The Multi-GNSS Space Service Volume

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BIOGRAPHIES

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ABSTRACT

Global Navigation Satellite Systems (GNSS), now routinely used for navigation by spacecraft in low Earth orbit, are being used increasingly by high-altitude users in geostationary orbit and high eccentric orbits as well, near to and above the GNSS constellations themselves. Available signals in these regimes are very limited for any single GNSS constellation due to the weak signal strength, the blockage of signals by the Earth, and the limited number of satellites. But with the recent development of multiple GNSS constellations and ongoing upgrades to existing constellations, multi-GNSS signal availability is set to improve significantly. This will only be achieved if these signals are designed to be interoperable and are clearly documented and supported.

All satellite navigation constellation providers are working together through the United Nations International Committee on GNSS (ICG) to establish an interoperable multi-GNSS Space Service Volume (SSV) for the benefit of all GNSS space users. The multi-GNSS SSV represents a common set of baseline definitions and assumptions for high-altitude service in space, documents the service provided by each constellation, and provides a framework for continued support for space users. This paper provides an overview of the GNSS SSV concept, development, status, and achievements within the ICG. It describes the final adopted definition and performance characteristics of the GNSS SSV, as well as the numerous benefits and use cases

enabled by this development, and summarizes extensive technical analysis that was performed to illustrate these benefits in terms of signal availability, both on a global scale, and for multiple distinct mission types.

INTRODUCTION

Global navigation satellite systems (GNSS), which were originally designed to provide positioning, velocity, and timing services for terrestrial users, are now increasingly utilized for autonomous navigation in space as well. Historically, most space users have been located at low altitudes, where GNSS signal reception is similar to that on the ground. More recently, however, users are relying on these signals at high altitudes, near to or above the GNSS constellations themselves. High-altitude applications of GNSS are more challenging than terrestrial or low Earth orbit (LEO) applications due to a number of factors. As shown in Figure 1, a significant portion of the GNSS Earth-pointing main-lobe signal is occulted by the Earth. Some of this signal, however, passes the limb of the Earth and is received by high-altitude user spacecraft beyond, but with reduced coverage. Because of the longer path length, signal strength is up to an order of magnitude weaker, as compared to that received by LEO or terrestrial users. Finally, from the point of view of the receiving spacecraft, the GNSS satellites are clustered in a smaller portion of the sky, reducing the geometric diversity of the received signals and, thus, reducing precision of the final navigation solution.

The first flight experiments tracking the US Global Positioning System (GPS) above the constellation were launched in 1997 and successfully demonstrated that such signals could be tracked and acquired [1–2]. Later experiments, such as AMSAT OSCAR-40 [3] in 2001 and the later GIOVE-A GPS experiment [4] in 2013 collected on-orbit tracking data over an extended period and revealed performance characteristics of the GPS signal structure itself for high-altitude users. Operational high-altitude use has been documented as early as 2000 for users of GPS at geostationary altitude [5], and for multi-GNSS using both GPS and Russia's GLONASS starting in 2007 [6]. Recent published examples include NASA's Magnetospheric Multiscale (MMS) mission [7], which successfully uses GPS at 40% of lunar distance, and the US Geostationary Operational Environmental Satellite-R (GOES-R) series of weather satellites [8]. A major finding of the AMSAT OSCAR-40 experiment was that in addition to the inherent challenges of high-altitude GNSS use, the characteristics of the transmitted signals reaching this regime were also changing as the design of the GPS satellites evolved. This prevented accurate mission planning, as designers could not make assumptions about future GPS signal availability and power. The GPS Space Service Volume (SSV) [9] was created to address this issue. The GPS SSV specifies the volume of GPS service around the Earth and establishes formal requirements for signal received power, availability, and accuracy. Thus, the SSV defines a guaranteed lower limit on the GPS signal capabilities in this region, which can be employed by space mission planners to design on-board receiver equipment and simulate mission performance.

The recent and ongoing expansion of GNSS beyond just one or two constellations opens up new opportunities for high-altitude users. There will soon be four operational global constellations and two regional augmentations, respectively: the US' Global Positioning System (GPS), Russia's GLONASS, Europe's Galileo, China's BeiDou (BDS), Japan's Quasi-Zenith Satellite System (QZSS), and India's Navigation with Indian Constellation (NavIC). Table 1 provides an overview of these systems and their high-level characteristics. When combined, this "super-constellation" of 100+ GNSS satellites has the potential to greatly improve the signal coverage available in the high-altitude regime, as well as to increase the diversity of system architectures, signal frequencies, and signal geometries. Together, these constellations have the potential to improve overall performance and resiliency for users. But this potential can only be realized if these systems and signals are designed to be interoperable, and if they are designed with sufficient signal performance to benefit high-altitude users. All satellite navigation constellation providers are now working together through the United Nations (UN) International Committee on GNSS (ICG) to establish a coordinated, interoperable multi-GNSS SSV with the goal to ensure that these benefits are extended to the emerging class of high-altitude space users that wish to exploit the use of multi-GNSS navigation and timing.

Table 1. Overview of global and regional navigation satellite systems

System name	Nation	Coverage	Status	No. of civil frequencies / Signals	No. spacecraft (nominal) / orbital planes	Semi-major axis (km)	Inclination (°)	Comments
GPS	USA	Global	Operational	3/4	27/6	26560	55	

System name	Nation	Coverage	Status	No. of civil frequencies / Signals	No. spacecraft (nominal) / orbital planes	Semi-major axis (km)	Inclination (°)	Comments
GLONASS	Russia	Global	Operational	2/6	24/3	25510	64.8	
Galileo	European Union	Global	Operational	5/10	24/3	29600	56	Initial Service: 2016 FOC[5] planned: 2020
BDS	China	Global	Operational (Regional) In build-up (Global)	3/5	MEO[1]: 24/3 IGSO[2]: 3/3 GEO[3]: 5/1	27906 42164 42164	55 55 0	Service planned: Regional FOC: 2012 Global Initial Service: 2018 FOC: 2020
QZSS	Japan	Regional (Japan)	In build-up	4/7	HEO[4]: 3/3 GEO: 1/1	42164	40 0	Service planned: 2018
NavIC	India	Regional (India)	In build-up	2/2	IGSO: 4/2 GEO: 3/1	42164	29 0	Service planned: 2018
[1] medium Earth orbit [2] inclined geosynchronous orbit [3] geostationary orbit [4] high eccentric orbit [5] full operational capability								

