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Enabling a Fully Interoperable GNSS Space Service Volume

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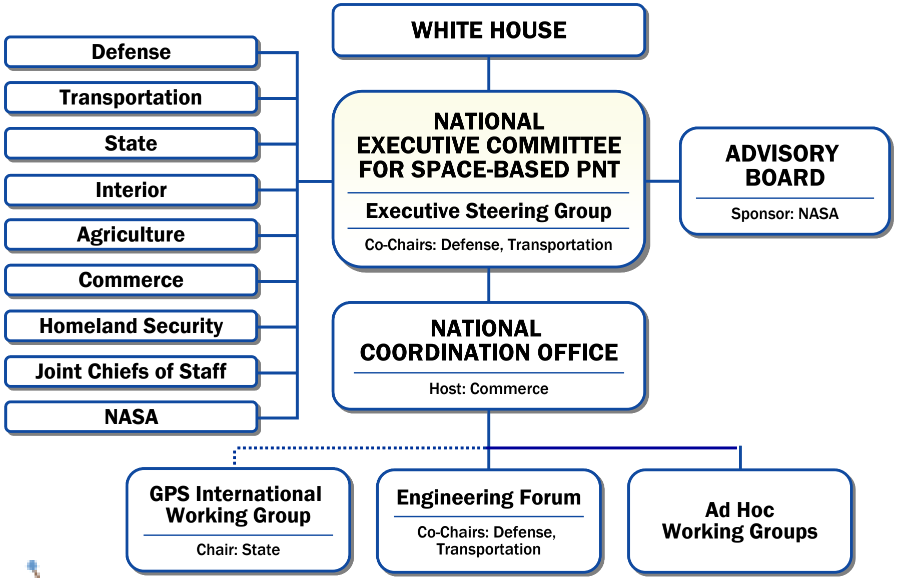
U.S. PNT / Space Policy and NASA's Role

- 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.

- 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.

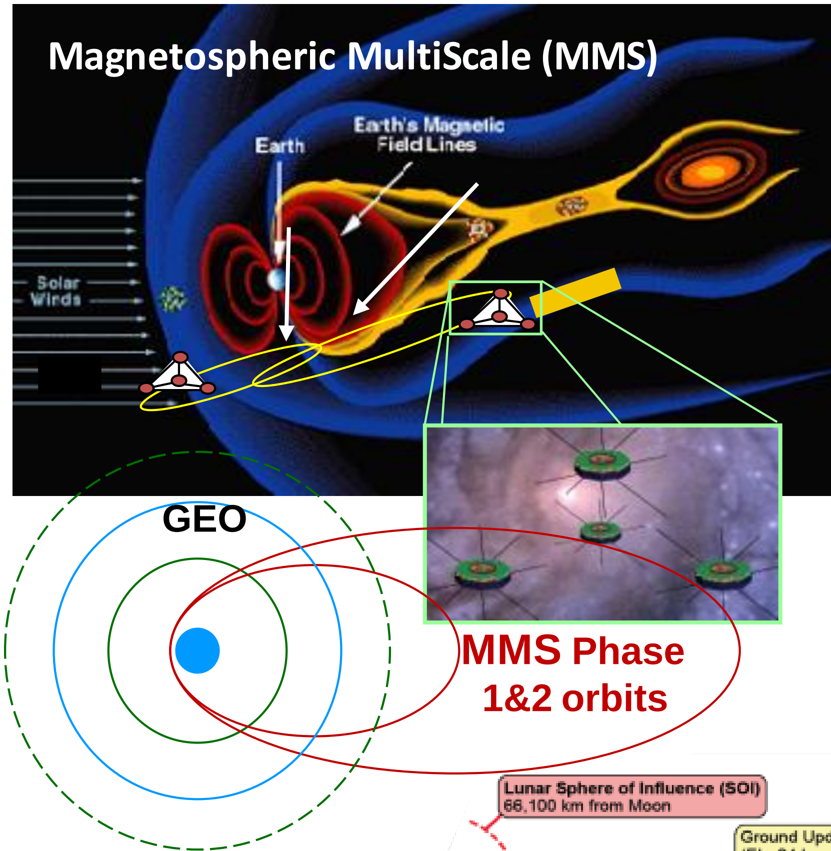
- NASA is engaging with other space agencies at venues such as the International Committee for GNSS (ICG) and the Interagency Operations Advisory Group (IOAG) to seek similar benefits from other PNT constellations to maximize performance, robustness, and interoperability for all.

