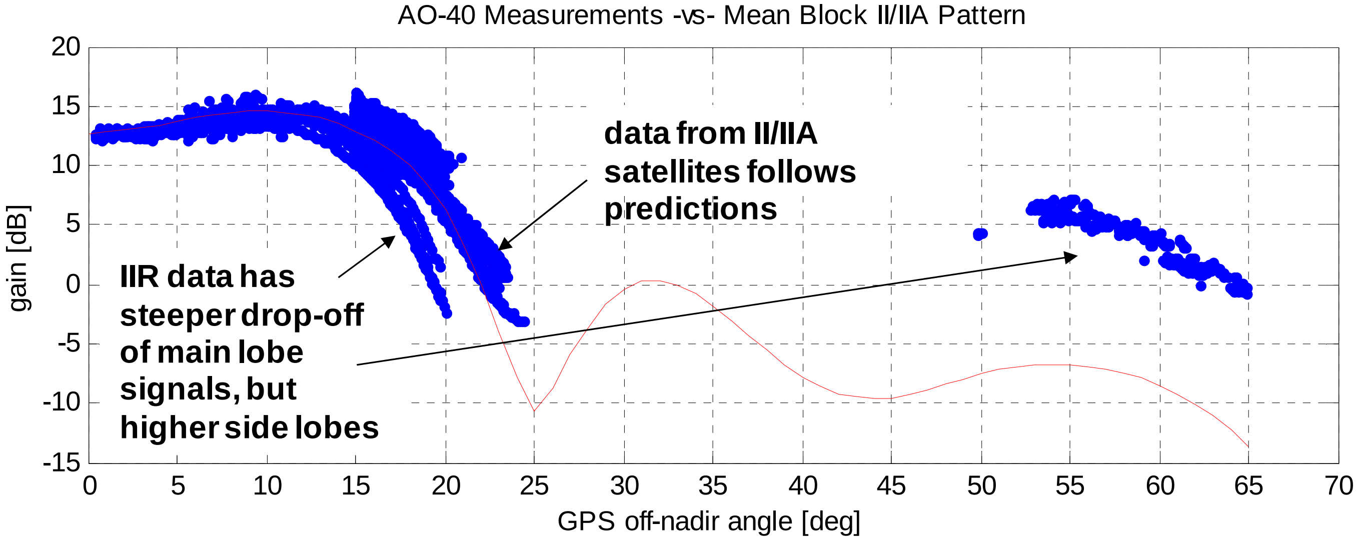


AO-40 Spacecraft



High Gain Antenna (1 of 4)

AO-40 GPS Data -vs- Predicted



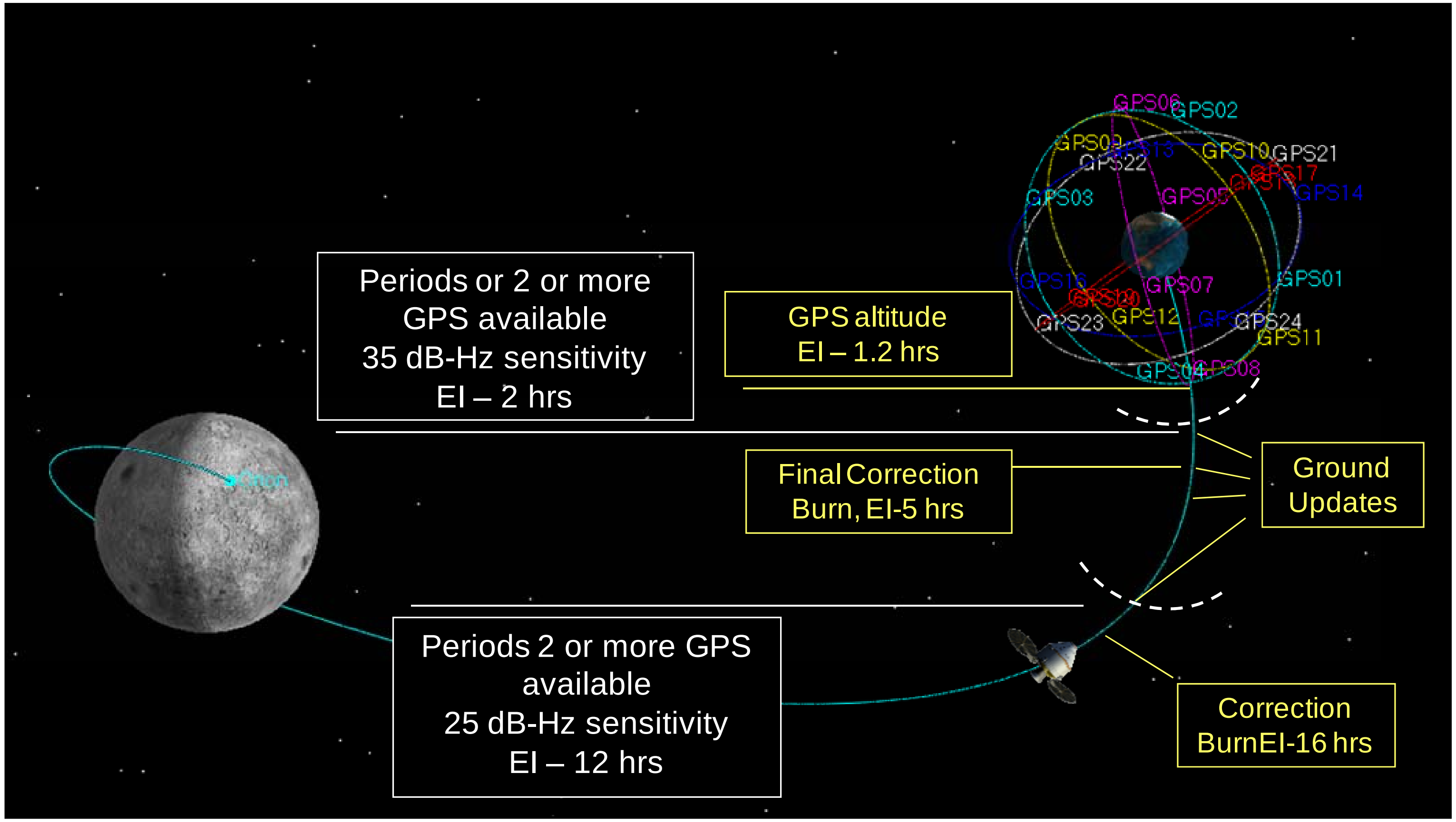
data from II/IIA satellites follows predictions

IIR data has steeper drop-off of main lobe signals, but higher side lobes

- Measurements from AO-40 GPS receiver were used to reconstruct GPS satellite transmitter gain patterns, which were compared to predicted gain for Block II/IIA satellites
- Data showed large variations in power levels transmitted between different blocks of GPS satellites, and as a function of transmitter azimuth angle
- Data from this experiment highlighted the importance of specifying performance characteristics for GNSS signals transmitted in the Space Service Volume
- AO-40 measured data demonstrated that GPS side lobe signals **significantly** improve signal availability in higher orbit

GPS Use in Cislunar Space

- Weak GPS signal tracking technology enables tracking signals well beyond the Geostationary altitude
- For example, for a spacecraft returning from the Moon, navigation accuracy can be improved in the critical 12-24 hours preceding Earth entry interface



Periods or 2 or more GPS available
35 dB-Hz sensitivity
EI – 2 hrs

GPS altitude
EI – 1.2 hrs

Final Correction Burn, EI-5 hrs

Ground Updates

Periods 2 or more GPS available
25 dB-Hz sensitivity
EI – 12 hrs

Correction BurnEI-16 hrs