ICG AND THE SSV DEVELOPMENT PROCESS

In the early 2000's, several bilateral meetings were held to discuss GNSS signal interoperability. These included meetings with the US and Russia on GPS/GLONASS interoperability and with the US and Europe on GPS/Galileo. These bilateral GNSS discussions ultimately became a multilateral dialog in 2005 when the United Nations formed the International Committee on GNSS (ICG). The ICG was created "to encourage and facilitate compatibility, interoperability[1] and transparency between all the satellite navigation systems, to promote and protect the use of their open service applications and thereby benefit the global community." [11] To maximize the utility of GNSS for high-altitude space users, coordination among all GNSS service providers is taking place within two working groups: Working Group B (WG-B) on "Enhancement of GNSS Performance, New Services and Capabilities", which leads SSV development, coordination, and outreach; and Working Group S on "Systems, Signals and Services", which coordinates the underlying GNSS signal interoperability [12].

The WG-B team undertook a series of activities in support of Task 3 of the WG-B Work Plan [13], which directs it to continue "the implementation of an interoperable GNSS Space Service Volume and provide recommendations to Service Providers regarding possible evolution needs arising from users/application developers." To further emphasize SSV critical strategies, WG-B also forwarded a series of recommendations, shown later in this section, to the ICG delegates for formal adoption. All initiatives were coordinated within the semi-annual ICG and intercessional meetings and in monthly WG-B teleconferences, and were conducted by the WG-B international team.

The following represents a snapshot of activities undertaken in support of the WG-B Work Plan:

- **SSV Definition/Assumption Maturation**: Development of standard definitions, ground rules, and assumptions of the multi-GNSS SSV and related concepts to support coordinated technical analyses across the international team and to be employed for formal SSV specification efforts.
- **Constellation-Specific SSV Performance Data:** Documenting and publishing the SSV performance metrics for each individual constellation in standard template form. This data is summarized in Table 2 and Table 3.
- **Multilateral SSV Analysis**: An international analysis effort to characterize single-constellation and multiple-constellation performance expectations within the SSV, using both a coverage grid (global) approach, and a suite of

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[1] The ICG defines interoperability as "the ability of global and regional navigation satellite systems, and augmentations and the services they provide, to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system." [10]

example mission profiles. The results of these analyses are captured in the GNSS SSV Booklet and in a set of coordinated conference and journal papers and will serve as a reference for space mission analysts.

- **GNSS SSV Booklet**: Development of an authoritative public ICG document that documents the multi-GNSS SSV, including coordinated definitions; benefits and use cases of the interoperable GNSS SSV; constellation-specific SSV signal performance data; and the results of technical analysis to estimate the performance capabilities of an interoperable multi-GNSS SSV. This booklet will be updated with new GNSS provider data and additional information as needed.
- **SSV Capabilities Outreach**: Coordination of a joint international outreach activity, targeted at space agencies, researchers, spacecraft mission designers, navigation engineers, GNSS providers, and others, to ensure that the capabilities and benefits of the interoperable GNSS SSV are understood, supported, and utilized.

The products from these WG-B activities are included in the SSV Booklet [14], which captures the definitions, template data and analysis results, and will be summarized in the outreach presentations and conference and journal papers. A major SSV milestone was reached at the 2015 ICG-10 meeting held in Boulder, Colorado, US, where all 6 GNSS providers (China, Europe, India, Japan, Russia, and the United States) formally submitted their SSV template data, and a recommendation was formally adopted to develop the Booklet. The multi-GNSS SSV Booklet is now complete and is awaiting final publication by the UN, expected by Fall 2018. The Booklet will be available to the public and will be available on several international GNSS web sites. The internationally-coordinated SSV analysis effort, which presents a conservative technical baseline for expected space user performance, is complete, has been adopted by all providers, and is documented in the Booklet and in a paper by Enderle, et al [15]. Outreach activities have commenced by members of the WG-B team, who presented the SSV initiative in a paper by Bauer, et al. in January 2017 [16], conducted a panel discussion at the Munich Satellite Navigation Summit in March 2017, and are planning further outreach events upon publication of the Booklet.

Four formal WG-B recommendations were adopted and endorsed by the ICG to encourage continued development, support, and expansion of the multi-GNSS SSV concept. For the community of GNSS providers, the following recommendations are aimed at continuing development of the SSV and providing the user community adequate data to utilize it:

- ICG/WGB/2014 Rec. 2: *GNSS providers are recommended to support the SSV outreach by making the booklet on "Interoperable GNSS Space Service Volume" available to the public through their relevant websites once the booklet is available. [17]*
- ICG/WGB/2016 Rec. 1: *Service Providers, supported by Space Agencies and Research Institutions, are encouraged to define the necessary steps and to implement them in order to support SSV in future generations of satellites. Service Providers and Space Agencies are invited to report back to WG-B on their progress on a regular basis. [18]*
- ICG/WGB/2016 Rec. 3: *GNSS providers are invited to consider for the future, to provide the following additional data if available:*
  - *GNSS transmit antenna gain patterns for each frequency, measured by antenna panel elevation angle at multiple azimuth cuts, at least to the extent provided in each constellation's SSV template.*
  - *In the long term, GNSS transmit antenna phase centre and group delay patterns for each frequency. [18]*

For the user community, there is one recommendation, to ensure that the full capabilities of the multi-GNSS SSV can be utilized:

- ICG/WGB/2013 Rec. 1: *The authors encourage the development of interoperable multi-frequency space borne GNSS receivers that exploit the use of GNSS signals in space. [19]*

DEFINITION OF THE MULTI-GNSS SPACE SERVICE VOLUME

The following is the formal definition of the multi-GNSS SSV, as adopted by the ICG WG-B.

