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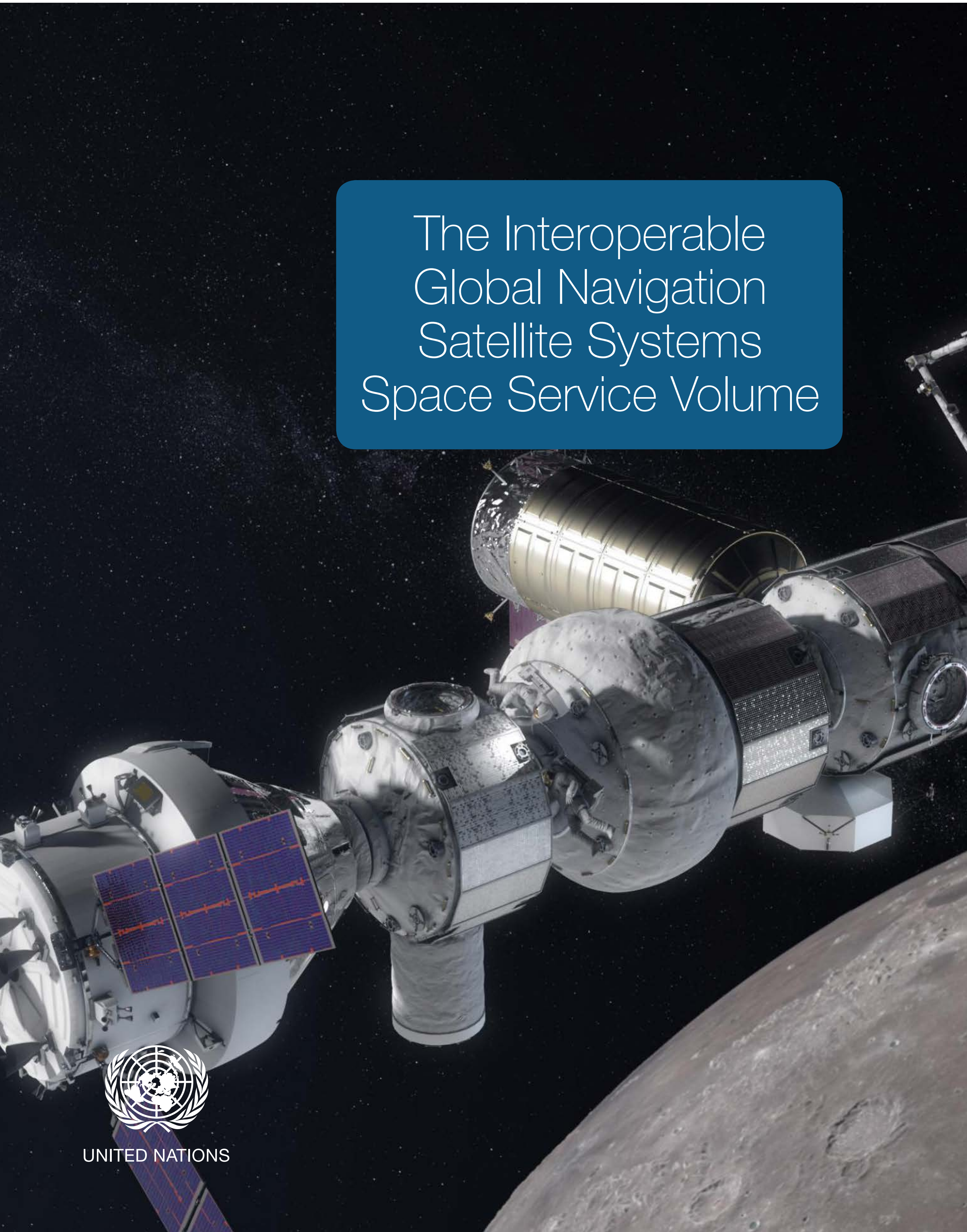
The Interoperable Global Navigation Satellite Systems Space Service Volume



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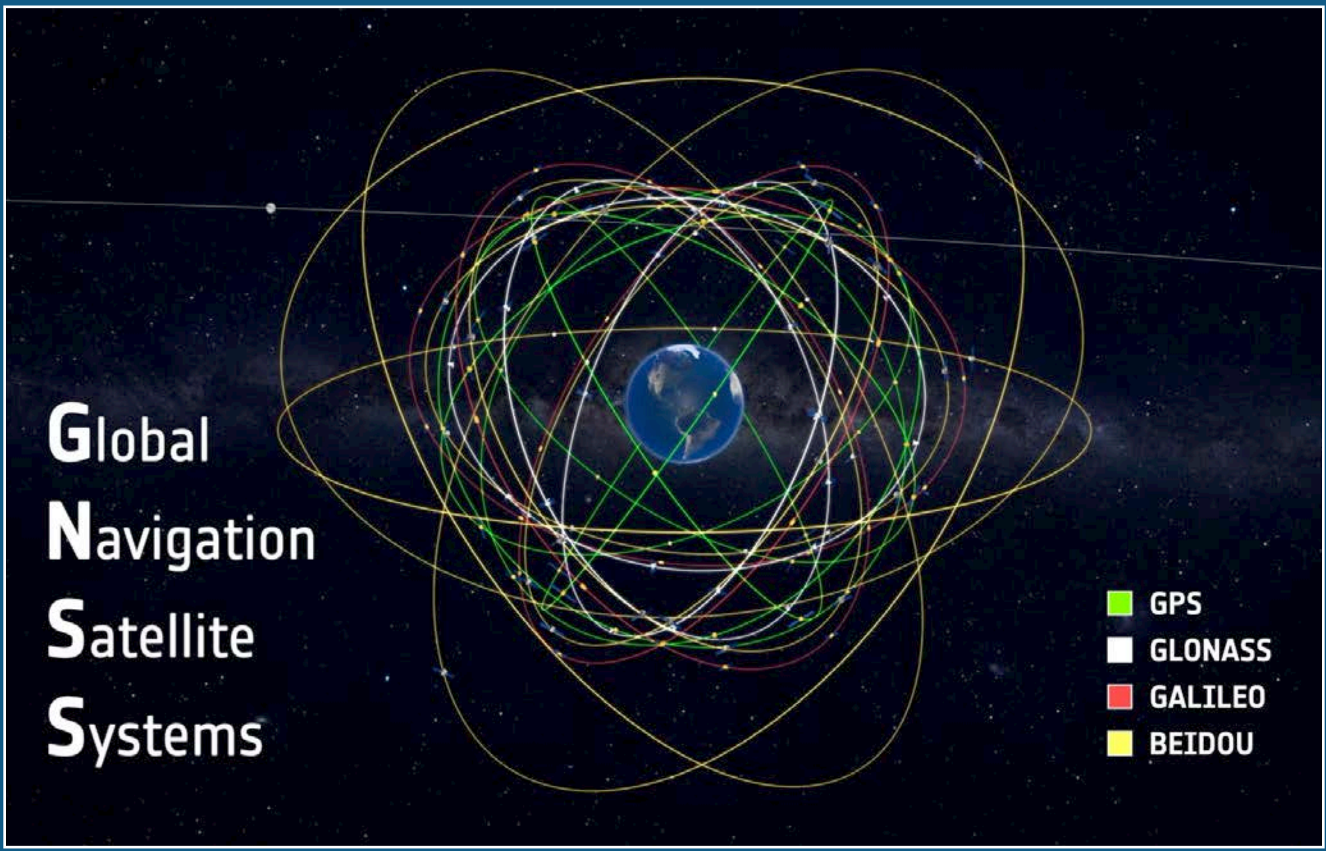
Global
Navigation
Satellite
Systems
GPS
GLONASS
GALILEO
BEIDOU

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OFFICE FOR OUTER SPACE AFFAIRS
UNITED NATIONS OFFICE AT VIENNA

The Interoperable Global Navigation Satellite Systems Space Service Volume

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Executive summary

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 due to reduced signal power levels and visibility, potentially reduced pseudorange accuracy, less optimal geometric diversity, and in the case of elliptical orbits, highly dynamic motion. In these environments, an increased number of available GNSS signals of sufficient power and accuracy would substantially improve the potential signal visibility, and thus mission navigation performance. Via interoperability, multiple GNSS constellations can be used in combination to increase overall performance over any single constellation. The benefits of employing interoperable, multi-constellation GNSS at these higher altitudes are numerous, including more precise, real-time position, velocity, and timing knowledge on-orbit; increased resiliency due to multi-GNSS signal diversity; reduced reliance on ground support infrastructure; increased responsiveness to trajectory manoeuvres resulting in improved on-orbit agility; and the ability to utilize lower-cost components such as on-board clocks.

The availability and performance of GNSS signals at high altitude is documented as the GNSS Space Service Volume (SSV). While different definitions of the SSV exist and may continue to exist for the different service providers, within the context of this booklet it is defined as the region of space between 3,000 km and 36,000 km above the Earth's surface, which is the geostationary altitude. For space users located at low altitudes (below 3,000 km), the GNSS signal reception is similar to that for terrestrial users and can be conservatively derived from the results presented for the lower SSV in this booklet.

The SSV is itself divided in the context of this booklet into two regions, based on differing signal usage scenarios: the lower SSV, covering 3,000–8,000 km altitude, and the upper SSV, covering 8,000–36,000 km. Within these regions, the performance of a single GNSS constellation or combination of constellations for a particular mission is determined by three parameters:

- Pseudorange accuracy
- Received signal power
- Signal availability for one signal and four signals simultaneously

These three parameters are interrelated; if a signal is too weak, if Earth blocks the signal, or if the signal does not have sufficient accuracy, it is not considered as available. Signal availability in particular is critically important for all GNSS users; by using on-board navigation filters in combination with orbit knowledge, space users can achieve navigation and timing solutions with only one available signal at a time. The performance associated with each GNSS constellation is different, but within the lower SSV, single-signal availability from a single constellation is nearly 100% for the entire time, while within the upper SSV, which extends to geostationary altitude, it can be as low as 36% with long outages.

In addition to the global characterization of the GNSS availability and performances in the lower and upper SSV, the booklet also provides performance indications for specific mission profiles which cross the boundaries of the SSV defined in this booklet. The specific mission-specific performance assessments contained in this booklet are geostationary Earth orbit, highly elliptical Earth orbit, and lunar transfer cases.

Within the United Nations International Committee on GNSS (ICG), there is an initiative under way to ensure that GNSS signals within the SSV are available and interoperable across all international global constellations and regional augmentations. This initiative is being carried out within the ICG Working Group B (WG-B) on "Enhancement of GNSS Performance, New Services and Capabilities". The individual efforts led by the WG-B participants include documenting and publishing the SSV performance metrics for each individual constellation, developing standard assumptions and definitions to perform multi-GNSS SSV performance analyses, encouraging the design and manufacturing of GNSS receivers that can operate in the SSV, characterizing GNSS antenna performance to more accurately predict SSV mission performance, providing a reliable reference for space mission analysts, and working towards the formal specification of SSV performance by each GNSS provider.

The multi-constellation, multi-frequency analysis described in this booklet shows availability improvements over any individual constellation when all GNSS constellations are employed. Within the high-altitude SSV, single-signal availability reaches 99% for the L1 band when all GNSS constellations are employed, and four-signal availability jumps from a maximum of 5% for any individual constellation to 62% with all. For the L5 band, continuous signal availability with no outages is provided at geostationary altitude via use of the multi-GNSS SSV, leading to the potential for fully autonomous navigation on demand for these users. The simulations described in this document are based on the constellation-provided data shown in annex A and summarized in chapter 4, and are intended to be more conservative than actual on-orbit performance. In particular, the data provided derive from the main lobe of the transmit antenna patterns only, capture only minimum transmit power and worst-case pseudorange accuracy, and derive from a set of conservative assumptions as described in chapter 5. On-orbit users may see significantly higher performance.

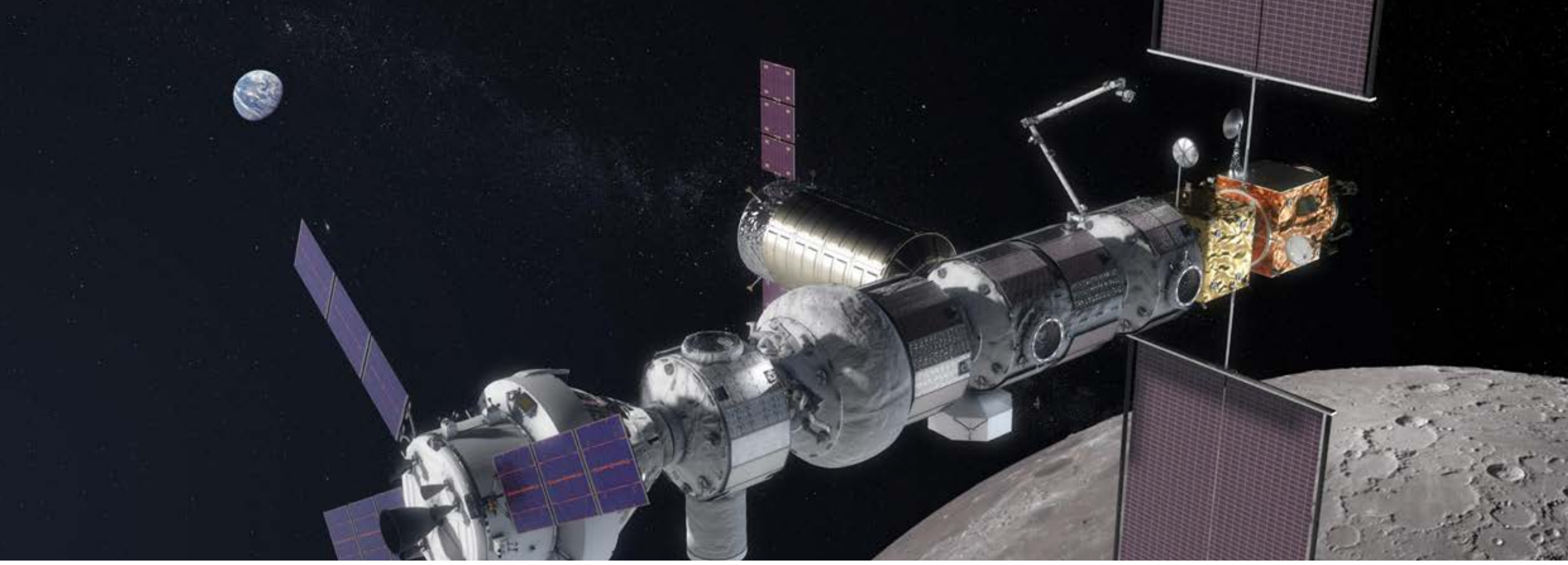
These benefits are only possible through the continued cooperation of all GNSS providers. Through the ICG, all providers have agreed on the information presented in this booklet, and on a number of recommendations to continue development, support, and expansion of the multi-GNSS SSV concept. For the community of GNSS providers, there are three WG-B recommendations that have been formally endorsed by ICG, aimed at continuing development of the SSV, and providing the user community adequate data to utilize it.

- *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.*
- *Service Providers, supported by Space Agencies and Research Institutions, are encouraged to define the steps necessary 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.*
- *GNSS providers are invited to consider providing 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.*

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

- *The authors encourage the development of interoperable multi-frequency spaceborne GNSS receivers that exploit the use of GNSS signals in space.*

Humanity is now beginning to benefit from GNSS usage in the SSV, starting with applications that use only individual constellations, and ultimately expanding to multi-constellation GNSS. For example, weather satellites employing GNSS signals in the SSV will enhance weather prediction and public-safety situational awareness of fast-moving events, including hurricanes, flash floods, severe storms, tornadoes and wildfires. All participants in this study agree that there is the enormous potential of this capability in the future, including lives saved and critical infrastructure and property protected. When fully utilized, an interoperable multi-GNSS SSV will result in orders of magnitude return on investment to national Governments, as well as extraordinary societal benefits.



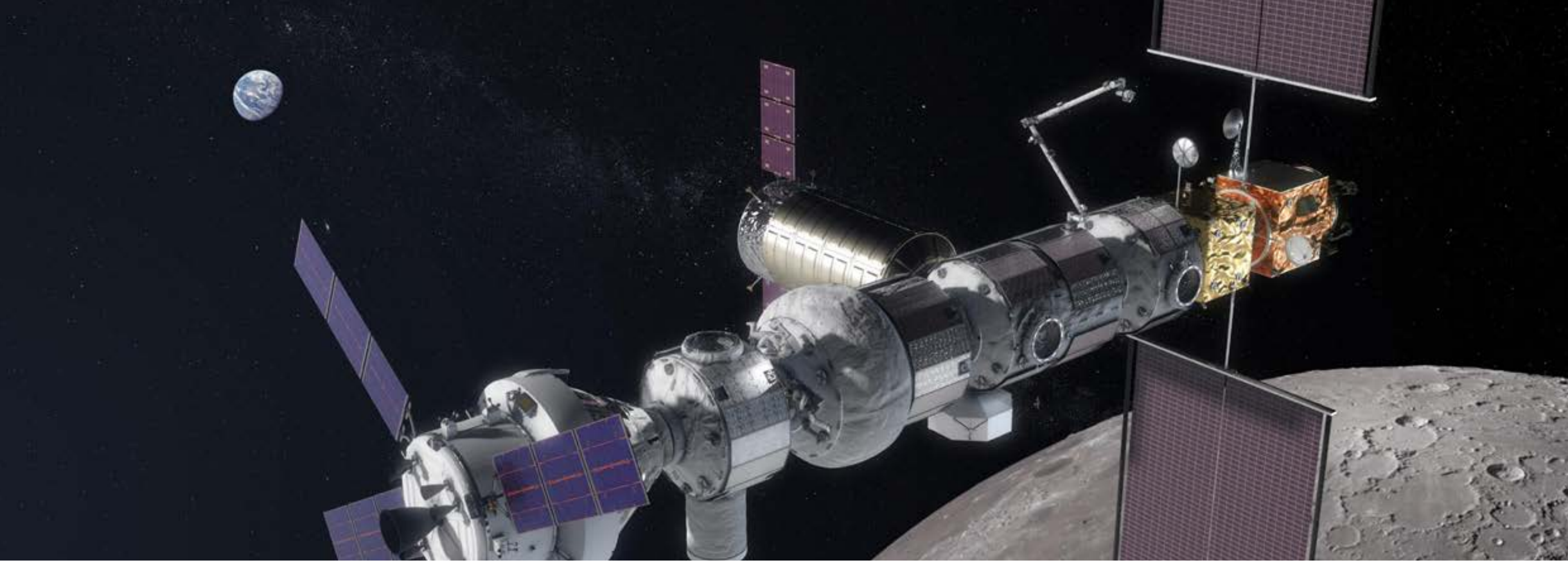
1. Introduction

The vast majority of Global Navigation Satellite System (GNSS) users are located on the ground, and the GNSS systems are designed to serve these users. However, the number of satellites utilizing on-board GNSS space receivers is steadily growing. Space receivers in the SSV operate in an environment significantly different than the environment of a classical terrestrial receiver or GNSS receiver in low Earth orbit. SSV users span very dynamic and changing environments when traversing above and below the GNSS constellation. Users located below the GNSS constellation can make use of direct line of sight (LoS) signals, while those above the orbit of the GNSS constellations must rely on GNSS signals transmitted from the other side of the Earth, passing over the Earth's limb. These space users experience higher user ranging error, lower user-received power levels, and significantly reduced satellite visibility.

An interoperable GNSS SSV can significantly enhance the GNSS performance. The International Committee on GNSS (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".

This document has been produced by Working Group B (WG-B) of the ICG, with the objectives of defining, establishing, and promoting an interoperable GNSS SSV for the benefit of GNSS space users and GNSS space receiver manufacturers. The information in this document provides to GNSS space users and GNSS space receiver manufacturers a single resource with a concise overview on the characteristics provided by every GNSS as their contribution to an interoperable GNSS SSV.

Chapter 2 of this booklet illustrates the importance of interoperability of GNSS in the SSV by identifying some of the user benefits. Chapter 3 defines the SSV and provides an overview of relevant background information. GNSS constellation parameters relevant to the SSV are collected from each provider in chapter 4. WG-B has taken these parameters and simulated the service that users can expect in different regimes, both from individual constellations, and from the combination of constellations enabled by interoperability. Simulation results are presented in chapter 5, and the ICG WG-B conclusions and recommendations in chapter 6. Chapter 7 identifies potential topics that might be addressed in future releases of this booklet. Further details on the constellation parameters and the WG-B simulation results are contained in the annexes.



2. Benefits to users

The number and scope of GNSS-based space applications has grown significantly the since the first GNSS space receiver was flown. The vast majority of space users are operating in low Earth orbit (LEO), where use of GNSS receivers has become routine. For spacecraft in the SSV, however, the first demonstrated uses came in the late 1990s. Use of GNSS receivers aboard high-altitude spacecraft remains limited due to the challenges involved, including much weaker signals, reduced geometric diversity, and limited signal availability. By focusing on interoperability, the multi-GNSS SSV will provide numerous benefits, expanding the opportunity for full exploitation of the existing potential.

The potential benefits for space users in the SSV are numerous, and fall into several categories, such as navigation performance, mission-enabling technology advancement, and operational flexibility as well as resiliency.

In terms of spacecraft navigation performance, the interoperable multi-GNSS SSV will:

- Significantly increase the number of GNSS signals available to a given user, allowing nearly continuous generation of on-board navigation solutions and reducing "navigation jitter" for improved stability
- Improve the relative geometry between GNSS satellites and the user, improving overall navigation accuracy
- Foster the development of new concepts and algorithms to take advantage of the availability of multi-constellation, multi-frequency and multi-signal GNSS
- Allow higher accuracy for Position, Velocity and Time (PVT) determination, precise orbit determination (POD), and attitude determination
- Allow use of less expensive on-board clocks by reducing the need for time stability between GNSS signal measurements

Related to mission-enabling technology advancement, the interoperable multi-GNSS SSV will:

- Foster the development and availability of GNSS space receivers that can take advantage of the available high-altitude capabilities
- Enable new mission concepts, such as advanced weather observations, precise relative positioning, autonomous cislunar, agile proximity operations, and co-location of spacecraft in geostationary orbit (GEO) longitude boxes
- Promote use of combined antenna arrays for satellite orbit and attitude determination, allowing both states to be based on a single sensor

Enhancing operational flexibility and resiliency, the interoperable multi-GNSS SSV will:

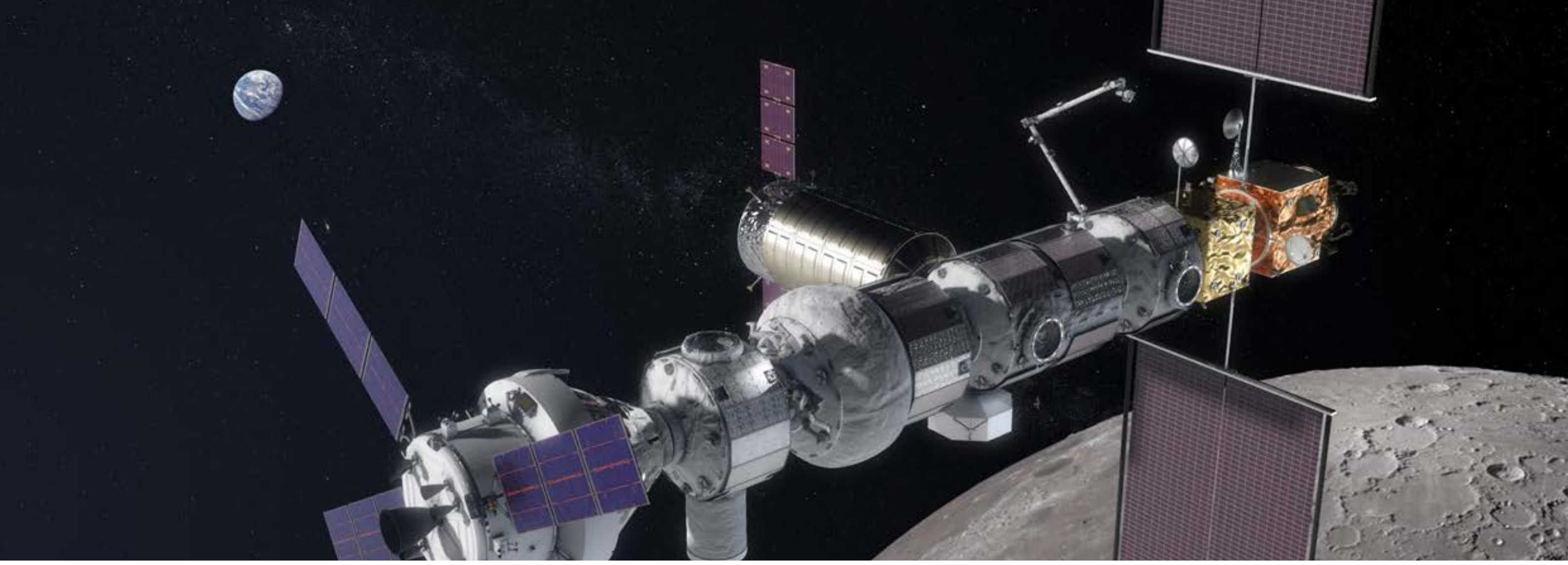
- Enable development of new operations concepts with reduced ground interactions
- Increase feasibility of satellite on-board autonomy at high altitude
- Increase the operational robustness for spacecraft navigation due to the redundant use of multiple independent GNSS signals
- Reduce ground operational needs by reducing ranging requests, lowering mission costs, and allowing ground stations to focus on communications activities
- Simplify mission architectures, leading to the potential for standardization of satellite navigation design from LEO to GEO and beyond

These benefits are applicable to a wide range of mission classes and applications, including (but not limited to) the following examples:

- *Earth weather observation:* The United States' Geostationary Operational Environmental Satellite-R series of spacecraft (GOES-R) is designed to collect observations continually, with outages of less than 2 hours per year, even with daily station-keeping manoeuvres. To accomplish this, they rely on nearly continuous GNSS signals.
- *Precision formation flying:* The 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. The highly precise relative positioning of the two spacecraft will rely on 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 travelling all the way to lunar distance. GNSS is planned to be used by these vehicles for its high accuracy and high cadence, which improve insertion accuracy when returning to Earth. Weak-signal receivers are enabling use of GNSS signals at extremely long distances as well, potentially allowing for use as a supplemental measurement source in lunar orbit.
- *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 orbit for commercial users is 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 manoeuvres, and reduce burden on the ground control centre, even while utilizing the available space at GEO more efficiently.



3. Interoperable GNSS space service volume

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. The availability and performance of GNSS signals at high altitude is documented as the GNSS SSV. While different definitions of the SSV exist and may continue to exist for the different service providers, within the context of this booklet it is defined as the region of space between 3,000 km and 36,000 km above the Earth's surface, which is the geostationary altitude. For space users located at low altitudes (below 3,000 km), the GNSS signal reception is similar to that for terrestrial users and can be conservatively derived from the results presented for the lower SSV in this booklet.