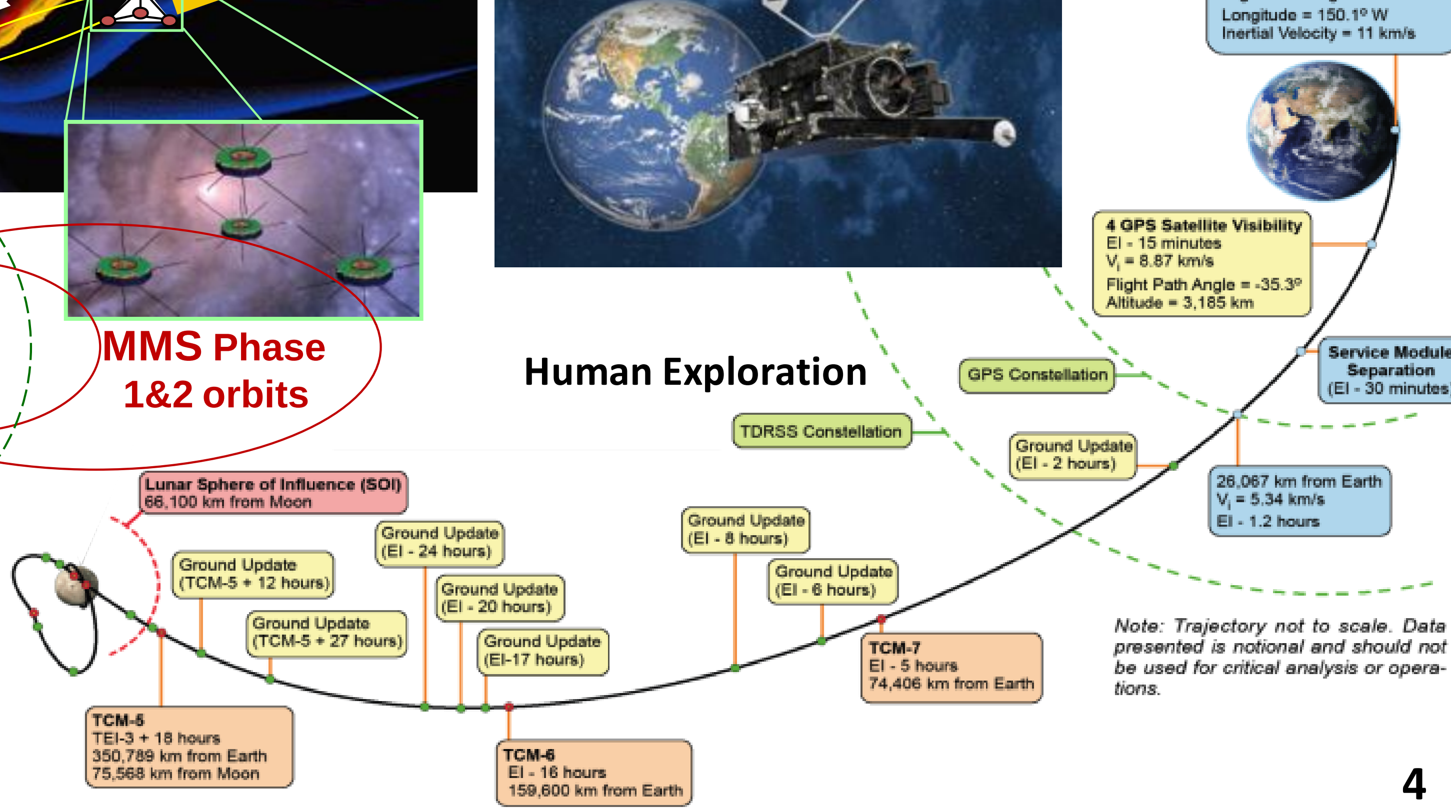


Expanding Space Applications of GPS

- GPS performance for Positioning, Navigation, and Timing (PNT) services was originally specified for users on or near the Earth surface:
  - For example, transmitted power levels specified at edge-of-Earth, 14.3 degrees off-nadir
- Space programs rely on GPS for spacecraft navigation and science applications
  - Most space users are in Low-Earth Orbits
  - Increasing number of users in higher orbits (altitudes > 3,000 km)