The GNSS Space Service Volume (SSV) is defined in the context of the SSV Booklet [14] as the region of space extending from 3,000 km to 36,000 km altitude, where terrestrial GNSS performance standards may not be applicable. GNSS system service in the SSV is defined by three key parameters:

- Pseudorange accuracy
- Minimum received power
- Signal availability

The SSV covers a large range of altitudes, and the GNSS performance will degrade with increasing altitude. In order to allow for a more accurate reflection of the performance variations, the SSV itself is divided into two distinct areas that have different characteristics in terms of the geometry and quantity of signals available to users in those regions:

1. **<u>Lower Space Service Volume for Medium Earth Orbits:</u>** 3,000–8,000 km altitude. This area is characterized by reduced signal availability from a zenith-facing antenna alone, but increased availability if both a zenith and nadir-facing antenna are used.
2. **<u>Upper Space Service Volume for Geostationary and High Earth Orbits:</u>** 8,000–36,000 km altitude. This area is characterized by significantly reduced signal received power and availability, due to most signals traveling across the limb of the Earth.

Users with adequate antenna and signal processing capabilities will also be able to process GNSS signals above the identified altitude of 36,000 km.

The relevant regions of the GNSS SSV are depicted in Figure 1, along with the altitude ranges of the contributing GNSS constellations that are located in Medium-Earth Orbit (MEO). It is noted that some GNSS also offer satellites at Geostationary Orbits (GEO) and/or Inclined Geosynchronous Orbits (IGSO).

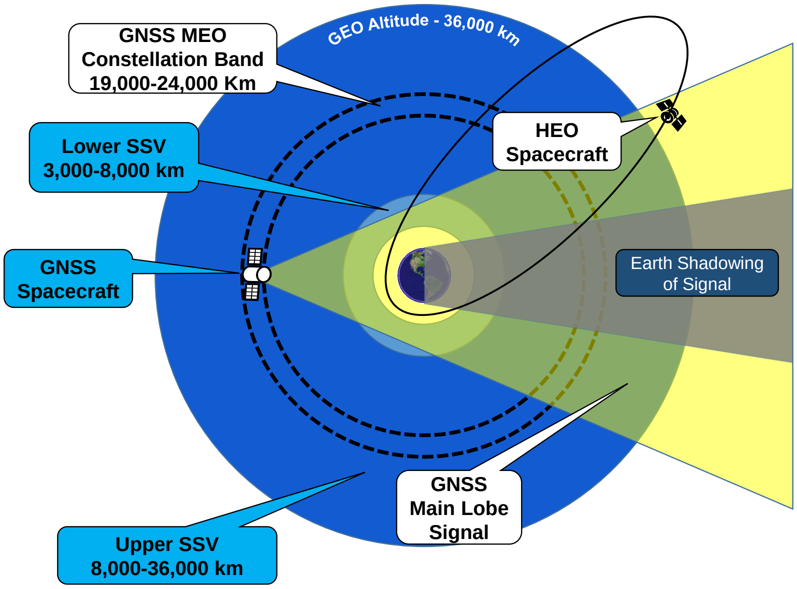


Figure 1. The GNSS Space Service Volume and its regions

The characterization of the SSV performance of an individual GNSS constellation relates at a minimum to the characterization of the following three parameters for every ranging signal:

1. **Pseudorange Accuracy:** Since users in the SSV do not typically generate Position, Velocity and Time (PVT) solutions using multiple simultaneous GNSS measurements, this instead measures the error in the ranging signal itself. This relates to the orbit determination and clock stability errors, and additional systematic errors.

2. **Received Signal Power:** This is the minimum user-received signal power obtained by a space user in the relevant orbit, assuming a 0 dBic user antenna. Generally, this power is calculated at the highest altitude in the given SSV region.

3. **Signal Availability:** Signal availability is calculated as the percent of time that GNSS signals are available for use by a space user. It is calculated both as the availability of a single signal in view, and as the availability of four signals in view, to capture the various requirements of space users. In both cases, in order to declare a signal available, it needs to be both:
    a. received at a signal power level higher than the minimum specified for SSV users, and
    b. observed with a user range error smaller than the maximum user range error specified for SSV users.

The signal availability is measured as a metric over a shell at a given altitude (e.g. at 36,000 km) and is generated as a statistic over both location and time. The exact calculation used for this metric by an individual GNSS constellation is specified explicitly in Annex A of the SSV Booklet.

A sub-metric to Signal Availability is **Maximum Outage Duration**, defined as the maximum duration when a space user at a particular orbit will not obtain availability for at least one single signal or at least four signals simultaneously, depending on the exact metric being calculated. The definition of maximum outage duration is closely linked to the definition of signal availability.

These three parameters characterize at a minimum the contribution of an individual GNSS to an interoperable GNSS SSV. In addition to these parameters, constellation service providers may identify additional parameters useful to characterize their particular contribution to the interoperable GNSS SSV.

INDIVIDUAL CONSTELLATION CONTRIBUTIONS TO GNSS SSV

A primary outcome of the multi-GNSS SSV development process was the publication of expected performance in the SSV by each GNSS constellation provider, and thus its contribution to the total multi-GNSS SSV. To convey a consistent set of capabilities across all constellations, an SSV capabilities template was completed by each GNSS service provider to capture their contributions to each of the parameters identified in the previous section. The full text of these completed templates, along with appropriate context, is available in Annex A of the SSV Booklet. Table 2 and Table 3 contain a summary of the key data, focusing specifically on the Upper SSV and the L1/E1/B1 ("L1") and L5/L3/E5/B2 ("L5") bands. The full templates contain data for the Lower SSV and the L2/E6 band, along with other details.