3.1 Definition

The GNSS SSV is defined in the context of this booklet 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; 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:

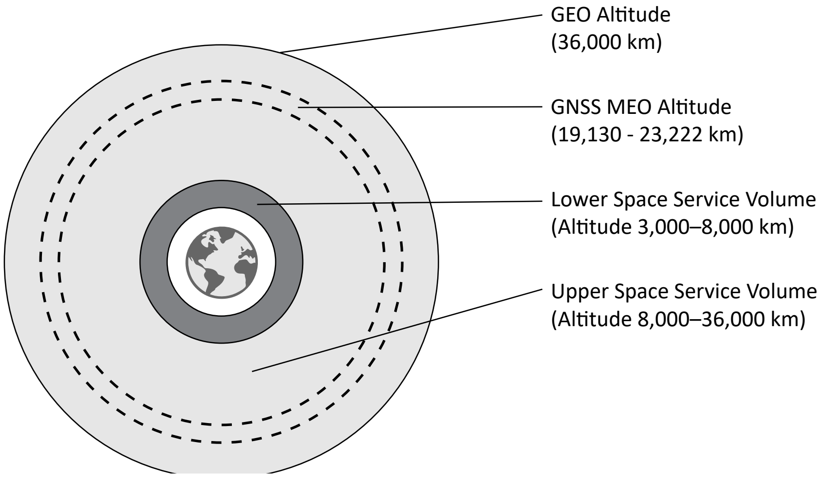
1. *Lower SSV for medium Earth orbits:* 3,000–8,000 km altitude. This area is characterized by reduced signal availability from a zenith-facing antenna alone, but increased availability if both a zenith and nadir-facing antenna are used.

2. *Upper SSV for geostationary and high Earth orbits:* 8,000–36,000 km altitude. This area is characterized by significantly reduced signal received power and availability, due to most signals travelling 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 3.1, 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).

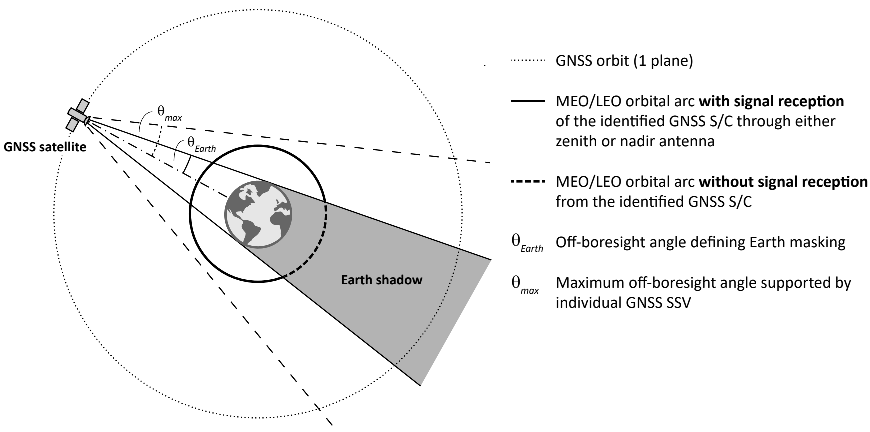
Figure 3.1 The GNSS SSV and its regions



3.1.1 Lower space service volume

Figure 3.2 shows the signal reception geometry for a receiving spacecraft in the SSV for the lower SSV.

Figure 3.2 Signal reception geometry in the lower SSV



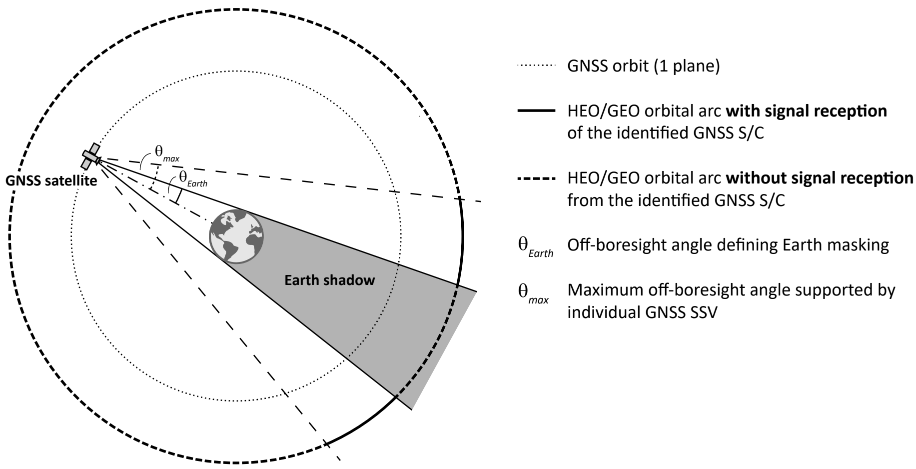
GNSS space receivers located between 3,000 km and 8,000 km altitude can receive GNSS signals from the spacecraft nadir direction and the spacecraft zenith direction with respect to the Earth. Zenith signals are received in-line with LEO spacecraft and Earth-based GNSS signal reception. The signals arriving from spacecraft nadir are emitted by GNSS satellites located at the opposite side of the Earth and pass the limb of the Earth before arriving at the receiver. This is highlighted in figure 3.2.

When employing an entire GNSS constellation, or multiple combined constellations, signal availability is expected to exceed four simultaneous signals when viewed from a spacecraft zenith-facing antenna, and even more with multiple spacecraft antennas.

3.1.2 Upper space service volume

Figure 3.3 shows the signal reception geometry for a receiving spacecraft in the upper SSV, defined as the region between 8,000 km and 36,000 km altitude.

Figure 3.3 Signal reception geometry in the upper SSV



In the high-altitude SSV, especially at altitudes above the GNSS constellations, no signal reception from the spacecraft zenith direction is possible, necessitating all signals to be received from a nadir-facing antenna. Generally, all GNSS signals arrive from the opposite side of the Earth and pass over the limb of the Earth. As illustrated in figure 3.3, the Earth blocks a large portion of the signal for users within the upper SSV. The signal is further limited to the extent of usable signals from the GNSS transmitting antennas, which may be limited to approximately 16–34 degrees from the GNSS satellite nadir direction, depending on the constellation.

Although figure 3.3 only shows a single satellite out of a full constellation, it is evident that for GNSS space users located within the upper SSV that the availability of GNSS signals is significantly constrained. Thus, space users in the upper SSV will significantly benefit from an interoperable GNSS SSV, in which multiple GNSS signals from different constellations can be used simultaneously. The interoperable GNSS SSV will significantly improve the number of visible satellites and thus the availability of GNSS signals.

3.2 SSV performance characterization metrics

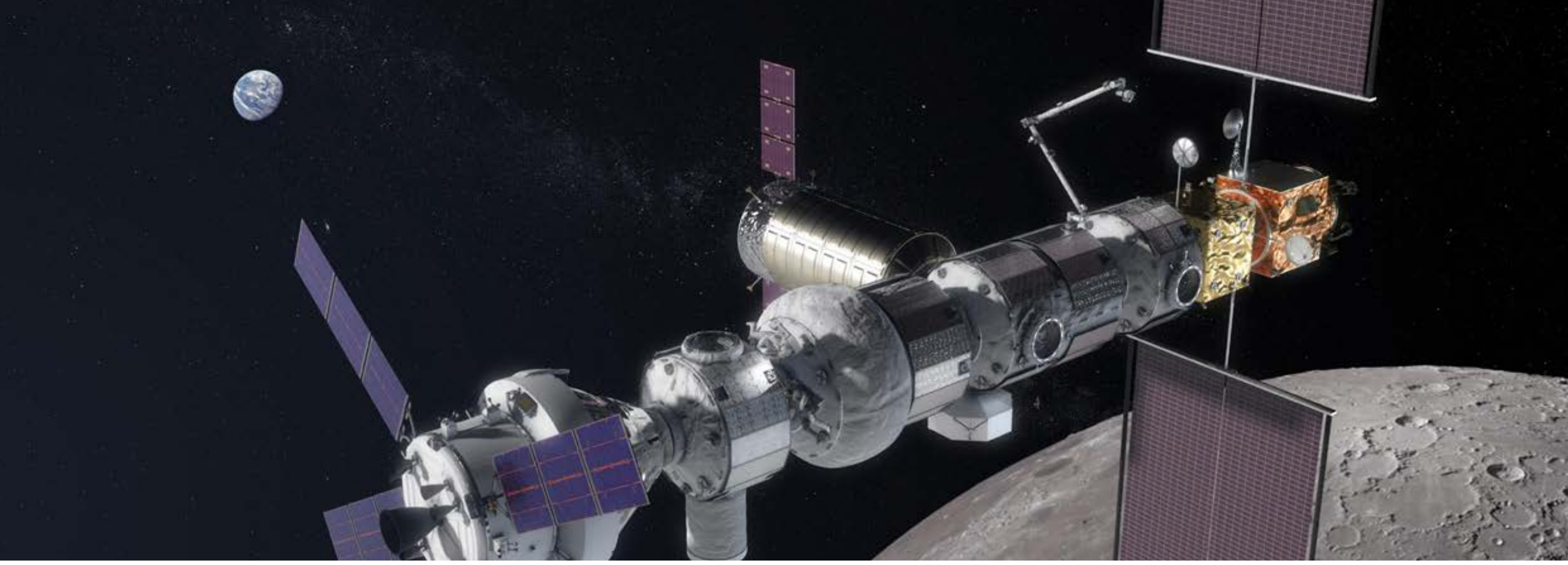
The characterization of the SSV performance of an individual GNSS constellation relates at a minimum to the characterization of the following three parameters for every ranging signal:

1. *Pseudorange accuracy:* Since users in the SSV do not typically generate 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 percentage 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.

   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.



4. Individual constellation contributions to multi-GNSS space service volume

To convey a consistent set of capabilities across all GNSS constellations, an SSV capabilities template has been completed by each GNSS service provider to capture their contributions to each of the parameters identified in section 3.2. The full text of these completed templates, along with appropriate context, is available in annex A. This chapter presents an aggregated subset of the full data so that the individual SSV characteristics of each constellation can be readily compared and contrasted.

Note that the SSV service characteristics outlined here and in annex A represent the service documented by each individual GNSS service provider, either by formal specification or by characterization and analysis. On-orbit flight results will differ from these characteristics due to mission-specific geometry, receiver sensitivity, time-dependent service characteristics, and other factors. In all cases, only service provided by the main-lobe signal is captured here; the extent of this main-lobe service is documented in table 4.2 as the reference off-boresight angle. For full details, see annex A.

Table 4.1 presents an overview of the configuration of each constellation, including operational status, constellation configuration, and general orbit parameters. Further, table 4.2 aggregates SSV signal characteristics for each constellation, including signal, minimum received power and signal availability. Finally, table 4.3 aggregates the user range error for each constellation.

Table 4.1. Overview of global and regional navigation satellite systems

System name	Nation	Coverage	Status	No. frequencies / signals	No. spacecraft (nominal)/ orbital planes	Semi-major axis (km)	Inclination (°)	Comments
GPS	USA	Global	Operational	3/4	24/6	26560	55	
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 planned: 2020
BDS	China	Global	Operational (regional) In build-up (global)	3/5	MEO: 24/3 IGSO: 3/3 GEO: 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: 3/3 GEO: 1/1	42164	40 0	Service planned: 2018
NavIC	India	Regional (India)	In build-up	2/2	GSO: 4/2 GEO: 3/1	42164	29 0	Service planned: 2018

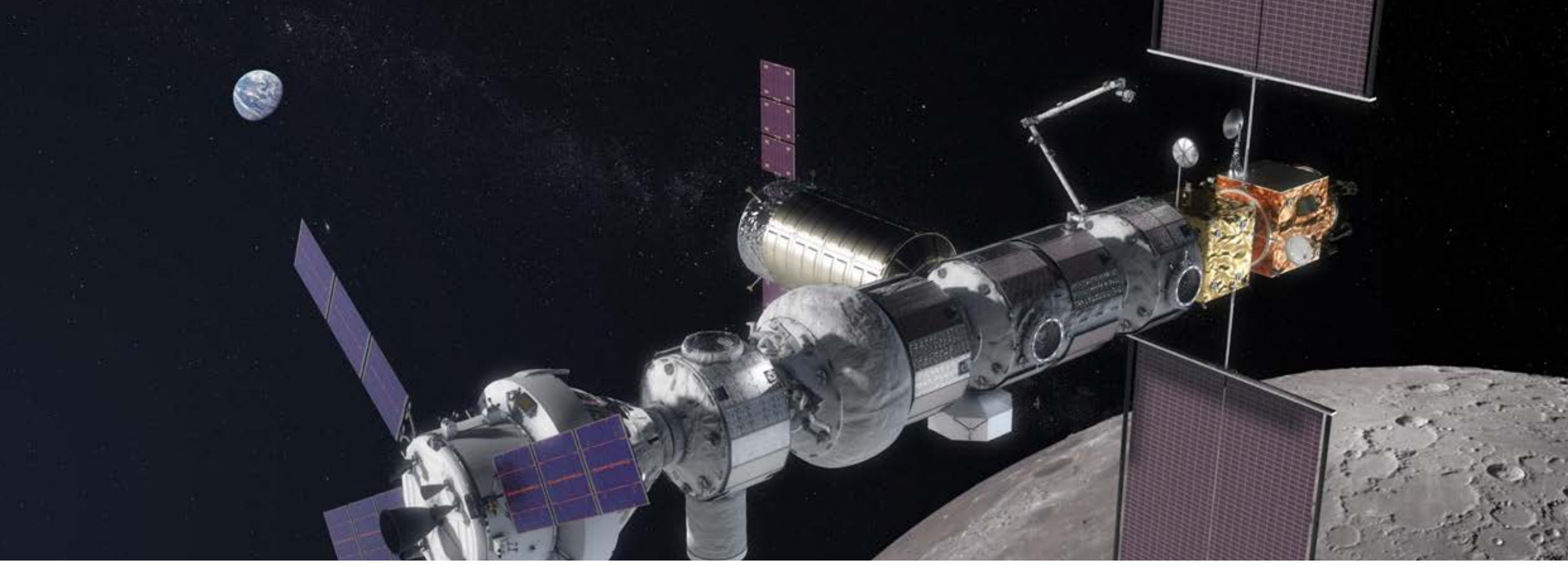
Table 4.2. SSV signal characteristics for each GNSS service provider

Band	Constellation	Frequency (MHz)	Minimum received civilian signal power		Signal availability (%)			
					Lower SSV		Upper SSV	
			0dBi RCP antenna at GEO (dBW)	Reference off-boresight angle (°)	At least 1 signal	4 or more signals	At least 1 signal	4 or more signals
L1/E1/B1	GPS	1575.42	-184 (C/A) -182.5 (C)	23.5	100	97	80	1
	GLONASS	1605.375[a]	-179	26	100	99.8	93.9	7.0
	Galileo	1575.42	-182.5	20.5	100	99	64	0
	BDS	1575.42	-184.2 (MEO) -185.9 (I/G)	25 19	99.90	96.20	97.40	24.10
	QZSS	1575.42	-185.5	22	100	N/A	54	N/A
L2/E6	GPS	1227.6	-183	26	100	100	92	6.5
	GLONASS	1248.6251	-178	34	100	66	100	29
	Galileo	1278.75	-182.5	21.5	100	100	72	0
	QZSS	1227.6	-188.7	24	100	N/A	54	N/A
	GPS	1176.45	-182	26	100	100	92	6.5
L5/L3/E5/B2	GLONASS	1201	-178	34	100	100	99.9	60.3
	Galileo	1206.45 (E5b)	-182.5	22.5	100	100	80	0
		1191.795 (E5ABOC)	-182.5	23.5	100	100	86	0
		1176.45 (E5a)	-182.5	23.5	100	100	86	0
	BDS	1191.795	-182.8 (MEO) -184.4 (I/G)	28 22	100	99.90	99.90	45.40
	QZSS	1176.45	-180.7	24	100	N/A	54	N/A
	NavIC	1176.45	-184.54	16	98	51.40	36.90	0.60

[a]Centre of FDMA band

Table 4.3. User range error as defined in annex A for each GNSS service provider

Constellation	GPS	GLONASS	Galileo	BDS	QZSS	NavIC
User range error	0.8 metres	1.4 metres	1.1 metres	2.5 metres	2.6 metres	2.11 metres



5. Simulated performance of interoperable space service volume

The Working Group B of the International Committee on GNSS (ICG WG-B), has simulated the GNSS single- and multiple-constellation performance expectations in the SSV, based on the individual constellation signal characteristics documented in chapter 4. As outlined in chapter 3, navigation performance in the SSV is primarily characterized by three properties: user range error (URE), received signal power, and signal availability. The focus of these simulations is on signal availability, which serves as a proxy for navigation capability.

An available signal from a GNSS satellite is one that a space user with adequate equipment is able to detect with sufficient strength to form a usable measurement, that is, above the carrier power to noise power spectral density (C/No) threshold value required to acquire and track the signal, and with unobstructed LoS. In addition to availability, the results include maximum outage duration (MOD), the longest duration that a user can expect to be without a signal. MOD is a critical parameter for space users employing GNSS for time or concerned with navigation stability and short-term navigation effects, such as during trajectory manoeuvres. Availability and MOD estimates are calculated for the case in which a single signal is detected by a user, as well as for the case in which four signals are available simultaneously. Four-signal-in-view coverage enables kinematic positioning and one-signal-in-view coverage is the minimum needed for GNSS to contribute to a navigation solution. For many users, signal availability and signal outages are the primary drivers for navigation performance.

Two types of performance estimates are provided: globally averaged, and mission-specific. Global performance is estimated by simulating signal availability at a fixed grid of points in space, at both the lower SSV altitude of 8,000 km, and the upper SSV at 36,000 km. This availability is then calculated by simulating navigation receiver operation over a two-week duration, and over all the points in each grid. This can be interpreted as a measure of the performance that space missions can expect while employing GNSS in the SSV.

Mission-specific performance estimates are obtained by estimating signal availability for a spacecraft on a particular trajectory within the SSV. Mission-specific scenarios considered in this study include: 1) geostationary orbit, 2) a highly elliptic orbit, and 3) a lunar trajectory. The purpose of this phase of analysis is to provide “real-world” estimates for a concrete mission using similar methods to those used for estimation of global performance. In total, this information will provide prospective SSV users simulation results that demonstrate the benefits and possibilities offered by an interoperable SSV.

The simulations described in this document are based on the constellation-provided data shown in annex A and summarized in chapter 4, and are intended to be more conservative than actual on-orbit performance. In particular, the provided data derive from the main lobe of the transmit antenna patterns only, capture only minimum transmit power and worst-case pseudorange accuracy, and derive from a set of conservative assumptions as described in chapter 4. The objective is to demonstrate the value of the multi-GNSS SSV in terms of combined performance, as compared to that provided by any specific constellation. It is not intended to validate or predict real-world flight results, or to validate the contents of chapter 4 or annex A, which may differ based on the assumptions used. See annex B for more details on the simulated simulation methodology and full results.

The characteristics of the constellations and signals being simulated are captured in chapter 4, and in the appropriate annexes. The transmit beamwidth specification (given in terms of ‘reference off-boresight angle’) and delivered power levels at GEO altitude are used to define the geometric reach and the minimum radiated transmit power (MRTP) in the simulation—see annex B for its definition and further details. Only the L1/E1/B1 and L5/L3/E5/B2 bands (see also table 4.3 for further details on the signals provided by each system in these bands) are used in the simulation. Additional simulation results and more in-depth descriptions and data on the specific simulation parameters are contained in annex B.

5.1 Global space service volume performance

Global performance estimates of availability and MOD are given in table 5.1. These results show available performance at GEO altitude (the upper limit of the upper SSV) considering a zero-gain user antenna. The user space is simulated in this case by a sphere at GEO altitude. Both availability and MOD are calculated at the worst-case grid point. An asterisk (*) marks cases in which an availability threshold is never reached over the full duration of the simulation for the worst-case grid location.

Simulations were performed using three different C/No thresholds. Performance results are provided for thresholds of C/No of 15, 20, and 25 dB-Hz. These thresholds roughly correspond to the performance levels of space GNSS receivers that exist or are in development.

In calculating availability, the MRTP value is assumed to be constant over the entire beamwidth of the transmit antenna. A zero-gain antenna is applied in the calculation of C/No, the effects of a Low Noise Amplifier (LNA) or any other aspects of the Radio Frequency/ Intermediate Frequency (RF/IF) are not considered. These simplifying assumptions lead to conservative Position, Navigation, Timing (PNT) performance estimates.

The performance values for signal availability and MOD in this chapter may not necessarily match the figures provided in chapter 4 by the different service providers for the following reasons:

1. Different receiver parameters may have been assumed.
2. The implementation of the availability figure of merit and the MOD figure of merit may have been realized differently.

5.1.1 Performance in the upper space service volume

Table 5.1 shows the signal availability and the MOD for a user in the upper SSV as a function of different C/No thresholds for each individual constellation and for all constellations combined. The C/No thresholds relate to the tracking threshold of the assumed space receiver and values of 15 dB-Hz, 20 dB-Hz and 25 dB-Hz are analysed.

Figure 5.1 shows an example of simulated signal availability for the 20 dB-Hz C/No threshold case. Note that the better availability estimated in the L5/L3/E5/B2 case over the L1/E1/B1 case is due to generally wider beamwidths for the lower frequency band for each constellation.

General observations concerning the results shown in table 5.1 indicate the following:

- One-signal availability significantly exceeds four-signal availability, underscoring the benefit of employing an on-board navigation filter, which can process individual measurements at a time, for missions in the SSV.
- At the highest threshold of 25 dB/Hz, availability is nearly 0%. This indicates the challenge of extremely low GNSS signal levels for missions in the upper SSV, and the importance of using specialized high-altitude receivers and high-gain antennas.
- When the constellations are used together, one-signal availability is nearly 100% for all but one case (25 dB-Hz threshold, L1). The abundance of signals available in an interoperable multi-GNSS SSV greatly reduces constraints imposed by navigation at high altitudes.

Figure 5.1. Estimated number of satellites visible, by individual constellation and combined, for sample L1/E1/B1 GEO user with 20 dB-Hz C/No threshold. Actual visibility changes with location and time

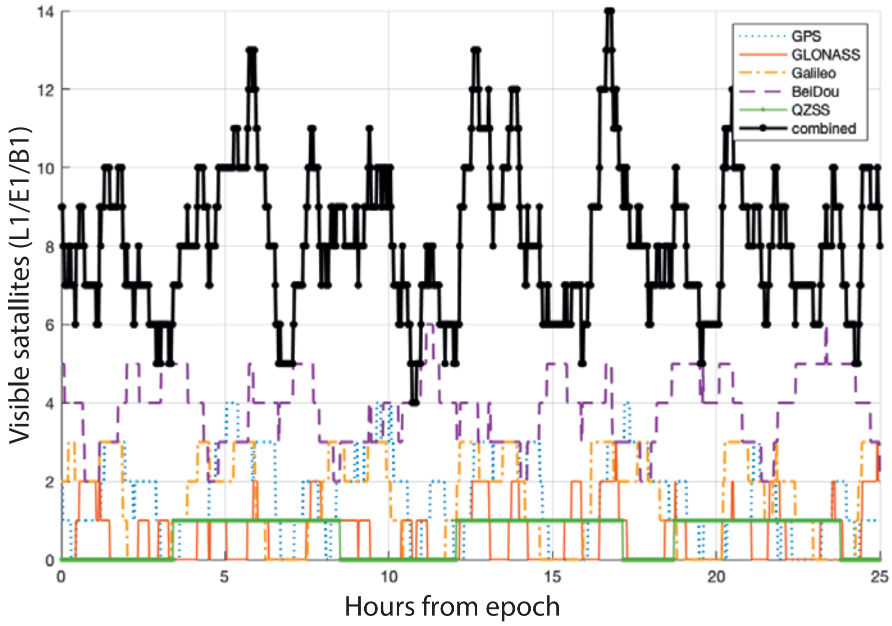


Table 5.1. Global performance estimates of availability and maximum outage duration for each constellation and all constellations together. Results for nadir-pointing antenna in the upper SSV

Band	Constellation	$C/N0_{min}$ = 15 dB-Hz				$C/N0_{min}$ = 20 dB-Hz				$C/N0_{min}$ = 25 dB-Hz			
		At least 1 signal		4 or more signals		At least 1 signal		4 or more signals		At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	90.5	111	4.8	*	90.5	111	4.8	*	0.0	*	0	*
	GLONASS	93.9	48	7	*	93.9	48	7	*	93.9	48	7	*
	Galileo	78.5	98	1.2	*	78.5	98	1.2	*	0.0	*	0	*
	BDS	97.4	45	24.1	*		70	0.6	*	0.0	*	0	*
	QZSS	26.7	*	0.8	*	0.0	*	0	*	0.0	*	0	*
	Combined	**99.9**	**29**	**98.1**	**93**	**99.9**	**33**	**89.8**	**117**	**93.9**	**48**	**7**	*
L5/L3/E5a/B2	GPS	96.9	77	15.6	1180	96.9	77	15.6	1180	0.0	*	0	*
	GLONASS	99.9	8	60.3	218	99.9	8	60.3	218	99.9	8	60.3	218
	Galileo	93.4	55	4.2	*	93.4	55	4.2	*	0.0	*	0	*
	BDS	99.9	7	45.4	644	99.9	7	32.4	644	0.0	*	0	*
	QZSS	30.5	*	1.5	*	30.5	*	1.5	*	0.0	*	0	*
	NavIC	36.9	*	0.6	*	1.0	*	0	*	0.0	*	0	*
	Combined	**100**	**0**	**99.9**	**15**	**100**	**0**	**99.9**	**15**	**99.9**	**8**	**60.3**	**218**

*No signal observed for the worst-case grid location for maximum simulation

5.1.2 Performance in the lower space service volume

Global performance estimates of availability and MOD for the lower SSV (represented by a user sphere at 8,000 km altitude) are shown in table 5.2. These results were generated based on geometrical availability only. In this case, availability is constrained only by obstruction of the LoS visibility between the transmitter and the grid point.

Similar observations hold for these results as above. Performance in the lower SSV is estimated to be significantly better than that in the upper SSV, due to the improved geometric availability at the lower altitude. Single-satellite availability is nearly 100% for all individual systems and combined-constellation availability is 100% in all cases. For the lower SSV, the C/No is typically higher than the assumed 25dB-Hz minimum tracking threshold. Therefore, no sensitivity of the results against different receiver tracking thresholds is presented.

Table 5.2. Global performance estimates of availability and maximum outage duration for each constellation and all constellations together. Results for omni pointing antenna (nadir and zenith) in the lower SSV

Band	Constellation	Signal availability (%)		Max outage duration (min)	
		At least 1 signal	4 or more signals	At least 1 signal	4 or more signals
L1/E1/B1	GPS	100	99.6	0	45
	GLONASS	100	99.8	0	24
	Galileo	99.9	95.0	11	60
	BDS	100	100	0	0
	QZSS	99.6	79.4	197	*
	Combined	**100**	**100**	**0**	**0**
L5/L3/E5a/B2	GPS	100	99.9	0	16
	GLONASS	100	100	0	0
	Galileo	100	100	0	0
	BDS	100	100	0	0
	QZSS	99.6	79.4	197	*
	NavIC	98.0	51.4	348	*
	Combined	**100**	**100**	**0**	**0**

* No signal observed for the worst-case grid location for maximum simulation

5.2 Mission-specific performance

Mission-specific simulations use scenarios that are considered to be realistic use cases of GNSS space users. When defining the mission scenarios, particular care was taken to ensure that realistic assumptions were made, including selection of user antenna characteristics that are representative of existing space-qualified hardware. Three representative mission scenarios were selected for simulation, a geostationary orbit mission, a highly elliptical orbit mission, and a lunar mission.