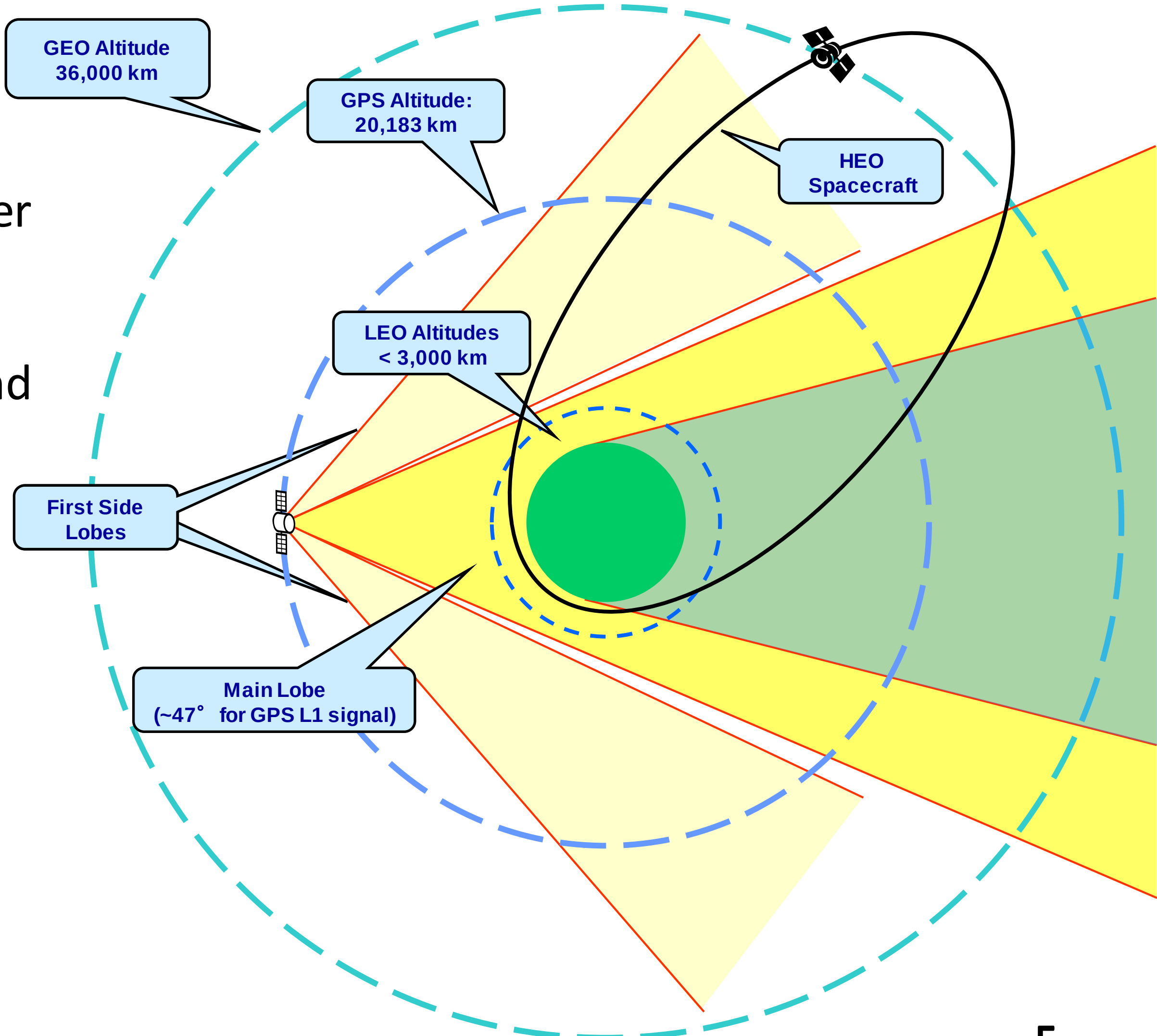
GNSS Important to Many Future Beyond-Low-Earth-Orbit Missions