Table 2. Individual Constellation SSV Template Data—Received Power and Upper SSV Availability

Band	**Constellation**	**Minimum Received Civilian Signal Power**		**Upper SSV Signal Availability (%)**	
		0dBi RCP antenna at GEO (dBW)	**Reference off-boresight angle (°)**	**At least 1 signal**	**4 or more signals**
L1/E1/B1	GPS	-184 (C/A)[1] -182.5 (C)[2]	23.5	80	1
	GLONASS	-179	26	93.9	7.0
	Galileo	-182.5	20.5	64	0
	BDS	-184.2 (MEO)[3] -185.9 (I/G)[4]	25 19	97.40	24.10
	QZSS	-185.5	22	54	N/A
L5/L3/E5/B2	GPS	-182	26	92	6.5
	GLONASS	-178	34	99.9	60.3
	Galileo	-182.5 (E5b) -182.5 (E5a)	22.5 23.5	80 86	0 0
	BDS	-182.8 (MEO) -184.4 (I/G)	28 22	99.90	45.40
	QZSS	-180.7	24	54	N/A
	NavIC	-184.54	16	36.90	0.60

[1] L1 C/A signal
[2] L1C signal
[3] Medium Earth Orbit satellites
[4] Inclined geostationary (I) and geostationary (G) satellites

Table 3. Individual Constellation SSV Template Data—Pseudorange Accuracy

Constellation	**GPS**	**GLONASS**	**Galileo**	**BDS**	**QZSS**	**NavIC**
Pseudorange accuracy	0.8 m	1.4 m	1.1 m	2.5 m	2.6 m	2.11 m

Note that the SSV template data outlined here and in the Booklet represent the service documented by each individual GNSS service provider, either by formal specification or by characterization and analysis. This data is intended to be conservative, to be used as a baseline estimate of the capability provided to the multi-GNSS SSV by each constellation for mission planning purposes, and based on constellation-specific assumptions as documented in Annex A of the SSV Booklet [14]. On-orbit flight results will vary based on mission-specific geometry, receiver sensitivity, time-dependent service characteristics, and other factors. In particular, only service provided by the main-lobe signal services are captured here; the boundary of this main-lobe service is documented in the templates as the reference off-boresight angle.

ESTIMATED PERFORMANCE OF THE MULTI-GNSS SSV

To evaluate the technical benefit of the combined multi-GNSS SSV, the ICG WG-B performed a collaborative multilateral simulation of the GNSS single-constellation and multiple-constellation performance expectations in the SSV, based on the individual constellation signal characteristics. Both global and mission-specific analyses were performed, to capture both overall performance characteristics and representative performance in different orbit regimes. Navigation performance in the SSV is primarily characterized by three properties: pseudorange accuracy, minimum received signal power, and signal availability. The focus of these simulations was on signal availability, which serves as a proxy for navigation capability, and on the L1 and L5 bands. L2-band performance is expected to be similar to that of the L5 band. Key methods and results of these analyses are summarized here; for full details, see the SSV Booklet [14].

Two types of performance estimates were produced: globally-averaged, based on estimating signal availability at a fixed grid of points in space; and mission-specific, based on simulated availability through specific example user trajectories. In both cases, the full complement of GNSS satellites from all constellations was simulated in their nominal orbits and orientations, summarized in Table 1, and signal availability was calculated at a receiver location or locations over a fixed time interval. For each constellation, a minimum radiated transmit power (MRTP) value was calculated from the minimum received power value and the maximum path distance of an SSV signal (just skimming the Earth limb). Then the link budget was calculated from the transmitting satellite to the receiver, including only the transmit antenna characteristics in Table 2 and the path loss. An available signal from a GNSS satellite was one for which a space user has an unobstructed line of sight (LOS) and is able to detect the signal with sufficient strength to form a useable measurement, i.e., the signal is above the carrier power to noise spectral density (C/N_0) threshold value required to acquire and track the signal. Several combined metrics were produced over the entire simulation period: signal availability as a percent of the simulation time that signals were available; and maximum outage duration (MOD), the longest duration that the receiver was found to be without a signal. Availability and MOD estimates were calculated for the case in which at least one signal was detected by the receiver (the minimum contribution to a receiver navigation solution), as well as for the case in which four signals were available simultaneously (which allows for kinematic positioning).

The constellation-specific SSV service characteristics used in the analysis were taken from Table 2 and represent the baseline service documented by each individual GNSS service provider. As a result, the results generated are intended to be conservative estimates. On-orbit flight performance will differ from these estimates based on mission-specific geometry, receiver sensitivity, time-dependent service characteristics, and other factors. As previously stated, only service provided by the main-lobe signal is captured here; the boundary of this main-lobe service is documented in Table 2 as the reference off-boresight angle.

Global Performance Estimates

Global SSV performance was estimated by simulating signal availability at a fixed grid of points in space, at both the lower SSV altitude of 8000 km, and the upper SSV at 36,000 km. The availability was calculated at all points in each grid over a two-week duration. Each point was assumed to represent a receiver with a zero-gain omnidirectional antenna, and simulations were performed for receiver C/N_0 thresholds of 25, 20, and 15 dB-Hz. The results for percent availability were calculated over the simulation duration and by averaging over all grid locations. Maximum continuous outage duration was recorded for each grid point, and is quoted in the results at the worst-case location.