For mission-specific analysis, an antenna beam pattern for the user spacecraft is included in the link power calculation. In particular, two different user antenna gain characteristics were used: a patch antenna with gain of approximately 2 dBi, and a "high-gain" antenna with gain of 8 to 9 dBi. The patch antenna would be used when a wider beam is desired, and the high-gain antenna would be chosen for longer-range missions.

5.2.1 Geostationary orbit mission

The GEO mission scenario analyses multi-GNSS signal reception for six geostationary satellites. The objective is to obtain more representative signal strength values than in the global analysis by using realistic user antenna patterns on-board the space users for receiving the B1/E1/L1 and B2/E5A/L5 signals.

Spacecraft trajectory

Six GEO satellites are simulated and share the same orbital plane apart from a 60-degree separation in longitude (see table 5.3). The right ascension of the ascending node (RAAN) angle is used to synchronize the orbit with the Earth rotation angle at the start of the simulation. The true anomaly is used to distribute the six GEO user receivers along the equator. This placement of the satellites was chosen to ensure that even signals from regional GNSS satellites in (inclined) geosynchronous orbits would be visible to at least one of the GEO user receivers (see figure 5.2).

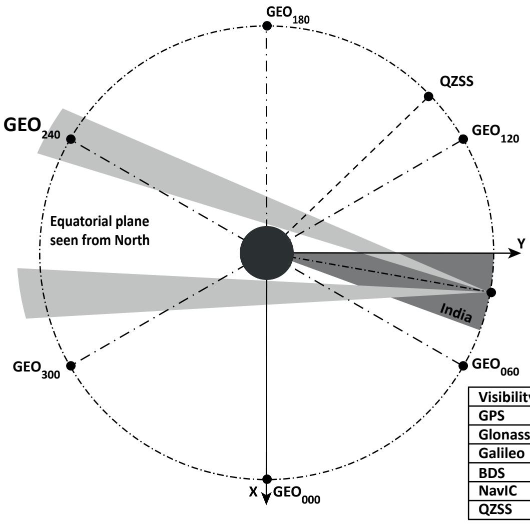
Table 5.3. GEO osculating Keplerian orbital elements

Epoch	1 Jan 2016 12:00:00 UTC		
Semi-major axis	42164.0 km	Right ascension of the ascending node	100.379461 deg
Eccentricity	0.0	Argument of perigee	0.0 deg
Inclination	0.0 deg	True anomaly	0/60/120/180/240/300 deg

Spacecraft attitude and antenna configuration

The user antenna on-board the user spacecraft is a high-gain antenna that permanently points towards the nadir (centre of the Earth). The user antenna patterns used on the two signals are specified in table B10. The assumed acquisition threshold of the space user receiver is 20 dB-Hz.

Figure 5.2. Example for visibility of NavIC satellite from the GEO at 240 degree longitude



Visibility	0	60	120	180	240	300
GPS	1	1	1	1	1	1
Glonass	1	1	1	1	1	1
Galileo	1	1	1	1	1	1
BDS	1	1	1	1	1	1
NavIC	0	0	0	0	1	0
QZSS	1	0	0	0	0	1

Results

The six GEO satellites are all in the equatorial orbital plane but phased by 60 degrees in longitude, or four hours in time. The MEO GNSS satellites have orbital periods in the order of 12 - 14 hours, or about half that of the GEO. This means that the GEO and MEO orbits are almost in phase with each other, in such a way that the visibility patterns at the GEO receiver repeat almost exactly with periods of one day. The MEO satellites move 120 degrees during the four-hour interval between GEO satellites, but there are multiple GNSS MEO in each orbital plane. This means that the visibility patterns in terms of number of visible MEO signals are very similar to all six GEO receivers.

The situation is different for the inclined geosynchronous GNSS satellites of the Navigation with Indian Constellation (NavIC), Quasi-Zenith Satellite System (QZSS) and BDS constellations. The GEO and IGSO longitudes are frozen relative to each other. At most GEO longitudes, the GNSS satellites in IGSO orbits are never visible, either because the GEO is located outside the half-cone angle of the transmitting satellite, or because the signal is blocked by the Earth. This means that reception of the IGSO GNSS signals is an exception rather than the rule. However, those GEO receivers that do see signals from these transmitters will see them continuously, or at very regular patterns (see NavIC B2/E5A/L5 signal).

Examples are given in figure 5.3 and figure 5.4 for the simulated cases with the lowest number of visible satellites and the highest number of visible satellites. The difference is mainly caused by visible BDS and QZSS satellites in the second case. Even for the worst case, the combined constellations offer four visible satellites at L1 almost continuously. At L5, the combined constellations offer between 12 and 20 signals all the time. Complete visibility six GEO receivers and at both carrier frequencies are provided in annex B.

Table 5.4 to table 5.9 show the visibility of at least one or at least four satellites, as a percentage of time. For the combined GNSS constellations, four or more B2/E5A/L5 signals are available at every simulated GEO longitude for 100% of the time. The slightly weaker B1/E1/L1 signal drops to around 93% visibility for four satellites, but there is always at least one signal available. This is a considerably better result than for any of the individual MEO constellations (GPS, Galileo, GLONASS individual solutions), which reach at most 53% visibility at GEO height for four signals, individually.

The conclusion is that when using the combined GNSS constellations, it is possible to continuously form an on-board PVT solution. In addition to this, it is also possible to perform a real-time kinematic orbit determination process on-board the GEO satellite. This may allow real-time positioning of GEO at a few metres accuracy level. This enables new concepts for GEO co-location due to more accurate positioning information from GNSS than from terrestrial ranging.

Figure 5.3. Worst-case example: L1 visibility for GEO at 180 deg east

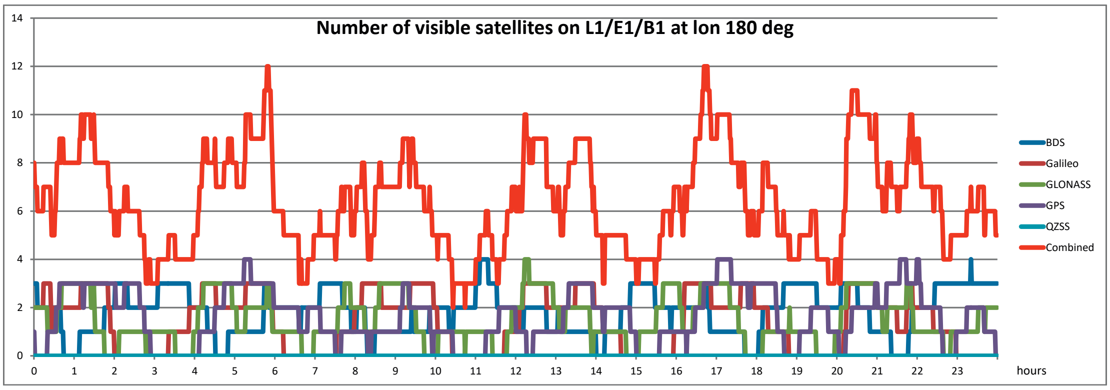


Figure 5.4. Best-case example: L5 visibility for GEO at 60 deg west

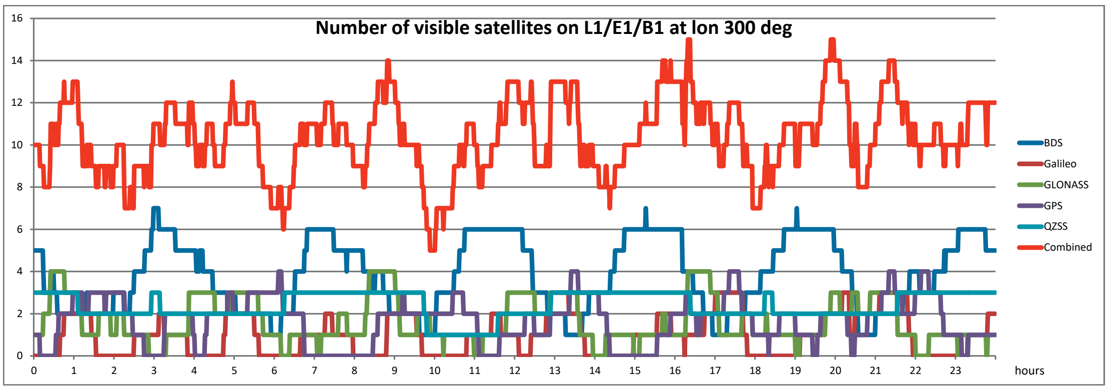


Table 5.4. Performance for GEO receiver at longitude 0 deg

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	82.24	72	3.29	697
	GLONASS	84.84	38	0.71	3808
	Galileo	63.4	82	0	20160
	BDS	100	0	28.47	200
	QZSS	64.31	210	0	20160
	Combined	**100**	**0**	**99.7**	**11**
L5/L3/E5a/B2	GPS	94.29	50	14.55	425
	GLONASS	100	0	43.99	189
	Galileo	86.43	41	0	20160
	BDS	100	0	96.44	21
	QZSS	90.26	117	0	20160
	NavIC	0	0	0	20160
	Combined	**100**	**0**	**100**	**0**

Table 5.5 Performance for GEO receiver at longitude 60 deg

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	80.01	89	2.44	748
	GLONASS	90.7	34	5.21	475
	Galileo	62.83	82	0	20160
	BDS	92.27	28	0.92	724
	QZSS	0	20160	0	20160
	Combined	**100**	**0**	**94.93**	**36**
L5/L3/E5a/B2	GPS	94.77	55	10.04	402
	GLONASS	100	0	53.14	90
	Galileo	86.87	42	0	20160
	BDS	100	0	10.65	262
	QZSS	0	20160	0	20160
	NavIC	0	20160	0	20160
	Combined	**100**	**0**	**100**	**0**

Table 5.6. Performance for GEO receiver at longitude 120 deg

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	79.56	103	3.68	462
	GLONASS	90.48	37	5.07	474
	Galileo	63.12	82	0	20160
	BDS	92.38	26	0.93	732
	QZSS	0	20160	0	20160
	Combined	**100**	**0**	**94.62**	**51**
L5/L3/E5a/B2	GPS	91.85	66	9.17	419
	GLONASS	100	0	52.81	94
	Galileo	86.55	41	0	20160
	BDS	100	0	11.72	255
	QZSS	0	20160	0	20160
	NavIC	0	20160	0	20160
	Combined	**100**	**0**	**100**	**0**

Table 5.7. Performance for GEO receiver at longitude 180 deg

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	82.15	73	3.31	697
	GLONASS	84.93	41	0.72	3805
	Galileo	63.4	82	0	20160
	BDS	91.85	27	0.94	722
	QZSS	0	20160	0	20160
	Combined	**100**	**0**	**93.24**	**41**
L5/L3/E5a/B2	GPS	94.28	50	14.55	425
	GLONASS	100	0	44.08	195
	Galileo	86.43	41	0	20160
	BDS	100	0	10.37	263
	QZSS	0	20160	0	20160
	NavIC	100	0	0	20160
	Combined	**100**	**0**	**100**	**0**

Table 5.8. Performance for GEO receiver at longitude 240 deg

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	79.92	89	2.46	748
	GLONASS	90.85	34	5.19	476
	Galileo	62.83	82	0	20160
	BDS	100	0	28.63	200
	QZSS	0	20160	0	20160
	Combined	**100**	**0**	**99.34**	**19**
L5/L3/E5a/B2	GPS	94.75	55	10.06	402
	GLONASS	100	0	53.12	91
	Galileo	86.87	42	0	20160
	BDS	100	0	54.16	118
	QZSS	0	20160	0	20160
	NavIC	100	0	5.18	371
	Combined	**100**	**0**	**100**	**0**

Table 5.9. Performance for GEO receiver at longitude 300 deg

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	79.43	103	3.68	462
	GLONASS	90.47	33	5.02	939
	Galileo	63.12	82	0	20160
	BDS	100	0	50.5	142
	QZSS	100	0	0	20160
	Combined	**100**	**0**	**100**	**0**
L5/L3/E5a/B2	GPS	91.81	66	9.19	419
	GLONASS	100	0	52.96	94
	Galileo	86.55	41	0	20160
	BDS	100	0	100	0
	QZSS	100	0	0	20160
	NavIC	67.78	216	0	20160
	Combined	**100**	**0**	**100**	**0**

5.2.2 *Scientific highly elliptical orbit mission*

Spacecraft trajectory

A highly elliptical orbit (HEO) mission scenario with apogee altitude of about 58,600 km and perigee altitude of 500 km is used to demonstrate the GNSS visibility performance through all the GNSS SSV altitudes, both below and above the GNSS constellations.

GNSS visibility conditions near the perigee are similar to those of space user receivers in LEO, with the important difference that the spacecraft is moving very fast – around 8 km/s to 11 km/s – so extreme Doppler shifts occur on the GNSS signals, and visibility times between any particular GNSS satellite and the HEO space user receiver are much shorter than for terrestrial receivers.

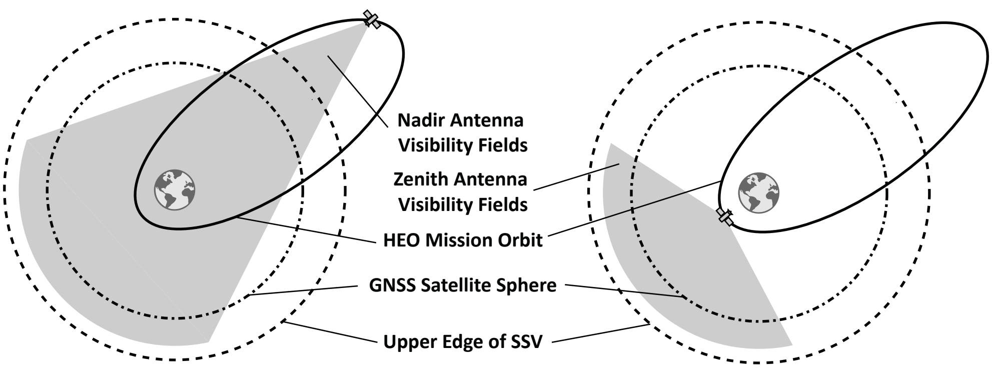
Table 5.10. Osculating Keplerian HEO orbital elements

Epoch	1 Jan 2016 12:00:00 UTC		
Semi-major axis	35937.5 km	RAAN	0 deg
Eccentricity	0.80870	Argument of perigee	270 deg
Inclination	63.4 deg	True anomaly	0 deg

Spacecraft attitude and antenna configuration

The on-board GNSS antennas are configured in both nadir and zenith-facing sides of the spacecraft. As shown in figure 5.5 the nadir-pointing antenna with high gain and narrow beam-width can ensure the GNSS signal link from the opposite side of the Earth, including when flying above the GNSS altitude and during the apogee period. The zenith-pointing patch antenna can provide visibility during the perigee period. The antenna patterns for both type of antennas are given in table B10. The acquisition and tracking thresholds of the user receiver were both set to 20 dB-Hz when evaluating the signal availability in the HEO simulation.

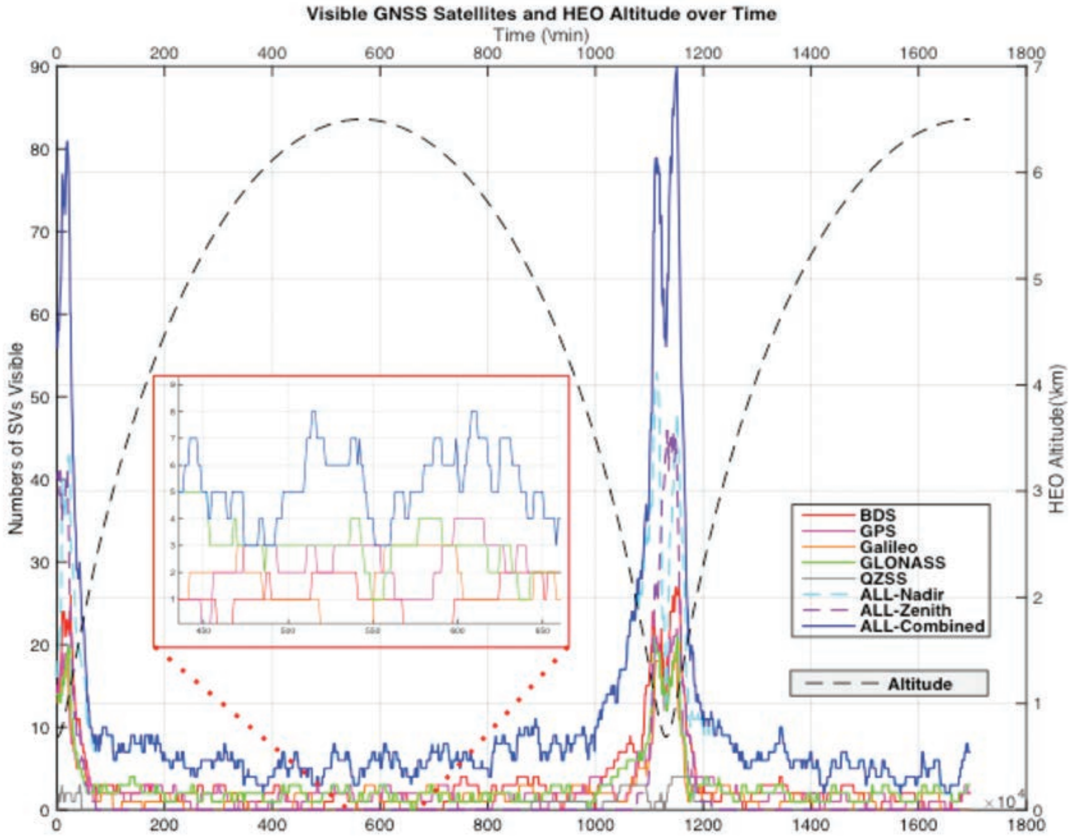
Figure 5.5. Schematic of the HEO mission with nadir and zenith-pointing antennas



Results

Figure 5.6 shows the GNSS signal availability of all GNSS constellations and L5/L3/E5a/B2 signal for the HEO nadir and zenith-pointing antennas over the time of 1.5 HEO orbital periods. Note that when the spacecraft is below the GNSS constellation altitude, the visibility can be significantly improved by combining the signals from both nadir and zenith antennas at the same time. However, within this simulation only the strongest signal from either is employed at a given time. Around apogee, only the nadir-pointing antenna provides signal availability.

Figure 5.6. Visible GNSS satellites over 1.5 orbital periods of HEO (L5/L3/E5a/B2)



The simulated results for the signal availability and MOD of the HEO mission are shown in table 5.11. The signal availability was evaluated with 20 dB-Hz C/No threshold for each individual constellation and all constellations combined.

Table 5.11. HEO mission simulated performance result

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	87.3	70	12.7	1036
	GLONASS	98.8	12	14.1	986
	Galileo	74.3	85	9.9	1026
	BDS	88.1	51	16.1	1008
	QZSS	27.5	1031	2.5	2175
	Combined	**100**	**0**	**94.5**	**47**

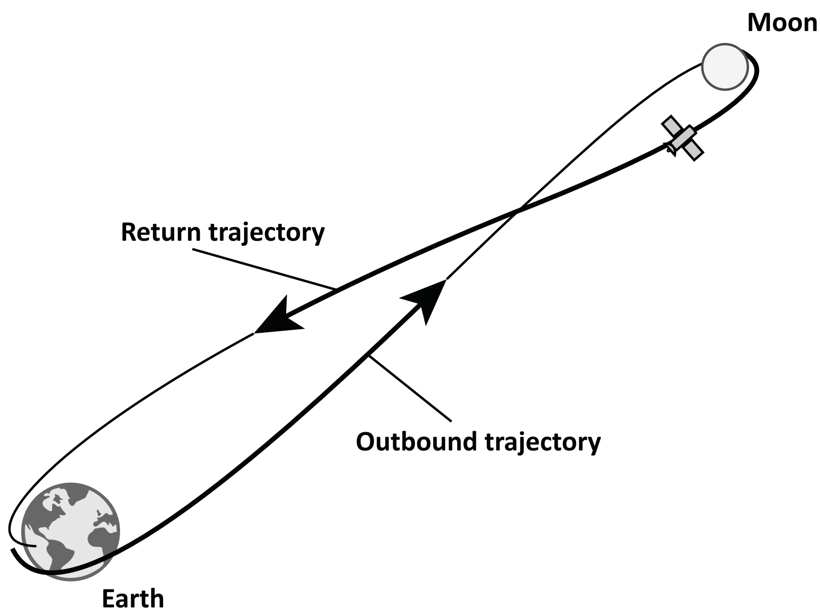
L5/L3/E5a/B2	GPS	94.7	53	17.4	911
	GLONASS	100	0	55.5	133
	Galileo	87.1	63	11.6	980
	BDS	96.9	30	26.0	925
	QZSS	32.1	1021	5.8	1091
	NavIC	35.1	989	5.8	1091
	Combined	**100**	**0**	**100**	**0**

For both L1/E1/B1 and L5/L3/E5/B2 the one-signal availability can reach 100% with all constellations combined. In case of L1, four-signal availability is below 20% and the MOD is around 1,000 minutes, which is close to the HEO orbital period of 1,130 minutes, for an individual constellation. The performance is significantly improved by receiving signals from all constellations combined to nearly 100%. The result of L5 case is similar and the four-signal availability is 100% with all constellations combined. The table also shows that signal availability for the L5 case is better than the L1 case.

5.2.3 Lunar mission

The lunar mission case models a simple ballistic cislunar trajectory from LEO to lunar orbit insertion, similar to the trajectories flown by the 1968 United States Apollo 8 mission and many others. This case seeks to explore the boundaries of the GNSS SSV beyond Earth orbit.

Figure 5.7. Lunar trajectory phases; only the outbound trajectory segment is analysed.



Spacecraft trajectory

Figure 5.7 shows a diagram of the trajectory being modelled; only the outbound portion is being modelled for this analysis. Earth orbit, lunar orbit, and return trajectories are projected to have known or similar performance. Table 5.12 shows the fundamental characteristics of the simulation.

Table 5.12. Lunar simulation parameters

Parameter	Earth departure	Lunar arrival
Epoch (UTC)	1 Jan 2016 12:00:00.000	5 Jan 2016 22:07:59.988
Altitude	185 km	100 km
Eccentricity	0	0
Inclination (body-centred J2000)	32.5°	75°
RAAN	30°	165°
Argument of perigee (AOP)	32°	319°
True anomaly	0°	0°

Spacecraft attitude and antenna configuration

A generic spacecraft is modelled, with two GNSS antennas: one zenith-pointing with peak gain less than 5 dB for reception at low altitudes, and one nadir-pointing with peak gain of approximately 10 dB for reception above the GNSS constellations. The results presented assume that the antenna with the greatest number of tracked satellites is used. As in the other HEO and GEO cases, the acquisition and tracking thresholds were both set to 20 dB-Hz.

Results

Table 5.13 contains the simulated performance results for this mission. In the case of both L1 and L5 bands, the availability of four simultaneous signals is nearly zero for any individual constellation, though combined there is coverage to approximately 30 Earth radii (RE) (approximately half the distance to the Moon) near 10–15%. Single-satellite availability reaches 36% for the combined case at L5, though as shown in figure 5.8, this availability primarily occurs at low altitudes. The benefit of the combined case is best seen above 10 RE, where the combined case has 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.

Figure 5.8. Signal visibility by trajectory altitude, to the limit of available signals at 30 RE (approx. 50% of lunar distance)

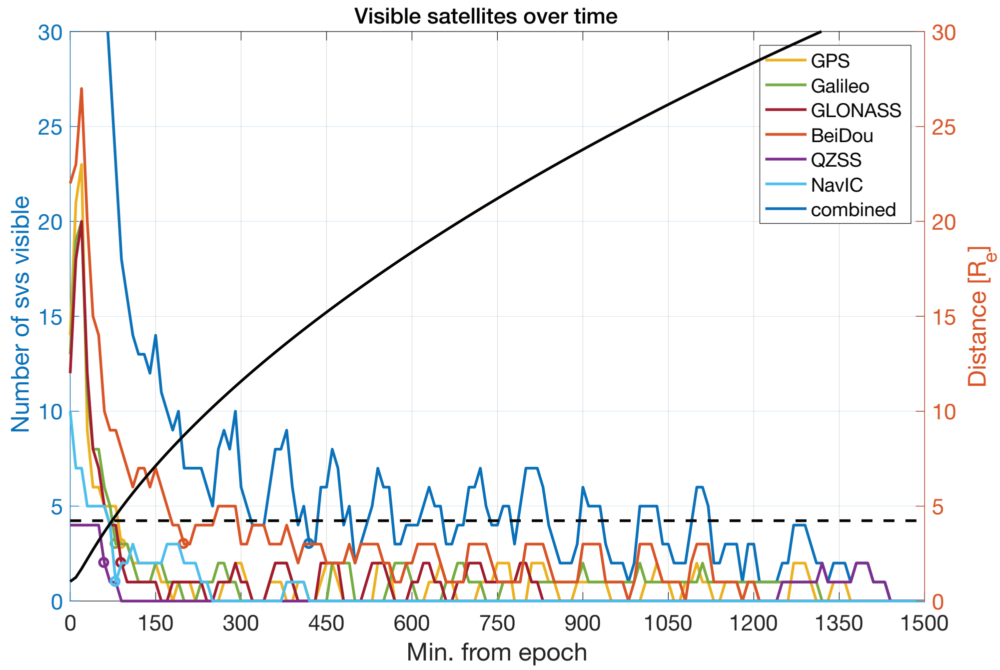
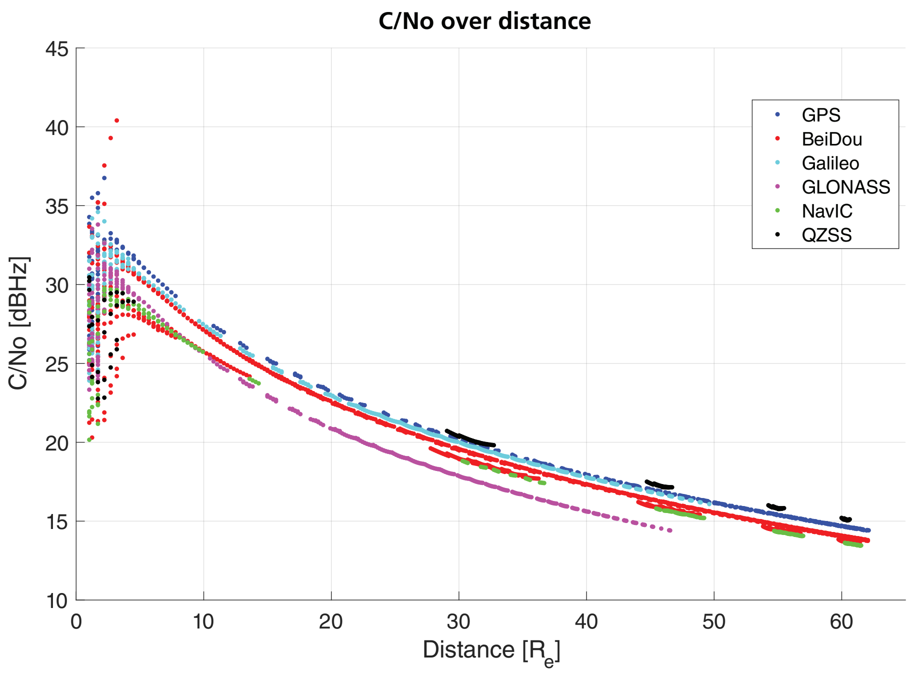


Table 5.13. Lunar mission simulated performance results

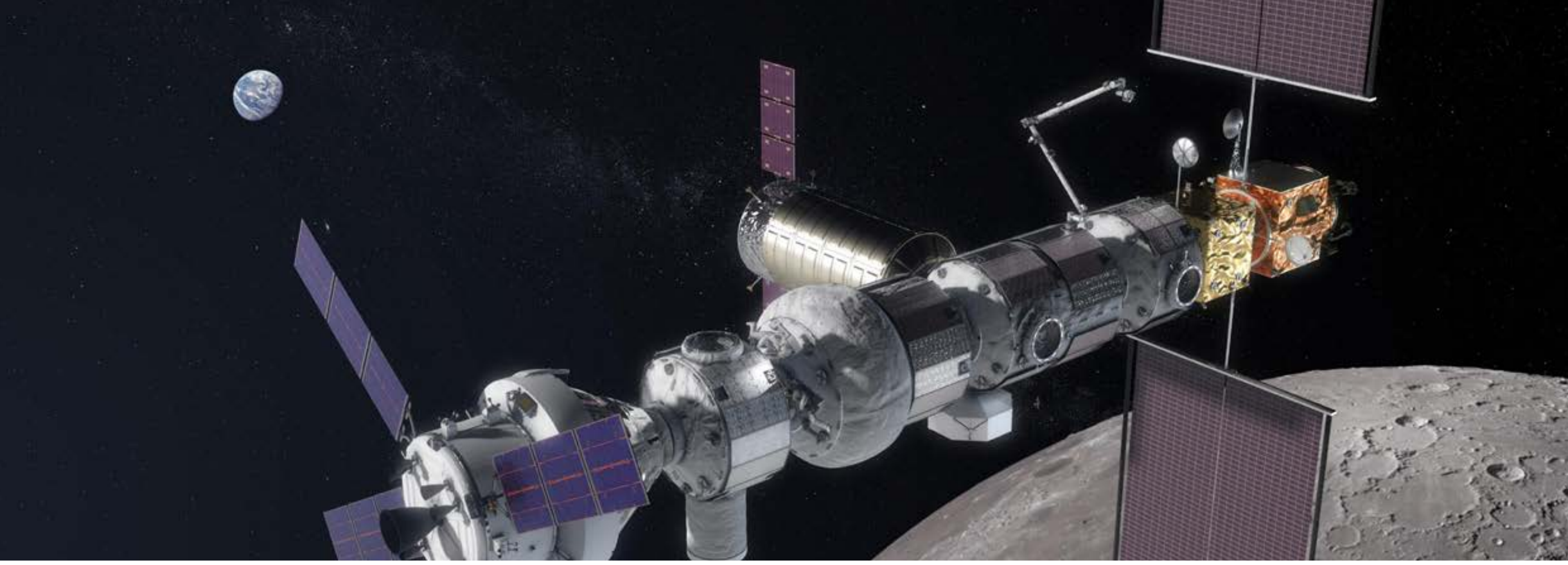
Band	Constellation	Signal availability (%)	
		At least 1 signal	4 or more signals
L1/E1/B1	GPS	9%	1%
	GLONASS	8%	0%
	Galileo	14%	1%
	BDS	14%	3%
	QZSS	1%	0%
	Combined	**21%**	**9%**
L5/L3/E5a/B2	GPS	12%	1%
	GLONASS	33%	1%
	Galileo	16%	1%
	BDS	18%	5%
	QZSS	4%	0%
	NavIC	4%	1%
	Combined	**36%**	**16%**

Figure 5.9 shows the simulated C/No received by the example spacecraft for each individual constellation. The figure shows the reason for the visibility drop-off near 30 RE shown in figure 5.8: the C/No of signals at the receive antenna drops below the 20 dB-Hz minimum threshold beyond that point. If a more sensitive receiver or higher-gain antenna was used such that 15 dB-Hz were usable, however, signal availability would be achievable for the entire trajectory to lunar distance.

