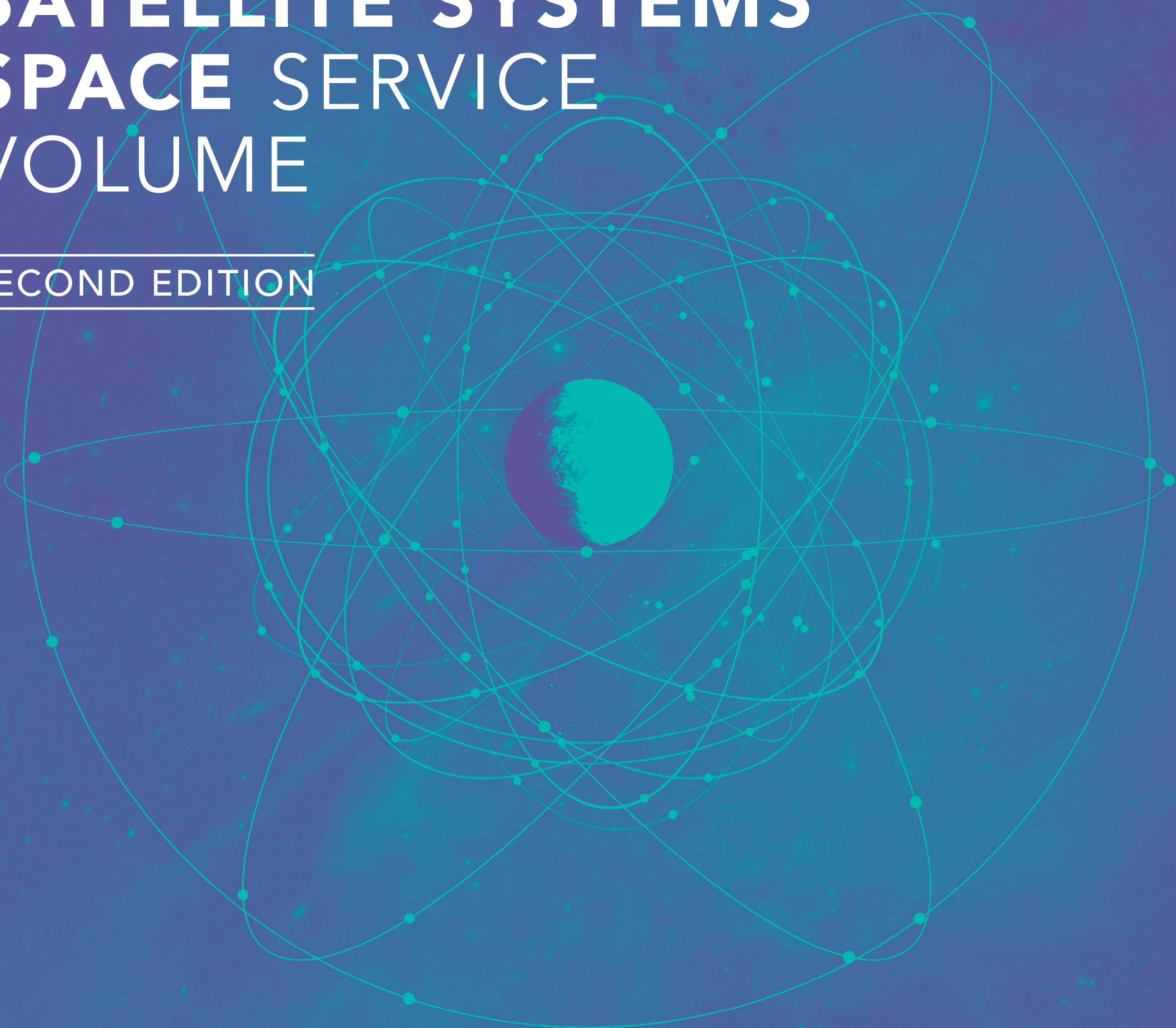
UNITED NATIONS
OFFICE FOR OUTER SPACE AFFAIRS

THE INTEROPERABLE GLOBAL NAVIGATION SATELLITE SYSTEMS SPACE SERVICE VOLUME

SECOND EDITION



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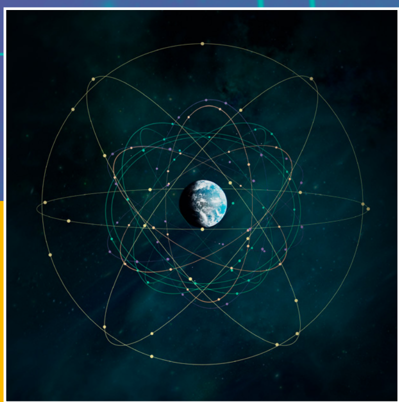

An artistic depiction of the four global and two regional navigation satellite systems surrounding the Earth. Credit: NASA

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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 also being increasingly utilized for autonomous navigation in space. 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 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.

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 global constellation is 100%, while within the upper SSV, which extends to geostationary altitude, it can be as low as 69% with long outages assuming commercial high-altitude receiver equipment.

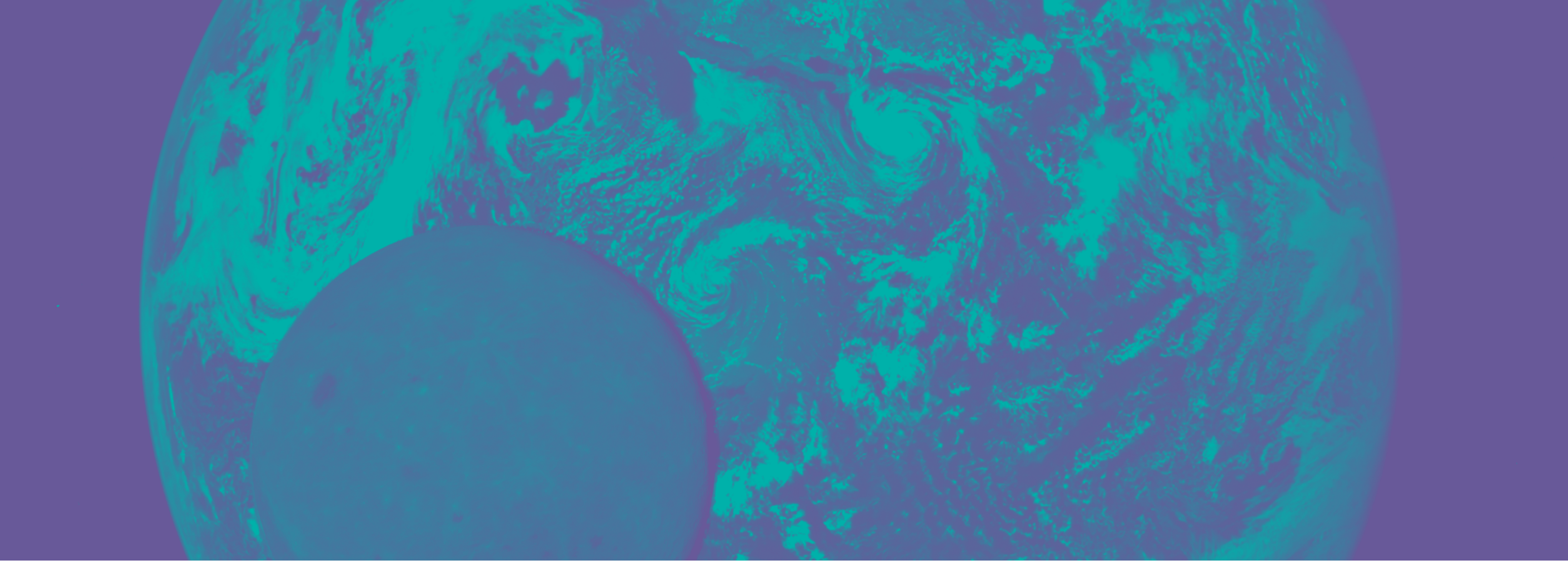
In addition to the global characterization of GNSS availability and performance in the lower and upper SSV, this booklet also provides performance indications for specific mission profiles which cross the formal boundaries of SSV. The mission profiles contained in this booklet are geostationary Earth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

Within the International Committee on GNSS (ICG), there is an initiative underway to ensure that GNSS signals within SSV are available and interoperable across all international global constellations and regional augmentations. This initiative is being carried out by the Space Use Subgroup 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 SSV performance metrics for each individual constellation, developing standard assumptions and definitions to perform multi-GNSS SSV performance analyses, encouraging the design and manufacture of GNSS receivers that can operate in 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 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 57% for any individual constellation to 89% 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 ICG, all providers have agreed on the information presented in this booklet, and on several recommendations adopted and formally endorsed by ICG over nearly a decade to continue the development, support and expansion of the multi-GNSS SSV concept. For the community of GNSS providers, recommendations are aimed at continuing development of SSV, and providing the user community with adequate data to utilize it. For the user community, recommendations are intended to ensure that the full capabilities of the multi-GNSS SSV can be utilized. All recommendations are listed in annex B.

Humanity is now beginning to benefit from GNSS usage in SSV, starting with applications that use only individual constellations, and ultimately expanding to multi-constellation GNSS. For example, weather satellites employing GNSS signals in 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 this capability has enormous benefits, 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

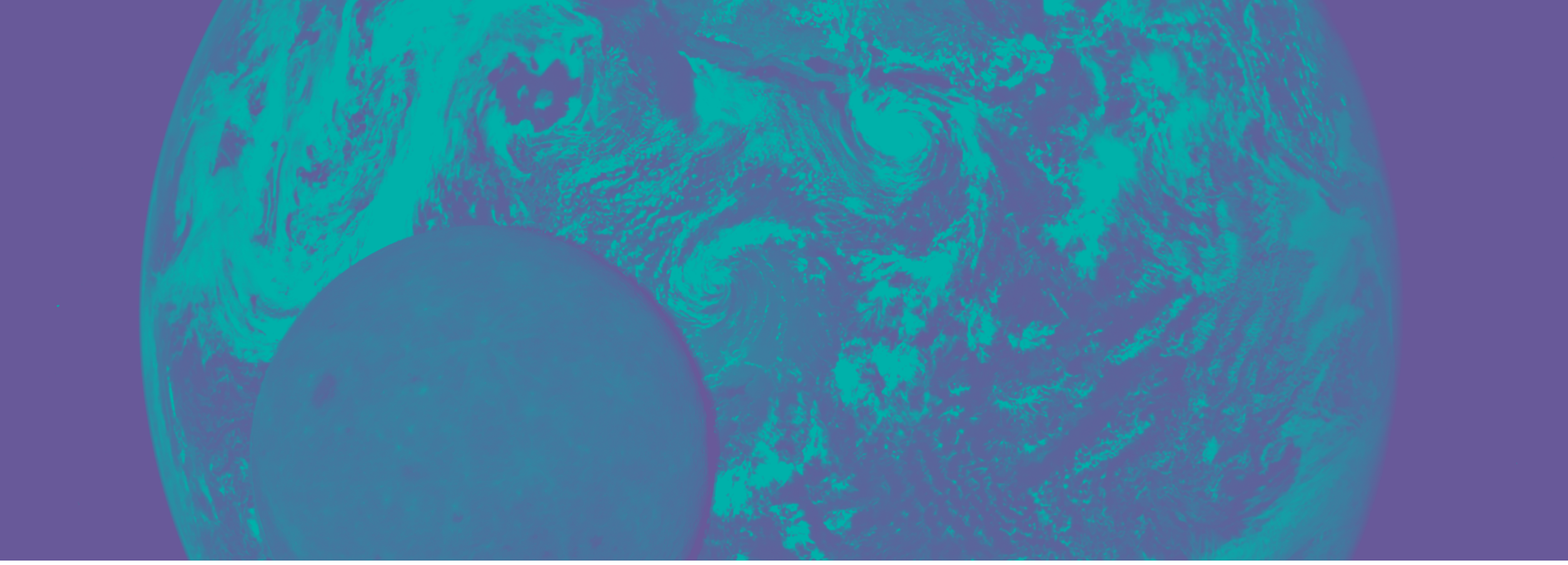
The vast majority of Global Navigation Satellite System (GNSS) users are located on the ground, and the GNSS systems are designed to serve these users. However, the number of satellites utilizing on-board GNSS space receivers is steadily growing. Space receivers in SSV operate in an environment significantly different than the environment of a classical terrestrial receiver or GNSS receiver in low Earth orbit (LEO). 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.

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". An interoperable multi-GNSS SSV can significantly enhance GNSS-based navigation performance for space users by combining individual constellation services into one unified capability.

This document has been produced by the Space Use Subgroup (SUSG) of Working Group B (WG-B) of 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 GNSS space users and GNSS space receiver manufacturers with a single resource offering 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 SSV by identifying some of the user benefits. Chapter 3 defines SSV and provides an overview of relevant background information. GNSS constellation parameters relevant to SSV are collected from each provider in chapter 4. SUSG 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 assumptions and results are presented in chapter 5, and several relevant real-world space mission examples are described in chapter 6. Chapter 7 contains ICG conclusions and recommendations, and chapter 8 identifies potential topics that might be addressed in future releases of this booklet. Further details on the constellation parameters and SUSG simulation results are contained in the annexes.

The first edition of this booklet was published at the 13th meeting of the ICG in December 2018. This fully revised second edition includes updates to the GNSS constellations and simulation results according to the latest information from each provider. Chapter 6 has been added to demonstrate the on-orbit capability of GNSS space use, beyond the formal characteristics of each constellation. Finally, simulation results now include a geometric dilution indicator (GDI) representing the quality of signal geometry. The geometric diversity of available signals is an important factor in navigation performance and is often improved by an interoperable GNSS SSV.



2. Benefits to users

The number and scope of GNSS-based space applications has grown significantly 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 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 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 improved navigation 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

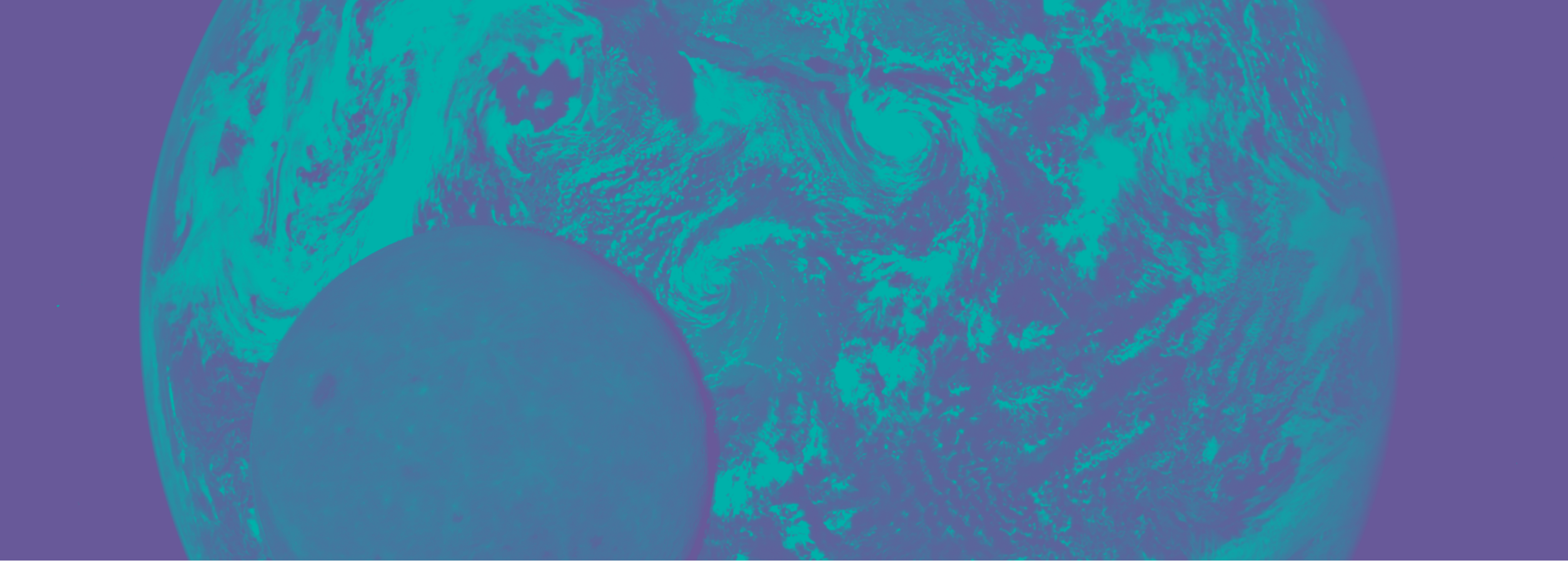
Enhancing operational flexibility and resiliency, the interoperable multi-GNSS SSV will:

- 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
- Enable the implementation of advanced operations concepts, which will support increasing the robustness of space safety operations

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 an altitude of approximately 60,000 km.
- *Cislunar trajectories:* Launch vehicle upper stages and cislunar exploration missions travel well beyond GEO altitude, with some travelling all the way to lunar distance and onto the lunar surface. 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 the use of GNSS signals at extremely long distances as well, potentially allowing for use as a supplemental measurement source in lunar orbit and/or on the lunar surface.