Table 4. Summarized Upper SSV Global Performance Estimates (20 dB-Hz C/N_0 threshold)

Band	**Constellation**	**At least 1 signal**		**4 or more signals**	
		Avail. (%)[1]	**MOD (min)[2]**	**Avail. (%)[1]**	**MOD (min)[2]**
L1/E1/B1	Global systems	78.5–94	48–111	0.6–7	*
	QZSS	0	*[3]	0	*
	Combined	**99.9**	**33**	**89.8**	**117**
L5/L3/E5a/B2	Global systems	93.4-99.9	7–*	4.2–60.3	218–*

	Regional systems	1–30.5	*	0–1.5	*
	Combined	**100**	**0**	**99.9**	**15**
[1] average across all grid locations [2] at worst-case grid location [3] no signal observed for the worst-case grid location for full simulation duration					

Table 4 contains summarized results from the global availability analysis for the Upper SSV (36,000 km altitude). The full set of results for each individual constellation and for the combined multi-GNSS SSV is captured in Section 5.1 of the Booklet [1]. At the middle threshold of 20 dB-Hz, four-signal availability at L1 in the Upper SSV for any individual constellation is very low, reaching only 7%. When the systems are used together, however, four-signal availability reaches nearly 90%, allowing kinematic solutions throughout the SSV with less than two hours of outage, and indicating the importance of using specialized high-altitude receivers and high-gain antennas. Furthermore, one-signal visibility is at 100% for L5, and nearly so for L1, indicating continuous signal coverage for the purposes of provided measurements to a navigation filter, or providing time updates. The abundance of signals available in an interoperable multi-GNSS SSV greatly reduces constraints for navigation at high altitudes.

Mission-Specific Performance Estimates

Mission-specific performance estimates were calculated by simulating signal availability for a spacecraft on a particular trajectory within and beyond the SSV, rather than on a global basis. The purpose of this phase of analysis was to provide more "real-world" estimates for concrete mission types using similar methods to those used for estimation of global performance. These more concrete performance estimates will provide prospective SSV users relevant results that demonstrate the benefits and possibilities offered by an interoperable SSV to specific mission classes.

Three scenarios were considered in this analysis: 1) geostationary orbit, 2) a highly-elliptic orbit, and 3) a lunar trajectory. In addition to a specific trajectory, a custom attitude profile and antenna beam pattern for the user spacecraft was included in the link budget calculation. In particular, two different user antennas were simulated, depending on the application: a patch antenna with peak gain of 4.5 dBi, and a high-gain antenna with peak gain of approximately 9 dBi. Full details on all scenarios are available in Chapter 5 of the Booklet [14].

Geostationary Orbit Mission

The geostationary orbit mission scenario consisted of six geostationary satellites in the same 0° inclination orbit plane and separated by 60° (or four hours) in longitude, in order to capture location-specific effects. The results were intended to be similar to those for the equivalent points in the global analysis, but are more representative because they were simulated using realistic user antenna patterns.

Multi-GNSS visibility for GEO satellites is highly variable with location around the GEO belt. The MEO GNSS satellites, with orbital periods close to 12 hours, are almost in phase with GEO users with orbital periods of 24 hours, so the visibility patterns for these satellites repeat daily. But visibility to the inclined geosynchronous and geostationary GNSS satellites of BDS, QZSS, and NavIC are fixed by longitude of the user spacecraft. Visibility is lowest at a longitude near 180° (western Pacific), and highest near 60° W (east of the US). This indicates that GEO space users positioned over the western hemisphere are benefiting from the spillover of signals from the regionally-focused constellations positioned over Asia.

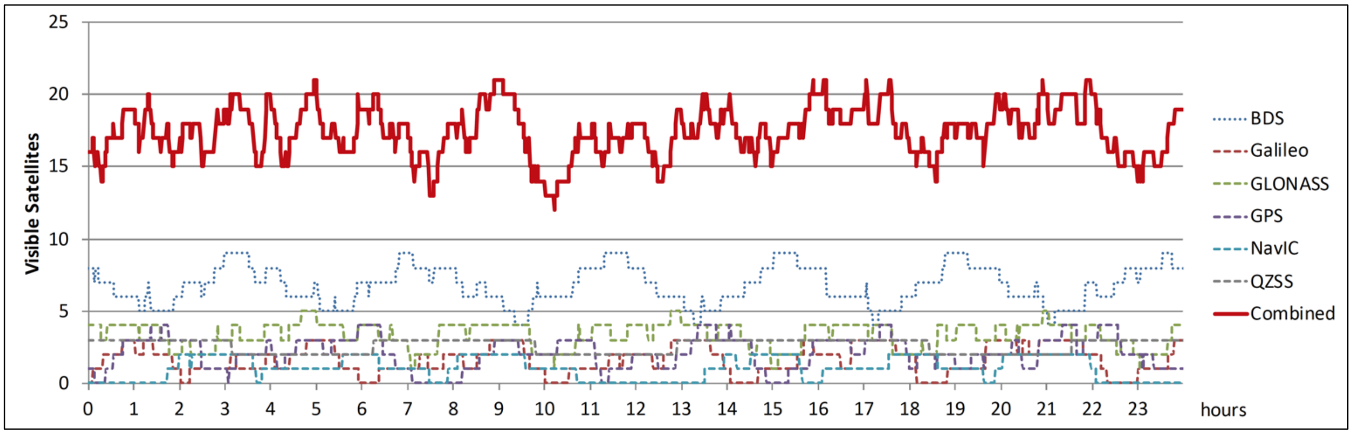


Figure 2. Best case example: L5 visibility for GEO at 60 degrees West

Figure 2 shows the high case for the L5 band, in which the features are clearly visible. Each of the MEO constellations contributes 1–5 satellites to the overall visibility, but because of the location of the user in this example, BDS contributes up to 9 visible satellites. With all constellations combined, an average of approximately 17 satellites are visible, more than double the average contribution of any individual constellation. Even in the worst location (not shown), an average of approximately 9 are visible at any time, more than double the highest individual contributor. In all cases, when using combined GNSS constellations, it is possible to continuously form an on-board PVT solution and perform real-time kinematic orbit determination on-board a GEO satellite.

Scientific Highly-Elliptical Orbit Mission

A HEO mission scenario with apogee altitude of approximately 58,600 km and a perigee altitude of 500 km was used to demonstrate GNSS signal visibility through all of the SSV altitudes, both below and above the GNSS constellations. The simulated user GNSS antennas were configured in both the nadir- and zenith-facing directions. As shown in Figure 3, a high-gain, narrow beamwidth, nadir-pointing antenna ensures GNSS availability around apogee (above the GNSS constellations) while a zenith-pointing antenna provides visibility around perigee. For these results, only the best antenna (zenith or nadir) was used at a given time; they were not combined. In a real-world case, the two antennas could be combined for greater availability when below the constellations. Acquisition and tracking thresholds of the user receiver were both set to 20 dB-Hz for the HEO simulation.