Figure 5.9. Simulated C/No for lunar trajectory



These results show that GNSS-based navigation with the combined interoperable 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 possibly a solution for navigation beyond the outbound trans-lunar injection (TLI) burn and return trajectory correction manoeuvres (TCMs). With further user modifications, it could provide on-board navigation at even higher altitudes.



6. Conclusions and recommendations

GNSS, which were originally designed to provide positioning and timing services to users on the ground, are increasingly being utilized for on-board autonomous navigation in space. While use of GNSS in LEO has become routine, its use in higher orbits has historically posed unique and difficult challenges, including limited geometric visibility and reduced signal strength. Only recently have these been overcome by high-altitude users through weak-signal processing techniques and on-board estimation filters.

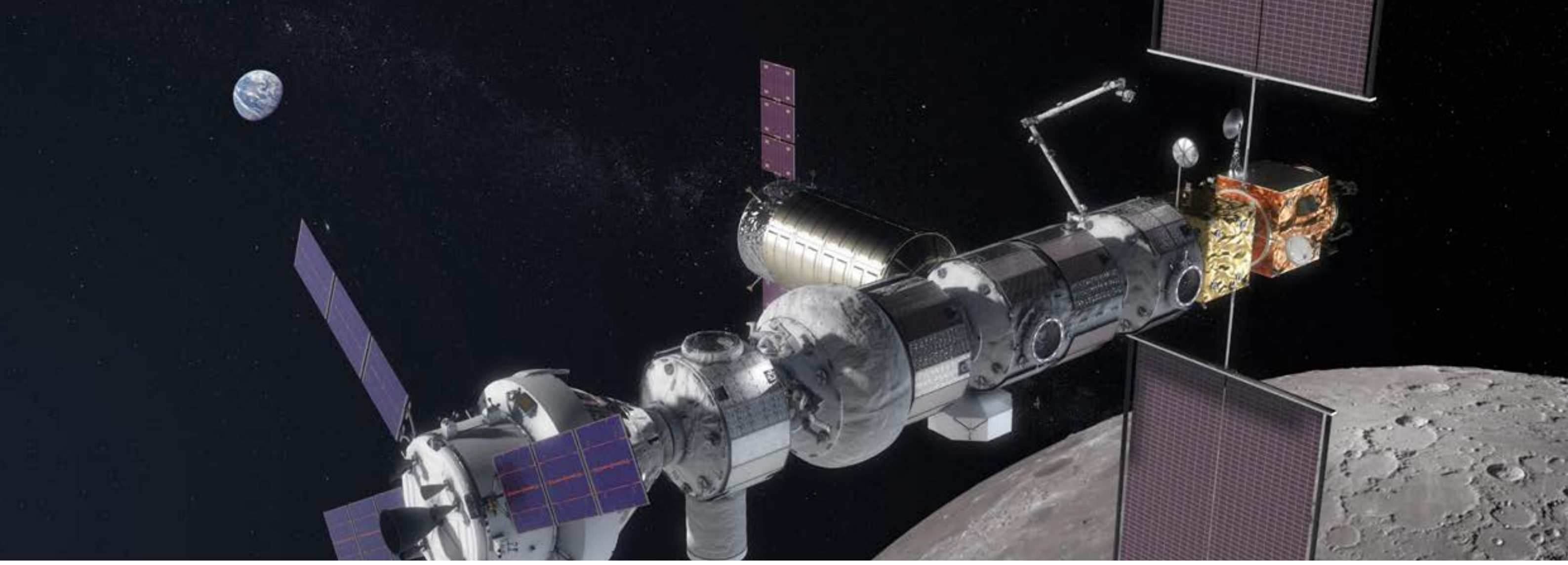
The SSV was defined to provide a framework for documenting and specifying GNSS constellation performance for these users, up to an altitude of 36,000 km. The United Nations International Committee on GNSS (ICG) has worked on a collaborative basis to publicize the performance of each GNSS constellation 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.

There are many benefits to an interoperable 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.

This booklet captures SSV characteristics of each individual GNSS constellation, in terms of pseudorange accuracy, minimum received signal power, and signal availability (including MOD). In addition, the multi-constellation analysis documented here shows the benefits of the interoperable multi-GNSS SSV. In particular, there are significant availability improvements over any individual constellation when all GNSS constellations are employed. Within the high-altitude SSV, single-signal availability reaches 99% for the L1 band, and four-signal availability jumps from a maximum of 7% for any individual constellation to 89% with all, with a maximum signal outage duration of only 33 minutes. Further, similar benefits are shown explicitly for geostationary, highly elliptical, and lunar use cases.

The analyses presented clearly show the benefit and importance of interoperability of GNSS for high-altitude space users. To fully realize this benefit, the ICG makes the following recommendations:

1. *The authors encourage the development of interoperable multi-frequency space-borne GNSS receivers that exploit the use of GNSS signals in space.*
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.*
3. *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 the future generations of satellites. Service providers and space agencies are invited to report back to WG-B on their progress on a regular basis.*
4. *Looking ahead, GNSS providers are invited to consider supplying 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*



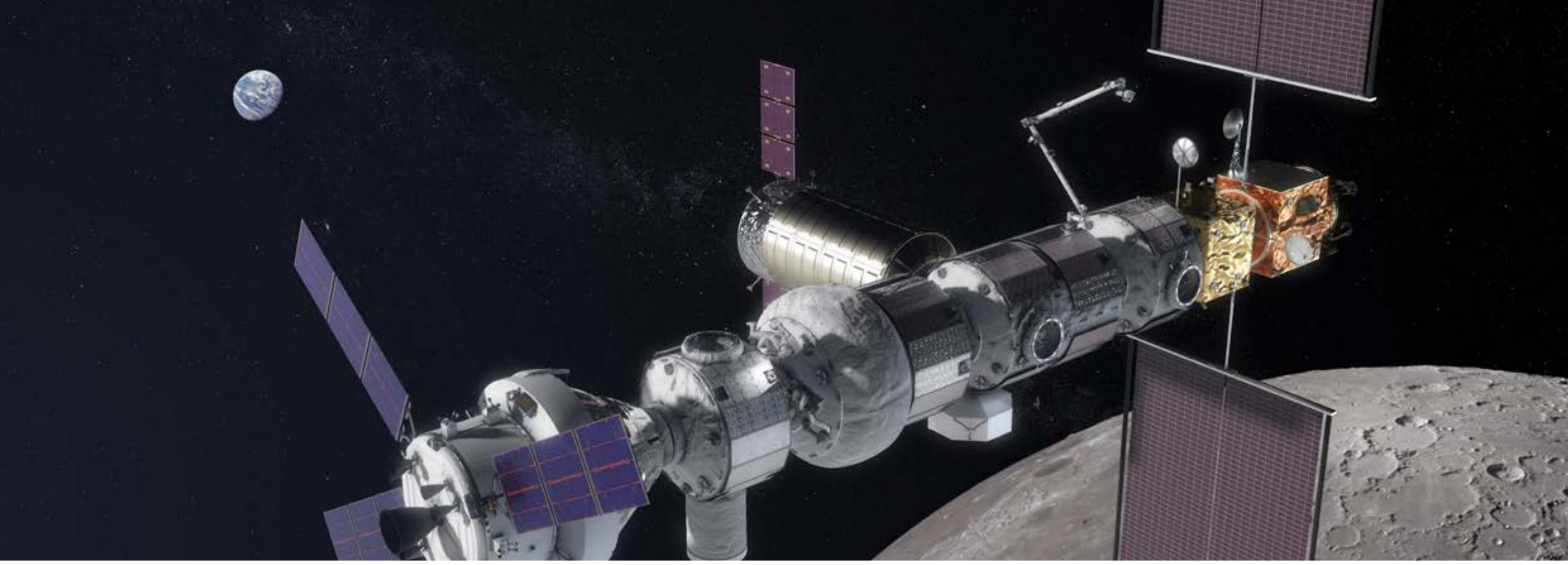
7. Potential future evolutions of this SSV booklet

To promote the multi-GNSS SSV for the purpose of safe robotic or manned missions in SSV as defined in this booklet and beyond including cislunar space it will be necessary to update this booklet, extend efforts on simulation and modelling as well as elaborating further on recommendations for GNSS providers. Some potential evolutions of the booklet could include:

- More accurate models of transmit antenna patterns and transmit power, based on provider published data and on-orbit derived observations
- Improved simulation models of end-to-end antenna systems to more accurately compute link analyses
- Recommended antenna system types for specific missions and orbits
- Improved simulations models, based on flight observed data, to more accurately represent the expected performance of missions for various orbits
- Expanding the user benefits and mission types, based on a more in-depth understanding of international use of GNSS in the SSV
- Expanding the SSV and improving user performance and SSV resiliency through trade studies on additional beacons or augmentations and service provider upgrades

The following process will be used to update the booklet contents:

- Updates of data can be provided by the service providers and other ICG members and will be processed by the ICG via WG-B.
- New releases of this booklet will be issued periodically, as necessary, after endorsement by ICG and all service providers.



Annex A. Description of individual GNSS support to SSV

A1. Global Positioning System SSV characteristics

Introduction

The Global Positioning System (GPS) is a United States-owned utility that provides users with positioning, navigation, and timing (PNT) services. GPS represents a "system of systems" consisting of three segments: a space segment, employing a nominal constellation of 24 space vehicles (SV) transmitting one-way signals with the GPS satellite's position and time; a control segment consisting of a global network of ground facilities that track the GPS satellites, monitor their transmissions, perform analyses, and send commands and data to the constellation; and a user segment that consists of GPS receiver equipment, which receives the signals from at least four GPS satellites and uses the transmitted information to calculate in real-time the three dimensional position and the time. The United States Air Force develops, maintains, and operates the space and control segments. Official United States Government information about GPS and related data topics is available at the National Coordination Office (https://www.gps.gov/).

Space segment

The United States is committed to maintaining the availability of at least 24 operational GPS satellites, 95% of the time to support PNT operations between the surface and 3,000 km altitude. In June 2011, the Air Force successfully completed a GPS constellation expansion known as the "Expandable 24" configuration. Three of the 24 slots were expanded, and six satellites were repositioned, so that three of the extra satellites became part of the constellation baseline. As a result, GPS now effectively operates as a 27-slot constellation with improved coverage in most parts of the world. To ensure this commitment, the Air Force is flying 31 operational GPS satellites.

The first satellite of what is now the GPS constellation was launched in 1978. Since then, the GPS space segment has evolved through three block architectures and multiple upgrades (Block I, Block IIA, Block IIR, Block IIR-M, Block IIF, Block III SV 1-10). At the time of writing, GPS is currently on-bid for its newest block upgrade—Block III SV11+.

GPS is configured in six orbital planes, inclined at 55 degrees and at an altitude of 20,182 km above the Earth. These orbital parameters result in an orbit period of a half-sidereal day (11 hours, 58 minutes) and a ground track that repeats every sidereal day.

Control segment

The current Operational Control Segment (OCS) includes a master control station, an alternate master control station, 11 command and control antennas, and 16 monitoring sites. OCS acquires the GPS signals, checks signal integrity and uplinks PNT correction and satellite ephemeris data. The control segment is currently undergoing a systems modernization to support Next Generation Operational Control System (OCX) operations. OCX will be delivered in increments, with increasingly more capable and sophisticated operations support. Block 0 will support launch and checkout of the GPS III satellites. Block 1 will operate and manage the GPS constellation. It will replace the Architecture Evolution Plan (AEP) system that is currently operational, and it will add modernized operational capabilities. Block 2 will enable the modernized civilian and military signals to become fully operational. This includes the civilian L1C, L2C & L5 signals and the military M-code signal.

Signal structure

GPS signal capabilities and structure have evolved with the evolution of the constellation block architecture. At full operational capability (mid-1990s), the GPS signal structure included an L1 C/A signal downlink at 1575.42 MHz for civilian applications and an L1/L2 P(Y) signal downlink at 1575.42 MHz/1227.6 MHz for military applications.

Subsequent improvements to the GPS signal structure have evolved to support GNSS interoperability and safety-of-life needs. These employ the long-used L1 (1575.42 MHz) and L2 (1227.6 MHz) frequencies with augmented modulations to support interoperability, enhanced civilian use and more robust military application. L5 was added using the 1176.45 MHz frequency to support safety-of-life operations. Block IIR-M (2005) inaugurated the second GPS civilian signal (L2C) designed specifically to meet commercial needs (for example, surveying), and also jam-resistant M (military) codes. Block IIF (2010) inaugurated the third civilian signal (L5) designed to meet demanding requirements for safety-of-life transportation and other high-performance applications. Block III satellites, the first of which at the time of writing is ready for launch, include a fourth civilian signal (L1C) designed to enable interoperability between GPS and international satellite navigation systems. L2C, L5, and M-code are currently pre-operational. These will become fully operational after control segment upgrades (e.g. OCX) and constellation replenishment results in sufficient signals to support full operations.

Space service volume

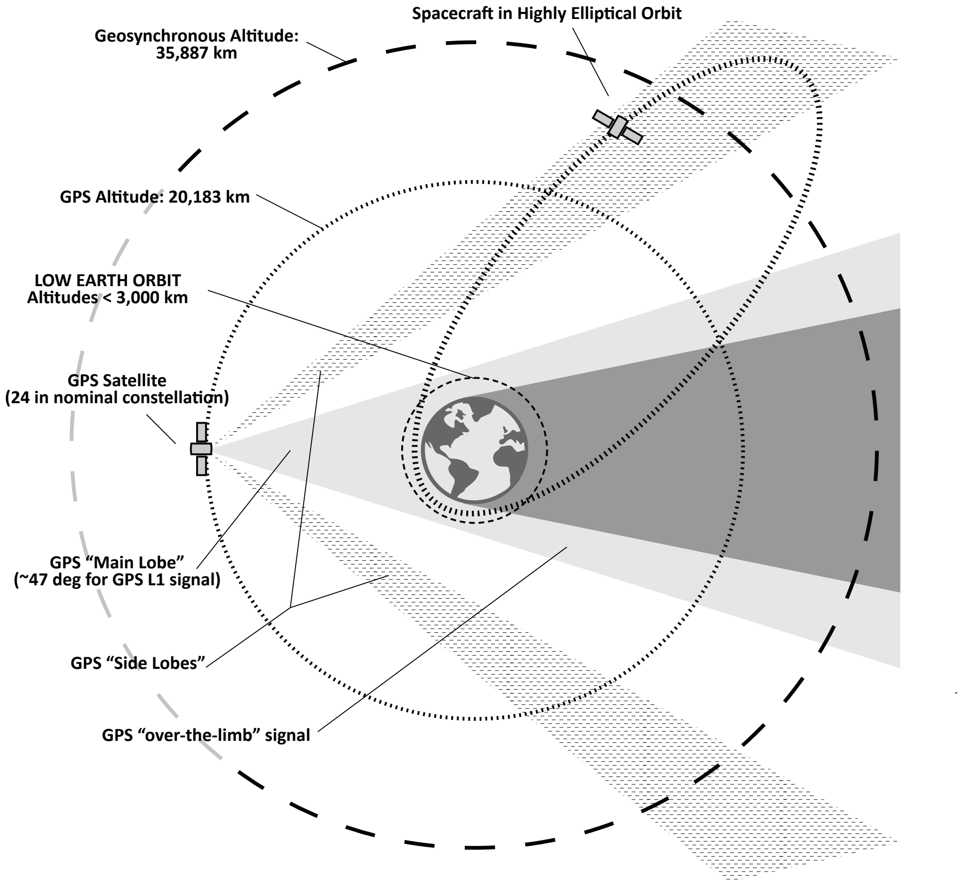
The signal information shown in the template conforms to the SSV requirements that are embedded in the GPS III vehicle specification. To date, GPS is the only GNSS constellation with a formal SSV specification. The current SSV specification addresses performance supplied by the spacecraft main-lobe signals.

Table A1. GPS III SSV characteristics

Definitions	Notes
Lower SSV: 3,000 to 8,000 km altitude	Four GPS signals available simultaneously a majority of the time, but GPS signals over the limb of the Earth become increasingly important. One-metre orbit accuracies are feasible (post-processed).
Upper SSV: 8,000 to 36,000 km altitude	Nearly all GPS signals received over the limb of the Earth. Users will experience periods when no GPS satellites are available. Accuracies ranging from 10 to 100 metres are feasible (post-processed) depending on receiver sensitivity and local oscillator stability.

Parameters	Value	
User range error [1]	0.8 metres	
Signal centre frequency		
L1 C/A	1575.42 MHz	
L1C	1575.42 MHz	
L2 (L2C or C/A)	1227.60 MHz	
L5 (I5 or Q5)	1176.45 MHz	
Minimum received civilian signal power	0 dBi RCP antenna at GEO	Reference off-boresight angle
L1 C/A	-184.0 dBW	23.5 deg
L1C	-182.5 dBW	23.5 deg
L2 (L2C or C/A)	-183.0 dBW	26 deg
L5 (I5 or Q5)	-182.0 dBW	26 deg
Signal availability [2]		
Lower SSV	**At least 1 signal**	**4 or more signals**
L1	100%	> 97%
L2, L5	100%	100%
Upper SSV	**At least 1 signal**	**4 or more signals**
L1	≥ 80% [3]	≥ 1%
L2, L5	≥ 92% [4]	≥ 6.5 %
Note 1: This value represents pseudorange accuracy, not the final user position error, which is dependent on many mission-specific factors such as orbit geometry and receiver design.		
Note 2: Assumes a nominal, optimized 27-satellite constellation and no GPS spacecraft failures. Signal availability at 95% of the areas at a specific altitude within the specified SSV.		
Note 3: Assumes less than 108 minutes of continuous outage time.		
Note 4: Assumes less than 84 minutes of continuous outage time.		

Figure A1. GPS geometry for SSV characteristics



A2. GLONASS SSV characteristics

Introduction

GLONASS has three main segments: a space segment, generating and broadcasting navigation signals; a ground control segment, performing the functions of satellites operation control, continuous orbits and clocks parameters correction, delivering temporal programs, control commands and navigation data to satellites; and a user segment.

Space segment

The first GLONASS satellite was launched in 1982. Since then, there have been three generations of GLONASS satellites: GLONASS, GLONASS-M and GLONASS-K. The next generation of satellites being currently developed is GLONASS-K2. The additional L-band code division multiple access (CDMA) mission payload including the dedicated antenna is planned to be installed on-board satellites of the second phase of GLONASS modernization.

The current orbital constellation consists of GLONASS-M and GLONASS-K satellites. The GLONASS satellites are placed in roughly circular orbits with an altitude of 18,840…19,440 km (the nominal orbit altitude is 19,100 km) and the orbital period of 11h 15 min 44 sec ±5 sec. The orbital planes are separated by the 120° right ascension of the ascending node. Eight navigation satellites are equally spaced in each plane with the 45° argument of latitude. The orbital planes have an argument of latitude displacement of 15° relative to each other. With full orbital constellation, the repetition interval of satellites ground tracks and radio coverage zones for ground users is 17 orbit passes (7 days 23 hours 27 minutes 28 seconds).

The GLONASS orbital constellation is highly stable and does not demand additional corrections during satellites' life cycle. So maximum satellite drift of the ideal satellite orbital position does not exceed ±5° at a 5-year interval, while the average orbital planes precession rate is $0.59251 \cdot 10^{-3}$ rad/s.

A nominal orbital constellation consists of 24 satellites. The current orbital constellation has 24 operational satellites.

Control segment modernization

Ground Control Segment (GCS) Development Plans before 2020 involve all basic GCS elements for the purpose of their performance improvement (including upgrading one-way measuring and computing stations, master clock, measuring and laser ranging stations network extension).

The modernized ground control segment will additionally include:

Annex A: On-board intersatellite measurement equipment ground control loop providing orbit and clock data insertion to navigation satellite

Annex B: One-way measuring stations network for generating orbit and clock data to improve accuracy and integrity

Signal structure

The existing GLONASS constellation is comprised of GLONASS-M and GLONASS-K satellites broadcasting five navigation signals: L1OF (open Frequency Division Multiple Access (FDMA) in L1); L2OF (open FDMA in L2); L1SF (secured FDMA in L1); L2SF (secured FDMA in L2); L3OC (open CDMA in L3).

Space service volume

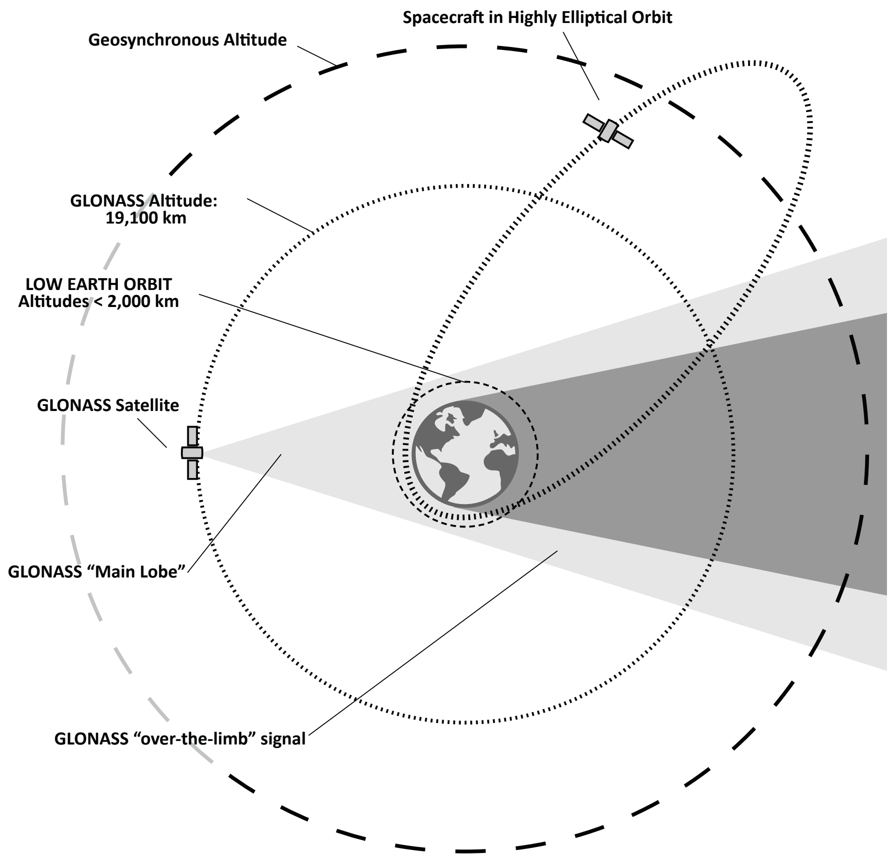
The GLONASS contribution to the interoperable GNSS SSV is provided in the following table.

Table A2. GLONASS SSV characteristics

Definitions	Notes
Lower SSV: 3,000 to 8,000 km altitude	Four GLONASS signals available simultaneously a majority of the time, but GLONASS signals over the limb of the Earth become increasingly important. One-metre orbit accuracies are feasible (post-processed).
Upper SSV: 8,000 to 36,000 km altitude	Nearly all GLONASS signals received over the limb of the Earth. Accuracies ranging from 20 to 200 metres are feasible (post-processed) depending on receiver sensitivity and local oscillator stability.