- *Satellite servicing:* Satellite servicing missions are being developed for spacecraft at GEO, and are expected to be employed in cislunar space. These missions 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 the burden on the ground control centre, even while utilizing the available space at GEO more efficiently.
- *Space safety (collision avoidance):* The number of active space vehicles and the amount of space debris will grow significantly over the next decade. In particular, reduced launch costs, the expanded use of large constellations and CubeSats, and also the increased number of satellites in general, will significantly increase the challenges for space traffic management, space safety and especially collision avoidance. Future space vehicles with on-board GNSS receivers, coupled with advanced automated operations procedures, will enable better detection and estimation of potential collision risks, as well as improved calculation, execution and timely calibration of the necessary mitigation manoeuvres.



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 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), 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 SSV is defined by three key parameters:

- Pseudorange accuracy
- Minimum received power
- Signal availability

SSV covers a large range of altitudes and GNSS performance will degrade with increasing altitude. In order to allow for a more accurate reflection of the performance variations, 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:

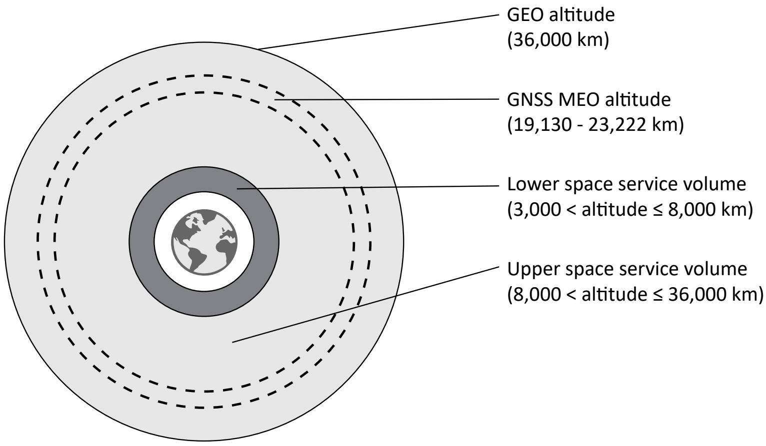
1. *Lower SSV for medium Earth orbits:* 3,000–8,000 km altitude. This area is characterized by reduced signal availability from a zenith-facing antenna alone, but increased availability if both a zenith and nadir-facing antenna are used.

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).

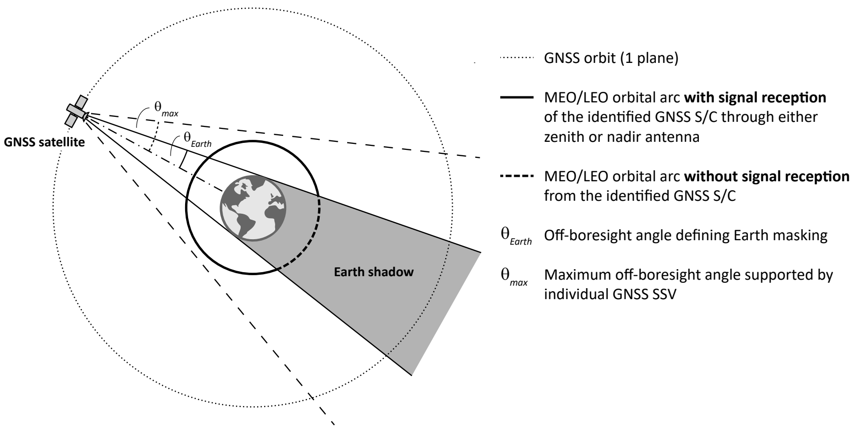
Figure 3.1 The GNSS space service volume and its regions



3.1.1 Lower space service volume

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

Figure 3.2 Signal reception geometry in the lower space service volume



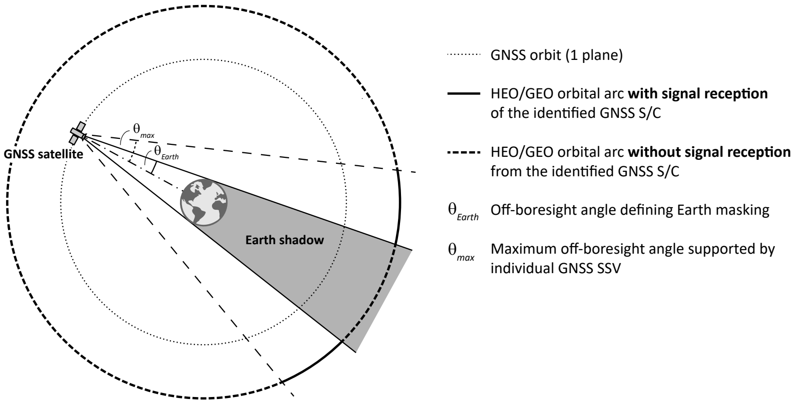
GNSS space receivers located between 3,000 km and 8,000 km altitude can receive GNSS signals from the spacecraft nadir direction and the spacecraft zenith direction with respect to the Earth. Zenith signals are received in line with LEO spacecraft and Earth-based GNSS signal reception. The signals arriving 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 space service volume



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 Space service volume performance characterization metrics

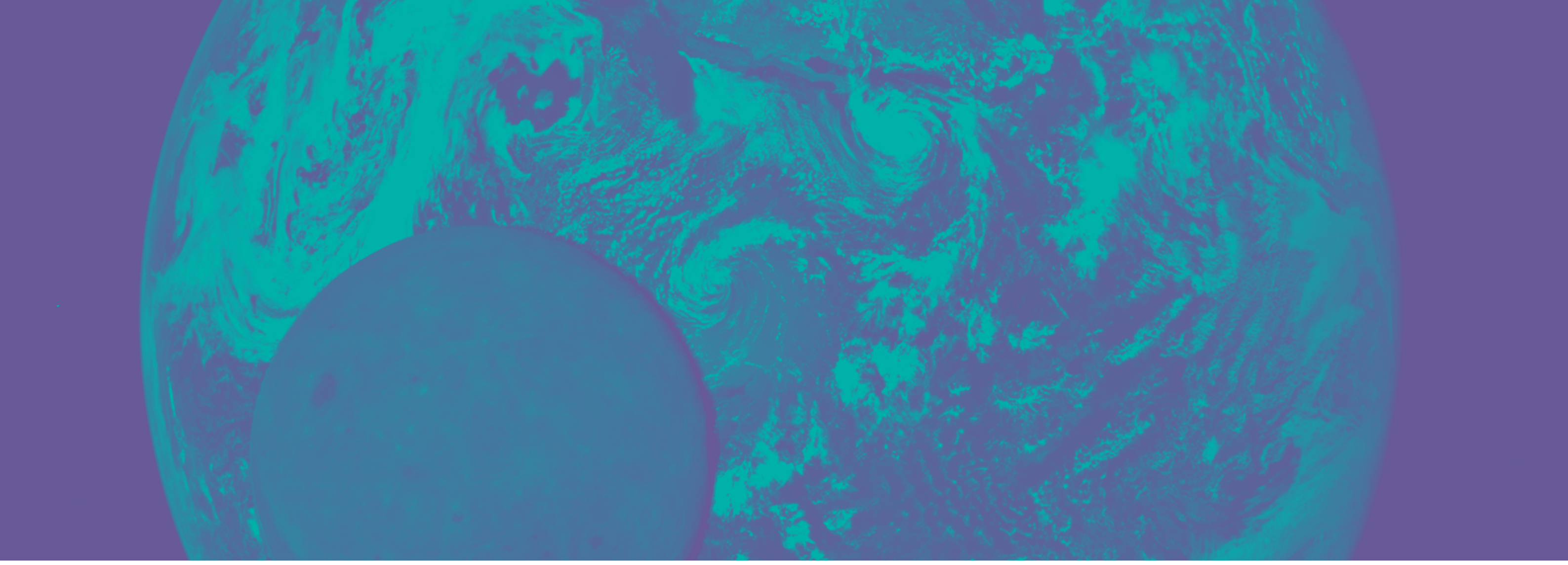
The characterization of the SSV performance of an individual GNSS constellation relates at a minimum to the characterization of the following three parameters for every ranging signal:

1. *Pseudorange accuracy:* Since users in 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 submetric 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, reception of signals from GNSS transmit antenna side lobes, 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 frequency, 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	United States	Global	Operational	3/4	27/6	26,560	55	
GLONASS	Russian Federation	Global	Operational	2/6	24/3	25,510	64.8	
Galileo	European Union	Global	Operational	5/10	24/3	29,600	56	Initial service: 2016
BDS	China	Global	Operational	3/5	MEO: 24/3 IGSO: 3/3 GEO: 3/1	27,906 42,164 42,164	55 55 0	FOC: 2020
QZSS	Japan	Regional (Japan)	Operational	4/7	IGSO: 4/4 Near-GEO: 1/1 GEO: 2/1	42,164	40 1–8 0	4-SV constellation: 2018 7-SV constellation: around 2023
NavIC (IRNSS)	India	Regional (India)	Operational	2/2	IGSO: 4/2 GEO: 3/1	42,164	29 0	

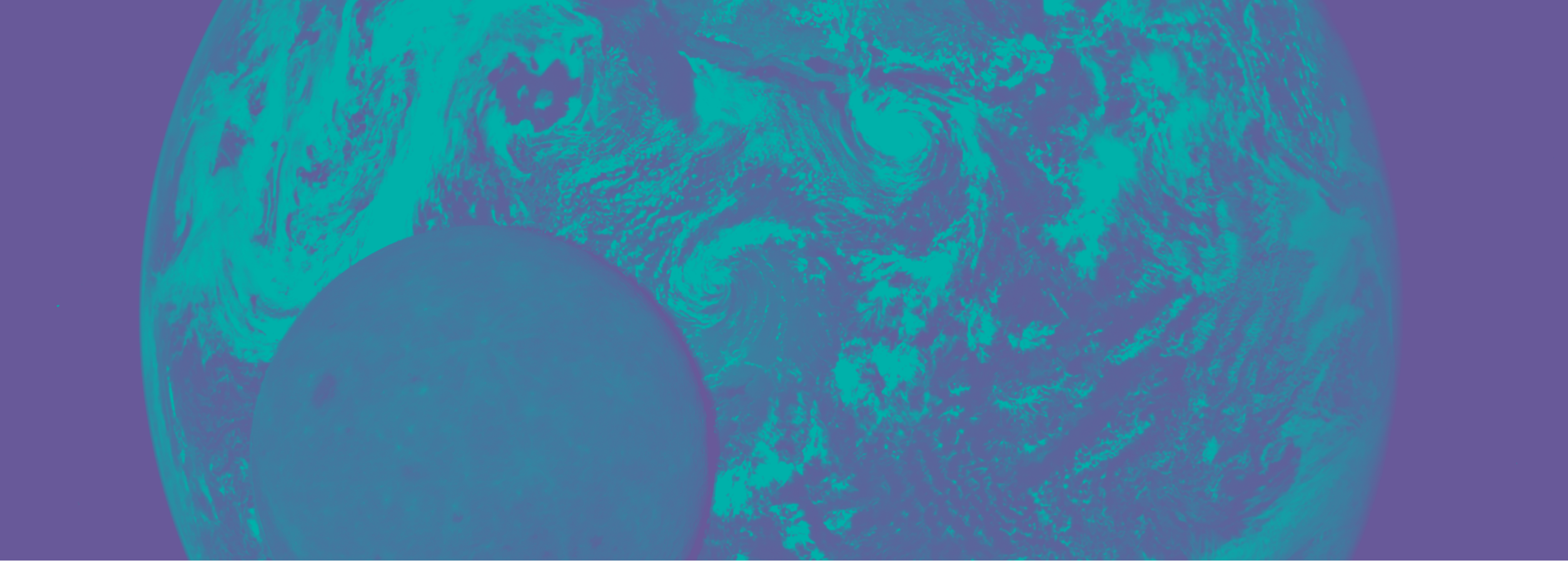
Table 4.2 Space service volume signal characteristics for each GNSS service provider

Band	Constellation	Frequency (MHz)	Minimum received civilian signal power		Signal availability (%): Lower space service volume		Signal availability (%): Upper space service volume	
			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	1,575.42	-184 (C/A) -182.5 (C)	23.5	100	97	80	1
	GLONASS	1,605.375[a]	-179	26	100	99.8	93.9	7.0
	Galileo	1,575.42	-182.5	20.5	100	99	64	0
	BDS	1,561.098 (B1I)	-184.2 (MEO)	25	100	100	91	0.5
			-185.9 (I/G)	19				
		1,575.42 (B1C)	-184.2 (MEO)	25				
			-185.9 (IGSO)	19				
	QZSS	1,575.42	-185.5	22	99.4	83.8	39.8	6.7
L2/E6/B3	GPS	1,227.6	-183	26	100	100	92	6.5
	GLONASS	1,248.625[a]	-178	34	100	66	100	29
	Galileo	1,278.75	-182.5	21.5	100	100	72	0
	BDS	1,268.52	-182.8 (MEO)	28	100	100	99	3
			-184.4 (I/G)	22				
	QZSS	1,227.6	-188.7	24	100	N/A	54	N/A
L5/L3/E5/B2	GPS	1,176.45	-182	26	100	100	92	6.5
	GLONASS	1,201[a]	-178	34	100	100	99.9	60.3
	Galileo	1,206.45 (E5b)	-182.5	22.5	100	100	80	0
		1,191.795 (E5ABOC)	-182.5	23.5	100	100	86	0
		1,176.45 (E5a)	-182.5	23.5	100	100	86	0
	BDS	1,191.795[b]	-182.8 (MEO)	28	100	100	99	3
			-184.4 (IGSO)	22				
	QZSS	1,176.45	-180.7	24	99.4	83.8	44.5	9.6
	NavIC	1,176.45	-184.54	16	98	51.40	36.90	0.60

[a] Centre of FDMA band.
[b] Average of B2I, B2a frequencies.

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 m	1.4 m	1.1 m	1.0 m	2.6 m	2.11 m



5. Simulated performance of interoperable space service volume

The Working Group B (WG-B) of the International Committee on Global Navigation Satellite Systems (ICG), through its Space Use Subgroup, has simulated the GNSS single- and multiple-constellation performance expectations in SSV, based on the individual constellation signal characteristics documented in chapter 4. As outlined in chapter 3, navigation performance in 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 and geometry, which serve as proxies 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/N_0) 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. Any duration of availability is considered valid, even for only a single timestep. 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 SSV. Mission-specific performance estimates are obtained by estimating GNSS signal availability and geometric diversity for a spacecraft on a particular trajectory within SSV. Mission-specific scenarios considered in this study include: geostationary orbit, a highly elliptic orbit, and 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 with 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 C 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 C 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 C.