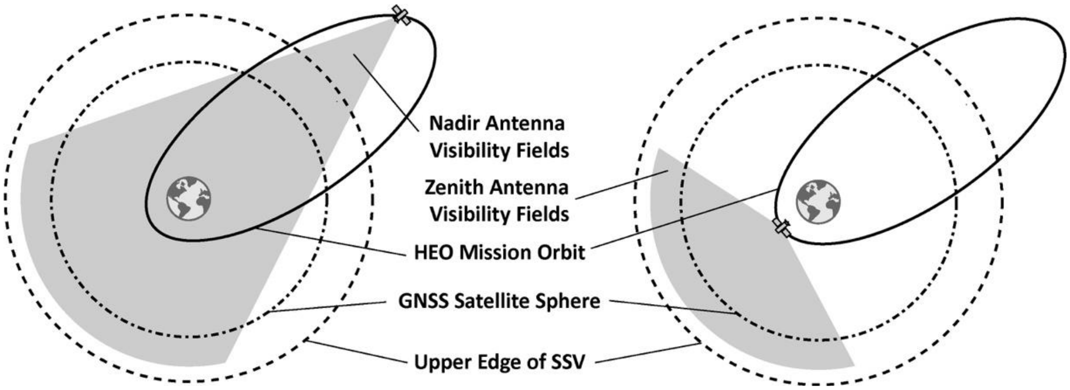


Figure 3. Schematic of the HEO mission with nadir and zenith pointing antennas

Figure 4 shows the simulated GNSS signal availability over 1.5 orbital periods for the L5 band. For both L1 and L5, nearly continuous single-signal availability is provided by individual constellations (even at apogee), but fully reaches 100% when all GNSS constellations are used. Four-signal availability at apogee remains mainly below 20% individually, but is nearly 100% when used together, with maximum outages of less than 1 hour. L5 availability is better than that for L1, due to wider beamwidths and slightly higher minimum received power values, and the addition of NavIC.

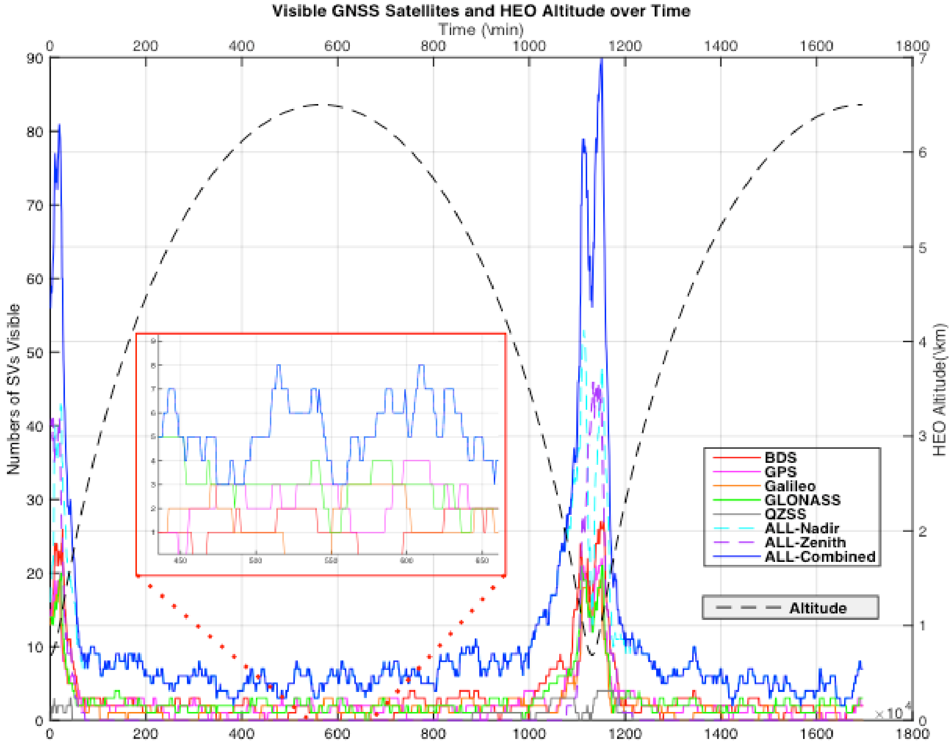


Figure 4. Visible GNSS satellites for HEO orbit over 1.5 orbital periods (L5 band)

Lunar Mission

A lunar scenario was considered in order to explore the boundary of the GNSS SSV beyond Earth orbit. A simple ballistic cislunar trajectory from low-Earth orbit to lunar orbit insertion was simulated, similar to the trajectories flown by the 1968 U.S. Apollo 8 mission and others.

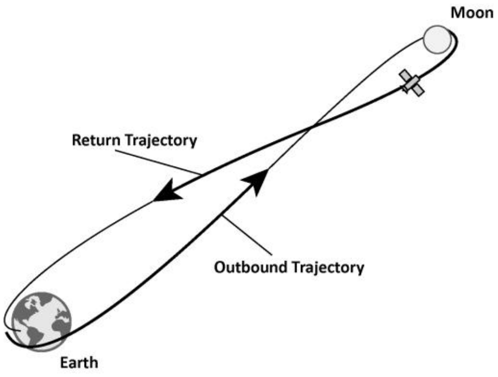


Figure 5 shows a diagram of the trajectory modeled; only the outbound portion was used in this analysis. As in the HEO case, both zenith-pointing and nadir-pointing user antennas were modeled, with peak gain of 4.5 dBi and 9 dBi, respectively. The spacecraft attitude was kept nadir-pointing. The receiver acquisition and tracking thresholds were both set to 20 dB-Hz.