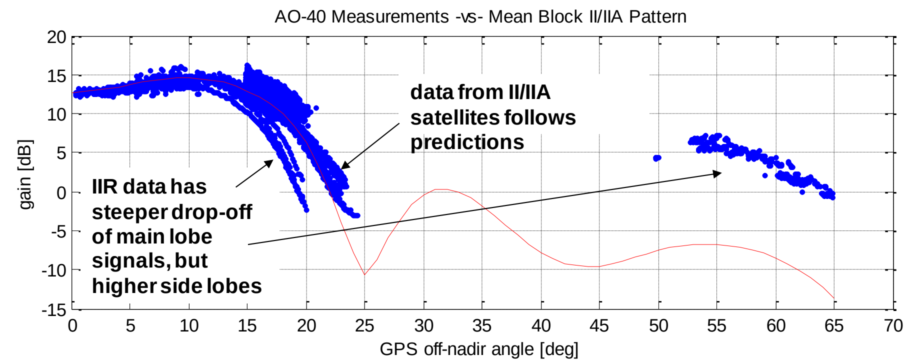
Using GPS Beyond LEO: Reception Geometry for GPS Signals

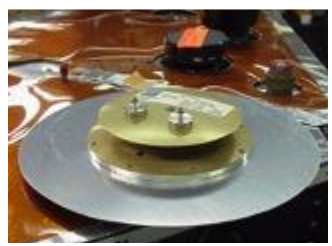
- When operating at higher orbits, the GPS receiver collects signals broadcast by the GPS satellites on the other side of the Earth
- Fewer signals are available, and signals are weaker than for Earth-based users
- Originally, no performance specifications existed for GPS signals transmitted above the Earth's limb
- Achievable navigation performance was uncertain



AO-40 Mission –Early High Earth Orbit GPS Experiment Sponsored by NASA

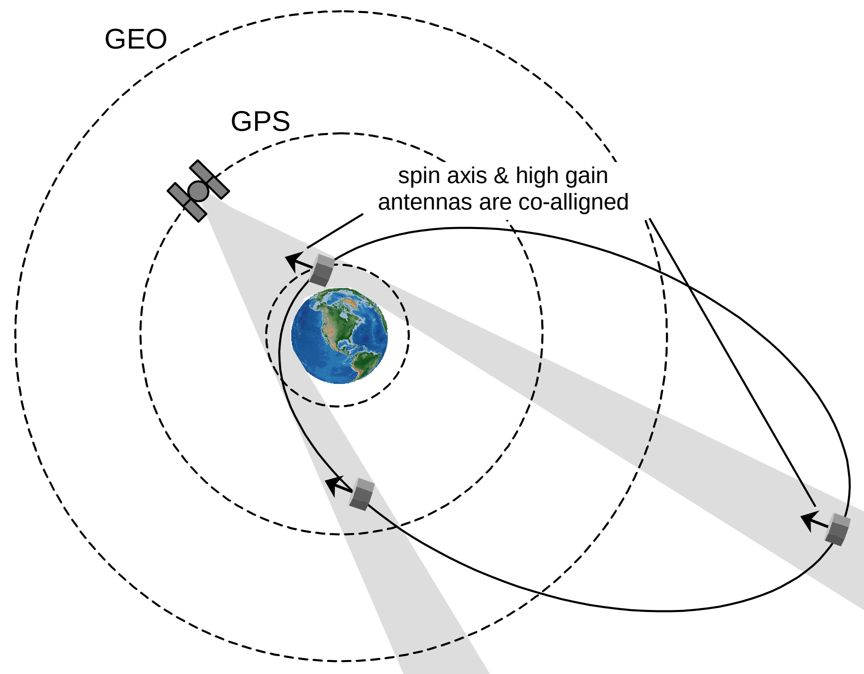
- AMSAT (amateur radio satellite) AO-40 spacecraft
- Included a NASA experiment to measure GPS L1 *main* and *side lobe* signals
- High apogee, high inclination, Molniya- type orbit