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. The availability is calculated as an average over all grid points and over the entire simulation time, whereas MOD is calculated at the worst-case grid point of the specific scenario and simulation. 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/N_0 thresholds. Performance results are provided for thresholds of C/N_0 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/N_0, 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 values provided in chapter 4 by the different service providers as different receiver parameters may have been assumed, and 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 MOD for a user in the upper SSV as a function of different C/N_0 thresholds for each individual constellation and for all constellations combined. The C/N_0 thresholds relate to the tracking threshold of the assumed space receiver and values of 15, 20 and 25 dB-Hz are analysed.

Figure 5.1 shows an example of simulated signal availability for the 20 dB-Hz C/N_0 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 SSV.
- At the highest threshold of 25 dB/Hz, availability is 0% for most constellations. 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/N_0 threshold. Actual visibility changes with location and time.

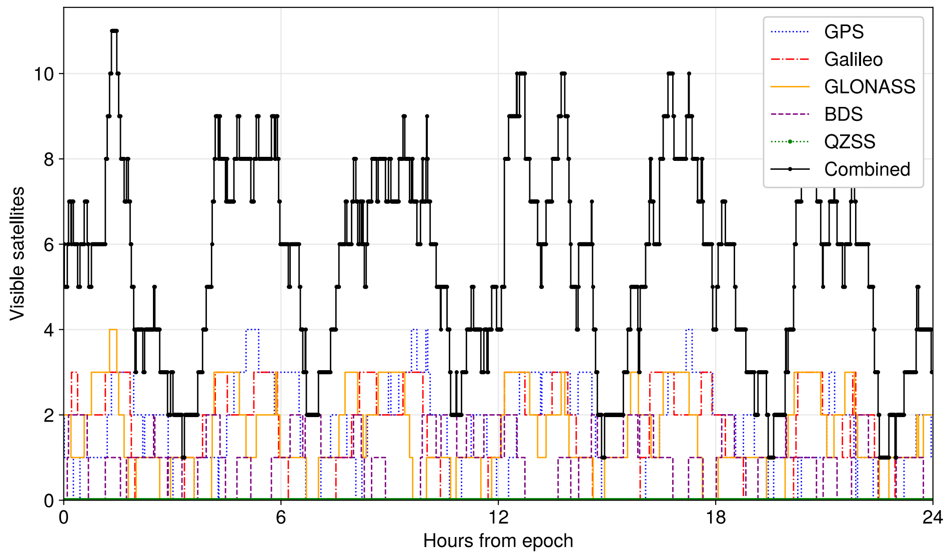


Table 5.1 Global performance estimates of availability and maximum outage duration for each constellation and all constellations together. Results for nadir-pointing antenna in the upper space service volume

Band	Constellation	$C/N_{0_{min}}$ = 15 dB-Hz				$C/N_{0_{min}}$ = 20 dB-Hz				$C/N_{0_{min}}$ = 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	97.2	45	19.6	*	69.8	70	0.6	*	0.0	*	0	*
	QZSS	39.8	*	6.6	*	0.0	*	0	*	0.0	*	0	*
	Combined	**99.9**	**26**	**98.2**	**93**	**99.9**	**33**	**89.8**	**117**	**93.9**	**48**	**7**	*****
L5/L3/E5a/B2	GPS	96.9	77	15.6	1,180	96.9	77	15.6	1,180	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	32.7	644	99.9	7	27.2	644	0.0	*	0	*
	QZSS	44.4	*	9.5	*	44.4	*	9.5	*	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 at the worst-case grid location for duration of 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/N_0 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 space service volume

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	100	95.6	0	*
	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	100	95.6	0	*
	NavIC	98.0	51.4	348	*
	Combined	**100**	**100**	**0**	**0**

* No signal observed at the worst-case grid location for duration of simulation

5.2 Mission-specific performance

The mission-specific simulations use scenarios that are considered to be realistic GNSS space use cases. 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 peak gain of approximately 4 dBi, and a "high gain" antenna with peak 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.

In addition, the effect of geometric diversity of the available signals was considered by calculating a geometric dilution indicator (GDI) for each mission case. GDI is intended as an illustrative parameter that provides a general indication of the quality of signal geometry. Like the familiar dilution of precision (DOP) property, lower GDI values indicate generally better geometry. GDI, however, does not include the effects of time biases and offsets between constellations, constellation-specific URE, or user aspects such as the use of a navigation filter. See annex C for a complete definition of GDI.

5.2.1 Geostationary orbit mission

The GEO mission scenario examines 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 L1/E1/B1 and L5/L3/E5a/B2 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).

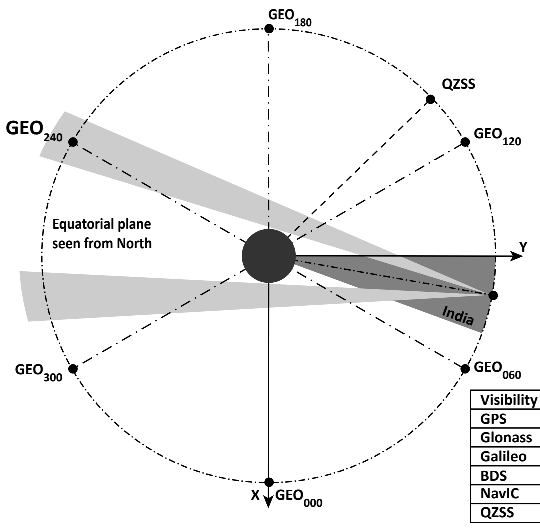
Table 5.3 GEO osculating Keplerian orbital elements

Epoch	1 Jan 2016 12:00:00 UTC		
Semi-major axis	42,164.0 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 configured as 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 C10. 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 geostationary and inclined geosynchronous GNSS satellites of the BDS, Quasi-Zenith Satellite System (QZSS) and Navigation with Indian Constellation (NavIC) 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 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 L5/L3/E5a/B2 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, respectively. 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. GDI is shown below each visibility plot for the combined case in which all constellations are used. Complete visibility and GDI for all six GEO receivers at both carrier frequencies are provided in annex C.

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 L5/L3/E5a/B2 signals are available at every simulated GEO longitude for 100% of the time. The slightly weaker L1/E1/B1 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, GLONASS, Galileo, BDS (MEO)), 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 nearly 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 longitude 180 degrees

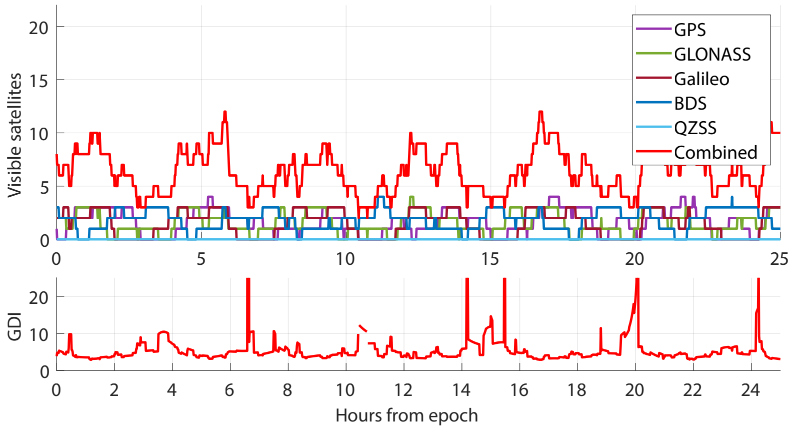


Figure 5.4 Best case example: L5 visibility for GEO at longitude 300 degrees

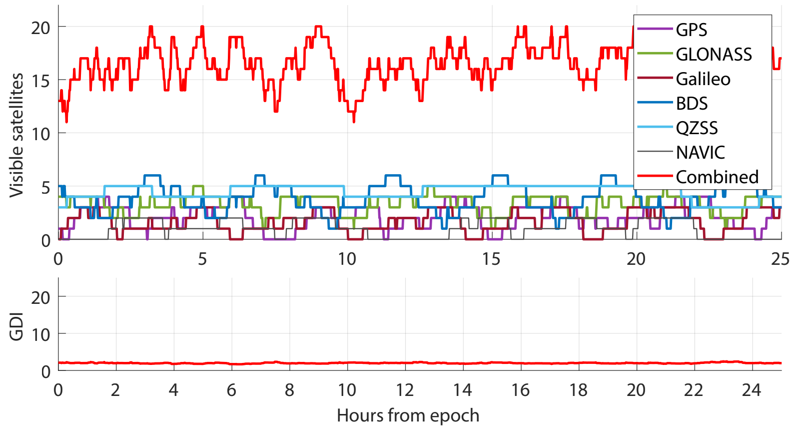


Table 5.4 Performance for GEO receiver at longitude 0 degrees

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	82	72	3	697
	GLONASS	84	38	0.7	3,808
	Galileo	63	82	0	20,160
	BDS	91	27	0.9	722
	QZSS	97	33	0	20,160
	Combined	**100**	**0**	**98**	**25**
L5/L3/E5a/B2	GPS	94	50	14	425
	GLONASS	100	0	44	189
	Galileo	86	41	0	20,160
	BDS	100	0	10	264
	QZSS	100	0	0.04	6,141
	NavIC	0	20,160	0	20,160
	Combined	**100**	**0**	**100**	**0**

Table 5.5 Performance for GEO receiver at longitude 60 degrees

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	20,160
	BDS	92.27	28	0.92	724
	QZSS	0	20,160	0	20,160
	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	20,160
	BDS	100	0	10.65	262
	QZSS	0	20,160	0	20,160
	NavIC	0	20,160	0	20,160
	Combined	**100**	**0**	**100**	**0**

Table 5.6 Performance for GEO receiver at longitude 120 degrees

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	79	103	3	462
	GLONASS	90	37	5	474
	Galileo	63	82	0	20,160
	BDS	92	26	0.9	732
	QZSS	0	20,160	0	20,160
	Combined	**100**	**0**	**94**	**51**
L5/L3/E5a/B2	GPS	91	66	9	419
	GLONASS	100	0	52	94
	Galileo	86	41	0	20,160
	BDS	100	0	11	255
	QZSS	0	20,160	0	20,160
	NavIC	0	20,160	0	20,160
	Combined	**100**	**0**	**100**	**0**

Table 5.7 Performance for GEO receiver at longitude 180 degrees

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	82	73	3	697
	GLONASS	84	41	0.7	3,805
	Galileo	63	82	0	20,160
	BDS	91	27	0.9	722
	QZSS	0	20,160	0	20,160
	Combined	**100**	**0**	**93**	**41**
L5/L3/E5a/B2	GPS	94	50	14	425
	GLONASS	100	0	44	195
	Galileo	86	41	0	20,160
	BDS	100	0	10	263
	QZSS	0	20,160	0	20,160
	NavIC	100	0	0	20,160
	Combined	**100**	**0**	**100**	**0**

Table 5.8 Performance for GEO receiver at longitude 240 degrees

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	79	89	2	748
	GLONASS	90	34	5	476
	Galileo	62	82	0	20,160
	BDS	100	0	28	200
	QZSS	100	0	0	20,160
	Combined	**100**	**0**	**100**	**0**
L5/L3/E5a/B2	GPS	94	55	10	402
	GLONASS	100	0	53	91
	Galileo	86	42	0	20,160
	BDS	100	0	10	262
	QZSS	100	0	0	20,160
	NavIC	100	0	5	371
	Combined	**100**	**0**	**100**	**0**

Table 5.9 Performance for GEO receiver at longitude 300 degrees

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	79	103	3	462
	GLONASS	90	33	5	939
	Galileo	63	82	0	20,160
	BDS	100	0	50	142
	QZSS	100	0	63	206
	Combined	**100**	**0**	**100**	**0**
L5/L3/E5a/B2	GPS	91	66	9	419
	GLONASS	100	0	53	94
	Galileo	86	41	0	20,160
	BDS	100	0	54	118
	QZSS	100	0	90	140
	NavIC	67	216	0	20,160
	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.

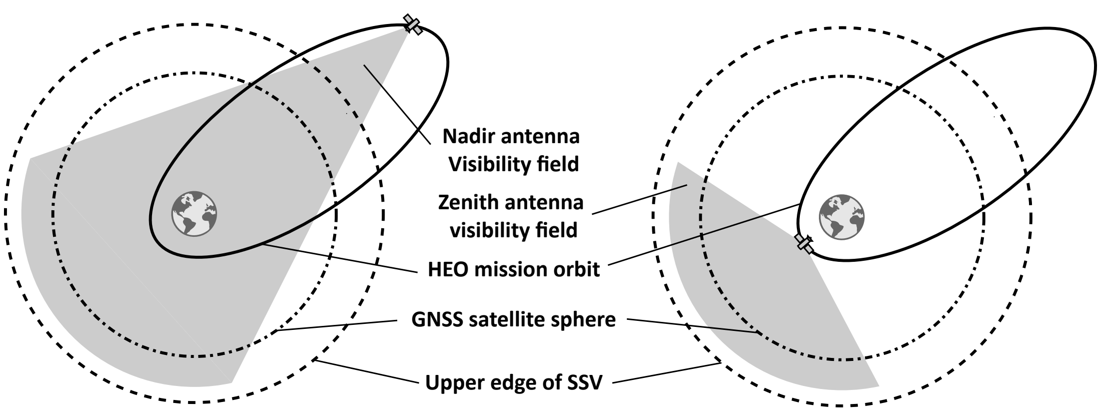
Table 5.10 Osculating Keplerian highly elliptical orbital elements

Epoch	1 Jan 2016 12:00:00 UTC		
Semi-major axis	35,937.5 km	**RAAN**	0 degrees
Eccentricity	0.80870	**Argument of perigee**	270 degrees
Inclination	63.4 degrees	**True anomaly**	0 degrees

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 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 types of antennas are given in table C10. 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.

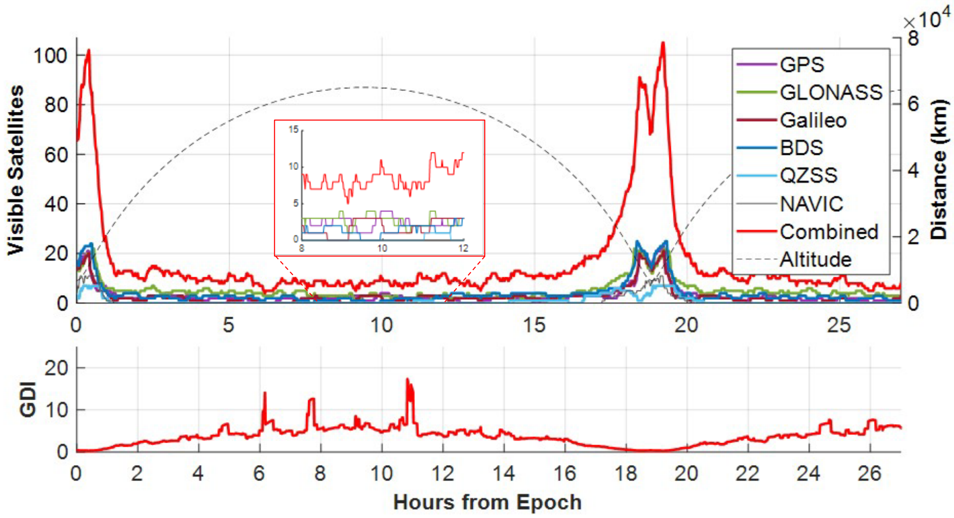
Figure 5.5 Schematic of the highly elliptical orbital mission with nadir- and zenith-pointing antennas



Results

Figure 5.6 shows the GNSS signal availability and GDI 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, 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 highly elliptical orbit (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/N_0 threshold for each individual constellation and all constellations combined.