Figure 6Figure 5a shows the general structure of the GNSS signal availability for this mission, using the L5 band as an example to capture the contributions of all constellations. Availability is highly dependent on distance from Earth, and on user receiver equipment assumptions such as the C/N$_0$ tracking threshold and the user antenna gain. When below the MEO GNSS constellations and the zenith-pointing antenna is primarily being used, availability is high. But as distance increases, especially above the GEO belt at 6.6 RE radial distance, availability drops quickly, and finally reaches zero above 30 RE, approximately 50% of lunar distance.

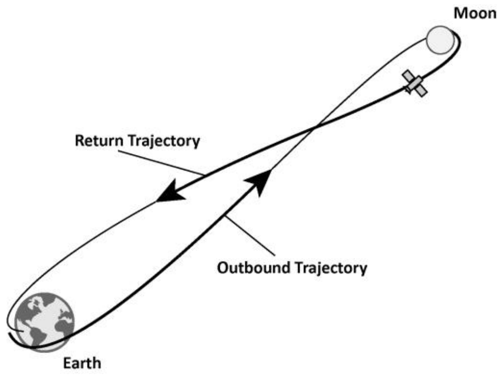
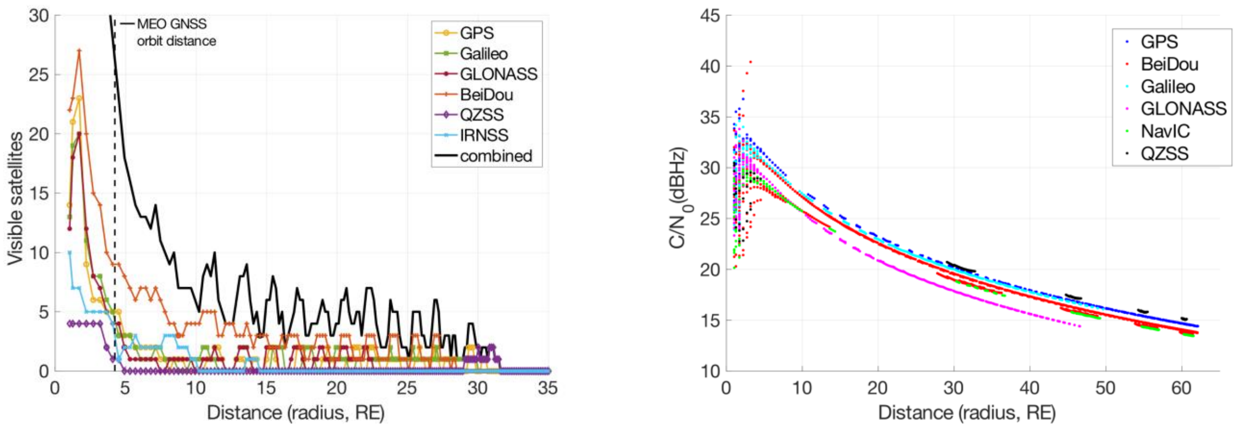


Figure 5. Lunar trajectory phases; only the outbound trajectory segment is analyzed

Using all constellations combined, single-satellite availability is nearly 100% to a distance of approximately 30 RE, then zero thereafter. The benefit of the combined multi-GNSS case is best seen above 10 RE, where it results in signal availability consistently higher than any individual constellation, and often nearly double. Notably, combining constellations does not increase the altitude at which such signals are available; rather, it increases the number of signals available at a given altitude.

These results show that GNSS-based navigation with the combined multi-GNSS SSV is feasible for nearly half the duration of a lunar outbound trajectory, well beyond the formal definition the upper bound of the SSV, and is possibly a solution for navigation for the outbound trans-lunar injection maneuver and return trajectory correction maneuvers that are typical for such missions. With further user modifications to lower the C/N$_0$ threshold or increase user antenna gain, it could provide on-board navigation at even greater distances. Figure 6b shows the simulated C/N$_0$ received by the example spacecraft for each individual constellation, for the entire trajectory to lunar distance. The figure shows the reason for the availability drop-off near 30 RE shown in the subfigure (a): The C/N$_0$ of signals at the receive antenna drops below the 20 dB-Hz minimum threshold beyond that point. If a moderately more sensitive receiver or higher-gain antenna was employed such that weaker signals were usable, signal availability would be achievable for the entire trajectory to lunar distance.



(a) (b)

Figure 6. L5 signal visibility by trajectory radial distance, to the limit of available signals at 30 RE (approx. 50% of lunar distance) (a) and simulated C/N$_0$ for entire lunar trajectory (b)

USER BENEFITS AND APPLICATIONS

The development of a multi-GNSS SSV will have numerous benefits for high-altitude space users, including improved navigation performance, enhanced operations, and mission-enabling technology advancement.

The most direct benefit to users is the improvement of spacecraft navigation performance in high-altitude regimes through a greater number of available signals, improved relative geometry, and reduced signal outages. In the global analysis performed as part of this development, the availability of four simultaneous L1 signals to support the generation of a kinematic position solution at GEO was improved from a maximum of 7% for any single constellation to 90% for all constellations combined, using moderate receiver performance assumptions [14]. While not specifically addressed in the current analysis, combining multiple constellations, especially those of different orbit regimes (e.g., MEO and GEO), will also reduce dilution of precision (DOP), improving overall navigation accuracy. Finally, the multi-GNSS SSV will reduce and even eliminate the maximum outage duration between GNSS measurements. This would, in turn, reduce the need for precise, on-board clocks to maintain accurate timing during the outage period.

