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Combined Global Navigation Satellite Systems in the Space Service Volume

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Abstract

Besides providing position, navigation, and timing (PNT) services to traditional terrestrial and airborne users, GPS is also being increasingly used as a tool to enable precision orbit determination, precise time synchronization, real-time spacecraft navigation, and three-axis attitude control of Earth orbiting satellites. With additional Global Navigation Satellite System (GNSS) constellations being replenished and coming into service (GLONASS, Beidou, and Galileo), it will become possible to benefit from greater signal availability and robustness by using evolving multi-constellation receivers.

The paper, "GPS in the Space Service Volume," presented at the ION GNSS 19th International Technical Meeting in 2006 (Ref. 1), defined the Space Service Volume, and analyzed the performance of GPS out to seventy thousand kilometers. This paper will report a similar analysis of the signal coverage of GPS in the space domain; however, the analyses will also consider signal coverage from each of the additional GNSS constellations noted earlier to specifically demonstrate the expected benefits to be derived from using GPS in conjunction with other foreign systems.

The Space Service Volume is formally defined as the volume of space between three thousand kilometers altitude and geosynchronous altitude circa 36,000 km, as compared with the Terrestrial Service Volume between 3,000 km and the surface of the Earth. In the Terrestrial Service Volume, GNSS performance is the same as on or near the Earth's surface due to satellite vehicle availability and geometry similarities. The core GPS system has thereby established signal requirements for the Space Service Volume as part of technical Capability Development Documentation (CDD) that specifies system performance. Besides the technical discussion, we also present diplomatic efforts to extend the GPS Space Service Volume concept to other PNT service providers in an effort to assure that all space users will benefit from the enhanced interoperability of GNSS services in the space domain.

A separate paper presented at the conference covers the individual GNSS performance parameters for respective Space Service Volumes.

Acronyms

GEO	geosynchronous Earth orbit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HEO	highly elliptical orbit
IOV	in Orbit validation
LEO	low Earth Orbit
MEO	medium Earth orbit
NASA	National Aeronautics and Space Administration
PNT	position, navigation, and timing
PVT	position, velocity, and timing
SCaN	Space Communication and Navigation
SSV	Space Service Volume
STK	Systems Tool Kit (formerly Satellite Tool Kit, Analytical Graphics, Inc.)
TSV	Terrestrial Service Volume

Introduction

Although GNSS constellations were created to provide position, navigation, and timing (PNT) services for terrestrial and airborne applications, they can also provide PNT functionality to space borne applications such as Earth orbiting satellites. GPS is already being widely used for this purpose, having first flown onboard Landsat 4 decades ago in 1982 (Ref. 2).

For satellites operating in low Earth orbit (LEO), GNSS receivers will see signals that are similar to those seen by terrestrial and airborne users, apart from the high dynamic effects due to orbital velocity. They can receive signals through a zenith-pointing antenna because they are within the primary transmitted beam of the GNSS satellites. For GNSS use, LEO extends to beyond 3,000 km.

For satellites in higher orbits, a zenith-pointing antenna can receive fewer signals, since the satellite will be outside the main beam of many satellites. Above GNSS medium Earth orbit (MEO) altitude, of course, the number of signals received from above the satellite will be zero. However, GNSS signals can still be used for PNT at these altitudes by taking advantage of tracking GNSS signals crossing the Earth's limb using a nadir-pointing antenna, as shown in Figure 1, while satellites at

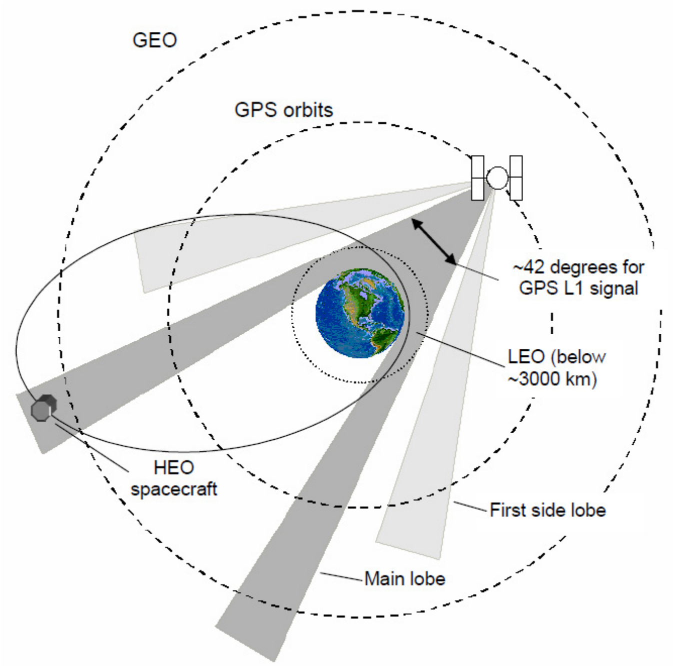

Figure 1.—Geometry for reception of GNSS signals by a HEO satellite (Ref. 1).