Antenna (1 of 4)

AO-40 Spacecraft



High Earth Orbit GPS Missions and GPS SSV Development Timeline

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

GPS III specifications include SSV requirements

Characterization of SSV

SSV in GPS ORD

2000

2010

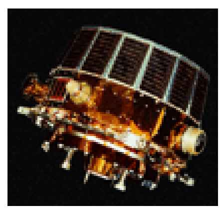
Magnetospheric Multiscale (MMS): Four satellite constellation in very highly eccentric orbits

GOES-R: GPS used for image registration for Geostationary weather satellites

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

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 2nd 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/factshefactsheet_print.asp?fsID=14314&page=1

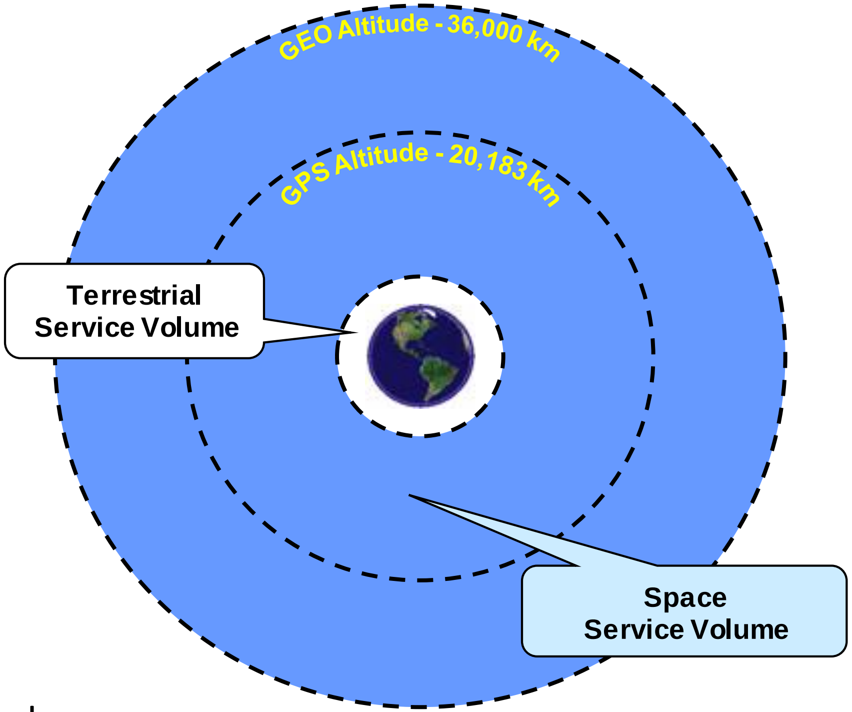
(*) Reference: **M. Moreau, E. Davis, J.R. Carpenter, G. Davis, L. Jackson, P. Axelrad, "Results from the GPS Flight Experiment on the High Earth Orbit AMSAT AO-40 Spacecraft," Proceedings of the ION GPS 2002 Conference, Portland, OR, 2002.**

Space Service Volume

- US Government has defined a “Space Service Volume” for GPS
  - Specifies minimum performance parameters applicable to space users in higher Earth orbits beginning with GPS III satellites
  - Allows future space users to evaluate performance of GPS for their applications

Defining the Space Service Volume: GPS Services in Space

- The volume of space where GPS provides PNT service is referred to as a *Service Volume*
- 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
  - –Thus, most space users operate within the Terrestrial Service Volume.
  - –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)
  - –The volume of space between 3,000 km altitude, and geosynchronous (GEO) altitude (36,000 km) is referred to as the Space Service Volume