Table 5.11 Highly elliptical orbit mission simulated performance result

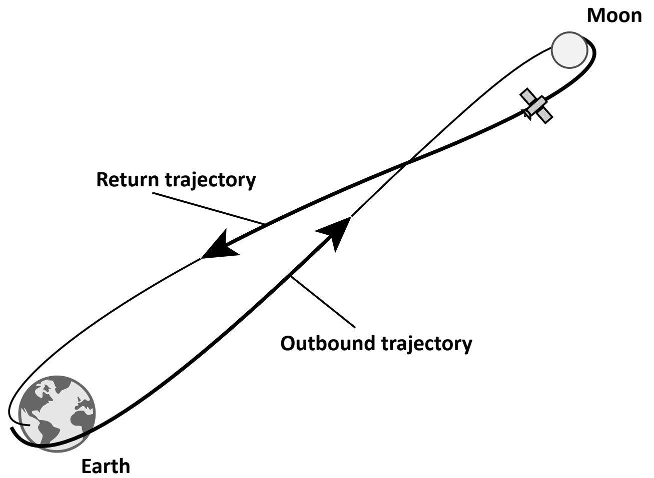
Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	87	69	12	1,036
	GLONASS	98	12	14	986
	Galileo	74	85	9	1,025
	BDS	88	51	15	1,013
	QZSS	31	1,009	7	1,066
	Combined	**100**	**0**	**94**	**47**
L5/L3/E5a/B2	GPS	94	53	17	911
	GLONASS	100	0	55	134
	Galileo	87	64	11	980
	BDS	96	30	24	925
	QZSS	36	998	10	1,032
	NavIC	35	990	5	1,091
	Combined	**100**	**0**	**100**	**0**

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

A lunar scenario was considered in order to explore the practical boundary of the GNSS SSV beyond Earth orbit. A lunar trajectory from LEO to a lunar fly-by with a return to Earth was simulated (figure 5.7). Only the outbound portion was used in this analysis. As with the HEO case, both the zenith-pointing and nadir-pointing user antennas were modelled, with peak gains of 4.5 dBi and 9 dBi, respectively. The spacecraft attitude was kept nadir-pointing.

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



Results

Figure 5.8 shows the general structure of GNSS signal availability, using the L5 band as an example to capture the contributions of all constellations. Availability is highly dependent on distance from Earth and user equipment assumptions for the C/N_0 tracking threshold and the antenna gain. As the distance from Earth increases, the availability drops quickly and reaches zero beyond 30 RE, which is approximately 50% of the distance to the moon. When using all constellations combined, the single-satellite availability is nearly 100% to a distance of 30 RE, and zero thereafter. The benefit of the combined multi-GNSS case is best seen above 10 RE, where signal availability is consistently higher than any individual constellation, and often nearly double. Notably, combining constellations does not increase the altitude at which such signals are available; rather, it increases the number of signals available at a given altitude. These results show that navigation with the combined multi-GNSS SSV is conservatively feasible for nearly half the duration of a lunar outbound trajectory, well beyond the upper limit of SSV, and is possibly a solution for navigation for the outbound trans-lunar injection manoeuvre and return trajectory correction manoeuvres.

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

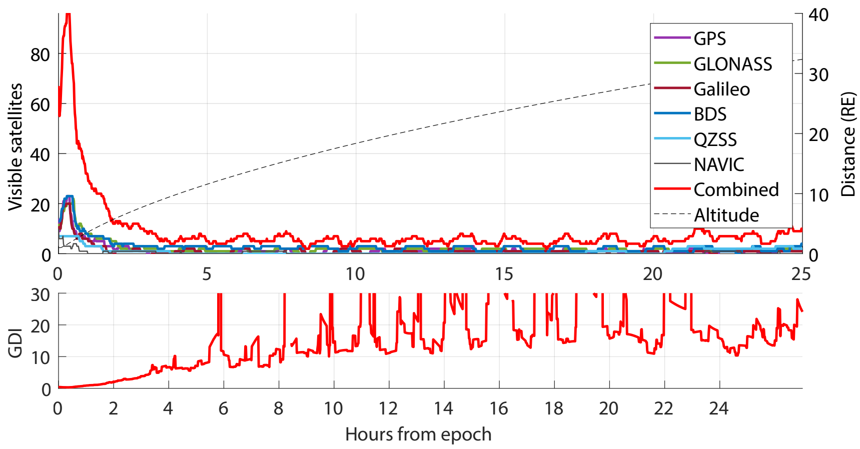
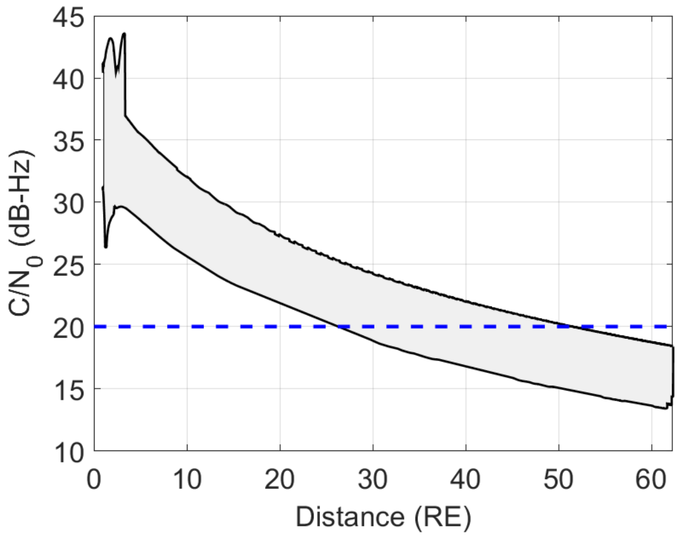
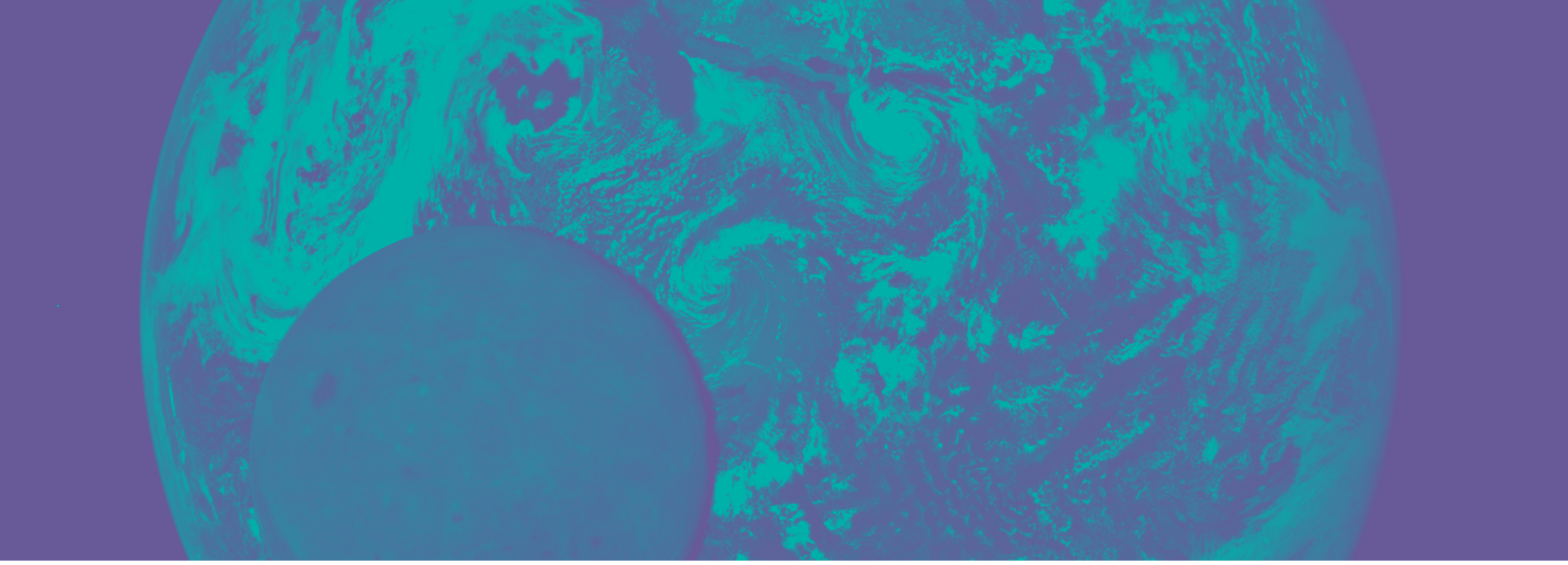


Figure 5.9 shows the simulated C/N_0 received by the example spacecraft as a range encompassing all individual GNSS constellations for the entire trajectory to lunar distance (60 RE). It shows the reason for the availability drop-off near 30 RE shown in figure 5.8. The C/N_0 of most GNSS signals at the user antenna drops below the 20 dB-Hz minimum threshold beyond 30 RE. If a moderately more sensitive receiver or higher-gain antenna were employed, the signal availability would be achievable up to the lunar distance. A simple improvement in antenna gain has been proposed to support lunar vicinity missions such as Gateway.

Figure 5.9 Simulated C/N_0 range for lunar trajectory with 20 dB-Hz analysis threshold marked





6. Flight experiences

Real-world examples of space missions employing GNSS in the space service volume (SSV) enable future GNSS space users to understand the full scope of achievable benefits and on-orbit performance expectations in this environment. The profiles in this section were solicited from GNSS provider teams and spacecraft mission developers to share relevant historical, on-orbit and near-future mission experiences and analysis. Specific information requested includes the mission description and purpose, GNSS receivers employed, performance benefits resulting from using GNSS in SSV, and details of observed or predicted on-orbit performance. These profiles describe the on-orbit capability of interoperable GNSS space use and use of GNSS in SSV, beyond the documented characteristics of each constellation described in annex A.

In order of launch, the missions included are:

- Magnetospheric Multiscale (MMS) Mission (United States: NASA)
- Geostationary Operational Environmental Satellite R (GOES-R) Series (United States: NOAA, NASA)
- GPS and Galileo Receiver for the ISS (GARISS) (Europe: ESA, United States: NASA)
- CARTOSAT-3 (India: ISRO)
- Proba-3: Project for Demonstration of Satellite Precise Formation Flying in High Eccentric Orbit (Europe: ESA)

6.1 Magnetospheric Multiscale (MMS) Mission (United States: NASA)

Launch date: 12 March 2015

Mission description: To study the mystery of how magnetic fields around Earth connect and disconnect, explosively releasing energy via a process known a magnetic reconnection

Science observation method: Coordinated measurements from tetrahedral formation of four spacecraft in highly eccentric orbits with typical formation spacing of 20–40 km at apogee

GNSS mission need:

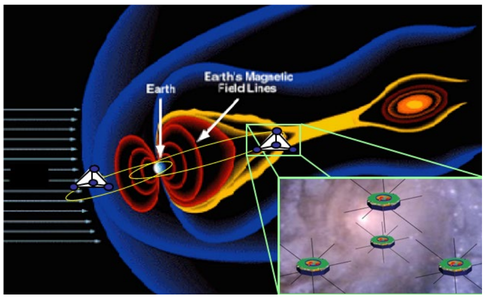
- Enables on-board (autonomous) navigation and near-autonomous station-keeping while rotating at 3 revolutions per minute
- Formation flying

Driving requirements:

- Semi-major axis estimation above 3 Re:
  - Phase 1: 50 m (99%)
  - Phase 2B: 100 m (99%)
- Timing accuracy: 325 μs

Mission orbit:

- *Phase 1 (Mar 2015–Feb 2017):* 1.2 x 12 Earth radii (Re) orbit (7,600 km perigee, 76,000 km apogee)
- *Phase 2B (May 2017–Feb 2019):* Extends apogee to 25 Re (~160,000 km)
- *Extended mission (Feb 2019–present):* Extends apogee to 29.34 Re (~187,000 km, 50% of lunar distance)



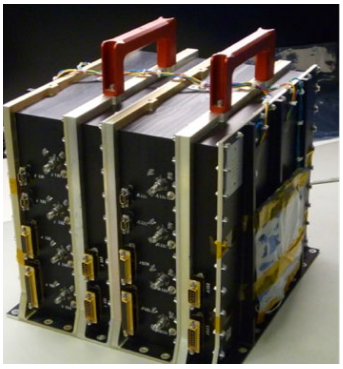
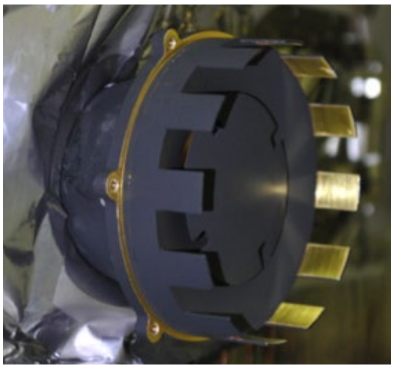
MMS science formation

MMS spacecraft stacked for launch

GNSS system:

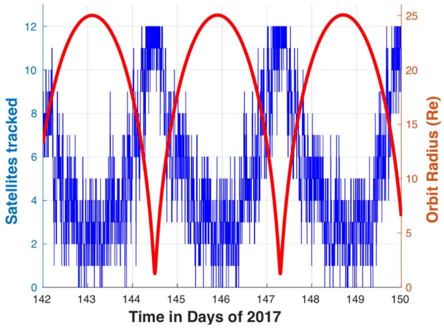
- NASA Goddard Space Flight Center Navigator
  - 8 receivers (2 per spacecraft)
  - 16 antennas (4 per spacecraft)
- GNSS signals used: GPS L1 C/A

- Channels: 12
- Acquisition threshold: 25 dB-Hz
- Tracking threshold: 23 dB-Hz
- Antenna: 7 dBi peak gain
- Uses GNSS Enhanced Orbit Navigation System (GEONS) orbit filter

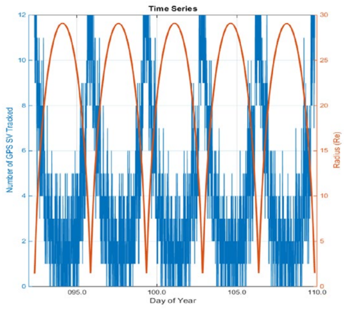



left: MMS navigator receiver
right: MMS GPS antenna

On-orbit results:



Signal visibility, phase 2B: 25 Re

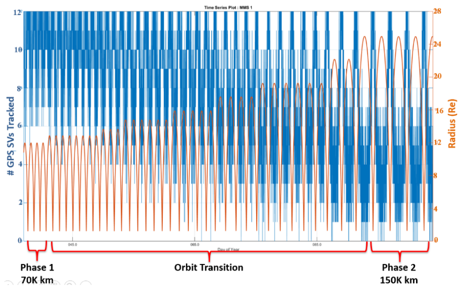


Signal visibility, extended mission: 29 Re

MMS navigation performance (1σ)		
Description	**Phase 1**	**Phase 2B**
Semi-major axis est. above 3 Re (99%)	2 m	5 m
Orbit position estimation (99%)	12 m	55 m

On-orbit navigation performance

Signal Tracking Performance During Phase 1 to Phase 2 Apogee Raising (70K km to 160K km)



Signal visibility phase 1 to phase 2B

Sources:

Winternitz, L. B., and others. Global Positioning System Navigation Above 76,000 KM for NASA's Magnetospheric Multiscale Mission. *Journal of the Institute of Navigation*, vol. 64, No. 2 (Summer 2017).

Winternitz, L. B., and others. New High-Altitude GPS Navigation Results from the Magnetospheric Multiscale Spacecraft and Simulations at Lunar Distances. In *Proceedings of the 30th International Technical Meeting of The Satellite Division of the Institute of Navigation* (ION GNSS+ 2017), Portland, Oregon, September 2017.