Parameters	Value	
User range error[1]	1.4 m	
Signal centre frequency		
L1	1605.375 MHz	
L2	1248.625 MHz	
L3	1201 MHz	
Minimum received civilian signal power (GEO)	0 dBi RCP antenna at GEO	Reference off-boresight angle
L1[2,3]	-179 dBW	26 deg
L2	-178 dBW	34 deg
L3[4]	-178 dBW	34 deg
Signal availability [5]		
MEO at 8,000 km	**At least 1 signal**	**4 or more signals**
L1	59.1%	64%
L2, L3	100%	66%
Upper SSV	**At least 1 signal**	**4 or more signals**
L1	70%	2.7%
L2, L3	100%	29%
Note 1: This value represents pseudorange accuracy, not the final user position error, which is dependent on many mission-specific factors such as orbit geometry and receiver design.		
Note 2: FDMA signals in L1 and L2 and CDMA signals in L3		
Note 3: L1, L2 signals are transmitted by GLONASS-M and GLONASS-K satellites. At present, the L3 signal is transmitted by the GLONASS-K satellite. Furthermore, the final seven GLONASS-M satellites will also transmit L3 signal (starting with the GLONASS-M No. 55 satellite).		
Note 4: L3 signals for GLONASS-K satellites.		
Note 5: Assumes at least one GLONASS satellite in view in the high-orbit service volume.		

Figure A2. GLONASS geometry for SSV characteristics



A3. Galileo full operational capability SSV characteristics

Galileo space segment

The nominal Galileo space segment consists of a constellation of 24 satellites, plus six active in-orbit spares, spaced evenly in three circular MEO planes inclined at 56 degrees relative to the equator. Their orbits have a nominal altitude of about 29,600 km and an orbital period of approximately 14 hours. Today the Galileo space segment consists of four in-orbit-validation (IOV) satellites and a series of full-operational-capability (FOC) satellites for which the number is continuously increasing thanks to the ongoing deployment process with the objective to reach full operational capability by 2020. Both IOV and FOC type of satellites belong to the operational Galileo constellation.

Ground segment

The Galileo ground segment controls the Galileo satellite constellation, monitors the health of the satellites, provides core functions of the navigation mission (satellite orbit determination, clock synchronization), performs the statistical analysis of the signal-in-space ranging error, determines the navigation messages, and uploads the navigation data for subsequent broadcast to users. The key elements of the transmitted data (such as satellite orbit ephemeris, clock synchronization, signal-in-space accuracy and the parameters for the NeQuick ionospheric model) are calculated from measurements made by a global network of reference sensor stations.

Galileo signals

Galileo transmits radio-navigation signals in four different frequency bands: E1 (1,559-1,594 MHz), E6 (1,260-1,300 MHz), E5a (1,164-1,188 MHz) and E5b (1,195-1,219 MHz). The details of the Galileo signal structure are summarized in the following tables and are specified in the Galileo Open Service Signal-in-Space Interface Control Document. Signals highlighted with (*) in these tables contribute to the interoperable GNSS SSV.

In relation to the definition of an interoperable GNSS SSV, it is to be noted that during the design phase of the Galileo open service signals interoperability with other GNSS was a major objective. The open service signal in E1, the so-called composite binary offset carrier or CBOC(6,1,1/11) signal, was originally designed in cooperation with the United States to aid interoperability with the GPS L1C signal. Similar spectral shapes have later also been adopted by BDS and QZSS, paving the way for multi-constellation interoperability. Also, the Galileo E5a signal is fully interoperable with GPS L5, BDS B2 and QZSS L5.

Table A3. Galileo E1 signal characteristics overview

Service name	E1 OS*		PRS
Centre frequency	1575.42 MHz		
Spreading modulation	CBOC(6,1,1/11)		BOCcos(15,2.5)
Sub-carrier frequency	1.023 MHz and 6.138 (Two sub-carriers)		15.345 MHz
Code frequency	1.023 MHz		2.5575 MHz
Signal component	Data	Pilot	Data
Primary PRN code length	4092		N/A
Secondary PRN code length	-	25	N/A
Data rate	250 sps	-	N/A

Table A4. Galileo E6 signal characteristics overview

Service name	E6 CS data*	E6 CS pilot*	E6 PRS
Centre frequency	1278.75 MHz		
Spreading modulation	BPSK(5)	BPSK(5)	BOCcos(10,5)
Sub-carrier frequency	-	-	10.23 MHz
Code frequency	5.115 MHz		

Signal component	Data	Pilot	Data
Primary PRN code length	5115	5115	N/A
Secondary PRN code length	-	100	N/A
Data rate	1,000 sps	-	N/A

Table A5. Galileo E5 signal characteristics overview

Service name	E5a data*	E5a pilot*	E5b data*	E5b pilot*
Centre frequency	1191.795 MHz			
Spreading modulation	AltBOC(15,10)			
Sub-carrier frequency	15.345 MHz			
Code frequency	10.23 MHz			
Signal component	Data	Pilot	Data	Pilot
Primary PRN code length	10230			
Secondary PRN code length	20	100	4	100
Data rate	50 sps	-	250 sps	-

Typical characteristics of Galileo FOC satellites for SSV

The typical characteristics of Galileo FOC satellites to support the interoperable GNSS SSV are provided in this section. Detailed and exhaustive measurement campaigns during the satellite ground testing were conducted for FOC-class satellites in order to characterize the typical emissions at SSV-relevant off-boresight angles. The results as obtained from different FOC-class satellites are summarized in the following tables.

The typical characteristics provided next shall not be interpreted as commitment from the Galileo Programme for existing or future Galileo FOC-class satellites. Official information related to SSV characteristics of Galileo will be published in the future through the Galileo Open Service - Service Definition Document.

In order to ensure the support of Galileo to SSV users, actions are put in place in to maintain and enforce these capabilities in the future.

The support of Galileo FOC satellites to the interoperable GNSS SSV is provided in the following table.

Table A6. Galileo SSV characteristics

Definition	Notes
Lower SSV: 3,000 to 8,000 km altitude	Four Galileo signals available simultaneously a majority of the time, but Galileo signals over the limb of the Earth become increasingly important. Capability of the user to receive both from nadir and from zenith is considered.
Upper SSV: 8,000 to 36,000 km altitude	Nearly all Galileo signals received over the limb of the Earth. Users will experience periods when no Galileo satellites are available.

Parameters	Typical characteristics of nominal GSAT02xx satellites	
User range error [1]	1.1 metres	
Signal centre frequency		
E1B/C	1575.42 MHz	
E6B/C	1278.75 MHz	
E5b	1206.45 MHz	
E5ABOC	1191.795 MHz	
E5a	1176.45 MHz	
Minimum received civilian signal power	0 dBi RCP antenna at GEO	Reference off-boresight angle
E1B/C	-182.5 dBW	20.5 deg
E6B/C	-182.5 dBW	21.5 deg
E5b	-182.5 dBW	22.5 deg
E5ABOC	-182.5 dBW	23.5 deg
E5a	-182.5 dBW	23.5 deg
Signal availability [2]		
Lower SSV	**At least 1 signal**	**4 or more signals**
E1B/C	100%	> 99% [7]
E6B/C	100%	100%
E5b	100%	100%
E5a or E5ABOC	100%	100%
Upper SSV	**At least 1 signal**	**4 or more signals**
E1B/C	>= 64% [3]	0%
E6B/C	>= 72% [4]	0%
E5b	>= 80% [5]	0%
E5a or E5ABOC	>= 86% [6]	0%
Note 1: This value represents pseudorange accuracy, not the final user position error, which is dependent on many mission-specific factors such as orbit geometry and receiver design.		
Note 2: Assumes a nominal, Galileo Walker 24/3/1 constellation, full navigation message availability and no Galileo spacecraft failures. Signal availability is provided at 95% of the areas within the specific altitude.		
Note 3: Assumes less than 93 minutes of continuous outage time.		
Note 4: Assumes less than 75 minutes of continuous outage time.		
Note 5: Assumes less than 64 minutes of continuous outage time.		
Note 6: Assumes less than 54 minutes of continuous outage time.		
Note 7: >99% at 21.5 deg (-182.5 dBW).		

A4. BDS SSV characteristics

BDS constellation

The current regional BeiDou Navigation Satellite System (BDS) space segment consists of five geostationary orbit satellites (GEO), five IGSO and four medium Earth orbit satellites (MEO). The GEO satellites are operating in orbit with an altitude of 35,786 kilometres and positioned at 58.75°E, 80°E, 110.5°E, 140°E and 160°E respectively. The IGSO satellites are operating in orbit with an altitude of 35,786 kilometres and an inclination of 55° to the equatorial plane. The phase difference of right ascensions of ascending nodes of those orbital planes is 120°. The sub-satellite tracks for three of those IGSO satellites are coincided while the longitude of the intersection point is at 118°E. The sub-satellite tracks for the other two IGSO satellites are coincided while the longitude of the intersection point is at 95°E. The MEO satellites are operating in orbit with an altitude of 21,528 kilometres and an inclination of 55° to the equatorial plane. The satellite recursion period is 13 rotations within seven days. The phase is selected from the Walker24/3/1 constellation, and the right ascension of ascending node of the satellites in the first orbital plane is 0°. The current four MEO satellites are in the seventh and eighth phases of the first orbital plane, and in the third and fourth phases of the second orbital plane respectively. The 5 GEO + 5 IGSO constellation provides regional coverage, and the MEO satellites were deployed for performance improvement, system redundancy and flight test for global service.

By 2020, the space constellation of BDS will consist of 5 GEO satellites, 3 IGSO satellites and 27 MEO satellites. Stationary positions of the 5 GEO satellites are consistent with the regional system. The crossing longitude of 3 IGSO satellites is 118°E. A total of 24 out of the 27 MEO satellites shape up into Walker 24/3/1 constellation, and the remaining 3 are separately taken as spare satellites in each orbit plane. The GEO and IGSO satellites are deployed to offer better anti-shielding capabilities, regional augmentation, short message communication and other active services.

BDS OS signals

The current regional BDS transmit two operational open service (OS) signals: B1I and B2I. The nominal frequency of the B1I signal is 1561.098 MHz, and the nominal frequency of the B2I signal is 1207.140 MHz. The detailed signal characteristics are specified in the BDS SIS-ICD 2.0.

The performance of modernized OS signals B1-C (1575.42MHz), B2-a and B2-b (1191.795MHz) broadcast by new-generation navigation satellites is enhanced significantly compared to the operational OS signals. The modernized signals of BDS can provide better compatibility and interoperability with other navigation satellite systems. Related documents will be updated and published in step with BDS construction and development.

Typical characteristics of BDS satellites for SSV

In this section the typical characteristics of BDS satellite are provided.

The parameters were measured from pre-flight ground test of the new-generation navigation satellites deployed in 2015. The parameters are provided to support the assessment of the interoperable GNSS SSV and do not represent a specification for existing or future

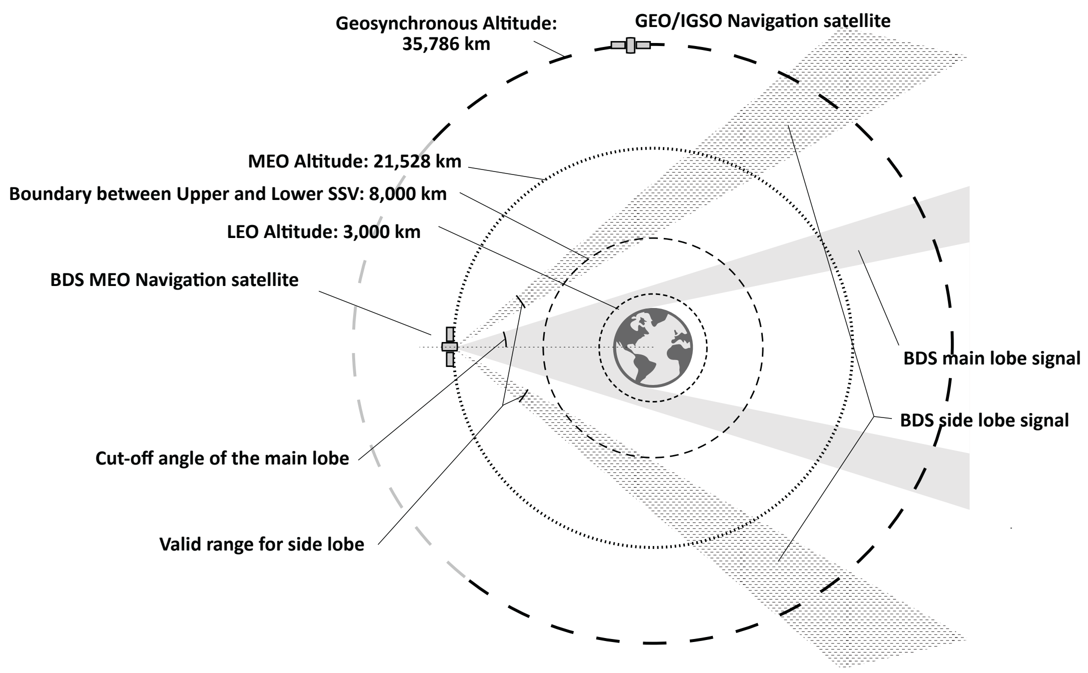
BDS satellites. BDS is taking actions in SSV performance characterization and specification. In future, official information related to SSV characteristics of BDS will be published through the BDS Open Service Performance Standard Document.

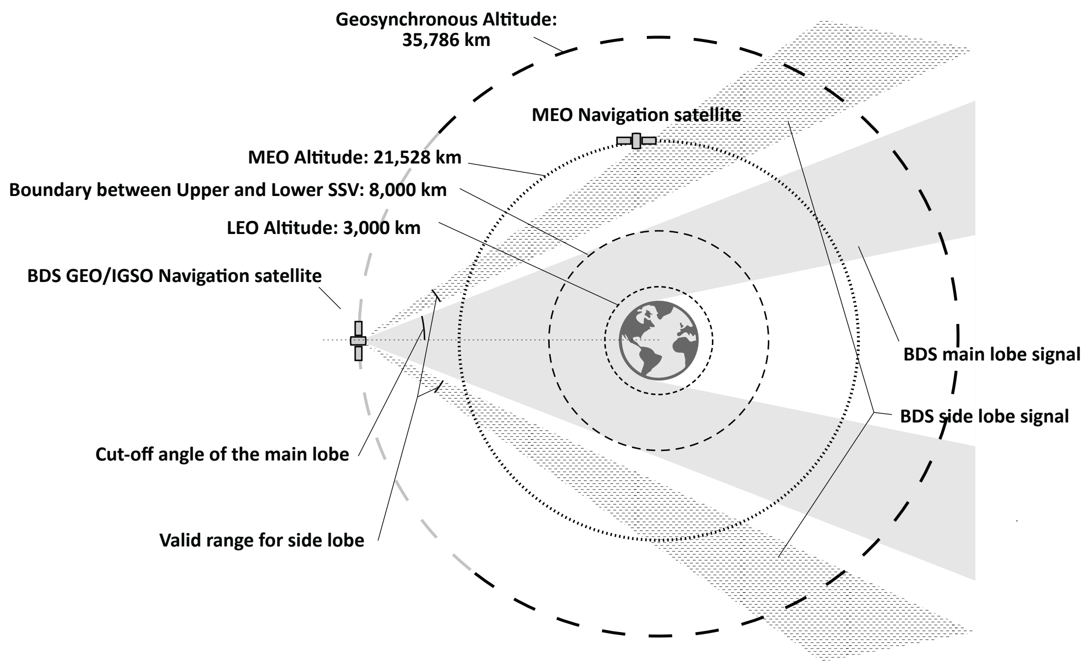
The signal availability below is evaluated by assuming a BDS constellation consists of 5 GEO satellites, 3 IGSO satellites and 24 MEO satellites. (The 3 spare MEO satellites are not incorporated.)

Table A7. BDS MEO/GEO/IGSO SSV characteristics

Parameters	Value	
User range error [1]	2.5 metres [9]	
Signal centre frequency		
B1	1575.42 MHz	
B2	1191.795MHz	
Minimum received civilian signal power	0 dBi RCP antenna at GEO	Reference off-boresight angle
B1 (MEO)	-184.2 dBW	25 deg
B1 (GEO/IGSO)	-185.9 dBW	19 deg
B2 (MEO)	-182.8 dBW	28 deg
B2 (GEO/IGSO)	-184.4 dBW	22 deg
Signal availability [2]		
Lower SSV [7]	At least 1 signal	4 or more signals
B1	99.9%	96.2%
B2	100%	99.9%
Upper SSV [8]	At least 1 signal	4 or more signals
B1	97.4% [3]	24.1% [4]
B2	99.9% [5]	45.4% [6]
Note 1: This value represents pseudorange accuracy, not the final user position error, which is dependent on many mission-specific factors such as orbit geometry and receiver design.		
Note 2: Signal Availability is evaluated by averaging performance over the 8,000km sphere for lower SSV and 36,000km for upper SSV.		
Note 3: Assumes less than 45 minutes of continuous outage time.		
Note 4: Partial region will be not visible for four signals.		
Note 5: Assumes less than 7 minutes of continuous outage time.		
Note 6: Assumes less than 644 minutes of continuous outage time.		
Note 7: The antenna for a user in the Lower SSV is considered to be omnidirectional.		
Note 8: The antenna for a user in the upper SSV is considered to be nadir-pointing.		
Note 9: The URE value is from specification of current regional BDS and will be enhanced significantly with the construction of global system.		

Figure A3. BDS geometry for SSV characteristics (left: MEO, right: IGSO/GEO)





A5. Quasi-zenith satellite system SSV characteristics

The QZSS is a regional satellite constellation whose objective is to provide a fully GPS-compatible and interoperable signal to the East Asia and Oceania region.

The Quasi-Zenith Satellite 1 (QZS-1) was launched in September 2010 and has been in service since then. QZS-2 to QZS-4 were launched in June, August and October 2017, respectively. Starting November 2018, the four-satellite constellation (including one geostationary satellite and three inclined geosynchronous orbit satellites) will be in service to provide positioning signals over the East Asia and Oceania Region. A replacement for QZS-1 is expected to be launched in 2020. Plans include three additional satellites which will constitute a seven-satellite constellation for QZSS. The completion of the seven-satellite constellation is expected to be around 2023.

The current specification for a four-satellite constellation is not applicable for SSV application (i.e. no specification for SSV.) However, the Government of Japan is planning to measure antenna pattern and phase characteristics of each satellite before launch, and the information will be available to the public. For the seven-satellite constellation and beyond, the Government of Japan is still reviewing the SSV application.

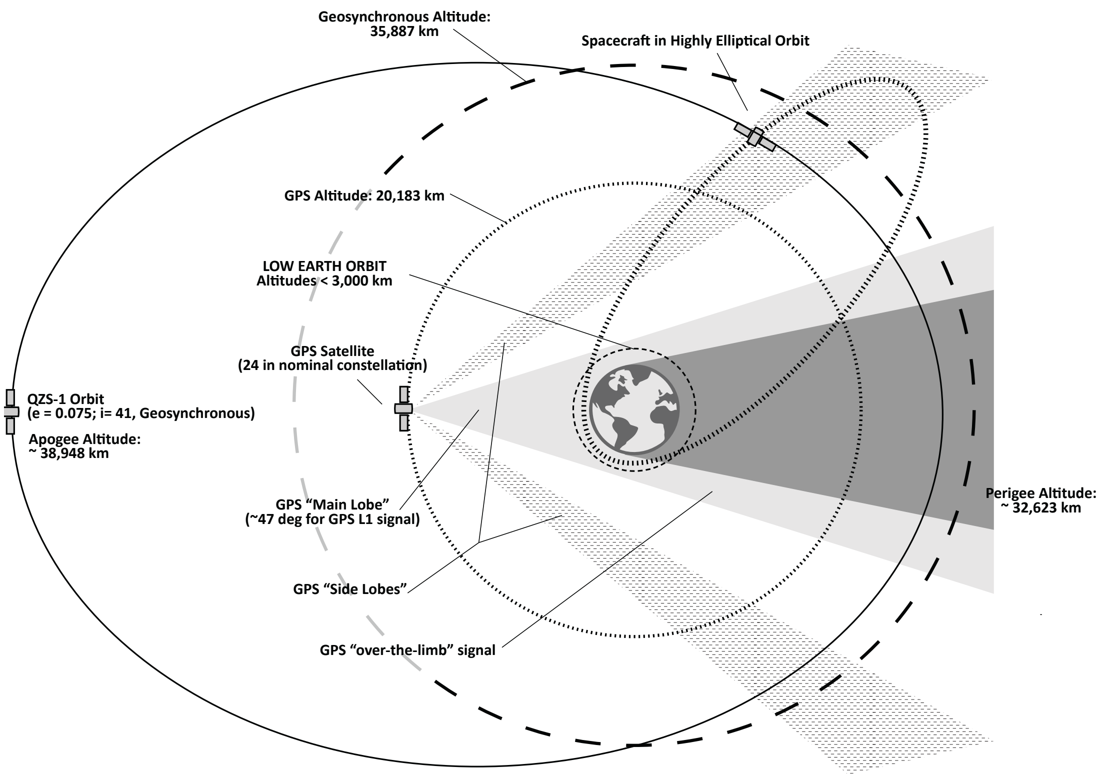
Table A8. QZSS SSV characteristics

Definition	Notes
Lower SSV: 3,000 to 8,000 km altitude	QZS-1 signals are available above the East Asia and Oceania region. Signal-in-space user range error accuracy is 2.6 metres (95%).
Upper SSV: 8,000 to 36,000 km altitude	QZS-1 signals received over the limb of the Earth. Accuracies ranging from 10 to 100 metres are feasible (post-processed) depending on receiver sensitivity and local oscillator stability.

Parameters	Value	
User range error[1]	2.6 metres (95%)	
Signal centre frequency		
L1 C/A	1575.42 MHz	
L1C	1575.42 MHz	
L2 C	1227.60 MHz	
L5 (I5 or Q5)	1176.42 MHz	
Minimum received civilian signal power	0 dBi RCP antenna at GEO	Reference off-boresight angle
L1 C/A	-185.3 dBW	22 deg
L1C	-185.3 dBW	22 deg
L2 C	-188.7 dBW	24 deg
L5 (I5 or Q5)	-180.7 dBW	24 deg

Signal availability[2]		
Lower SSV	At least 1 signal	4 or more signals
L1	100%[3]	N/A
L2, L5	100%[3]	N/A
Upper SSV	At least 1 signal	4 or more signals
L1	≥ 54%[4]	N/A
L2, L5	≥ 54%[4]	N/A
Note 1: This value represents pseudorange accuracy, not the final user position error, which is dependent on many mission-specific factors such as orbit geometry and receiver design.		
Note 2: Assumes a nominal, no QZS-1 spacecraft failures and no orbit manoeuvre. Signal availability at 95% of the areas within the specific altitude.		
Note 3: Assumes user satellites between 20 degrees (east) and 120 degrees (west).		
Note 4: Assumes user satellites between 9 degrees (east) and 99 degrees (west).		

Figure A4. QZSS geometry for SSV characteristics



A6. Navigation with Indian Constellation SSV characteristics

The NavIC is an ISRO initiative to build an independent satellite navigation system to provide precise PVT to users over the Indian region. The system is designed to provide position accuracy better than 20 metres (2 σ) and time accuracy better than ± 40 ns (2 σ) over the Indian subcontinent and a region extending to about 1,500 km around India for a dual frequency user. The NavIC system mainly consists of space segment, ground segment and user segment.

NavIC space segment

The space segment consists of seven satellites, three satellites in GEO and four satellites in IGSO with inclination of 29° to the equatorial plane. Along with these seven satellites, an additional four IGSO satellites are planned. These additional four satellites are yet to be coordinated. All the satellites will be visible in the service region for 24 hours and will transmit navigation signals in both L5 and S bands.

Ground segment

The ground segment is responsible for the maintenance and operation of the NavIC constellation. It provides the monitoring of the constellation status, correction to the orbital parameters and navigation data uploading. The ground segment comprises telemetry, tracking and command (TTC) & navigation data uplink stations, Navigation Control Centre, Spacecraft Control Centre, IRNSS/NavIC Network Timing Centre, IRNSS/NavIC Range and Integrity Monitoring Stations, CDMA Ranging Stations and data communication links.

User segment

The user segment mainly consists of:

1. A dual frequency NavIC receiver capable of receiving navigation signals in L5 and S band frequencies, download the navigation data and compute the user position solution for restricted service (RS) and standard positioning service (SPS)
2. A single frequency receiver for SPS
3. A combined GNSS receiver compatible with NavIC, BDS, Galileo, GPS, GLONASS and QZSS

NavIC signals

NavIC basically provides two types of services in the L5 (1176.45 MHz) frequency band, namely SPS and RS. The NavIC L5 SPS signal contributes to the interoperable GNSS SSV. The NavIC signal parameters in the L5 band are provided below.

Table A9. NavIC L5 signal parameters

Parameters	NavIC L5 signal parameters
Carrier frequency	1176.45MHz
Signal bandwidth	±12MHz
Modulation type	BPSK-R(1)
Chip rate	1.023 Mcps
Data rate	25 bps/50 sps
Spreading code type	Gold
Spreading code period	1 ms

Typical characteristics of NavIC SSV

The NavIC L5 SPS signal contributes to the interoperable GNSS SSV and the SSV parameters are provided in the table below.

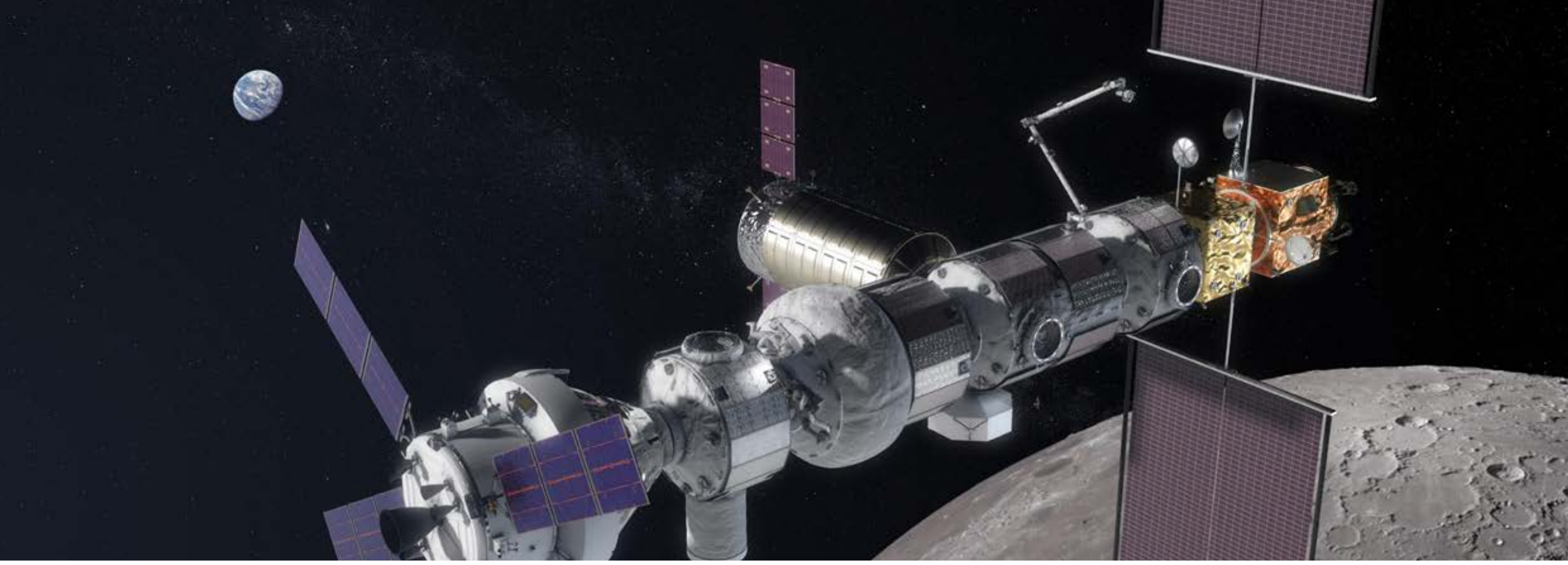
The typical characteristics provided next shall not be interpreted as commitment from the NavIC system. Official information related to SSV will be published in the future through the NavIC SIS ICD.