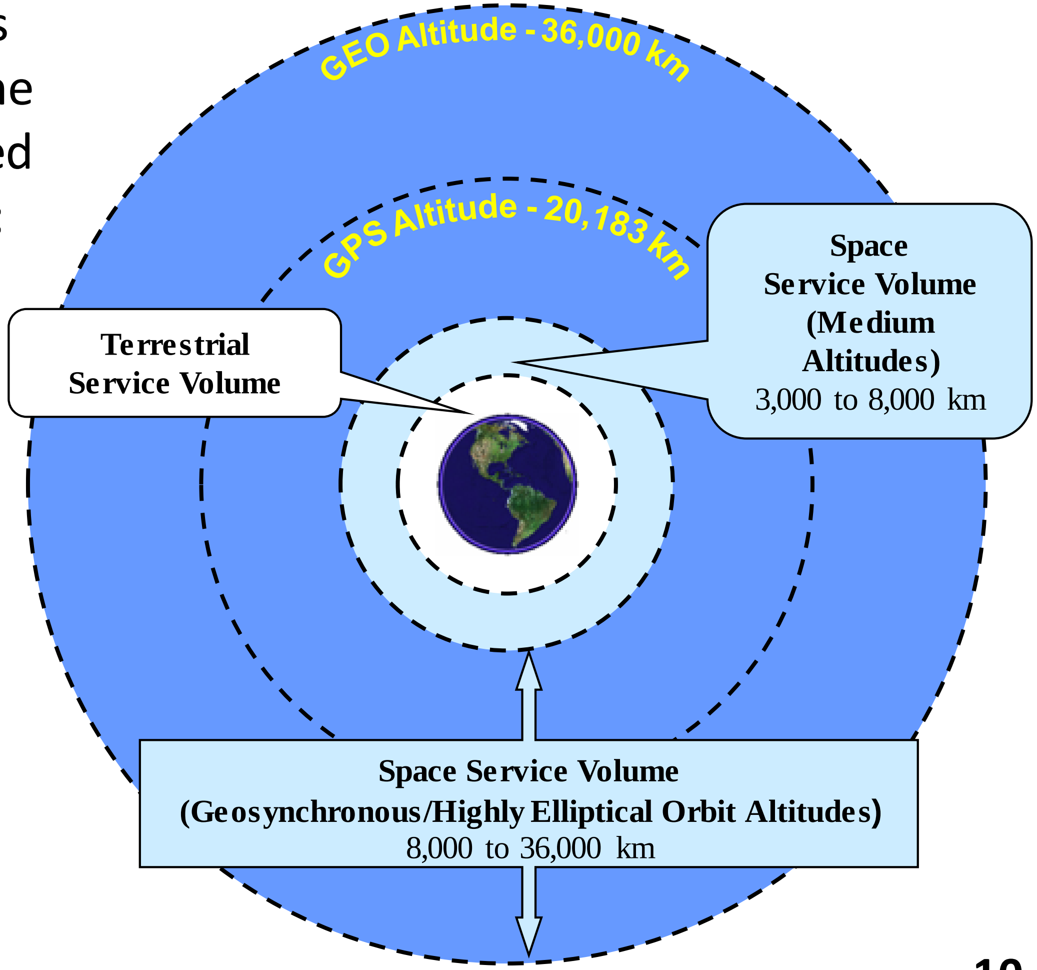


"To scale" visualization of the terrestrial and space service volumes defined to specify space use of GPS

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.

Defining the Space Service Volume

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



Space Service Volume Characteristics

- The characteristics that differentiate the SSV for Medium Altitudes & SSV for GEO/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

- **GEO/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
  - **Received Power:** the minimum power level at the GPS/GNSS receiver
  - **Pseudorange Accuracy:** measure of the error contributed by the GPS/GNSS system to the measurement of the distance between a GPS/GNSS satellite and a GPS/GNSS receiver
  - **Signal Availability:** the number of GPS/GNSS satellites in direct line-of-sight with the receiver at any given time

Specifications (1): Received Signal Power

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

(*) SSV Minimum power from a 0 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 off-nadir point

Specifications (2): Pseudorange Accuracy

- In the Terrestrial Service Volume, a position accuracy is specified. In the Space Service Volume, pseudorange accuracy is specified.
- Position accuracy within the space service volume is dependent on many mission specific factors, which are unique to this class of user, such as user spacecraft orbit, CONOPS, navigation algorithm, and User Equipment.
- Specification: The space service volume pseudorange accuracy shall be ≤ 0.8 m (rms) (**Threshold**); and ≤ 0.2 m (rms) (**Objective**).
- In order for GPS to meet the SSV accuracy requirement, additional data must be provided to users:
  - The group delay differential parameters for the radiated signal with respect to the Earth Coverage signal for users of the Space Service Volume will be provided at http://www.igs.org/products/ssv