6.2 Geostationary Operational Environmental Satellite R (GOES-R) Series (United States: NOAA, NASA)

Launch date:

- *GOES-R (GOES-16):* 19 November 2016 (operational)
- *GOES-S (GOES-17):* 1 March 2018 (operational)
- *GOES-T:* December 2021 (planned)
- *GOES-U:* 2024 (planned)

Organization:

- *Programme management:* NOAA
- *Flight project management:* NASA
- *Spacecraft:* Lockheed Martin

Mission description:

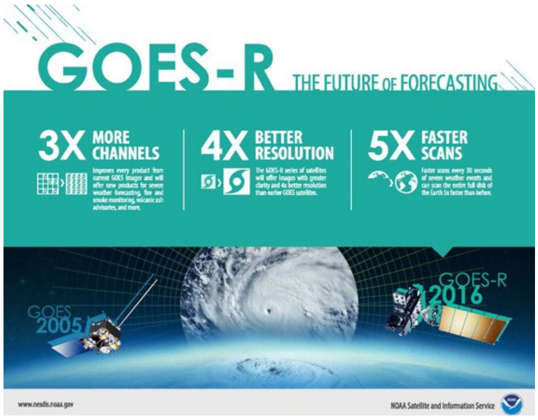
- Fourth-generation geostationary weather satellite series
- Features new advanced baseline imager instrument and GNSS-based navigation
- Benefits include:
  - Improved hurricane forecasts
  - Improved location of wildfires
  - Increased thunderstorm and tornado warning lead time
  - Better detection of heavy rainfall and flash flood risks
  - Enhanced weather prediction accuracy

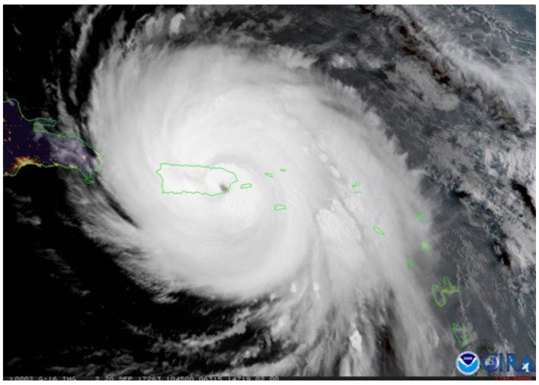
GNSS mission need:

- Onboard autonomous navigation to meet instrument
  pixel navigation requirements

Driving requirements:

- Orbit position knowledge (3σ): (100 m, 75 m, 75 m) (R, I, C)
- Requirements applicable through daily manoeuvres, <120 min/year allowed exceedances
- Stringent navigation stability requirements



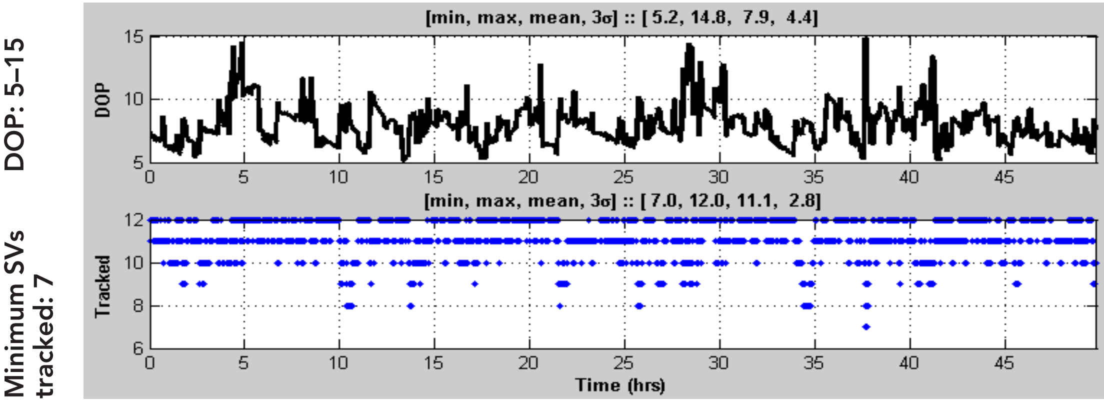


GOES-16 image of hurricane Maria making landfall over Puerto Rico

Mission orbit: GEO

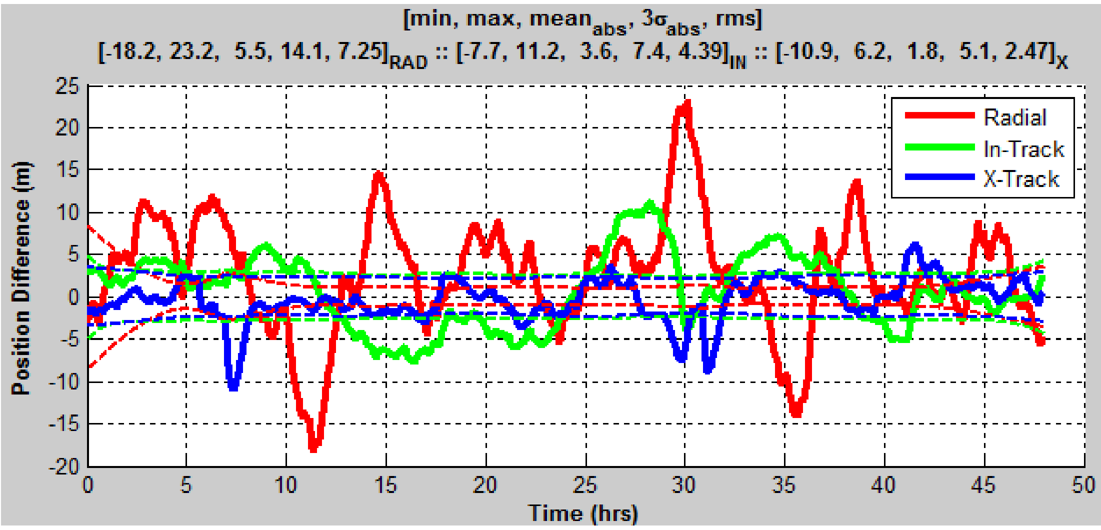
Receiver system:

- General Dynamics Viceroy-4
- GNSS signals: GPS, L1 C/A
- Channels: 12
- Fast cold start algorithm
- Uses embedded orbit navigation system filter



GPS visibility and DOP

	Observed performance (3σ)	Requirement (3σ)
Radial	14.1 m	100 m
In-track	7.4 m	75 m
Cross-track	5.1 m	75 m



GOES-16 Post-launch test performance results (February 2017)

Source:

Winkler, Stephen W., and others. GPS Receiver On-Orbit Performance for the GOES-R Spacecraft. *10th International ESA Conference on Guidance, Navigation & Control Systems*. Salzburg; Austria. 29 May–2 June 2017. Available at https://ntrs.nasa.gov/search.jsp?R=20170004849

6.3 GPS and Galileo Receiver for the ISS (GARISS) (Europe: ESA, United States: NASA)

Experiment started in first half of 2018[1]

Mission objectives:

- Implementation of a combined Galileo/GPS waveform within existing NASA hardware already operating in the challenging space environment – the FPGA-based Space Communications and Navigation (SCaN) software defined radio testbed – on-board the ISS
- Analysis of signal and on-board PVT performance
- Application of precise orbit determination based on post processing of GNSS raw data

Mission orbit: LEO circular orbit at 400 km altitude

Navigation uniqueness: First Galileo + GPS receiver in space that performed PVT, based on E5a/L5 only

GNSS receiver employed:

- GARISS on SCaN TestBed[2]
- Galileo and GPS constellations
- 8 channels
- E1/L1 (not usable) and E5a/L5 bands
- Minimum C/N_0: 15 dB-Hz

Navigation performance:

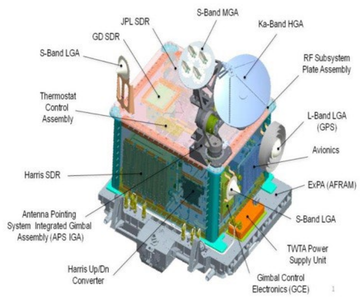
- ESA orbit determination (OD) shows 20 cm RMS residuals based on the single frequency E5a/L5 GRAPHIC linear combination[3]
- ESA OD solution shows 15 m 3D RMS orbital differences when compared to the on-board real-time PVT solution from a different GPS-only receiver
- The very good ESA OD residuals (20 cm) do not match with the ISS PVT solution. The ESA OD is expected to have a position accuracy < 1 m (1σ 3D)

GNSS visibility:

- 1 to 4 Galileo signals available
- 0 to 4 GPS signals available
- 2 to 8 combined signals available

GARISS logo

SCaN TestBed

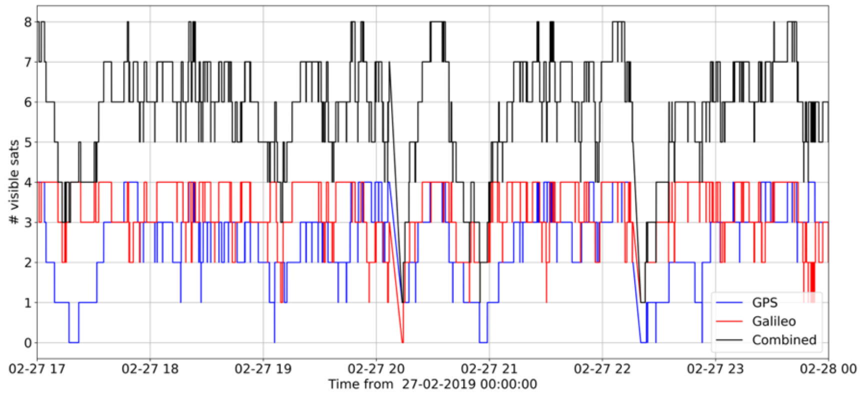


Components of SCaN TestBed

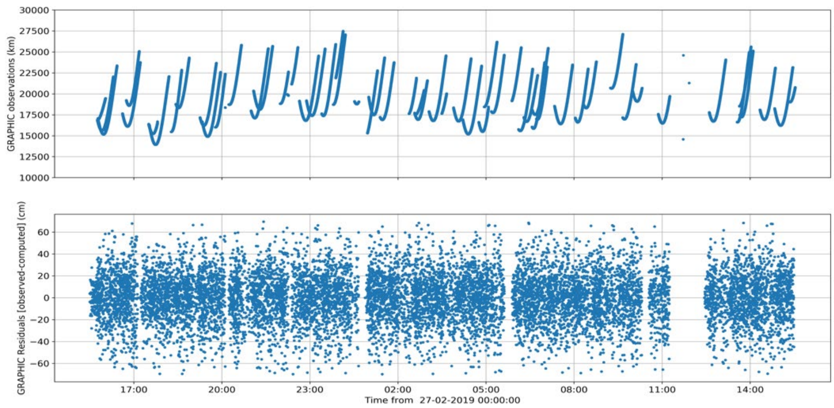
[1] Werner Enderle and James J. Miller, "First GPS/Galileo Receiver Flown in Space", *GPS World*, vol. 28, No. 7 (July 2017).

[2] S. Montagner and others, ESA-QAS-GARISS-SDD-3.1 2018.

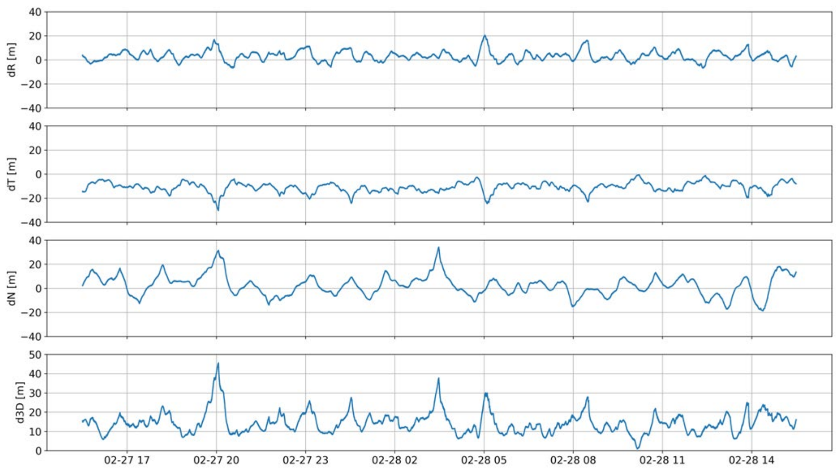
[3] Werner Enderle and others, "The Joint ESA/NASA Galileo/GPS Receiver Onboard the ISS – The GARISS Project", in *Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019) (Miami, Florida, September 2019).*



Visibility of Galileo and GPS satellites for receiver on-board the ISS



GRAPHIC observations (top) and GRAPHIC residuals



Comparison between the on-board real time PVT reference solution with ESOC's post-processed orbit determination solution

6.4 CARTOSAT-3 (India: ISRO)

Launch date: 27 November 2019

Mission description: Cartographic applications such as large-scale urban planning, rural resource and infrastructure development, etc. using the high-resolution imaging capability.

Mission orbit: Polar sun-synchronous orbit:

- *Altitude:* 509 km
- *Inclination:* 97.5°

GNSS mission need:

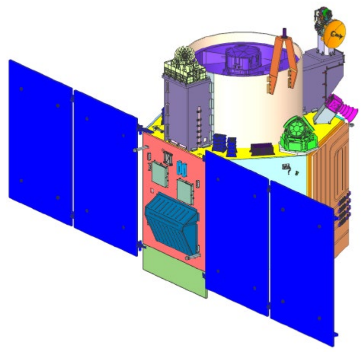
- On-board navigation for orbit determination and operations planning.
- On-board time correction through GNSS time and payload time stamping.

GNSS receiver employed:

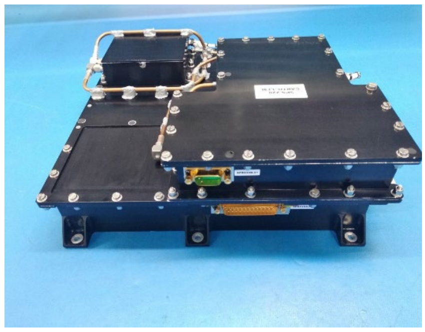
- In-house-developed multi-GNSS receiver
  - *Receiver:* MGR1
  - *GNSS constellation:* GPS + NavIC + SBAS
  - *Channels:* 12
  - *Frequency band:* L1, L5
  - *Modulation:* BPSK

Receiver performance:

- Orbit accuracy:
  - *Position:* 5 m
  - *Velocity:* 1.5 cm/s
  - *Time:* <1 ms



CARTOSAT-3



MGR1 GNSS receiver

6.5 Proba-3: Project for Demonstration of Satellite Precise Formation Flying in High Eccentric Orbit (Europe: ESA)

Launch date: Mid 2022

Mission objectives: Formation flying demonstrator in the context of a large-scale science experiment. The paired satellites will together form a 144-m long solar coronagraph to study the Sun's faint corona closer to the solar rim. The experiment will be a perfect instrument to measure the achievement of the precise positioning of the two spacecraft.[4]

Mission orbit: Highly elliptical Earth orbit (HEO):

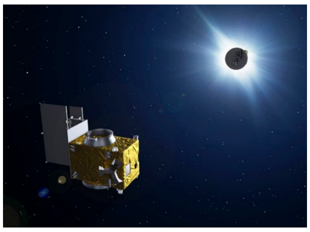
- Perigee at 600 km and apogee at 60,530 km altitude (eccentricity 0.8111)
- Inclination: 59 degrees

Navigation uniqueness: Closed-loop formation flying mission carrying a multi-GNSS (Galileo+GPS) receiver

GNSS receiver employed:

- RUAG PODRIX[5]
- Galileo and GPS constellations
- Up to 36 channels
- Tracking Galileo E1 B/C and E5a I/Q
- Tracking GPS L1 C/A, L2C-M and -L, L5 I/Q and L1 P(Y) and L2 P(Y)

RUAG PODRIX receiver



Proba-3

Navigation performance:

ESA/ESOC conducted an accurate navigation performance assessment in preparation for the mission.[6] Realistic GNSS observations have been simulated. A dynamical POD based on the batch approach has been performed and the following POD accuracy has been determined:

- 29 cm absolute and 14 cm relative orbital error (3D RMS) based on GRAPHIC single frequency linear combination observations
- 14 cm absolute and 3 mm relative orbital error (3D RMS) based on ionospheric-free dual frequency linear combination observations