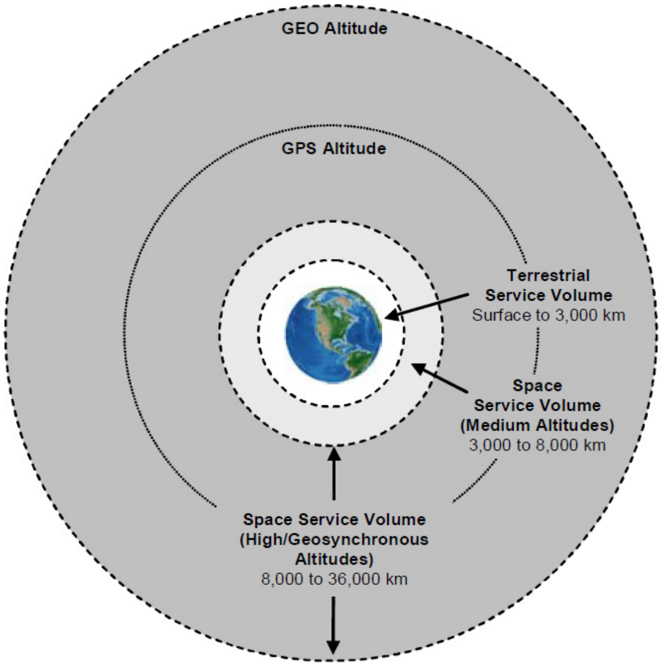

Figure 2.—Terrestrial and Space Service Volumes (Ref. 1).

intermediate altitudes can use a combination of zenith- and nadir-pointing antennas. Due to the increased range and reduced transmitter gain at the larger off-nadir angles, the signals will be much weaker than those available at the Earth's surface. However, specialized GPS receivers have demonstrated the increased acquisition and tracking sensitivity and integrated a navigation filter for state estimation when less than four satellites are available. Multi-constellation GNSS receivers for satellites are currently under development, and are already a fixture in terrestrial signal monitoring systems such as the International GNSS Service (IGS) managed by the NASA Jet Propulsion Laboratory (JPL).

Space Service Volume

Based on the unique nature of GNSS signals as a function of altitude, requirements for GNSS spacecraft services can be allocated to two service volumes. The terrestrial service volume (TSV) includes all terrestrial and space GNSS users up to an altitude of 3,000 km, and the space service volume from 3,000 km to the approximate geostationary altitude of 36,000 km.

Terrestrial Service Volume

Users in the TSV enjoy uniform received powers and have fully overlapping coverage. The use of multiple GNSS will have some benefit due to the increased number of pseudoranges available although individual GNSS constellations already provide very good coverage.

Space Service Volume

The SSV can be further divided into two regions: (1) the MEO SSV (3,000 to 8,000 km), and (2) the highly elliptical orbit (HEO)/geosynchronous Earth orbit (GEO) SSV (8,000 to 36,000 km). Figure 2 illustrates the relationship between the three altitude regions described above. In the TSV, adequate coverage can be supplied by a zenith pointing antenna; in the MEO region, a combination of zenith- and nadir- pointing antennas are needed, but even a single GNSS constellation will often allow for satellite coverage from at least four satellite vehicles; in the HEO/GEO region, nearly all GNSS signal will come from satellites transmitting across the Earth's limb; it is in this realm where the use of multiple GNSS constellations in combination will greatly increase availability and service performance.

Availability of GNSS Services

Currently GPS provides promises of future signal strength and quality within a guaranteed beamwidth out to GEO altitude (Ref. 3).

Signal Availability

This section summarizes the analyses of multi-constellation GNSS availability for spacecraft navigation.

STK simulations were used to evaluate the availability of GNSS signals for each of the new systems (GLONASS, Galileo, and Beidou) in combination with GPS; and for all four systems in combination. The availability for GPS alone is included in the tables for reference.

The GPS constellation used in the simulations is the 24+3 constellation currently planned for future availability. The GLONASS constellation is the current 24-satellite constellation. The Galileo constellation is the planned 24-satellite constellation. The Beidou constellation is the 24 MEO satellite portion.