Specifications (3): Signal Availability

- Assuming a nominal, optimized GPS constellation and no GPS spacecraft failures, signal availability at 95% of the areas at a specific altitude within the specified SSV should be as follows:

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

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

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

Space Service Volume Status

- Space Service Volume requirements were developed through inter-agency process and formally adopted as part of the GPS III baseline requirements in 2006 timeframe
- GPS III satellites designed to be compliant with SSV requirements
  - Legacy GPS satellites also meet the requirements
- Recent revisions to GPS Interface Specifications (IS) reflect these new parameters
- NASA and other scientific/high accuracy users of GPS continue to look for opportunities to improve the performance of GPS, and increase interoperability with other GNSS systems

Towards an Interoperable GNSS Space Service Volume

- NASA seeks to encourage other GNSS system providers to define Space Service Volume performance characteristics
  - Use of multiple GNSS signals contributes to greater overall system interoperability
  - Sparse signal availability in high Earth orbits means increased performance will be possible in the Space Service Volume if signals from multiple GNSS systems can be used together
  - Will enable more innovative space infrastructure applications to be developed

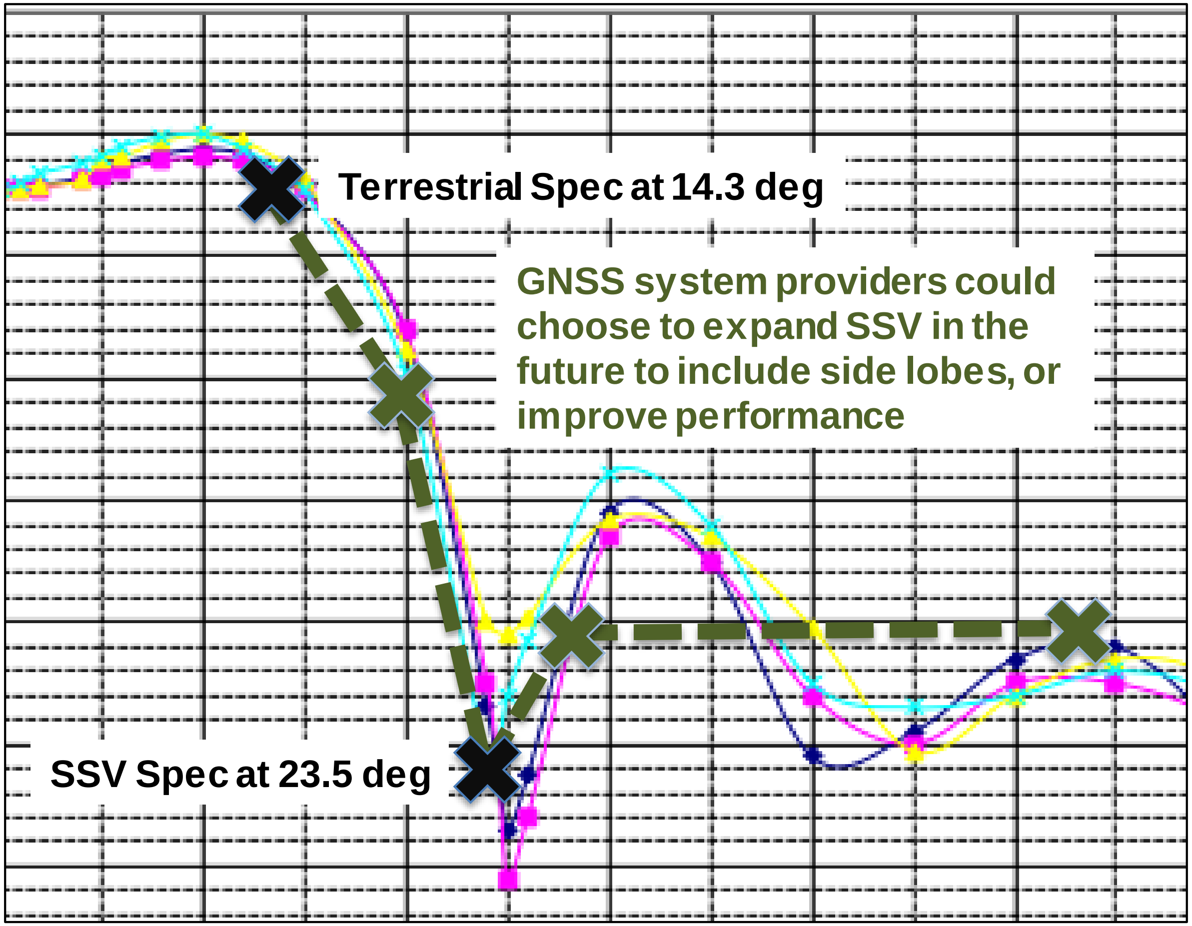
Analysis of Combined GNSS System Availability in the Space Service Volume