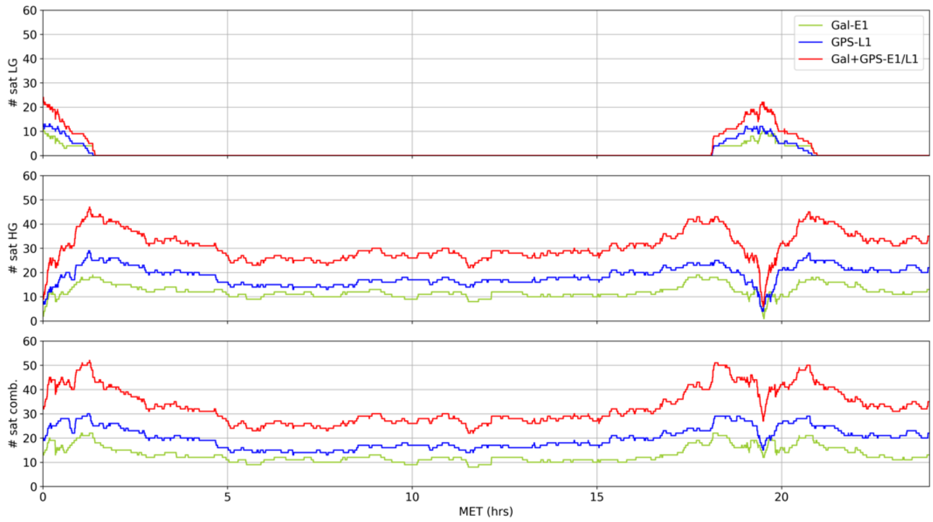
GNSS visibility:

- At least 10 Galileo signals available all over the orbit
- At least 15 GPS signals available all over the orbit
- At least 25 GNSS signals available all over the orbit

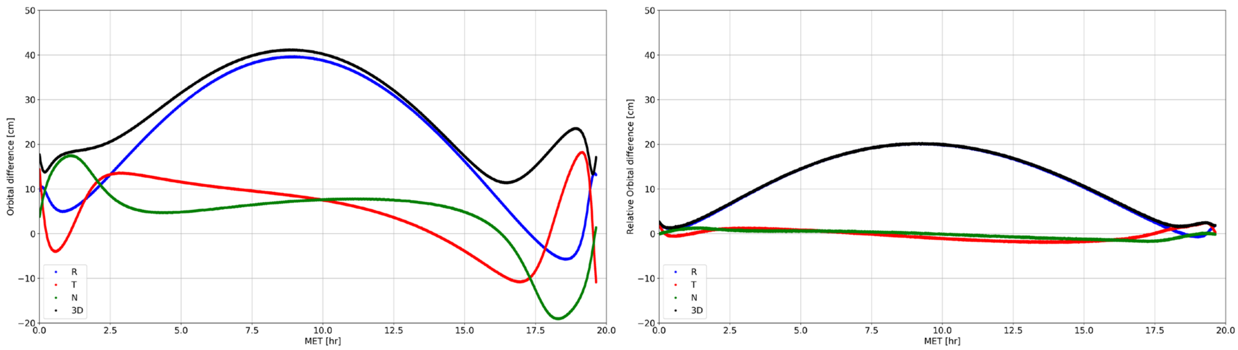
[4] European Space Agency, "About Proba-3". Available at www.esa.int/Enabling_Support/Space_Engineering_Technology/Proba_Missions/About_Proba-3 (accessed on 21 April 2020).

[5] RUAG Space, "PODRIX Multi-Constellation Precise Orbit Determination GNSS Receiver". Available at www.ruag.com/sites/default/files/media_document/2020-04/PODRIX%20V1.0.pdf.

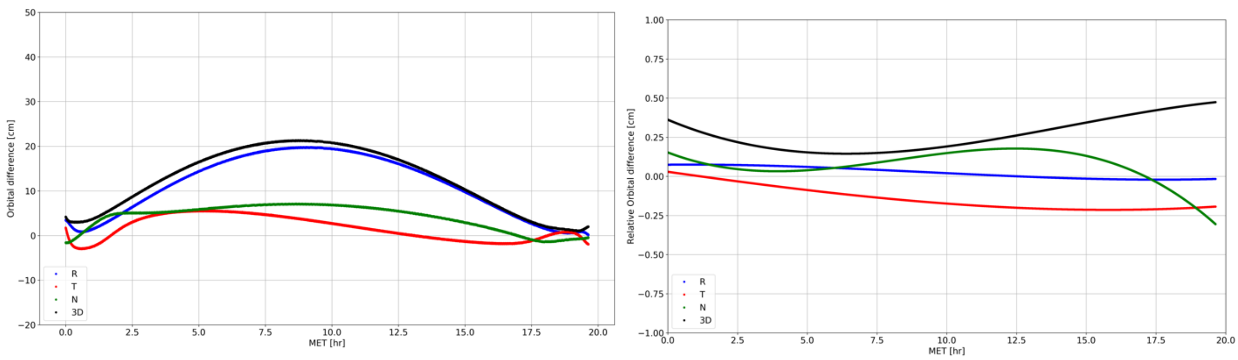
[6] Werner Enderle and others, "PROBA-3 Precise Orbit Determination based on GNSS Observations", in *Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation* (ION GNSS+ 2019) (Miami, Florida, September 2019).



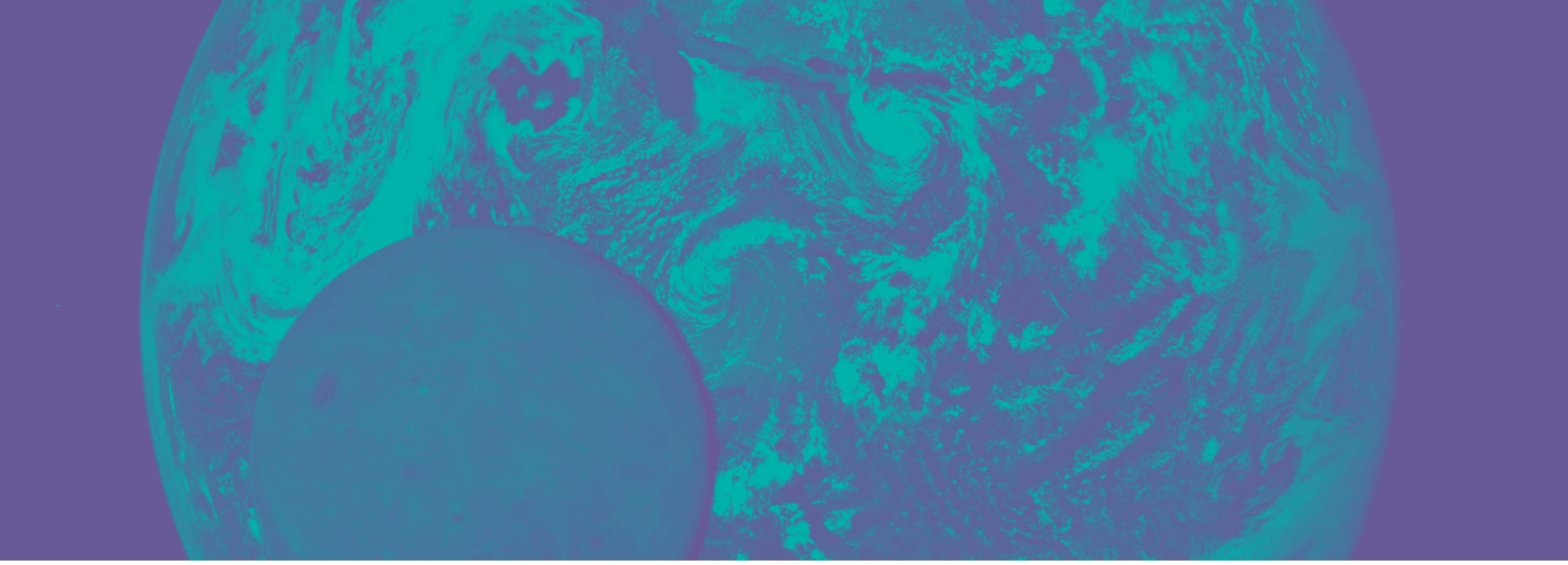
Visibility of Galileo and GPS signals for the receiver on-board Proba-3, for the low gain (LG, zenith-pointing) antenna, high-gain (HG, nadir-pointing) antenna and combined antennas



POD absolute and relative position accuracy, based on the single-frequency GRAPHIC linear combination observations



POD absolute and relative position accuracy, based on the dual-frequency ionospheric-free linear combination observations



7. 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.

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 International Committee on GNSS (ICG) has worked on a collaborative basis to publicize the performance of each GNSS constellation in 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.

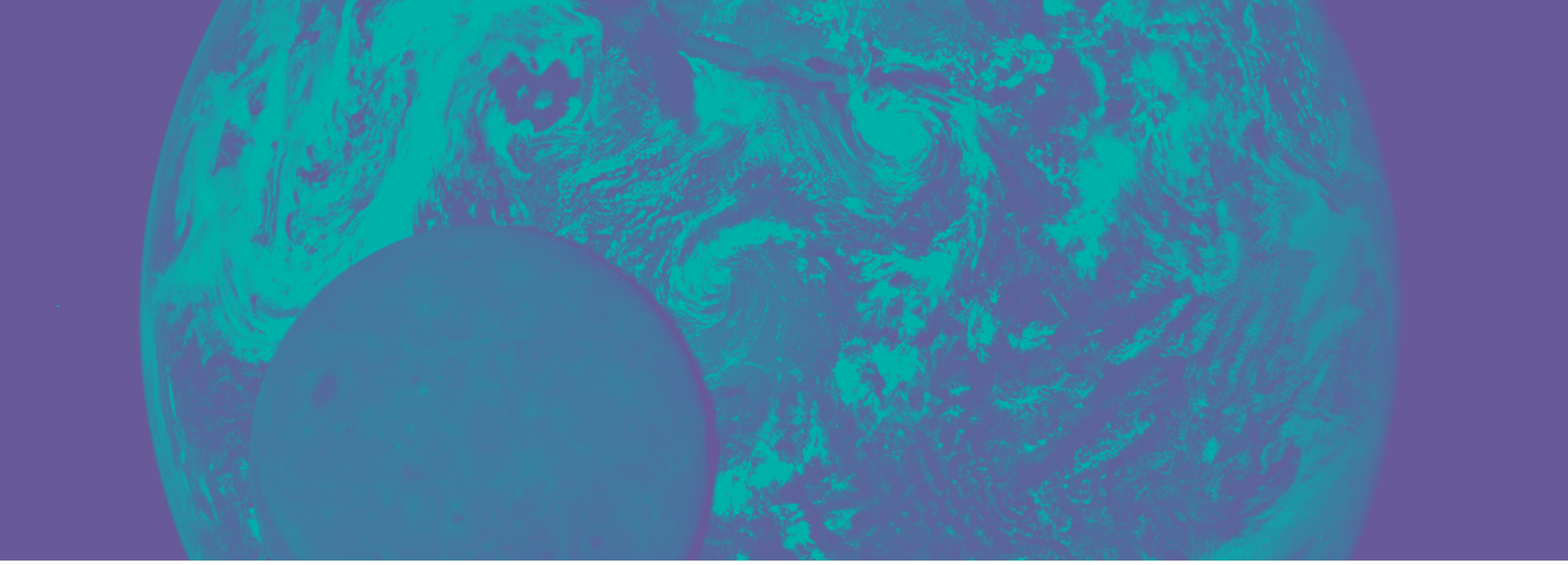
There are many benefits to an interoperable SSV, including increased signal availability for high-altitude users over that provided by any individual constellation alone, increased geometric diversity and thus accuracy in the final navigation solution, increased responsiveness and potential autonomy 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 with all GNSS constellations employed, 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, ICG makes eight specific recommendations as contained in annex B:

- Statement of Interest in GNSS Space Service Volume (ICG-7, 2012)
- Specifying and Characterizing an Interoperable GNSS Space Service Volume (ICG-8, 2013)
- Interoperable GNSS Space Service Volume (SSV) Characterization Outreach (ICG-9, 2014)
- Support to Space Service Volume (SSV) in Future Generation of Satellites (ICG-11, 2016)
- Additional Data for Space Service Volume (ICG-11, 2016)
- GNSS SSV – Use of GNSS for Exploration Activities in Cis-Lunar Space and Beyond (ICG-12, 2017)
- WG-B Space Applications Subgroup (ICG-13, 2018)
- Release of GNSS Transmit Antenna Patterns including Side Lobes (ICG-14, 2019)



8. Potential future evolutions of this space service volume booklet

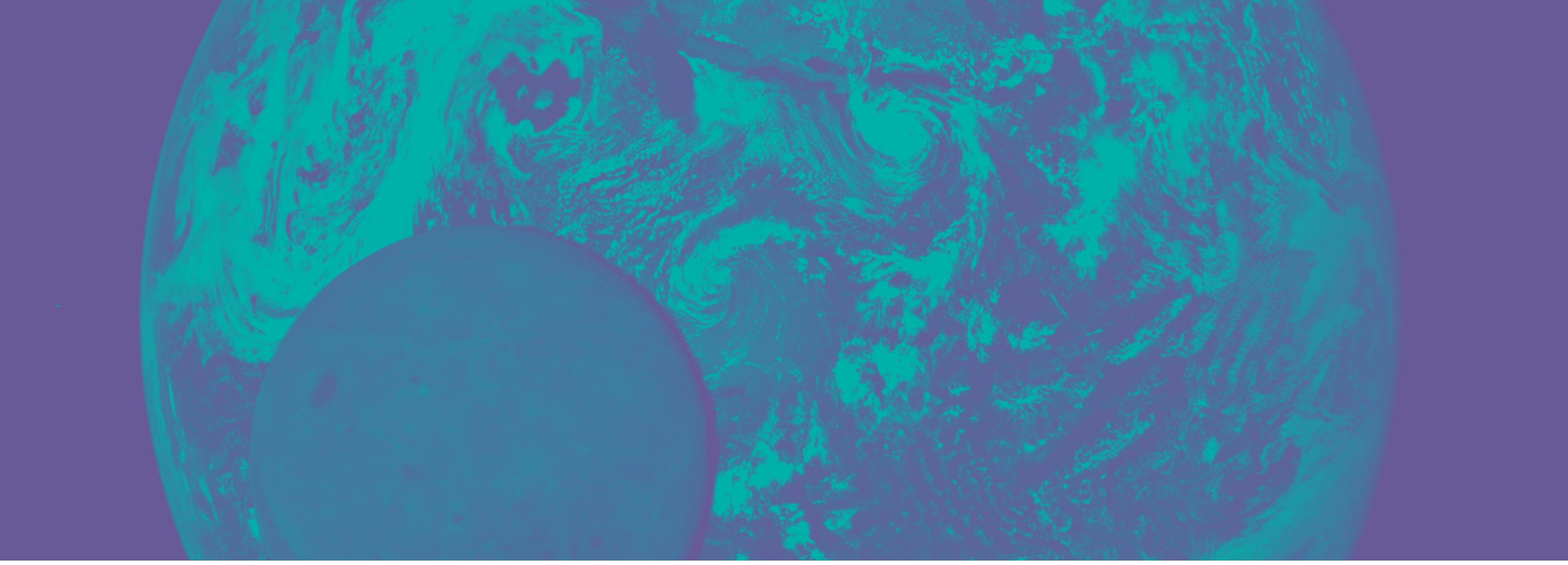
To promote the use of multi-GNSS for the purpose of safe robotic and/or crewed missions in the space service volume as defined in this booklet and beyond including cislunar space it will be necessary to update this booklet to extend efforts on simulation and modelling and elaborate further on recommendations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

- Improved and more accurate models of GNSS transmit antenna patterns including main lobe and side lobes and related transmit power, based on provider-published data and on publicly-available 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 in-flight observed data, to more accurately represent the expected performance of missions for various orbits
- Expanded discussion of user benefits and mission types, based on a more in-depth understanding of international use of GNSS in SSV
- Transition from a pure geometry-driven approach towards the use of pseudorange measurements for simulations, and migrating from the geometric dilution indicator (GDI) towards the position dilution of precision (PDOP) as a service performance parameter
- Identification of specific space user timing requirements in order to support the development of interoperable GNSS time
- Expansion of SSV and improvement of user performance and resiliency through trade studies on additional beacons or augmentations and service provider upgrades
- Provision of recommendations for the use of existing standards or development of new standards for GNSS space users to support and promote GNSS interoperable use for this specific community

The above potential elements for evolution of the booklet will be conducted in full coordination among all working groups of ICG.