Table A10. NavIC SSV characteristics

Definitions
Lower SSV: 3,000 to 8,000 km altitude
Upper SSV: 8,000 to 36,000 km altitude. The signals of all GNSS services together play a major role in ensuring accuracy in this service volume.

Parameters	Value	
User range error (without Iono)[1]	2.1 metres	
Minimum received civilian signal power, in dBW	**0 dBi RCP antenna at GEO**	**Reference off-boresight angle**
L5	-184.54	16 deg
Signal availability[2]	**At least 1 signal**	**4 or more signals**
Lower SSV[3]		
L5	98.00%[4]	51.40%[5]
Upper SSV[6]		
L5	36.9%[7]	0.6%[8]
Note 1: This value represents pseudorange accuracy, not the final user position error, which is dependent on many mission-specific factors such as orbit geometry and receiver design.		
Note 2: Assumes a nominal, optimized NavIC constellation of 11 satellites and no NavIC spacecraft failures.		

Note 3: The antenna for a user in the Lower SSV is considered to be omnidirectional.
Note 4: Maximum continuous outage time of the constellation is 348 mins (scenario duration of 14 days), signal availability at 96.5% of the areas at a specific altitude within the specified SSV.
Note 5: Maximum continuous outage time of the constellation is 20,160 mins (scenario duration of 14 days), signal availability at 47.4% of the areas at a specific altitude within the specified SSV.
Note 6: The antenna for a user in the upper SSV is considered to be nadir-pointing, signal availability at 35% of the areas at a specific altitude within the specified SSV.
Note 7: Maximum continuous outage time of the constellation is 20,160 mins in upper SSV (scenario duration of 14 days).
Note 8: Maximum continuous outage time of the constellation is 20,160 mins in upper SSV (scenario duration of 14 days), signal availability at 0% of the areas at a specific altitude within the specified space service volume.



Annex B. Detailed simulation configuration and results

This chapter provides the full set of SSV simulation results, as well as the configuration and methodology used to execute the simulations themselves. This information should allow the simulations to be independently implemented and the results to be independently reproduced.

B1. Global SSV simulations

This section will cover the globally averaged SSV simulations. These simulations analyse the SSV using both geometrical access constraints alone as well as combined geometrical and radio frequency access constraints. In both cases, a fixed grid of points is used to represent the set of receiver locations.

Geometrical analysis configuration

The geometrical access-only simulations are based on the orbit propagation set-up and access considerations specified in table B1, utilizing the orbital parameters specified for each constellation in annex C. Note that the effective Earth radius used when determining access is taken as the sum of the spherical Earth radius and the atmospheric radius.

Table B1. Keplerian orbital simulation assumptions

Parameter	Value
Initial simulation date and time (UTC)	1 January 2016 12:00:00
Simulation duration (days)	14
Simulation time step (minutes)	1
Earth universal gravitational parameter (m^3/s^2)	3.986004415e14

Parameter	Value
π (standard Matlab π)	3.141592653589793
Spherical Earth radius (km)	6378
Atmospheric radius (km)	50
Geostationary grid altitude (km)	36,000
Earth rotation rate (rad/day)	2π(1.002737811911135448)
Earth rotation angle at reference epoch (rad)	2π(0.7790572732640)

The global analysis represents the SSV receiver locations using an equal-area grid of points, as illustrated in figure B1. Each point represents a receiver's fixed ground track location on the Earth's surface from its target MEO or GEO altitude. The grid is specifically equal-area so that results computed using the points are not biased to regions containing many more points. It has roughly 4° spacing near the equator and comprises 2562 points.

Figure B1. User grid locations over Earth's surface

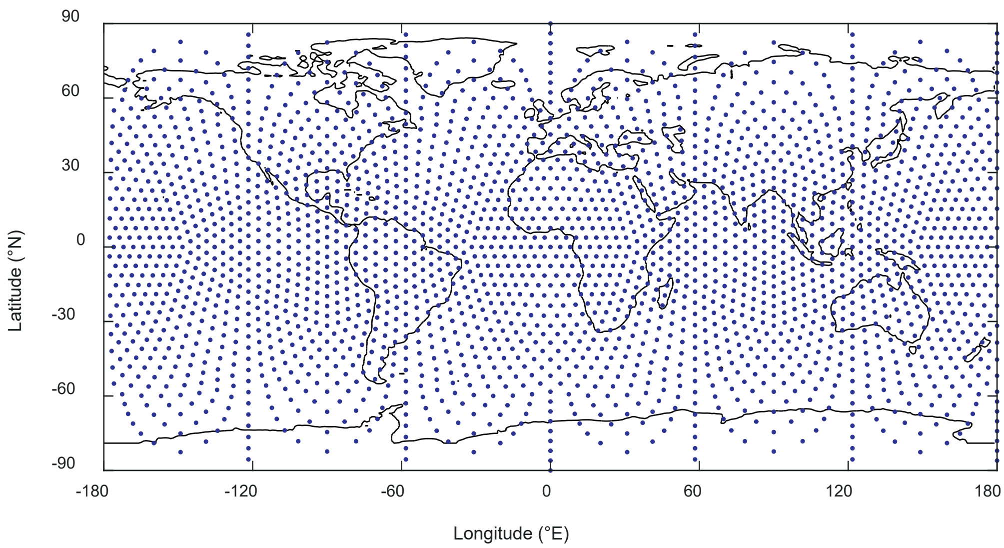


Table B2 summarizes the GNSS transmit beamwidths for both the L1 and L5 frequency bands that are studied in the simulations. Note that for the BDS constellation, the beamwidth is defined separately for the satellites in MEO and the satellites in GEO/IGSO. Also note that the NavIC L1 beamwidth is not applicable, as NavIC does not transmit in the L1 frequency band. It is also important to note that all L5 beamwidths are larger than their constellation's L1 beamwidth as a result of antenna physics, as that will directly impact performance results.

Table B2. GNSS transmitter beamwidths

GNSS constellation	L1 beamwidth (°)	L5 beamwidth (°)
BDS	25 (MEO) 19 (GEO/IGSO)	28 (MEO) 22 (GEO/IGSO)
Galileo	20.5	23.5
GLONASS	20	28
GPS	23.5	26
NavIC	N/A	16
QZSS	22	24

The attitude of each GNSS transmitting antenna is determined according to table B3, depending on which constellation the spacecraft belongs to. Additionally, depending on the simulation, the receiving antenna's boresight is pointed either nadir or zenith relative to the centre of the Earth, and its field of view is defined as either hemispherical or omnidirectional.

Table B3. Boresight pointing direction for GNSS transmit antenna

GNSS constellation	Transmitter boresight
NavIC	5°N, 83°E
All others	Nadir (Earth's centre)

Geometrical analysis methodology

The overall simulation methodology is performed in multiple steps, which are listed below:

1. Propagate orbit position vectors into Earth-centred Earth-fixed frame coordinates over scenario time instances.
2. Calculate angle off-GNSS-boresight vector to all SSV grid points over scenario time instances.
3. Calculate angle off-SSV-boresight vector to all GNSS orbit positions over scenario time instances.
4. Determine geometrical access using maximum GNSS beamwidth consideration, Earth blockage consideration, and SSV hemispherical/omnidirectional beamwidth consideration over scenario time instances for all SSV grid points.
5. Calculate figures of merit from access determination over scenario time instances over all SSV grid points.

Geometrical analysis results

Results in table B4 and table B5 provide the globally averaged SSV expected system performance when considering only geometrical access constraints. Please note that the reported availability figures are evaluated as the average availability over all grid points and all time epochs. Since the grid points are defined as having equal area pertaining to each grid point, averaging of performance over the grid points can be done using a pure mean calculation, without additional scale factors needing to be applied.

Note that all system availability metrics are rounded down to the next lowest tenths decimal place, and outage time is limited to integer numbers of minutes due to the nature that the simulations were performed on one-minute intervals.

Table B4. Geometrical access performance with GEO and MEO/omnidirectional scenarios

		Upper SSV (nadir antenna)				Lower SSV (omni antenna)			
Band	Constellation	At least 1 signal		4 or more signals		At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	90.5	111	4.8	*	100	0	99.6	45
	GLONASS	93.9	48	7	*	100	0	99.8	24
	Galileo	78.5	98	1.2	*	99.9	11	95	60
	BDS	97.4	45	24.1	*	100	0	100	0
	QZSS	26.7	*	0.8	*	99.6	197	79.4	*
	Combined	**99.9**	**29**	**98.1**	**93**	**100**	**0**	**100**	**0**
L5/L3/E5a/B2	GPS	96.9	77	15.6	1180	100	0	99.9	16
	GLONASS	99.9	8	60.3	218	100	0	100	0
	Galileo	93.4	55	4.2	*	100	0	100	0
	BDS	99.9	7	45.4	644	100	0	100	0
	QZSS	30.5	*	1.5	*	99.6	197	79.4	*
	NavIC	36.9	*	0.6	*	98	348	51.4	*
	Combined	**100**	**0**	**99.9**	**15**	**100**	**100**	**0**	**0**

*No signal observed for the worst-case grid location for maximum simulation

Table B5. Geometrical access performance with MEO/zenith and MEO/nadir scenarios

Band	Constellation	Lower SSV with zenith antenna				Lower SSV with nadir antenna			
		At least 1 signal		4 or more signals		At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	84.0	*	0	*	100	0	95.9	93
	GLONASS	80.8	195	0	*	100	0	95.5	97
	Galileo	84.0	*	0	*	99.8	13	71.5	262
	BDS	97.5	181	34.2	*	100	0	99.6	31
	QZSS	51.0	*	15.4	*	84.1	*	28.3	*
	Combined	**99.9**	**37**	**91**	*	**100**	**0**	**100**	**0**
L5/L3/E5a/B2	GPS	94.3	*	0.1	*	100	0	99.9	25
	GLONASS	100	0	78.4	245	100	0	100	0
	Galileo	96.0	*	2.4	*	100	0	97.4	40
	BDS	99.9	10	62.4	*	100	0	100	0
	QZSS	51.0	*	15.4	*	84.1	*	28.3	*
	NavIC	25.5	*	15.3	*	92.8	*	33.5	*
	Combined	**100**	**0**	**99.9**	**9**	**100**	**0**	**100**	**0**

*No signal observed for the worst-case grid location for maximum simulation

RF access analysis configuration

Please note that for the calculation of the user-received power along the arc where the GNSS satellite is visible, the following assumption has been applied: The minimum radiated transmit power (MRTP) resulting from the inverse link budget calculation is based on the user minimum received civilian signal power as established via the SSV template (annex A). The MRTP is constant for all off-boresight angles smaller than the reference off-boresight angle.

Table B6 provides the minimum received power level per GNSS constellation, along with maximum beamwidth and specific centre frequency, used to derive the MRTP to be considered over the beamwidth following an inverse link budget calculation. Note that for the BDS constellation, the beamwidth is defined separately for satellites in MEO than for those in GEO or IGSO. Table B7 provides additional parameters pertaining to general radio frequency (RF) assumptions used for these calculations and the simulations performed in this analysis.

Table B6. GNSS RF parameters

GNSS constellation	Signal name	Frequency (MHz)	Max beamwidth (°)	Minimum received power (dBW)	MRTP (dBW)
GPS	L1 C/A	1575.42	23.5	-184	9.1
Galileo	E1 B/C	1575.42	20.5	-182.5	10.9
GLONASS	L1	1605.375	20	-179	14.1
BDS MEO	B1	1575.42	25	-184.2	9
BDS GEO/IGSO	B1	1575.42	19	-185.9	9
QZSS	L1 C/A	1575.42	22	-186.1	9.0
GPS	L5	1176.45	26	-182	8.5
Galileo	E5a	1176.45	23.5	-182.5	8.4
GLONASS	L3	1201	28	-178	12.6
BDS MEO	B2	1191.795	28	-182.8	8
BDS GEO/IGSO	B2	1191.795	22	-184.4	8.1
QZSS	L5	1176.45	24	-183.4	9.2
NavIC	L5	1176.45	16	-184.54	7.8

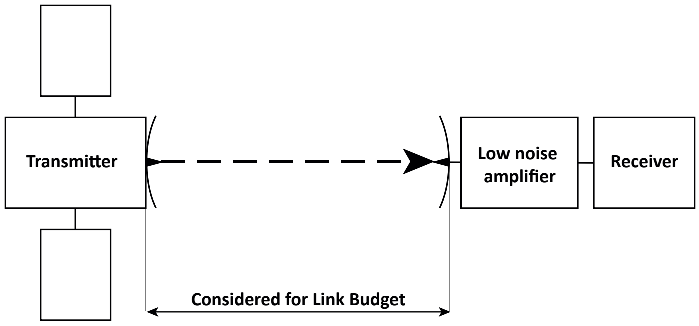
Table B7. General RF simulation assumptions

Parameter	Value
Speed of light (m/s)	299792458
Boltzmann's constant (m^2 kg s^{-2} K^{-1})	$1.38064852 \times 10^{-23}$
Receiver antenna gain (dBi)	0
System noise temperature (K)	290

MRTP inverse link budget calculation

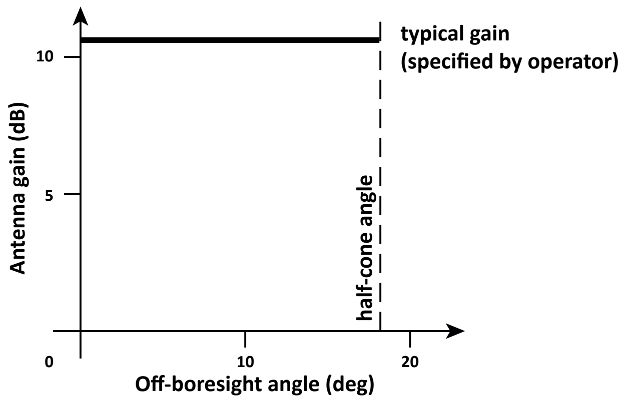
Because MRTP is not included in the SSV template completed by the GNSS service providers, this value must be derived for each constellation using an inverse link budget calculation with the constellation's specified minimum received power. The overall situation for the link budget calculation and the terms taken into account is outlined in figure B2.

Figure B2. Link Budget calculation scenario, where Tx is transmitter on-board the GNSS satellite, LNA is the low noise amplifier and Rx is the user receiver



For the transmitting antenna pattern, on-board the GNSS spacecraft, figure B3 visualizes the basic assumption.

Figure B3. Simplified GNSS satellite antenna pattern, as used in the simulations for GNSS SSV Phase 3



The inverse link budget is defined as

$$MRTP = P_{min} + L_S$$

where P_{min} is the specified minimum received power at GEO and L_S is the free space path loss at the worst-case Earth-limb distance:

$$L_S = 20\log_{10}\frac{4\pi(\theta_{limb})f}{c}$$

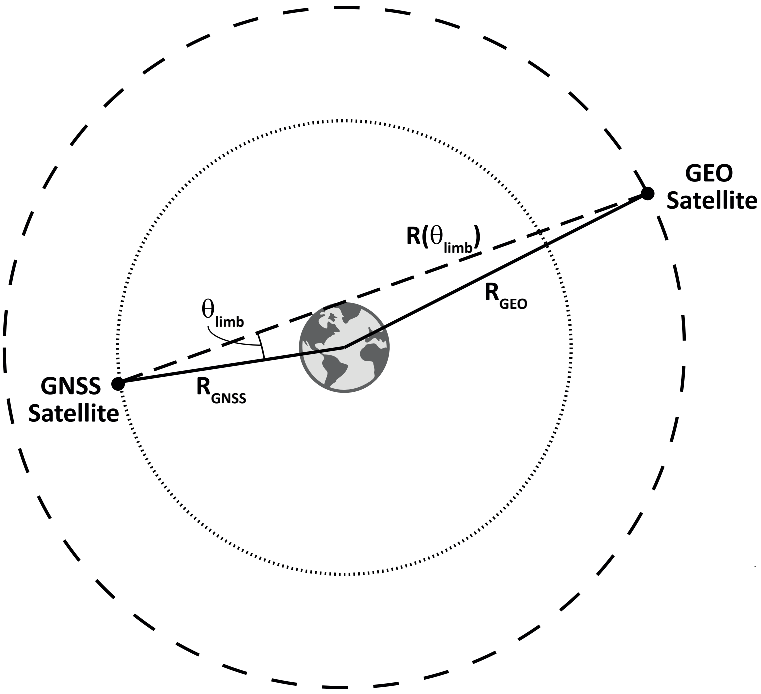
In this equation, f is the centre frequency of the signal from table B6, c is the speed of light from table B7 and $R(\theta_{limb})$ is the distance from the worst-case apogee altitude of the GNSS constellation (see table B8) to a GEO user at 36,000 km altitude, along the line that intersects the Earth's limb.

Table B8. Worst-case apogee altitude used for each constellation in MRTP calculation

GNSS constellation	Signal name	Altitude (km)
GPS	L1 C/A	20181.80
Galileo	E1 B/C	23221.80
GLONASS	L1	19140.33
BDS MEO	B1	21611.86
BDS GEO/IGSO	B1	35912.69
QZSS	L1 C/A	38948.48
GPS	L5	20181.80
Galileo	E5a	23221.80
GLONASS	L3	19140.33
BDS MEO	B2	21611.86
BDS GEO/IGSO	B2	35912.69
QZSS	L5	38948.48
NavIC	L5	35815.71

The geometry used in calculating $R(\theta_{limb})$ is shown in figure B4. Note that the Earth's radius from table B1 should be added to the GNSS and GEO altitudes to obtain R_{GNSS} and R_{GEO}, respectively.

Figure B4. Geometry used in MRTP calculation



Using this geometry, the Earth-limb angle can first be calculated with

$$\theta_{limb} = \arcsin \frac{R_{EARTH}}{R_{GNSS}}$$

This angle can then be used to calculate the Earth-limb distance using the following formula:

$$R(\theta_{limb}) = R_{GNSS} \cos(\theta_{limb}) + \sqrt{R_{GEO}^2 - R_{GNSS}^2 \sin(\theta_{limb})^2}$$

The resulting MRTPs calculated with this method are shown in table B6 for each GNSS constellation.

RF access analysis methodology

The overall simulation methodology adds additional steps compared to the geometrical-only analysis to take into account the RF constraints. The full set of analysis steps are listed below:

- Propagate orbit position vectors into Earth-centred Earth-fixed frame coordinates over scenario time instances.
- Calculate angle off-GNSS-boresight vector to all SSV grid points over scenario time instances.
- Calculate angle off-SSV-nadir-boresight vector to all GNSS orbit positions over scenario time instances.
- Determine geometric access using maximum GNSS beamwidth consideration, Earth blockage consideration, and SSV hemispherical beamwidth consideration over scenario time instances for all SSV grid points.
- Calculate received signal to noise ratio to all SSV grid points from all GNSS transmitters, where geometrical access is available, over scenario time instances.
- Determine RF access comparing received signal-to-noise ratio with minimum threshold signal-to-noise ratio.
- Calculate figures of merit from RF-augmented access determination over scenario time instances over all SSV grid points.

RF access analysis results

Results in table B9 provide the average globalized upper SSV expected system performance when RF-based signal strength constraints are applied to geometrical-0nly access calculations. As stated previously, all system availability metrics provided are rounded down to the next lowest tenths decimal place, and maximum outage time is limited to integer numbers of minutes, due to the nature that the simulations are performed on one minute intervals. The lower SSV was only simulated under geometric conditions; see table 5.2 for details.

Table B9. Upper SSV performance with RF constraints, for various C/No thresholds

Band	Constellation	C / NO_{min} = 15 dB Hz				C / NO_{min} = 20 dB Hz				C / NO_{min} = 25 dB Hz			
		At least 1 signal		4 or more signals		At least 1 signal		4 or more signals		At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	90.5	111	4.8	*	90.5	111	4.8	*	0.0	*	0	*
	GLONASS	93.9	48	7	*	93.9	48	7	*	93.9	48	7	*
	Galileo	78.5	98	1.2	*	78.5	98	1.2	*	0.0	*	0	*
	BDS	97.4	45	24.1	*		70	0.6	*	0.0	*	0	*
	QZSS	26.7	*	0.8	*	0.0	*	0	*	0.0	*	0	*
	Combined	**99.9**	**29**	**98.1**	**93**	**99.9**	**33**	**89.8**	**117**	**93.9**	**48**	**7**	*
L5/L3/E5a/B2	GPS	96.9	77	15.6	1180	96.9	77	15.6	1180	0.0	*	0	*
	GLONASS	99.9	8	60.3	218	99.9	8	60.3	218	99.9	8	60.3	218
	Galileo	93.4	55	4.2	*	93.4	55	4.2	*	0.0	*	0	*
	BDS	99.9	7	45.4	644	99.9	7	32.4	644	0.0	*	0	*
	QZSS	30.5	*	1.5	*	30.5	*	1.5	*	0.0	*	0	*
	NavIC	36.9	*	0.6	*	1.0	*	0	*	0.0	*	0	*
	Combined	**100**	**0**	**99.9**	**15**	**100**	**0**	**99.9**	**15**	**99.9**	**8**	**60.3**	**218**

*No signal observed for the worst-case grid location for maximum simulation

General observations concerning the availability estimates given in table B9 indicate the following:

- Comparing availability estimates between L5 and L1 bands, for the same system, indicates that L5 availability estimates are consistently better than those associated with L1 transmission when comparing codes from the same constellation. For one-signal coverage, L5 availability is 6% to 18% higher (relatively) than for L1 and for four-signal coverage, L5 availability is about 10% to 20% higher (absolutely) than L1. For MOD comparisons that are valid, L5 shows shorter MOD numbers by about 40 minutes. These improvements are averaged over all systems and vary by receiver C/No_{min}.
- Comparing availability estimates between one-signal and four-signal coverage, for the same system, indicates that one-signal availability estimates significantly exceed those associated with fourfold coverage when comparing codes from the same constellation. For C/No_{min} = 15 dB-Hz or 20 dB-Hz one-signal availability exceeds fourfold availability by 60% to 70% and in the L1 band and by about 50% in the L5 band. Insufficient data exist for comparisons of MOD between one-signal and four-signal coverage.
- However, an informal comparison of MOD and availability estimates (where valid) indicates a coarse inverse relationship between MOD and availability. For one-signal coverage when availability falls below about 50%, and for four-signal coverage when availability falls below about 10%, the MOD is likely to be equal to the simulation duration.
- At the threshold of 25 dB/Hz, performance drops to 0% availability for all but the GLONASS system. This set of results show that the required receiver capabilities are quite demanding in order to be able to utilize these extremely low GNSS signal levels.
- The most salient feature in all scenarios is the improvements in availability and MOD brought by the use of multiple constellations. For nearly all cases, L1 and L5 bands, one-signal and four-signal coverage, C/No_{min} = 15 dB-Hz, 20 dB-Hz and 25 dB-Hz, availability for the multi-constellation case is nearly 90% or better and MOD is limited to less than 120 minutes. Not until we get to the L1 band with four-signal coverage with C/No_{min} = 25 dB-Hz do availability and MOD drop precipitously (7% and "*"). These improvements for the multiple-system receiver are realized even in cases where individual systems are providing availability of less than 10% and MOD is at "*" (e.g. L1 band with four-signal coverage with C/No_{min}= 20 dB-Hz). For the global constellations (GPS, GLONASS, Galileo and BDS) a one-signal availability is indicated at a very high level: higher than 90% for the L5 band and C/No_{min} = 15 dB-Hz. However, only multi-constellation allows very high availability (> 99.5%) for four-signal coverage.

B2. Mission-specific SSV simulations

This section describes the detailed assumptions, methodology, and results associated with the three mission-specific SSV performance simulations performed: a geostationary mission, a highly elliptical Earth orbiting mission, and a lunar mission. These simulations are intended to illustrate the benefits of the multi-GNSS SSV to specific mission classes, beyond the globally characterized performance of the GNSS constellations themselves.

Common assumptions and methods

In all three mission simulations, certain common assumptions and methods were used for consistency.

The mission spacecraft was modelled in its mission-specific trajectory via either propagation from an initial state using the same assumptions as shown in table B1. The spacecraft attitude is modelled as nadir-pointing in all cases, though in the case of the HEO and lunar cases a zenith antenna is also simulated.

Two receiver antennas were modelled: a patch antenna (used for both L1 and L5 bands), and two different high-gain antennas, one each for L1 and L5. The antenna characteristics are captured in table B10 and correspond to characteristics of readily available antennas available on the open market.

Table B10. Antenna gain patterns for mission-specific simulations

Elevation angle [deg]	Patch antenna gain, L1 and L5 [dBi]	High-gain antenna	
		L1 [dBi]	L5 [dBi]
0	2.8	9.00	8.25
5	2.9	8.97	8.24
10	3.3	8.90	8.05
15	3.6	8.56	7.75
20	4.0	8.02	7.33
25	4.4	7.32	6.79
30	4.5	6.46	6.15
35	4.4	5.45	5.42
40	4.1	4.33	4.61
45	3.7	3.11	3.74
50	2.8	1.82	2.81
55	1.8	0.46	1.83
60	0.8	-0.93	0.83
65	-0.7	-2.34	-0.21
70	-1.7	-3.74	-1.25
75	-3.2	-5.12	-2.31
80	-5.2	-6.47	-3.38
85	-6.2	-7.78	-4.45
90	-8.7	-9.03	-5.52

The GNSS constellations and transmitter models were held identical to those used in the global simulations described above. The link budget characteristics and metrics for visibility were also held constant, with the notable exception of realistic receiver antenna models.

GEO mission

The GEO mission scenario analyses multi-GNSS signal reception for six geostationary satellites. The objective is to obtain more representative signal strength values than in the global analysis by using realistic user antenna patterns on-board the space users for receiving the B1/E1/L1 and B2/E5A/L5 signals.

Spacecraft trajectory

Six GEO satellites are simulated and share the same orbital plane apart from a 60-degree separation in longitude (see table B11). The right ascension of the ascending node (RAAN) angle is used to synchronize the orbit with the Earth rotation angle at the start of the simulation. The true anomaly is used to distribute the six GEO user receivers along the equator. This placement of the satellites was chosen to ensure that even signals from regional GNSS satellites in (inclined) geosynchronous orbits would be visible to at least one of the GEO user receivers (see figure B5).