- Assuming nominal GNSS constellation and no spacecraft failures, the combined GPS, GLONASS, Galileo, and Beidou systems would allow nearly continuous signal availability

	MEO SSV (up to 8000 km altitude)		**HEO/GEO SSV (up to GEO altitude)**	
	≥ 1	≥ 4	≥ 1	≥ 4
GPS only	100%	100%	≥ 92%	≥ 6.5%
All GNSS	100%	100%	≥ 99%	≥ 97%

- Calculated assuming nominal constellations using only MEO GNSS satellites, 26° beamwidth (except Galileo 25.5°), and line of sight at least 50 km above WGS84
- Maximum time with no signal: <108 minutes for GPS only; <8 minutes for combined GNSS

Going Beyond the Existing GPS SSV Specification…



- Previously GPS performance was specified only for signals transmitted within 14.3 degrees off-nadir
- SSV added a specification for *minimum power* and *signal accuracy* within wider off-nadir angle (23.5 degrees for L1)
- SSV *signal availability* at a given altitude follows from the specified reference point

- Other GNSS systems could go further – by specifying higher performance levels, specifying performance associated with larger off-nadir angles, etc.

Status of Coordination on an Interoperable GNSS SSV (1)

- NASA has developed a template to facilitate documentation of Space Service Volume performance of other GNSS systems
  - To assist other PNT service providers in documenting desired performance parameters for current and evolving system Interface Control Docs (ICDs), Interface Specs (ISs), etc.
  - To encourage capability and coverage improvements as PNT constellations evolve, modernize, and become more interoperable

Status of Coordination on an Interoperable GNSS SSV (2)

- The GNSS SSV concept has been presented and discussed at multiple ICG meetings, most recently in Vienna June 2012
- Working group members were invited to work with GNSS service providers to answer/comment on the following questions:
  – Are there any clarifications needed regarding the quantitative characteristics proposed by the U.S.?
  – Are there any questions or comments regarding the SSV description proposed by the U.S. (see Annex 2 of this report)?
  – Are other nations or entities developing similar SSV characteristics for their respective GNSS constellations?
  – Are there plans for future generations of GNSS satellites to serve the expanding cadre of civil and commercial space users with a defined SSV?

Status of Coordination on an Interoperable GNSS SSV (3)

- Objectives for IGC-7:
  - Joint agreement/statement from the service providers stating the mutual benefits of a fully interoperable GNSS Space Service Volume
  - Formal definition of GNSS Space Service for the ICG Glossary
  - A commitment from service providers to:
    - Provide preliminary information on the existing capabilities of their systems via the NASA provided template
    - Consider the formal adoption of requirements on the performance of their systems in the Space Service Volume in the future

Summary

- 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 GPS Space Service Volume introduces a formal specification for GPS performance available to space users, however there is a strong interest in continuing to improve future performance and interoperability with other emerging systems

- The opportunity now exists to expand the GPS SSV concept (**GNSS SSV**) so that all PNT constellation signals are fully interoperable out to GEO, enabling core space domain performance parameters to be well understood, documented, and used

- A template has been provided to facilitate coordination amongst PNT service providers, and NASA stands ready to assist interested stakeholders in establishing core SSV parameters to work through their own respective processes.

- **NOT** moving forwarding with establishing core interoperable SSV performance requirements may penalize many international space applications from reaching their full operational potential in the future.