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

- Updates of data can be supplied by the service providers and other ICG members and will be processed by ICG via the Space Use Subgroup of WG-B.
- New editions 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 space service volume

A1. Global Positioning System space service volume 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 (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 seven blocks in three major generations: Block I (1978), II (1989), IIA (1990), IIR (1997), IIR-M (2005), IIF (2010) and III (2018). Acquisition and production of 22 Block IIIF satellites is underway.

The GPS constellation 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 (1995), the GPS signal structure included an L1 C/A signal downlink at 1,575.42 MHz for civilian applications and an L1/L2 P(Y) signal downlink at 1,575.42 MHz/1,227.6 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 (1,575.42 MHz) and L2 (1,227.6 MHz) frequencies with augmented modulations to support interoperability, enhanced civilian use and more robust military application. L5 was added using the 1,176.45 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 (2018) 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 specification

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. Global positioning system III space service volume 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[a]	0.8 metres	
Signal centre frequency		
L1 C/A	1,575.42 MHz	
L1C	1,575.42 MHz	
L2 (L2C or C/A)	1,227.60 MHz	
L5 (I5 or Q5)	1,176.45 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[b]		
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%[c]	≥ 1%
L2, L5	≥ 92%[d]	≥ 6.5%

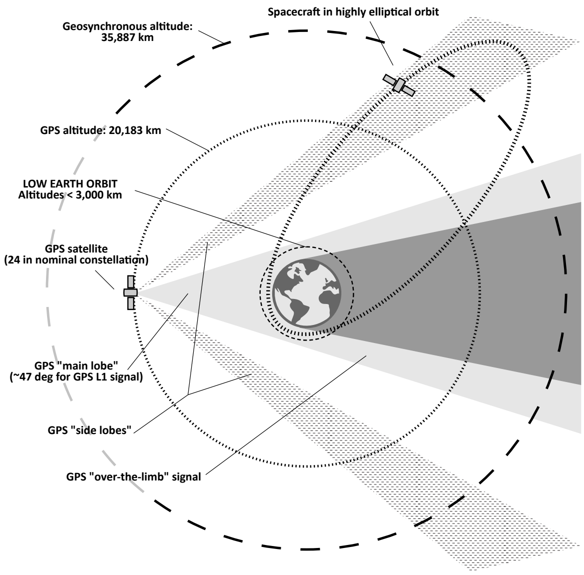
[a]This value represents pseudorange accuracy, not the final user position error, which is dependent on many mission-specific factors such as orbit geometry and receiver design.

[b]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.

[c]Assumes less than 108 minutes of continuous outage time.

[d]Assumes less than 84 minutes of continuous outage time.

Figure A1. Global positioning system geometry for space service volume characteristics



A2. GLONASS space service volume 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.

Current orbital constellation consists of GLONASS-M and GLONASS-K satellites.

The GLONASS satellites are placed in roughly circular orbits with an altitude of between 18,840 and 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 the life cycle of satellites. So the 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:

- On-board intersatellite measurement equipment ground control loop providing orbit and clock data insertion to navigation satellite
- 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 table A2.

Table A2. GLONASS space service volume 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[a]		1.4 m	
Signal centre frequency			
	L1	1,605.375 MHz	
	L2	1,248.625 MHz	
	L3	1,201 MHz	
Minimum received civilian signal power (GEO)		0 dBi RCP antenna at GEO	Reference off-boresight angle
	L1[b,c]	-179 dBW	26 deg
	L2	-178 dBW	34 deg
	L3[d]	-178 dBW	34 deg
Signal availability[e]			
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%

[a]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.

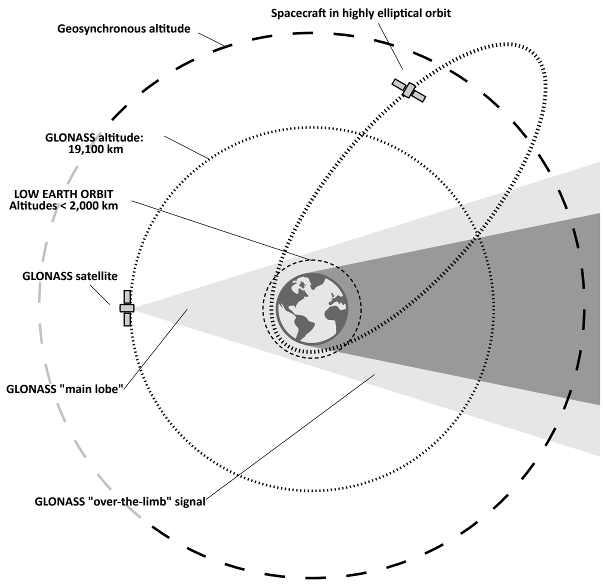
[b]FDMA signals in L1 and L2 and CDMA signals in L3

[c]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).

[d]L3 signals for GLONASS-K satellites.

[e]Assumes at least one GLONASS satellite in view in the high-orbit service volume.

Figure A2. GLONASS geometry for space service volume characteristics



A3. Galileo full operational capability space service volume 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 22 full-operational-capability (FOC) satellites. 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	1,575.42 MHz		
Spreading modulation	CBOC(6,1,1/11)		BOCcos(15,2.5)
Subcarrier frequency	1.023 MHz and 6.138 MHz (Two subcarriers)		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	1,278.75 MHz		
Spreading modulation	BPSK(5)	BPSK(5)	BOCcos(10,5)
Subcarrier 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	1,191.795 MHz			
Spreading modulation	AltBOC(15,10)			
Subcarrier 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 space service volume

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 should 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 to maintain and enforce these capabilities in the future. The support of Galileo satellites to the interoperable GNSS SSV is provided in the following table. Furthermore, it needs to be pointed out that in order to ensure formal support to space users, a Galileo SSV has been defined.

Table A6. Galileo space service volume 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[a]	1.1 metres	
Signal centre frequency		
E1B/C	1,575.42 MHz	
E6B/C	1,278.75 MHz	
E5b	1,206.45 MHz	
E5ABOC	1,191.795 MHz	
E5a	1,176.45 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[b]		
Lower SSV	**At least 1 signal**	**4 or more signals**
E1B/C	100%	> 99%[g]
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%[c]	0%
E6B/C	>= 72%[d]	0%
E5b	>= 80%[e]	0%
E5a or E5ABOC	>= 86%[f]	0%

[a]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.

[b]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.

[c]Assumes less than 93 minutes of continuous outage time.

[d]Assumes less than 75 minutes of continuous outage time.

[e]Assumes less than 64 minutes of continuous outage time.

[f]Assumes less than 54 minutes of continuous outage time.

[g]>99% at 21.5 deg (-182.5 dBW).

A4. BDS space service volume characteristics

Introduction

China upholds the principles of "independence, openness, compatibility and gradualness", to steadily push forward construction and development of the BeiDou Navigation Satellite System (BDS). By 2000, the construction of BDS-1 was completed to provide services to China; by 2012, the construction of BDS-2 was completed to provide services to the Asia-Pacific region; BDS-3 was formally commissioned and started to provide services worldwide in 2020. BDS is mainly comprised of three segments: a space segment, a ground segment and a user segment. BDS space segment is a hybrid constellation consisting of satellites in three types of orbits. The satellites in high orbits can offer better anti-shielding capabilities, which is particularly observable in terms of performance in the low-latitude areas. BDS provides multi-frequency navigation signals, and is able to improve the service accuracy by using combined signals. BDS integrates navigation and communication functions, and possesses multiple service capabilities, namely, positioning, navigation and timing, short message communication, international search and rescue, satellite-based augmentation, ground augmentation and precise point positioning, etc.

Space segment

The BDS space segment consists of a number of satellites located in geostationary Earth orbit (GEO), inclined geo-synchronous orbit (IGSO) and medium Earth orbit (MEO).

The nominal space constellation of BDS-3 consists of 3 GEO satellites, 3 IGSO satellites, and 24 MEO satellites. According to the actual situation, spare satellites may be deployed. The GEO satellites operate at an altitude of 35,786 km and are located at 80°E, 110.5°E, and 140°E respectively. The IGSO satellites, with an orbital altitude of 35,786 km and the orbital inclination of 55 degrees, are distributed in three orbital planes. The geographical longitudes of the ascending nodes locate at 118°E. The MEO satellites orbit at an altitude of 21,528 km and an inclination of 55 degrees, and are distributed in a Walker 24/3/1 constellation.

Ground segment

The ground segment is responsible for the BDS operation and control. It consists of various ground stations, including master control stations, time synchronization/uplink stations, monitoring stations, as well as operation and management facilities of the inter-satellite link.

BDS-3 has established high-precision time and space references, added inter-satellite link operation management facilities, and realized satellite orbit and clock difference measurement based on joint observations using satellite-ground and inter-satellite links. It possesses the capability to provide positioning, navigation and timing services. At the same time, ground facilities for short message communication, international search and rescue, satellite-based augmentation, ground augmentation, precise point positioning and other services have also been built.

BDS service and signals

BDS possesses the operation capability for users worldwide, while for the Asian-Pacific area BDS provides an enhanced service.

Table A7. The BDS service plan

Service types		Signal(s)/band(s)	Broadcast satellites
Worldwide	Positioning, navigation and timing (RNSS)	B1I, B3I	3GEO+3IGSO+24MEO
		B1C, B2a, B2b	3IGSO+24MEO
	Global short message communication (GSMC)	Uplink: L Downlink: GSMC-B2b	Uplink: 14MEO Downlink: 3IGSO+24MEO
	International search and rescue (SAR)	Uplink: UHF Downlink: SAR-B2b	Uplink: 6MEO Downlink: 3IGSO+24MEO
China and surrounding areas	Satellite-based augmentation system (SBAS)	BDSBAS-B1C, BDSBASB2a	3GEO
	Precise point positioning (PPP)	PPP-B2b	3GEO
	Regional short message communication (RSMC)	Uplink: L Downlink: S	3GEO

Note: China and surrounding areas means 75°E to 135 °E, 10°N to 55°N

BDS transmits positioning, navigation and timing (RNSS) signals in three frequency bands: B1 (1,575.42 MHz), B2 (1,191.795 MHz), B3 (1,268.52 MHz). Five types of open service (OS) signals are broadcasting in by BDS satellites. OS signals B1I and B3I are inherited from BDS-2 and broadcasting by all BDS satellites in orbit. B1C, B2a, B2b are new OS signals broadcasted by BDS-3 IGSO and MEO satellites. The detailed signal characteristics are specified in BDS SIS-ICD. (http://en.beidou.gov.cn/SYSTEMS/ ICD)

BDS keeps carrying out coordination and cooperation with other navigation satellite systems, and promotes compatibility and interoperability among systems to jointly provide higher quality services for global users. Users especially those in space service volume can enjoy better service performance by jointly using BDS and other GNSS open service signals without significantly increasing complexity and user cost. The BeiDou system time traces back to Coordinated Universal Time. The time offsets between BDS and other GNSS are broadcasted in the navigation messages. The BDS coordinate system is consistent with the International Earth Reference Frame (ITRF).

Typical characteristics of BDS satellites for space service volume

In this section the typical characteristics of BDS satellites for SSV are provided. The parameters shown in the template below were measured from pre-flight ground testing of BDS-3 satellites. 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.

Table A8. BDS-3 space service volume characteristics

Definition	Notes
Lower SSV: 3,000 to 8,000 km altitude	Four BDS signals available simultaneously a majority of the time but BDS 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 BDS signals received over the limb of the Earth. Users will experience periods when no BDS satellites are available.

Parameters	Value	
User range error[a]	1.0 metres	
Signal centre frequency		
B1I (MEO/IGSO/GEO)	1,561.098 MHz	
B1C (MEO/IGSO)	1,575.42 MHz	
B2a (MEO/IGSO)	1,176.45 MHz	
B2b (MEO/IGSO)	1,207.14 MHz	
B3I (MEO/IGSO/GEO)	1,268.52 MHz	
Minimum received civilian signal power	0 dBi RCP antenna at GEO	Reference off-boresight angle
B1I, B1C (MEO)	-184.2 dBW	25 deg
B1I (GEO/IGSO)	-185.9 dBW	19 deg
B2a, B2b (MEO)	-182.8 dBW	28 deg
B2a, B2b (IGSO)	-184.4 dBW	22 deg
B3I(MEO)	-182.8 dBW	28 deg
B3I (GEO/IGSO)	-184.4 dBW	22 deg
Signal availability[b]		
Lower SSV	**At least 1 signal**	**4 or more signals**
B1I, B1C	100%	100%
B2a, B2b	100%	100%
B3I	100%	100%
Upper SSV	**At least 1 signal**	**4 or more signals**
B1I, B1C	≥91%[c]	≥0.5%
B2a, B2b	≥99%[d]	≥3%
B3I	≥99%[d]	≥3%

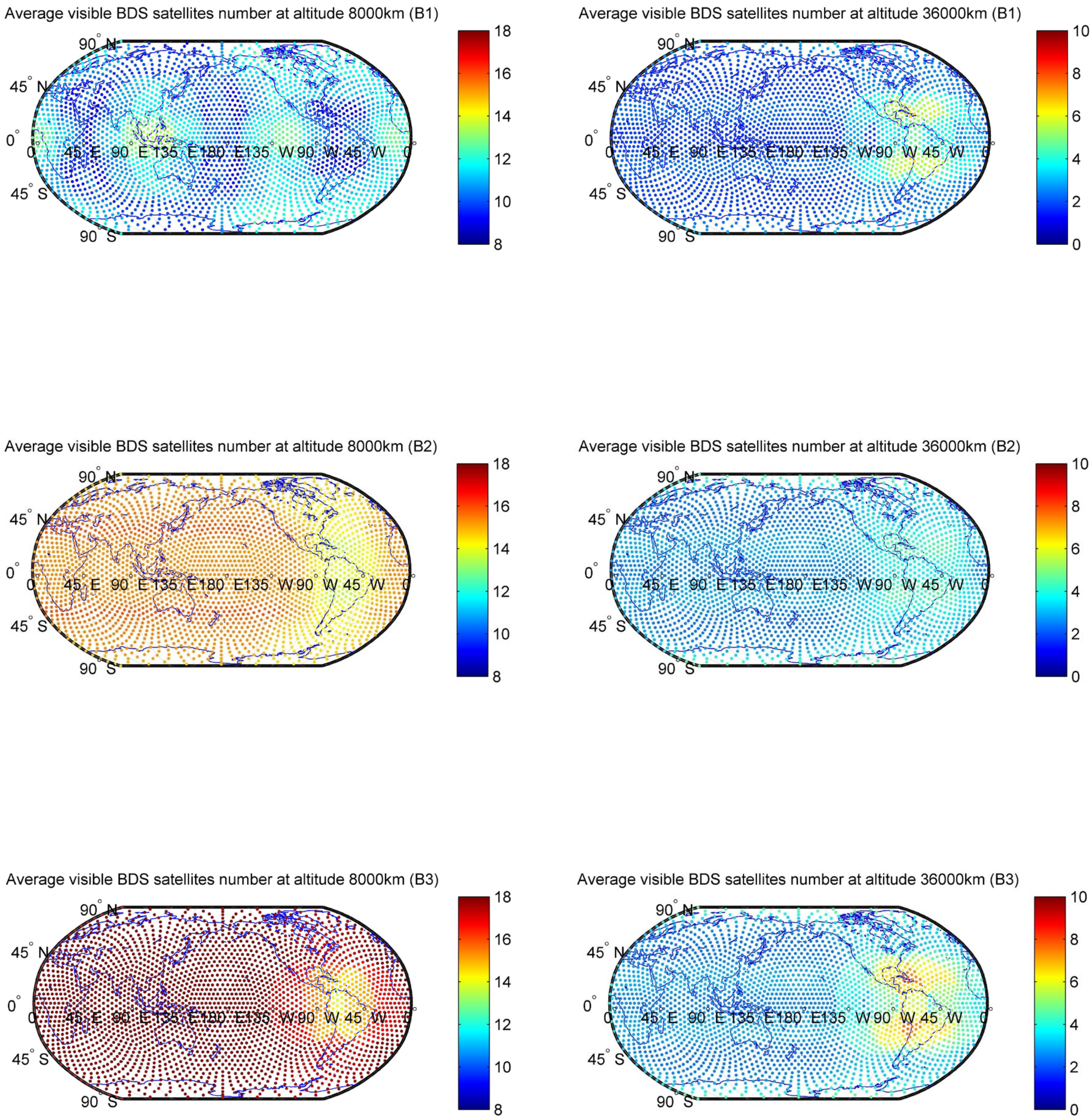
[a]This value represents pseudorange (signal in space) accuracy, not the final user position error, which is dependent on many mission-specific factors such as orbit geometry and receiver design.