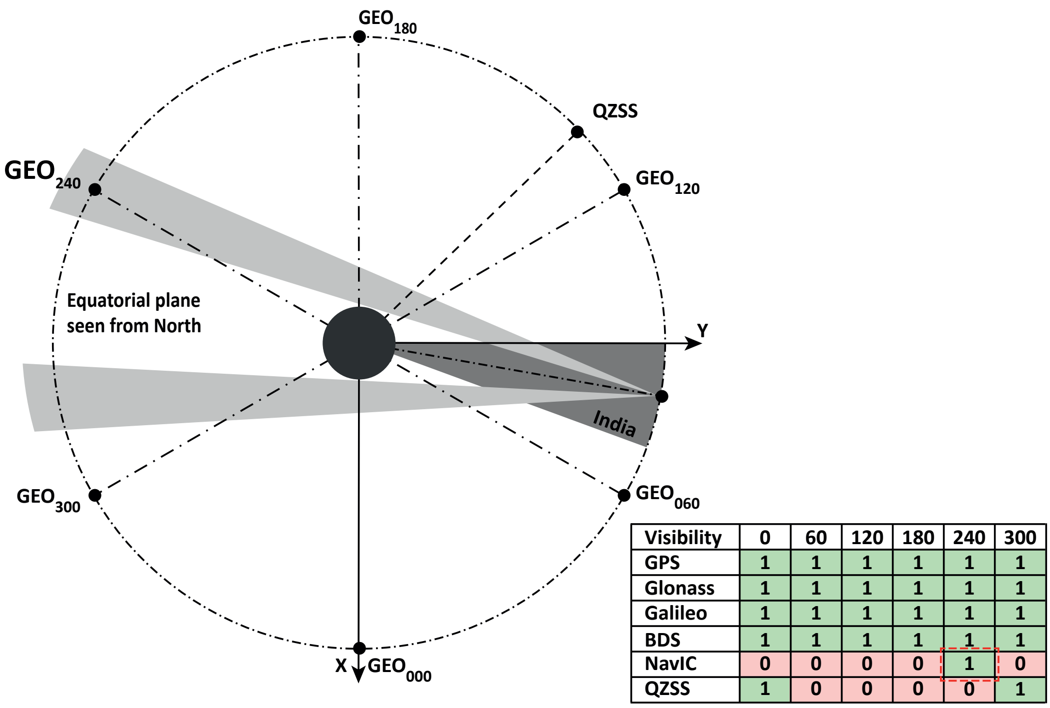
Table B11. GEO osculating Keplerian orbital elements

Epoch	1 Jan 2016 12:00:00 UTC		
Semi-major axis	42164.0 km	Right ascension of the ascending node	100.379461 deg
Eccentricity	0.0	Argument of perigee	0.0 deg
Inclination	0.0 deg	True anomaly	0/60/120/180/240/300 deg

Spacecraft attitude and antenna configuration

The user antenna on-board the user spacecraft is a high-gain antenna that permanently points towards the nadir (centre of the Earth). The user antenna patterns used on the two signals are specified in table B10. The assumed acquisition threshold of the space user receiver is 20 dB-Hz.

Figure B5. Example for visibility of NavIC satellite from the GEO at 240-degree longitude



Visibility	0	60	120	180	240	300
GPS	1	1	1	1	1	1
Glonass	1	1	1	1	1	1
Galileo	1	1	1	1	1	1
BDS	1	1	1	1	1	1
NavIC	0	0	0	0	1	0
QZSS	1	0	0	0	0	1

Results

The six GEO satellites are all in the equatorial orbital plane but phased by 60 degrees in longitude, or four hours in time. The MEO GNSS satellites have orbital periods in the order of 12-14 hours, or about half that of the GEO. This means that the GEO and MEO orbits are almost in phase with each other, in such a way that the visibility patterns at the GEO receiver repeat almost exactly with periods of one day. The MEO satellites move 120 degrees during the four hours interval between GEO satellites, but there are multiple GNSS MEO in each orbital plane. This means that the visibility patterns in terms of number of visible MEO signals are very similar to all six GEO receivers.

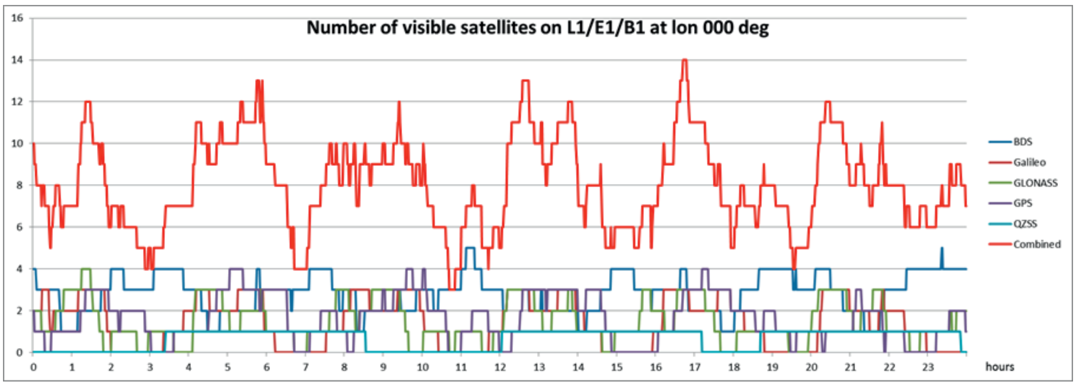
The situation is different for the inclined geosynchronous GNSS satellites of the NavIC, QZSS and BDS constellations. The GEO and IGSO longitudes are frozen relative to each other. At most GEO longitudes, the GNSS satellites in IGSO orbits are never visible, either because the GEO is located outside the half-cone angle of the transmitting satellite, or because the signal is blocked by the Earth. This means that reception of the IGSO GNSS signals is an exception rather than the rule. However, those GEO receivers that do see signals from these transmitters will see them continuously, or at very regular patterns (see figures below for B2/E5A/L5 signal).

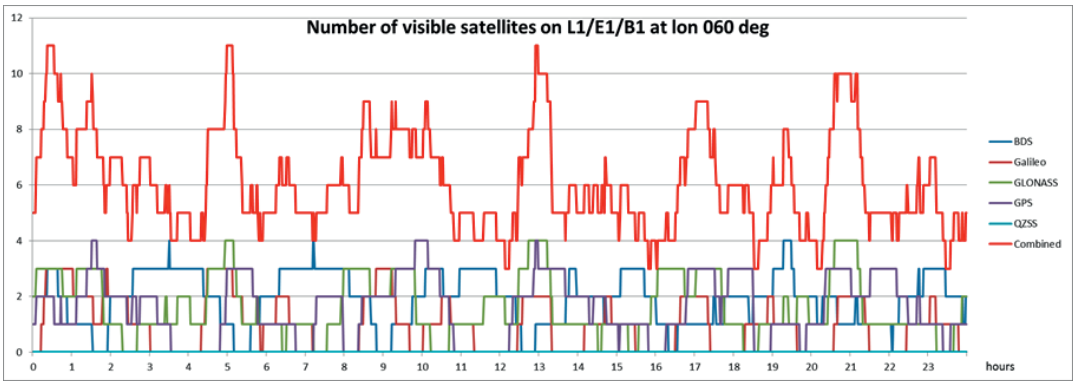
For all six GEO receivers, and at L1 and L5 frequencies, the satellite visibility is shown in the figure B6, figure B7, figure B8 and figure B9 below. The differences are mainly caused by the visibility of BDS, QZSS and NavIC regional geosynchronous satellites at certain GEO longitudes. Notably the GEO at 300-degree and 0-degree longitude appear to benefit from the Asian regional GNSS systems; these are GEO longitudes that are of specific interest to Europe and the North American East coast.

For GEO longitudes where no BDS, QZSS or NavIC geosynchronous satellites are visible, there are typically not more than three L1 signals available from any individual GNSS constellation. Combined, there are almost always four or more signals, and often up to ten signals.

For L5, the individual constellations are slightly better than for L1, and often provide four signals. The combined constellations almost always provide six or more signals. The red lines in figures B-8 and B-9 provide the signal visibility numbers for GEO. The number of signals is constantly varying, sometimes significantly, along an orbit and also at GEO longitude locations. The highest number of signals observed during the simulations was 21 signals at 300 degrees longitude. Note in particular the presence of BDS signals at GEO 300, which brings the combined visibility above 15 satellites through most of the simulation period.

Figure B6. L1/E1/B1 visibility for GEO at 0 deg, 60 deg and 120 deg





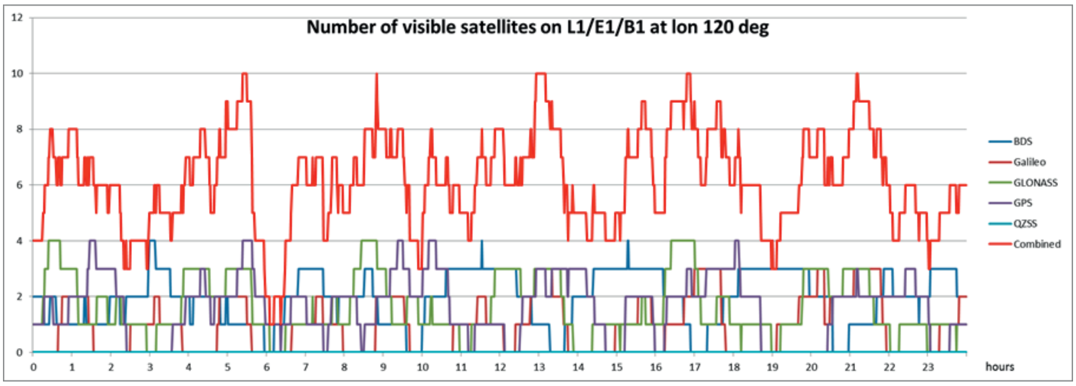
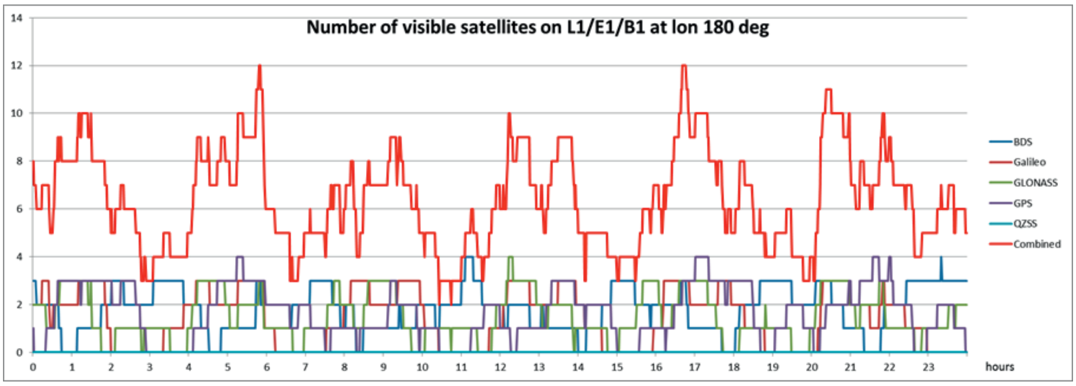
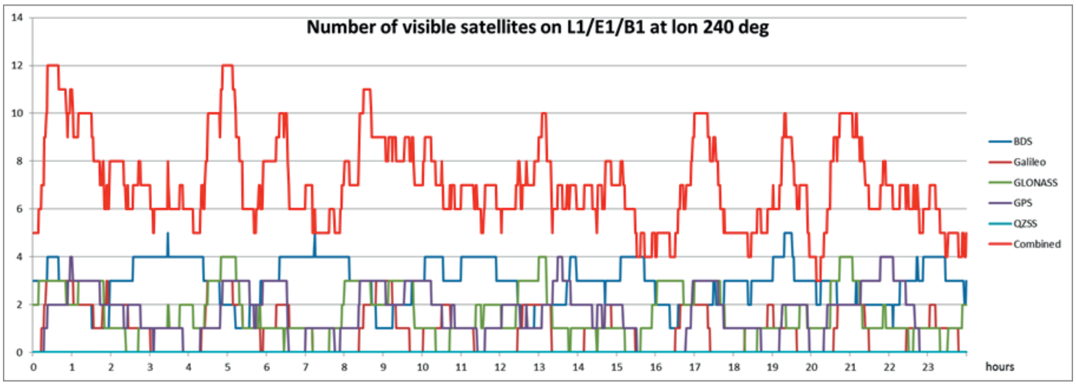


Figure B7. L1/E1/B1 visibility for GEO at 180 deg, 240 deg and 300 deg





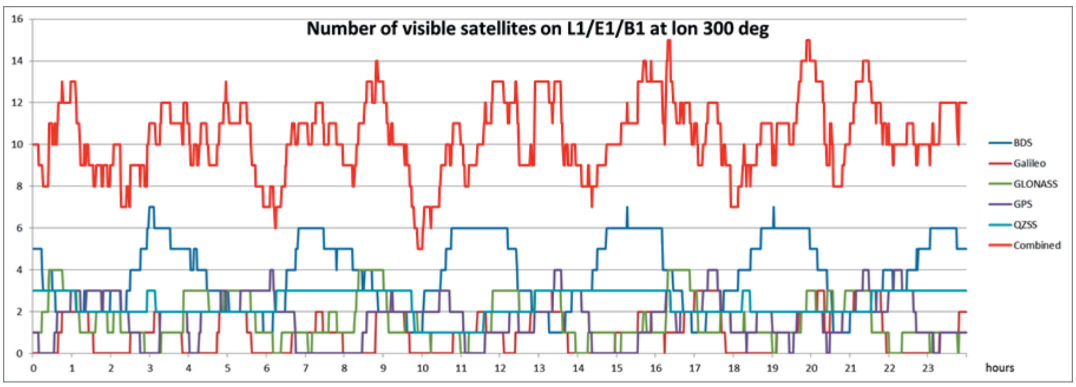


Figure B8. L5/E5a/B2 visibility for GEO at 0 deg, 60 deg and 120 deg

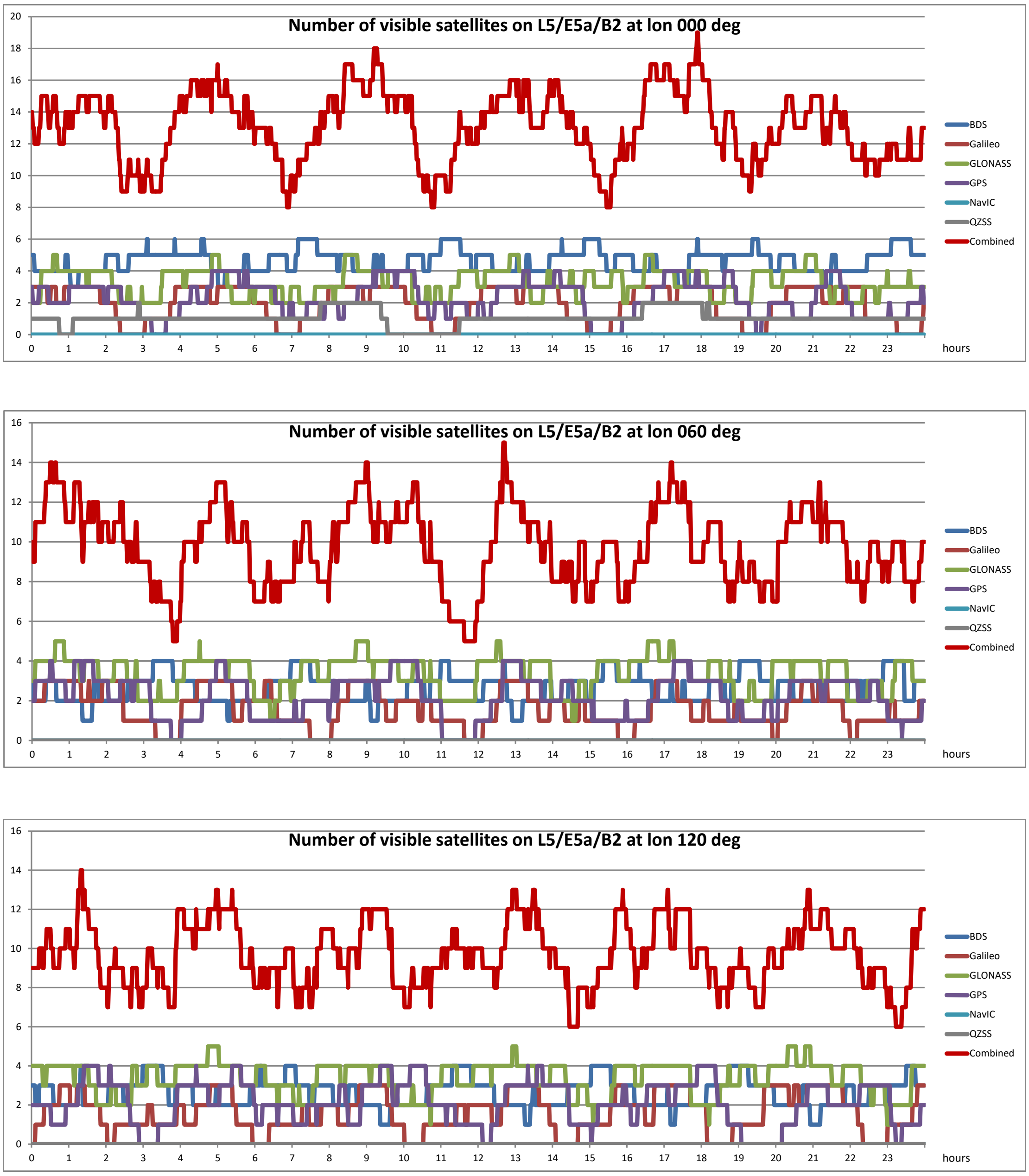
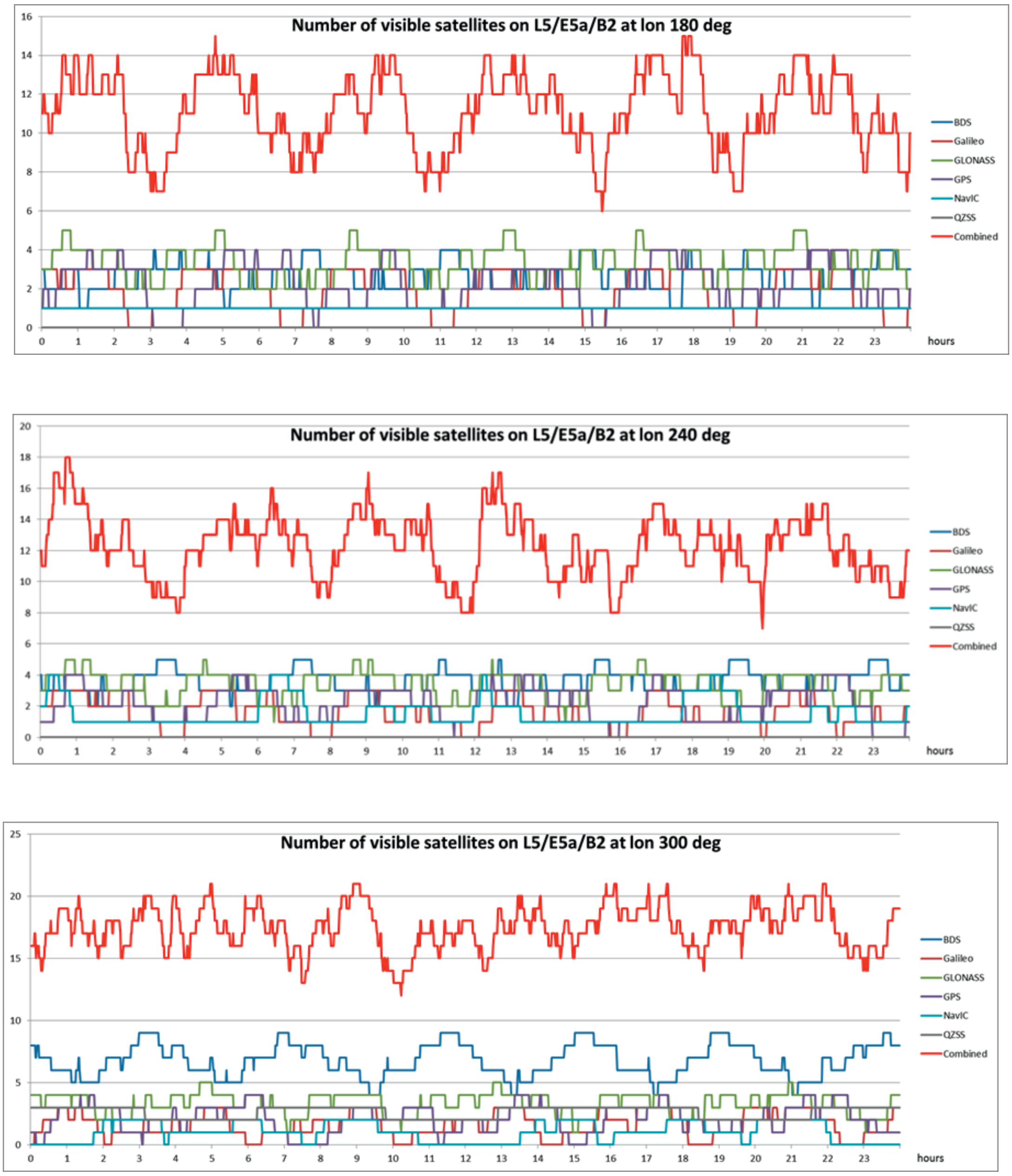


Figure B9. L5/E5a/B2 visibility for GEO at 180 deg, 240 deg and 300 deg



Scientific highly elliptical orbit mission

Spacecraft trajectory

An HEO mission scenario with apogee altitude of about 58,600 km and perigee altitude of 500 km is used to demonstrate the GNSS visibility performance through all the GNSS SSV altitudes, both below and above the GNSS constellations. GNSS visibility conditions near the perigee are similar to those of space user receivers in LEO, with the important difference that the spacecraft is moving very fast – around 8 km/s to 11km/s – so that extreme Doppler shifts occur on the GNSS signals, and visibility times between any particular GNSS satellite and the HEO space user receiver are much shorter than for terrestrial receivers.

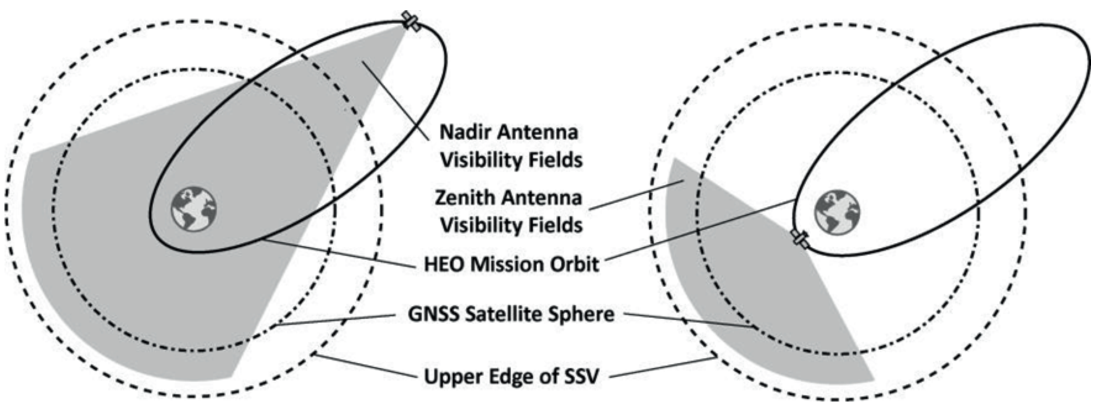
Table B12. Osculating Keplerian HEO orbital elements

Epoch	1 Jan 2016 12:00:00 UTC		
Semi-major axis	35937.5 km	RAAN	0 deg
Eccentricity	0.80870	Argument of perigee	270 deg
Inclination	63.4 deg	True anomaly	0 deg

Spacecraft attitude and antenna configuration

The on-board GNSS antennas are configured in both nadir and zenith-facing sides of the spacecraft. As shown in figure B10 the nadir-pointing antenna with high-gain and narrow-beamwidth can ensure the GNSS signal link from the opposite side of the Earth, including when flying above the GNSS altitude and during the apogee period. The zenith-pointing patch antenna can provide visibility during the perigee period. The antenna patterns for both type of antennas are given in table B10. The acquisition and tracking thresholds of the user receiver were both set to 20 dB-Hz when evaluating the signal availability in the HEO simulation.

Figure B10. Schematic of the HEO mission with nadir and zenith-pointing antennas



Results

Figure B11 and figure B12 shows the GNSS signal availability of all GNSS constellations for the HEO nadir and zenith-pointing antennas over the time of 1.5 HEO orbital periods. Note that when the spacecraft is below the GNSS constellation altitude, the visibility can be significantly improved by combining the signals from both nadir and zenith antennas at the same time. However, within this simulation only the strongest signal from either is employed at a given time. Around apogee, only the nadir-pointing antenna provides signal availability.