The beamwidths used in the simulation are the committed GPS half-beamwidths of 23.5° for GPS L1 and 26° for GPS L2 and L5 (Ref. 3). Since beam data for Beidou and GLONASS are not available, we assume half-beamwidths of 23.5° for GLONASS L1 and Beidou B1; and 26° for GLONASS L2 and L3, Beidou B2 and B3, similar to GPS beamwidths. The published Galileo IOV antenna data show somewhat narrower beams (appropriate for their higher altitude) so we used 24° for the half-beamwidth of E5 and E6 and 20° for the half-beamwidth of E1 (Ref. 4).

An earth atmosphere mask was applied requiring signals to pass at least 50 km above WGS84. While ionospheric effects can be important for signals passing less than 1,000 km above the earth’s surface, all GNSS satellites transmit multiple frequency signals through this region allowing multi-frequency receivers to correct for ionospheric effects.

At each altitude, a grid of approximately 2,000 evenly spaced points was generated covering all latitudes and longitudes. For each grid point, the GNSS constellations were propagated forward in time 48 hr (in 60-s steps) and line-of-sight vectors were evaluated for each step in time. The products of a run were time histories of GNSS satellite visibilities. From this availability, statistics were calculated, giving the following metrics listed in Table 1 to Table 8:

- Availability of at least 1 and of at least 4 GNSS satellites, both for an average point and for the worst point
- Duration of longest single-fold outages (intervals when no satellite visible)
- Duration of longest four-fold outages (intervals when less than four satellites were visible)
- Minimum, average, and maximum number of satellites visible

TABLE 1.—SIMULATED ALTITUDES

Altitude	Comment
300 km	Typical LEO Altitude
3,000 km	Border between TSV and SSV
8,000 km	Border between medium and high orbit service
15,000 km	Within high orbit service, below GNSS altitude
25,000 km	Within high orbit service, above GNSS altitude
36,500 km	Approximate GEO altitude
70,000 km	Approximately twice GEO altitude

TABLE 2.—A 300 km ALTITUDE

	GPS only	GPS + GLONASS	GPS + Galileo	GPS + Beidou	All
1+ (%)	100	100	100	100	100
4+ (%)	100	100	100	100	100
<1 (s)	0	0	0	0	0
<4 (s)	0	0	0	0	0
Min. (#)	10	20	22	22	44
Ave. (#)	14.3	26.9	27.3	27.1	52.7
Max. (#)	19	36	36	34	65

TABLE 3.—A 3,000 km ALTITUDE

	GPS only	GPS + GLONASS	GPS + Galileo	GPS + Beidou	All
1+ (%)	100	100	100	100	100
4+ (%)	100	100	100	100	100
<1 (s)	0	0	0	0	0
<4 (s)	0	0	0	0	0
Min. (#)	16	29	33	33	64
Ave. (#)	20.9	39.4	39.8	39.6	76.9
Max. (#)	24	46	44	44	85

TABLE 4.—A 8,000 km ALTITUDE

	GPS only	GPS + GLONASS	GPS + Galileo	GPS + Beidou	All
1+ (%)	100	100	100	100	100
4+ (%)	99.9+	100	100	100	100
<1 (s)	0	0	0	0	0
<4 (s)	595	0	0	0	0
Min. (#)	3	5	9	10	21
Ave. (#)	9.6	17.1	19.0	19.5	36.4
Max. (#)	15	26	27	27	49

TABLE 5.—A 15, 000 km ALTITUDE

	GPS only	GPS + GLONASS	GPS + Galileo	GPS + Beidou	All
1+ (%)	99.9+	99.9+	100	100	100
4+ (%)	80.0	99.0	99.4	99.4	99.9+
<1 (s)	604	159	0	0	0
<4 (s)	8289	2895	8289	6619	1259
Min. (#)	0	0	1	1	2
Ave. (#)	4.7	8.5	9.0	9.3	17.5
Max. (#)	10	20	17	18	34

TABLE 6.—A 25,000 km ALTITUDE

	GPS only	GPS + GLONASS	GPS + Galileo	GPS + Beidou	All
1+ (%)	99.4	99.9+	100	99.9+	100
4+ (%)	36.0	90.0	95.5	96.7	99.9+
<1 (s)	3158	2132	0	138	0
<4 (s)	30166	7452	8701	10119	672
Min. (#)	0	0	1	0	2
Ave. (#)	3.1	5.7	5.8	6.1	11.4
Max. (#)	8	15	14	14	25