The multi-GNSS SSV promises to be transformative in the operation of high altitude spacecraft. The improved navigation performance and signal availability provided will enable increased spacecraft autonomy, thereby reducing the overall required ground interactions for navigation and, in turn, reducing ground operational costs. The use of multiple, independent GNSS signals, frequencies, and constellations will increase operational robustness. And with fewer ground-based ranging requests and mission support needs for navigation, mission architectures can be simplified and even standardized. International efforts to establish a multi-GNSS SSV have raised the visibility of the high-altitude space user community, encouraging the development and availability of new multi-GNSS space receivers that can take advantage of high altitude capabilities. As a result, new mission concepts that rely on continuous, precise on-board timing and navigation will become feasible. Specific examples include advanced Earth weather observation, precise and autonomous formation flying, robust cislunar exploration in the absence of ground contact, satellite servicing, and improved colocation of GEO satellites, as described below.

Earth weather observation. The United States' Geostationary Operational Environmental Satellite R-series spacecraft (GOES-R) collects weather observations continually, with outages of less than 2 hours per year, even with daily low-thrust station-keeping maneuvers [20]. To accomplish this, they rely on nearly-continuous GPS signals in the SSV. Likewise, Russia's Elektro-L weather satellites have been using combined GPS/GLONASS signals in GEO since 2011. Increased capability in the multi-GNSS SSV will support the next-generation of Earth weather observation satellites with even more stringent navigation requirements.

Precision formation flying. The upcoming European Proba-3 solar occultation mission seeks to observe the Sun's corona by flying a solar-occulting spacecraft and an observing spacecraft in precise formation, in a highly-elliptical Earth orbit [16]. The highly-precise relative positioning of the two spacecraft will rely on highly-available GNSS signals up to approximately 60,000 km altitude.

Cislunar trajectories. Launch vehicle upper stages and cislunar exploration missions travel well beyond GEO altitude, with some traveling all the way to lunar distance. GNSS is planned to be used by these vehicles for its high accuracy and high cadence, which improves insertion accuracy when returning to Earth. Weak-signal receivers enable use of GNSS signals at extremely long distances as well, potentially allowing for use as a supplemental measurement source in lunar orbit to increase vehicle navigation responsiveness and autonomy.

Satellite servicing. Satellite servicing missions are being developed for spacecraft at GEO, where they will need to autonomously rendezvous with their target spacecraft. The precision and autonomy required for this type of mission will require continuous precise GNSS signals to be available.

New Concepts for GEO Co-location. The most highly sought-after orbits for commercial users are in the GEO belt, where the current number of spacecraft is limited by the longitude spacing requirements put in place to avoid collisions. With GNSS, these spacecraft could reduce relative navigation errors, recover quickly from maneuvers, and reduce burden on the ground operations infrastructure, potentially resulting in more efficient use of available space at GEO.

CONCLUSIONS

The number and scope of GNSS based space applications has grown significantly since the first GNSS space receiver was flown in the early 1980's. The vast majority of space users are operating in Low-Earth Orbit where use of GNSS receivers has become routine. However, the use of GNSS has expanded to other orbit regimes like Geostationary Orbits (GEO) and High Eccentric Orbits (HEO) but have been very limited due to the challenges involved, including much weaker signals, reduced geometric diversity, and limited signal availability. The GNSS Space Service Volume (SSV) was defined to provide a framework for documenting and specifying GNSS constellation performance for these users, up to an altitude of 36,000 km. The United Nations International Committee on GNSS (ICG) Working Group B (WG-B) has worked on a collaborative basis to publicize the performance of each GNSS constellation in the SSV, and to promote the establishment of an interoperable multi-GNSS SSV in which all existing GNSS constellations can be utilized together to improve mission performance.

This effort has resulted in an internationally-agreed definition of the multi-GNSS SSV and captures the SSV performance contributions of each individual GNSS constellation in terms of pseudorange accuracy, minimum received signal power, and signal availability. In addition, simulations show the performance benefits of the combined systems. In particular, there are significant availability improvements over any individual constellation when all GNSS constellations are employed. Within the Upper SSV, single-signal availability reaches 99% for the L1 band with a 20 dB-Hz C/N0 threshold and zero-gain antenna, and four-signal availability jumps from a maximum of 7% for any individual constellation to 90% with all. Further, similar benefits are shown explicitly for geostationary, highly-elliptical, and lunar use cases.

There are many benefits to an interoperable multi-GNSS SSV, including increased signal availability for high-altitude users over that provided by any individual constellation alone, increased geometric diversity and thus accuracy in the final navigation solution, increased responsiveness and potential autonomy due to reduced signal outages, and increased resiliency due to the diversity of signals and constellations used. These benefits are truly enabling for classes of emerging advanced users, including ultra-stable remote sensing from geostationary orbit (GEO), agile and responsive formation flying, and more efficient utilization of valuable slots in the GEO belt.

The ICG WG-B plans to continue to develop the multi-GNSS SSV concept and analyses, including evolving the analysis to include more consideration of geometric diversity, accurate GNSS transmit antenna patterns and characteristics, improved receiver mission and equipment data, identification of further benefits and use cases, and studying advanced “beyond-SSV” applications. The development of the multi-GNSS SSV was truly an international cooperative effort by all GNSS providers. The resulting high-altitude GNSS capability will enhance spacecraft navigation, enable new mission concepts, and advance spaceborne science, for the benefit of humanity.

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ACRONYMS

BDS	BeiDou System (China)
C/N_0	Carrier Power to Noise Spectral Density
FOC	Full Operational Capability
GEO	Geostationary Earth Orbit
GLONASS	Global Navigation Satellite System (Russia)
GNSS	Global Navigation Satellite Systems
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System (US)
ICG	UN International Committee on GNSS
IGSO	Inclined Geosynchronous Orbit
LEO	Low Earth Orbit
LOS	Line of Sight
MEO	Medium Earth Orbit
MMS	Magnetospheric Multiscale
MOD	Maximum Outage Duration
MRTP	Minimum Radiated Transmit Power
NavIC	Navigation with Indian Constellation (NavIC) (India)
PVT	Position, Velocity, and Time
QZSS	Quasi-Zenith Satellite System (QZSS) (Japan)
SSV	Space Service Volume
UN	United Nations
US	United States
WG-B	UN ICG Working Group B

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