Figure B11. Visible GNSS satellites over 1.5 orbital periods of HEO (L1/E1/B1)

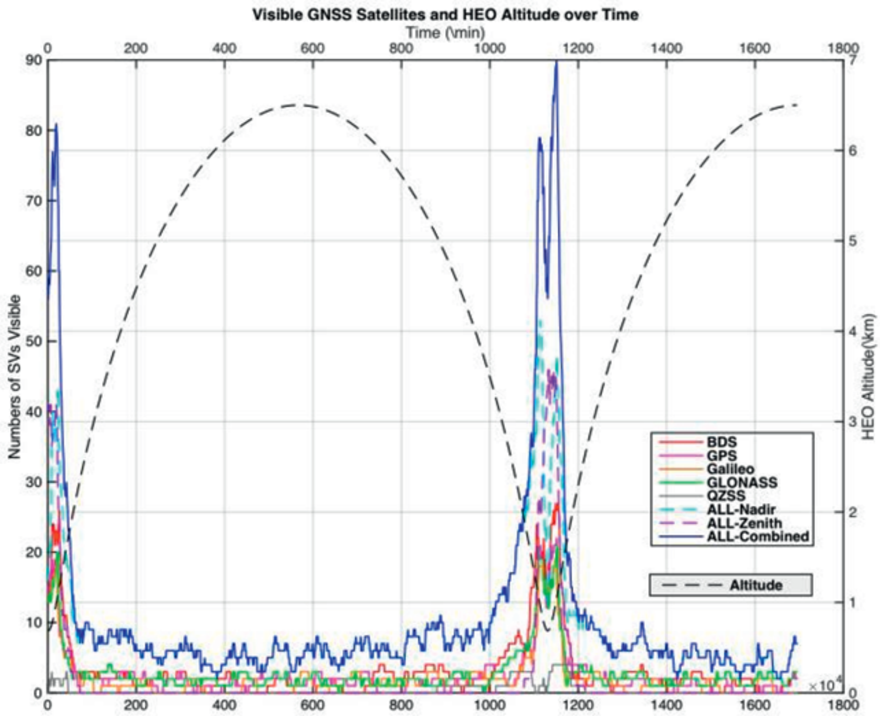


Figure B12. Visible GNSS satellites over 1.5 orbital periods of HEO (L5/L3/E5a/B2)

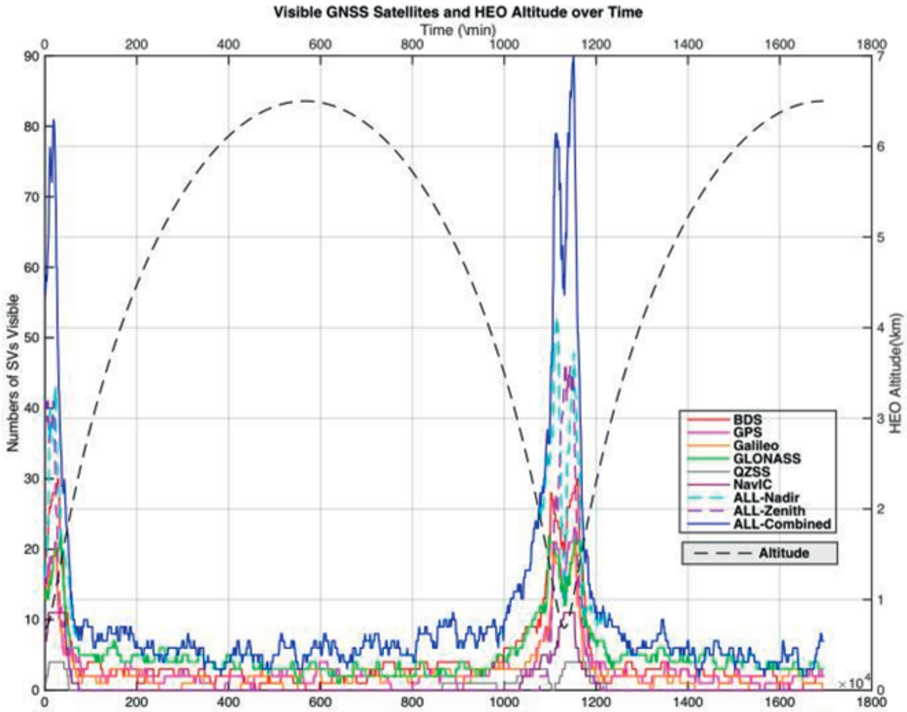


Figure B13. Visible satellites over HEO mission altitude (14 days)

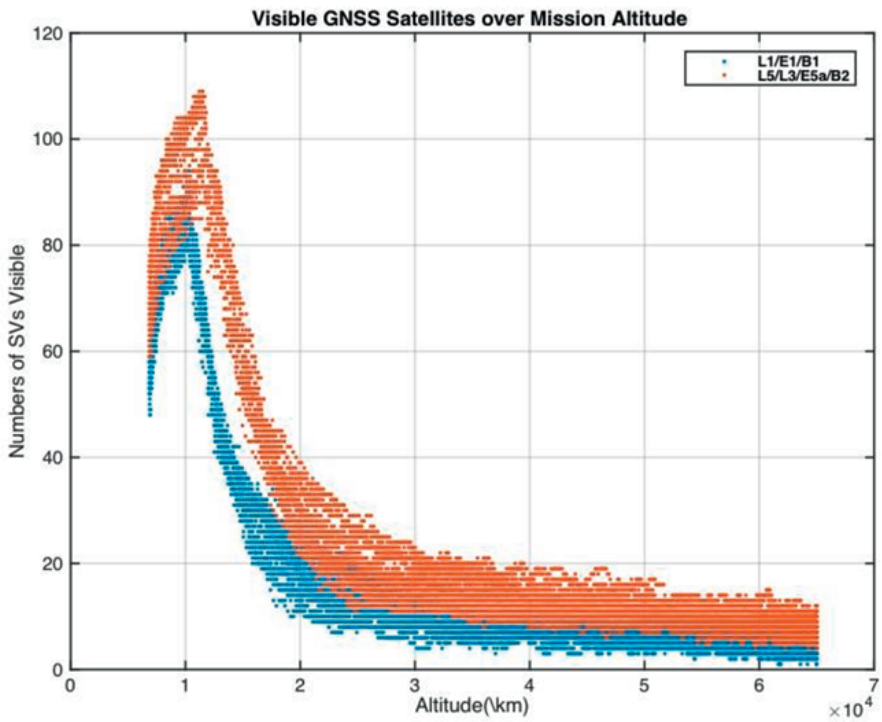


Table B13. HEO mission simulated performance result

Nadir-pointing antenna only					
Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	87.3	70	14.4	1036
	GLONASS	98.8	12	13.4	992
	Galileo	74.2	85	9.2	1027
	BDS	88	51	15.3	1031
	QZSS	22.1	1042	1.1	4537
L5/L3/E5a/B2	GPS	94.7	53	17.3	911
	GLONASS	100	0	55.2	133
	Galileo	87.1	63	11	990
	BDS	96.9	30	25.6	925
	QZSS	27.5	1083	2.2	2238
	NavIC	32.7	1023	3.1	1098
Zenith-pointing antenna only					
Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	7.4	1066	4.3	1086
	GLONASS	7.1	1059	4.4	1080
	Galileo	7.4	1059	4.1	1085
	BDS	10.1	1031	6	1076
	QZSS	5.7	2264	1.4	2296
L5/L3/E5a/B2	GPS	7.9	1059	4.9	1079
	GLONASS	8.3	1046	6.1	1061
	Galileo	8	1051	4.9	1075
	BDS	10.7	1026	7	1065
	QZSS	6.5	1130	2	2284
	NavIC	5.7	1130	3.3	2262
Nadir and zenith combined					
Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	87.3	70	12.7	1036
	GLONASS	98.8	12	14.1	986
	Galileo	74.3	85	9.9	1026
	BDS	88.1	51	16.1	1008
	QZSS	27.5	1031	2.5	2175
	Combined	**100**	**0**	**94.5**	**47**
L5/L3/E5a/B2	GPS	94.7	53	17.4	911
	GLONASS	100	0	55.5	133
	Galileo	87.1	63	11.6	980

	BDS	96.9	30	26	925
	QZSS	32.1	1021	5.8	1091
	NavIC	35.1	989	5.8	1091
	Combined	**100**	**0**	**100**	**0**

Figure B13 shows the visible satellites over the HEO mission altitude in the 14-day simulation timespan with all constellations combined for L1/E1/B1 and L5/L3/E5/B2. As shown in the figure B13, visibility for the L5 case is better than the L1 case.

The simulated results for the signal availability and MOD of the HEO mission are shown in table B13. The signal availability was evaluated with 20 dB-Hz C/No threshold for each individual constellation and all constellations combined.

For both L1/E1/B1 and L5/L3/E5/B2 the one-signal availability can reach 100% with all constellations combined. In case of L1, four-signal availability is below 20% and the MOD is around 1,000 minutes, which is close to the HEO orbital period of 1130 minutes, for an individual constellation. The performance is significantly improved by receiving signals from all constellations combined to nearly 100%. The result of L5 case is similar and the four-signal availability is 100% with all constellations combined. It also shows in the table that signal availability for the L5 case is better than the L1 case.

Lunar mission

The lunar mission case models a simple ballistic cislunar trajectory from LEO to lunar orbit insertion, similar to the trajectories flown by the 1968 United States Apollo 8 mission and many others. This case seeks to explore the boundaries of the GNSS SSV beyond Earth orbit.

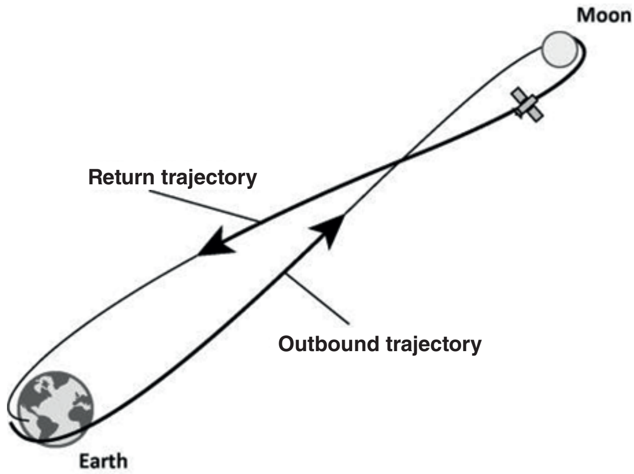
Spacecraft trajectory

A full lunar mission trajectory contains four phases:

1. Earth parking orbit
2. Outbound trajectory
3. Lunar orbit
4. Return trajectory

For the purposes of this analysis, only the outbound trajectory is modelled to illustrate the GNSS signal availability with increasing altitude. This is illustrated in figure B14.

Figure B14. Lunar trajectory phases



Unlike the GEO and HEO cases, an ephemeris was used to model the outbound trajectory. The trajectory was generated using the following parameters, starting at an Earth altitude of 185 km, and arriving in lunar vicinity at an altitude of 100 km.

Table B14. Lunar trajectory parameters

Parameter	Earth departure	Lunar arrival
Epoch (UTC)	1 Jan 2016 12:00:00.000	5 Jan 2016 22:07:59.988
Altitude	185 km	100 km
Eccentricity	0	0
Inclination (body-centred J2000)	32.5°	75°
RAAN	30°	165°
Argument of perigee (AOP)	32°	319°
True anomaly	0°	0°

The choice of Earth departure epoch fixes the required RAAN and argument of perigee (AOP) to reach lunar orbit. Therefore, there is a choice of epoch that will result in different inertial orientations of the trajectory, which may influence the predicted GNSS visibility. The simulated trajectory is one of these possibilities and is intended to be representative. The parameters listed in table B14 result in a trajectory aligned nearly along the inertial -Y axis.

Spacecraft attitude and antenna configuration

For this simplified lunar mission, the spacecraft attitude is fixed as nadir-pointing. Two GNSS antennas are used: one patch antenna that is permanently zenith-pointing (spacecraft -Z direction) and therefore relevant during the low-altitude portion of the mission, and one high-gain antenna that is permanently nadir-pointing (spacecraft +Z direction) and therefore relevant during the high-altitude portion of the mission. The patch and high-gain antenna characteristics are common to all mission-specific simulations and are shown in table B10. The assumed acquisition threshold of the receiver is 20 dB-Hz. Otherwise, all link budget calculations and parameters are as described in the global analysis.

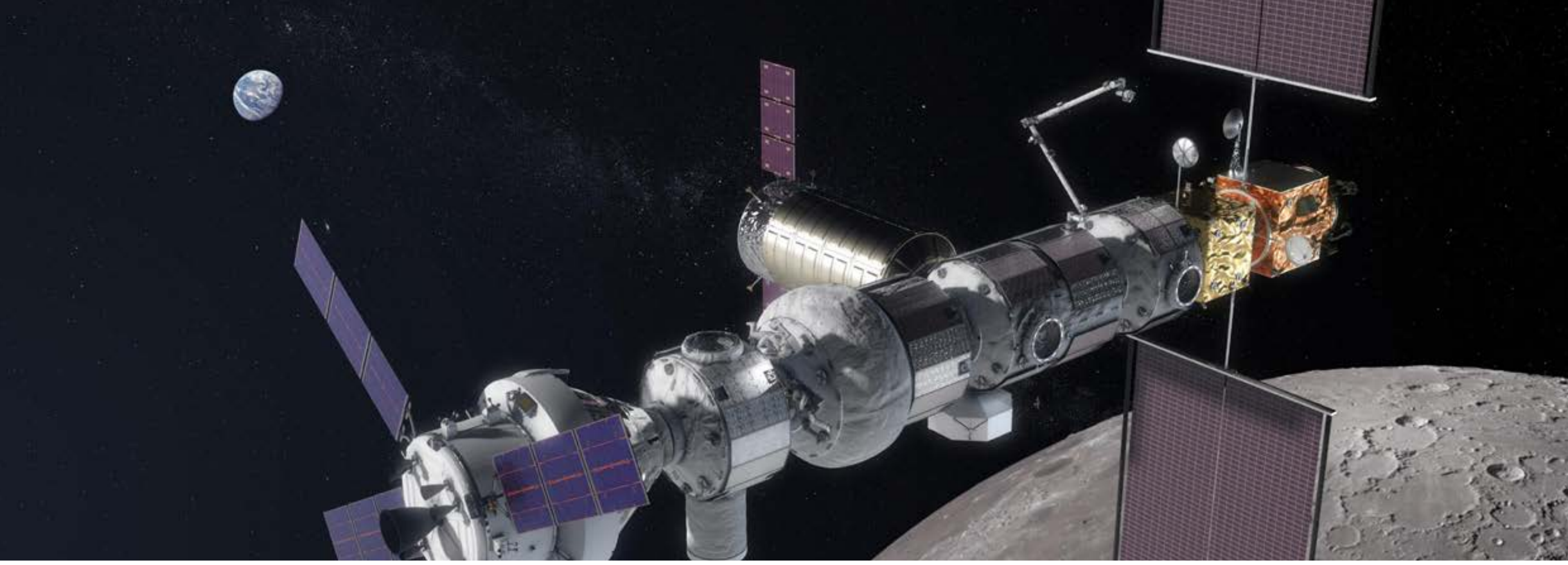
Results

Table B15 contains the full simulated performance results for this mission. In the case of both L1 and L5 bands, the availability of four simultaneous signals is nearly zero for any individual constellation, though in the combined case there is coverage to approximately 30 RE (approximately half the distance to the Moon) near 10–15%. Single-satellite availability reaches 36% for the combined case at L5, though this availability occurs primarily at low altitudes. The benefit of the combined case is best seen above 10 RE, where the combined case has 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. As noted in chapter 5, if a more sensitive receiver or higher-gain antenna were used such that signals at a C/No of 15 dB-Hz were usable, signal availability would be achievable for the entire trajectory to lunar distance.

Table B15. Lunar mission simulated performance results

Band	Constellation	Signal availability (%)		Max outage duration (min)
		At least 1 signal	4 or more signals	At least 1 signal
L1/E1/B1	GPS	9%	1%	5330
	GLONASS	8%	0%	5200
	Galileo	14%	1%	4870
	BDS	14%	3%	5350
	QZSS	1%	0%	6300
	Combined	**21%**	**9%**	**4870**
L5/L3/E5a/B2	GPS	12%	1%	5010
	GLONASS	33%	1%	3420
	Galileo	16%	1%	5060
	BDS	18%	5%	5170
	QZSS	4%	0%	4940
	NavIC	4%	1%	5960
	Combined	**36%**	**16%**	**3420**

Note that the MOD is of limited utility in these results, as it is measured for the duration of the mission and there is no visibility achieved above 30 RE. Other outage duration metrics could be explored here instead in a more detailed simulation, such as outage duration within the visible range, or under a particular altitude.



Annex C. Constellation specification for simulations

This annex provides the orbital parameters used for every constellation for the SSV simulations reported in this booklet. These parameters are defined at the simulation start epoch, 2016/01/01 12:00:00 UTC.

GPS orbital parameters

Table C1. GPS orbital state definition

Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
1	26559800	0	55	273.056	0	11.676
2	26559800	0	55	273.056	0	41.806
3	26559800	0	55	273.056	0	161.786
4	26559800	0	55	273.056	0	268.126
5	26559800	0	55	333.056	0	66.356
6	26559800	0	55	333.056	0	94.916
7	26559800	0	55	333.056	0	173.336
8	26559800	0	55	333.056	0	204.376
9	26559800	0	55	333.056	0	309.976
10	26559800	0	55	33.056	0	111.876
11	26559800	0	55	33.056	0	241.556
12	26559800	0	55	33.056	0	339.666
13	26559800	0	55	33.056	0	11.796
14	26559800	0	55	93.056	0	135.226
15	26559800	0	55	93.056	0	167.356
16	26559800	0	55	93.056	0	257.976
17	26559800	0	55	93.056	0	282.676

18	26559800	0	55	93.056	0	35.156
19	26559800	0	55	153.056	0	197.046
20	26559800	0	55	153.056	0	302.596
21	26559800	0	55	153.056	0	333.686
22	26559800	0	55	153.056	0	66.066
23	26559800	0	55	213.056	0	238.886
24	26559800	0	55	213.056	0	334.016
25	26559800	0	55	213.056	0	0.456
26	26559800	0	55	213.056	0	105.206
27	26559800	0	55	213.056	0	135.346

GLONASS orbital parameters

Table C2. GLONASS orbital state definition

Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
1	25508200	0.000397	64.16	201.81	28.75	295.76
2	25505500	0.001181	64.64	202.16	229.92	47.69
3	25507000	0.001152	64.47	202.24	242.46	349.96
4	25509600	0.000341	64.49	202.16	229.04	317.62
5	25508200	0.000593	64.15	201.75	71.12	71.67
6	25505600	0.000838	64.14	201.75	134.53	321.03
7	25507100	0.001027	64.48	202.28	239.38	172.44
8	25509600	0.00154	64.48	202.27	282.44	85.43
9	25509000	0.002309	64.93	322.43	13.68	322.87
10	25506000	0.001662	65.73	322.85	160.86	131.88
11	25506000	0.001846	65.34	322.22	357.58	250.24
12	25509100	0.003395	64.93	322.44	167.5	34.48
13	25509000	0.000449	65.33	322.18	95.45	60.38
14	25505900	0.001493	65.71	322.79	163.14	306.41
15	25505700	0.002211	65.71	322.78	345.48	85.17
16	25509300	0.001967	64.91	322.37	149.58	229.88
17	25509600	0.000831	64.79	82.98	220.69	132.36
18	25507100	0.001346	65.06	82.75	338.33	331.94
19	25505300	0.000102	65.28	83.61	167.08	95.28
20	25508100	0.00106	65.29	83.67	344.69	231.89
21	25509600	0.000685	65	82.79	185.84	348.48
22	25507200	0.002793	65.19	82.78	356.75	132.46
23	25505600	0.000142	65.17	82.74	135.86	306.03
24	25508000	0.000779	65.18	82.77	84.59	315.17

Galileo orbital parameters

Table C3. Galileo orbital state definition

Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argu-ment of perigee (°)	Mean anomaly (°)
1	29599801.224	0.0000001	56	326.60209225	0	107.1899147499
2	29599801.224	0.0000001	56	326.60209225	0	152.1899147499
3	29599801.224	0.0000001	56	326.60209225	0	197.1899147499
4	29599801.224	0.0000001	56	326.60209225	0	242.1899147499
5	29599801.224	0.0000001	56	326.60209225	0	287.1899147499
6	29599801.224	0.0000001	56	326.60209225	0	332.1899147499
7	29599801.224	0.0000001	56	326.60209225	0	17.1899147499
8	29599801.224	0.0000001	56	326.60209225	0	62.1899147499
9	29599801.224	0.0000001	56	86.60209225	0	122.1899147499
10	29599801.224	0.0000001	56	86.60209225	0	167.1899147499
11	29599801.224	0.0000001	56	86.60209225	0	212.1899147499
12	29599801.224	0.0000001	56	86.60209225	0	257.1899147499
13	29599801.224	0.0000001	56	86.60209225	0	302.1899147499
14	29599801.224	0.0000001	56	86.60209225	0	347.1899147499
15	29599801.224	0.0000001	56	86.60209225	0	32.1899147499
16	29599801.224	0.0000001	56	86.60209225	0	77.1899147499
17	29599801.224	0.0000001	56	206.60209225	0	137.1899147499
18	29599801.224	0.0000001	56	206.60209225	0	182.1899147499
19	29599801.224	0.0000001	56	206.60209225	0	227.1899147499
20	29599801.224	0.0000001	56	206.60209225	0	272.1899147499
21	29599801.224	0.0000001	56	206.60209225	0	317.1899147499
22	29599801.224	0.0000001	56	206.60209225	0	2.1899147499
23	29599801.224	0.0000001	56	206.60209225	0	47.1899147499
24	29599801.224	0.0000001	56	206.60209225	0	92.1890000000

BDS orbital parameters

Table C4. BDS orbital state definition

Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
1	27906137	0.003	55	0	0	225.631
2	27906137	0.003	55	0	0	270.631
3	27906137	0.003	55	0	0	315.631
4	27906137	0.003	55	0	0	0.631

Table C4. BDS orbital state definition (*cont'd*)

Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
5	27906137	0.003	55	0	0	45.631
6	27906137	0.003	55	0	0	90.631
7	27906137	0.003	55	0	0	135.631
8	27906137	0.003	55	0	0	180.631
9	27906137	0.003	55	120	0	240.631
10	27906137	0.003	55	120	0	285.631
11	27906137	0.003	55	120	0	330.631
12	27906137	0.003	55	120	0	15.631
13	27906137	0.003	55	120	0	60.631
14	27906137	0.003	55	120	0	105.631
15	27906137	0.003	55	120	0	150.631
16	27906137	0.003	55	120	0	195.631
17	27906137	0.003	55	240	0	255.631
18	27906137	0.003	55	240	0	300.631
19	27906137	0.003	55	240	0	345.631
20	27906137	0.003	55	240	0	30.631
21	27906137	0.003	55	240	0	75.631
22	27906137	0.003	55	240	0	120.631
23	27906137	0.003	55	240	0	165.631
24	27906137	0.003	55	240	0	210.631
25	42164200	0.003	0	0	2.204	336.229
26	42164200	0.003	0	0	23.459	336.229
27	42164200	0.003	0	0	54.082	336.229
28	42164200	0.003	0	0	83.582	336.229
29	42164200	0.003	0	0	103.582	336.229
30	42164200	0.003	55	61.445	0	336.229
31	42164200	0.003	55	301.445	0	96.229
32	42164200	0.003	55	181.445	0	216.229

QZSS orbital parameters

Table C5. QZSS orbital state definition

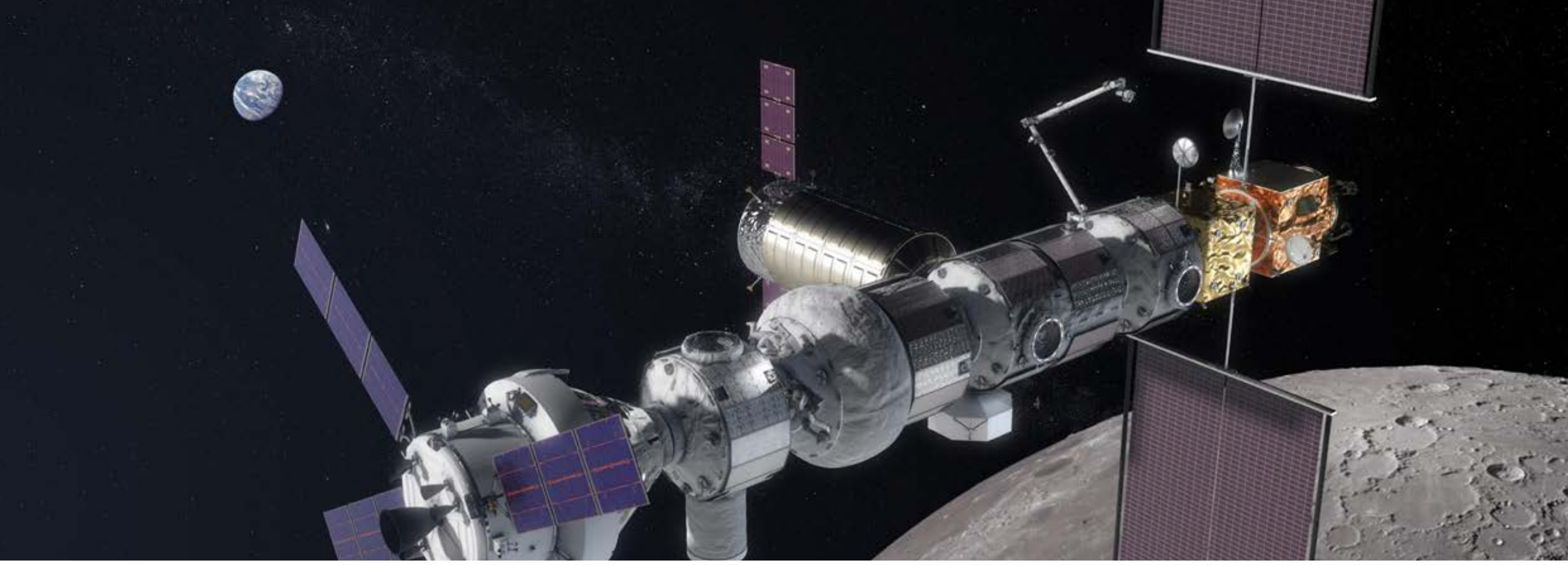
Satellite	Semi-major axis (m)	Eccentric-ity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
1	42164169.45	0.075	40	165	270	341.58
2	42164169.45	0.075	40	295	270	211.58
3	42164169.45	0.075	40	35	270	111.58
4	42164169.45	0	0	0	0	47.58

NavIC orbital parameters

Table C6. NavIC orbital state definition

Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
1	42164200	0.0007	28.1	124.08	0	211.3
2	42164200	0.0007	29.97	303.04	0	32.32
3	42164200	0.0007	4.01	264.62	0	98.963
4	42164200	0.0007	29.98	303.19	0	88.964
5	42164200	0.0007	28.1	124.08	0	267.8
6	42164200	0.0007	5	270	0	42.663
7	42164200	0.0007	5	270	0	139.568
8*	42164200	0.0007	42	318.5	0	8.7629
9*	42164200	0.0007	42	110	0	235.5129
10*	42164200	0.0007	42	290	0	84.5129
11*	42164200	0.0007	42	279	0	121.2629

* Note: These additional four IGSO satellites are yet to be coordinated, and some parameters may change.



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Abbreviations and acronyms

ACE	NASA GPS Antenna Characterization Experiment
AEP	Architecture Evolution Plan
AFSPC	Air Force Space Command
AOP	Argument of Perigee
BDS	Beidou Navigation Satellite System
BPSK	Binary Phase Shift Keying modulation
C/No	Carrier-to-Noise Ratio
CAO	Cabinet Office, Government of Japan
CAST	China Academy of Space Technology
CBOC	Composite Binary Offset Carrier
CDMA	Code Division Multiple Access
CS	Commercial Service
ESA	European Space Agency
FDMA	Frequency Division Multiple Access
FOC	Full Operational Capability
GCS	Ground Control Segment
GEO	Geostationary Orbit
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite-R series
GPS	Global Positioning System
GRC	NASA Glenn Research Center
GSFC	NASA Goddard Space Flight Center
GSO	Geosynchronous Orbit
GTO	Geo Transfer Orbit
HEO	Highly Elliptical Orbit
ICD	Interface Control Document
ICG	International Committee on GNSS
IF	Intermediate Frequency
IGSO	Inclined Geosynchronous Orbit
IOAG	International Operations Advisory Group
IOV	In-Orbit Validation
IRNSS	Indian Regional Navigation Satellite System
IS	Interface Specification
ISAC	ISRO Satellite Centre
ISRO	Indian Space Research Organisation
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
LNA	Low Noise Amplifier
LoS	Line of Sight
MEO	Medium Earth Orbit

MMS	Magnetospheric Multi-Scale
MOD	Maximum Outage Duration
MRTP	Minimum Radiated Transmit Power
NASA	United States National Aeronautics and Space Administration
NavIC	Navigation with Indian Constellation
NEC	Nippon Electric Company
NOAA	National Oceanic and Atmospheric Administration
OCS	Operational Control Segment
OCX	Next Generation Operational Control System
OOSA	United Nations Office for Outer Space Affairs
OS	Open Service
PNT	Positioning, Navigation and Timing
POD	Precise Orbit Determination
PRN	Pseudo-Random Noise
PRS	Public Regulated Service
PVT	Position, Velocity, Time
QZS	Quasi-Zenith Satellite
QZSS	Quasi-Zenith Satellite System
RAAN	Right Ascension of the Ascending Node
RCP	Right-hand Circular Polarised
RE	Earth Radius
RF	Radio Frequency
RS	Restricted Service
SIS	Signal in Space
SJTU	Shanghai Jiao Tong University
SMC	Space and Missile Systems Center
SPS	Standard Positioning Service
SSV	Space Service Volume
SV	Space Vehicle
TCM	Trajectory Correction Manoeuvres
TLI	Trans-Lunar Injection
TTC	Telemetry, Tracking and Command station
URE	User Range Error
UTC	Universal Time (Coordinated)
WG-B	ICG Working Group B

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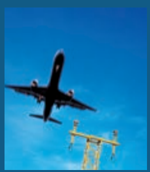
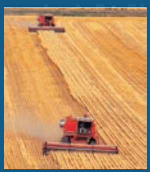
The United Nations Office for Outer Space Affairs (OOSA) is responsible for promoting international cooperation in the peaceful uses of outer space and assisting developing countries in using space science and technology.





ICG International Committee on Global Navigation Satellite Systems

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