TABLE 7.—A 36,500 km ALTITUDE

	GPS only	GPS + GLONASS	GPS + Galileo	GPS + Beidou	All
1+ (%)	97.0	99.8	99.8	99.9+	99.9+
4+ (%)	15.6	70.6	74.9	80.2	99.4
<1 (s)	9673	2697	4698	4232	528
<4 (s)	72272	13753	51634	44385	5397
Min. (#)	0	0	0	0	0
Ave. (#)	2.4	4.4	4.5	4.7	8.8
Max. (#)	6	13	10	10	19

TABLE 8.—A 70,000 km ALTITUDE

	GPS only	GPS + GLONASS	GPS + Galileo	GPS + Beidou	All
1+ (%)	89.6	97.8	97.8	98.3	99.9
4+ (%)	2.8	37.7	38.1	44.2	88.8
<1 (s)	Never	5347	Never	86556	3732
<4 (s)	Never	34696	Never	Never	22018
Min. (#)	0	0	0	0	0
Ave. (#)	1.7	3.1	3.1	3.3	6.2
Max. (#)	6	11	10	10	18

Conclusions and Summary

The results clearly show the increased availability and reduced outage durations from using multiple GNSS constellations for spacecraft PNT at the higher altitudes. At lower altitudes, the increase in number of GNSS satellites in view will allow even more accurate PNT, even though the use of multiple GNSS constellations is not necessary to prevent outages since more than four satellites are always within view.

The practical implications of this analysis clearly shows that there is definitive benefit for future space missions to take a multi-GNSS approach to meet PNT requirements out to the GEO boundary (36,000 km) in the space domain. At NASA, this has prompted investments in spacecraft multi-GNSS signal processing, as well as antennae configurations to optimize “over the limb of the Earth” signal processing.

A key point of this work also shows that onboard signal processing complexity can be significantly reduced when four or more satellite signals are always in view from various GNSS constellations. More signal availability naturally translates into greater real-time point positioning, thus negating the need for specialized predictive orbit software such as the Goddard Enhanced Onboard Navigation System (GEONS) required when fewer signals are in view (Ref. 5).

Since the technical success of using GPS, and other multi-GNSS solutions for space navigation in the Space Service Volume will become standard to enhance spacecraft autonomy and reduce network tracking burdens, it is paramount that the world’s space agencies work with their respective global PNT service providers to ensure that their own sovereign systems provide for some guaranteed level of service performance out to GEO. Otherwise satellite vehicle power levels, pseudoranges, and beam widths may continue to diverge away from meeting space user requirements unless a stated need is documented and adhered to as constellations continue to modernize.

To this end, NASA has been very active in the national and international community coordinating with the United Nations’ International Committee on GNSS (ICG), as well as the space agency standards body known as the Interagency Operations Advisory Group (IOAG), to secure recognition of the need for a formal, fully interoperable, Space Service Volume (SSV) based on the use of all emerging constellation signals. NASA does this under authority granted by the 2004 President’s National Space-based PNT Policy, where, “*The Administrator of the National Aeronautics and Space Administration, in cooperation with the Secretary of Commerce, shall develop and provide to the Secretary of Transportation requirements for the use of the Global Positioning System and its augmentations to support civil space systems*” (Refs. 6, 7, and 8).

In conclusion, it is obvious that the use of multi-GNSS solutions for future spacecraft positioning, navigation, and timing is a technical option that derives numerous benefits as indicated in the analyses conducted thus far. To make this scenario a true reality on a worldwide scale however, will require far more than a robust technical assessment and rationale; it will rather require the concentrated efforts of the very space agencies that stand to use their spacecraft to provide societal benefit in the most cost effective manner possible.

The GNSS constellation satellite vehicles themselves must be adapted for the emerging space user, which in turn will require further diplomatic efforts to ensure transparency amongst the respective bureaucratic organization of Russia’s GLONASS, Europe’s Galileo, and China’s Beidou constellations. In some cases a Space Service Volume capability may already exist; however this functionality must be formally recognized if it is to succeed over the long runs of modernization change. At the last UN ICG in Beijing, China, November 2012, the U.S., the Europeans, and even the Japanese with the augmentation satellite Quasi-Zenith Satellite System (QZSS) recognized the need to adopt the SSV as a future contributor of the multi-GNSS environment. NASA looks forward to continuing this dialogue, supported by analysis such as documented in this paper to continue the argument for SSV worldwide adoption.

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Biography

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