[b]Assumes a nominal 3GEO+3IGSO+24MEO satellite constellation and no BDS spacecraft failures. Signal availability at 95% of the areas at a specific worst-case altitude within the specified SSV.

[c]Assumes less than 45 minutes of continuous outage time.

[d]Assumes less than 7 minutes of continuous outage time.

Figure A3. Average visible BDS satellite number in space service volume (8,000 km/36,000 km, B1/B2/B3)



A5. Quasi-zenith satellite system space service volume characteristics

Japan has constructed the Quasi-Zenith Satellite System (QZSS), MICHIBIKI, which is composed of three IGSO and one GEO satellite. QZSS became fully operational on November 1, 2018.

The four-satellite constellation currently provides three types of services. The first is a GPS complementary service, transmitting ranging signals from satellites. QZSS ranging signals have the highest interoperability with GPS signals. Secondly, GNSS augmentation services can provide error corrections via QZSS. Finally, the third type of QZSS service supports disaster mitigation and relief operations through a messaging function.

A replacement of QZS-1 is expected to be launched around 2021. Future plans include three additional satellites which will constitute the seven-satellite constellation for QZSS. The completion of the seven-satellite constellation is expected to be around 2023.

The current specification for the four-satellite constellation is not applicable for SSV applications (i.e., no specification for SSV). However, the Government of Japan measured antenna pattern and phase characteristics of each satellite before launch and the information is available to the public. For the seven-satellite constellation and beyond, the Government of Japan is planning to maintain the same policy on SSV, i.e., no required specific performance; however, measurement characteristics will be released to the public.

Table A9. QZSS space service volume characteristics

Definition	Notes
Lower SSV: 3,000 to 8,000 km altitude	Signals from QZSS constellation 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	Signals from QZSS constellation 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[a]	2.6 metres (95%)	
Signal centre frequency		
L1 C/A	1,575.42 MHz	
L1C	1,575.42 MHz	
L2 C	1,227.60 MHz	
L5 (I5 or Q5)	1,176.42 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[b]		
Lower SSV	**At least 1 signal**	**4 or more signals**
L1	≥99.4%[c]	≥83.8%[c]
L2, L5	≥99.4%[c]	≥83.8%[c]
Upper SSV	**At least 1 signal**	**4 or more signals**
L1	≥39.8%[d]	≥6.7%[d]
L2, L5	≥44.5%[d]	≥9.6%[d]

[a]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.

[b]Assumes a nominal operational condition, no spacecraft failures and no orbit manoeuvres, all SVs transmitting healthy navigation signals. Signal availability at all distributed grid points and simulation epochs.

[c]Assumes user satellites at lower boundary (3,000 km altitude) for worst (See figures A4 and A5).

[d]Assumes user satellites at higher boundary (at the altitude of geosynchronous orbit) for worst (See figures A4 and A5).

Figure A4. One SV signal availability with 15 dB-Hz threshold

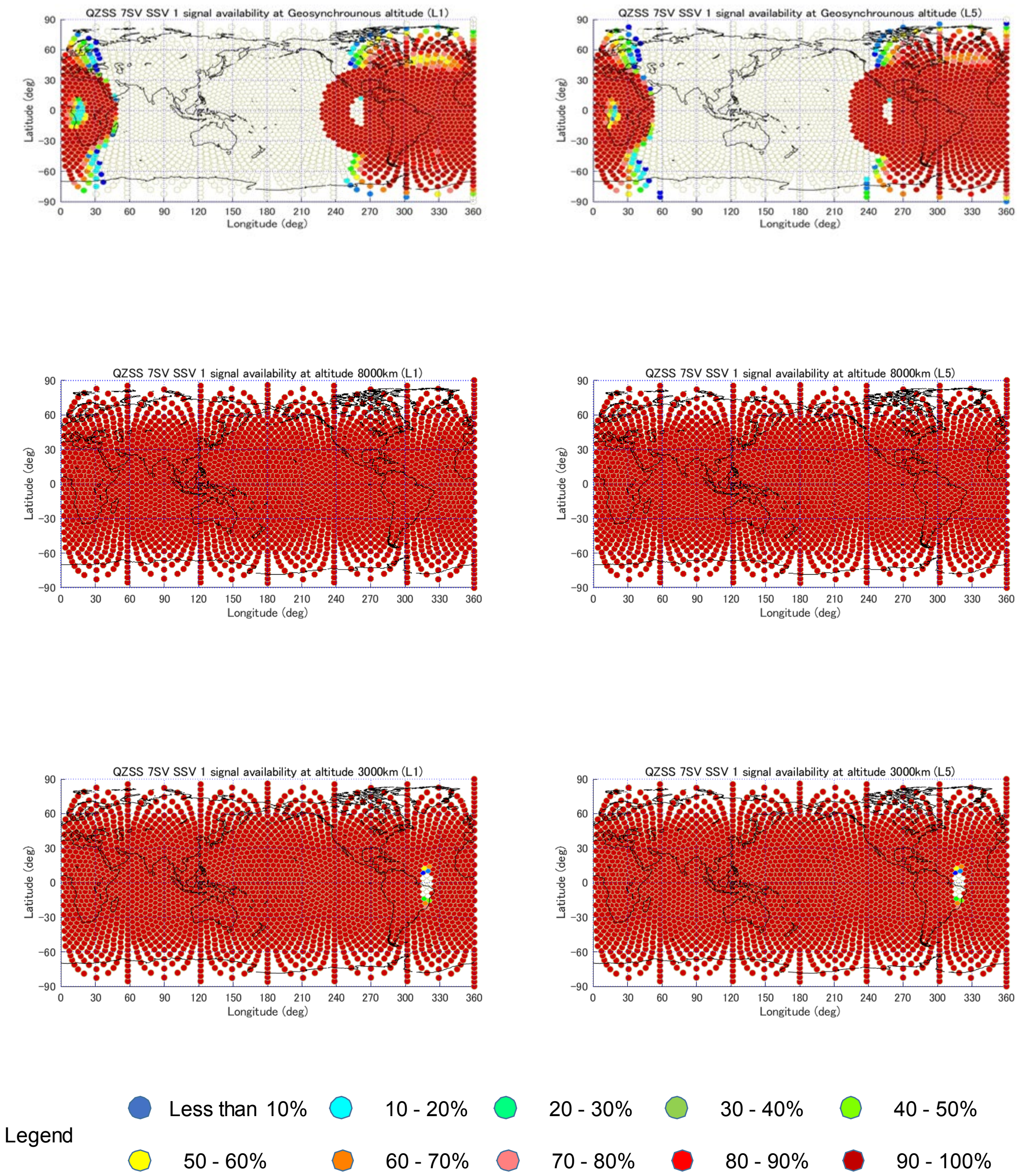


Figure A5: 4 or more SV signals availability with 15 dB-Hz threshold

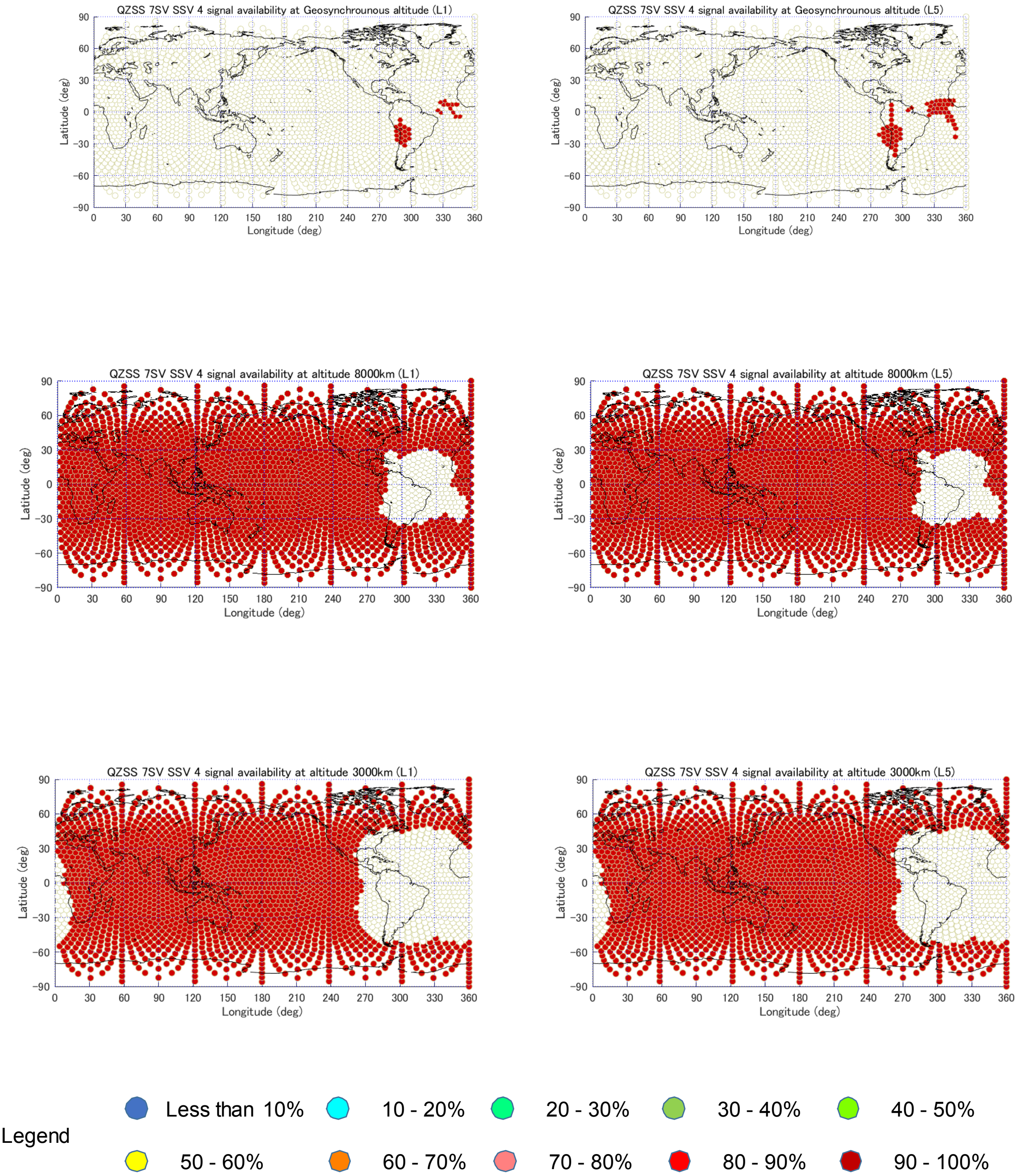
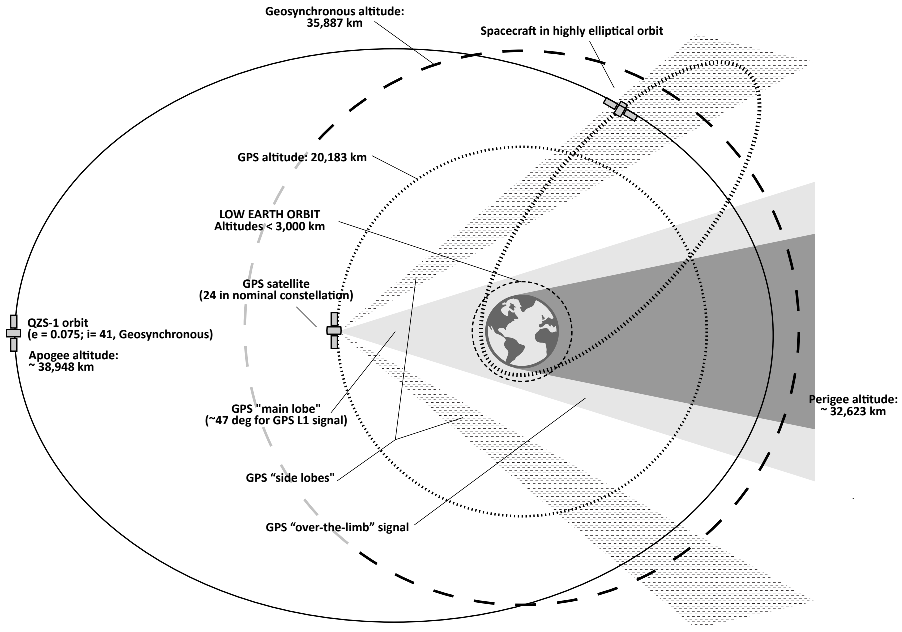


Figure A6. QZSS geometry for space service volume characteristics



A6. NavIC(IRNSS) space service volume characteristics

The NavIC(IRNSS) (Navigation with Indian Constellation) is an ISRO/India initiative for an independent satellite navigation system to provide precise PVT to users over the NavIC(IRNSS) service area defined as 5°S to 50°N latitude and 55°E to 110°E longitude. 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 NavIC(IRNSS) service area for a dual frequency user receiver. The NavIC(IRNSS) system consists of a space segment, ground segment and user segment.

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. 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(IRNSS) constellation. It provides the monitoring of the constellation status, correction to the orbital parameters and navigation data uploading. The ground segment comprises navigation data uplink stations, a navigation control centre, a network timing centre, range and integrity monitoring stations, CDMA ranging stations and data communication links.

User segment

The user segment consists of:

1. A dual frequency NavIC(IRNSS) receiver capable of receiving navigation signals in L5 and S frequency bands, for standard positioning services (SPS)
2. A single frequency receiver for SPS working in L5 or S band for SPS
3. A multi GNSS receiver incorporating NavIC(IRNSS) for SPS

NavIC(IRNSS) signals

NavIC(IRNSS) provides two navigation services in L5 and S frequency bands. The L5 signal contributes to the interoperable GNSS SSV. The signal parameters in the L5 band are provided below.

Table A10. NavIC(IRNSS) L5 signal parameters

Parameters	NavIC(IRNSS) L5 signal parameters
Carrier frequency	1,176.45 MHz
Signal bandwidth	±12 MHz
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(IRNSS) space service volume

The NavIC(IRNSS) L5 SPS signal contributes to the interoperable GNSS SSV and the SSV parameters are provided in table A11.

The typical characteristics provided should not be interpreted as commitment from the NavIC(IRNSS) system. Official information related to SSV is published in the NavIC(IRNSS) SIS ICD for SPS service Version 1.1 (Reference: www.isro.gov.in/sites/default/files/irnss_sps_icd_version1.1-2017.pdf).

Table A11. NavIC(IRNSS) space service volume 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)[a]		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[b]		**At least 1 signal**	**4 or more signals**
Lower SSV[c]			
	L5	98.00%[d]	51.40%[e]
Upper SSV[f]			
	L5	36.9%[g]	0.6%[h]

[a]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.

[b]Assumes a nominal, optimized NavIC(IRNSS) constellation of 11 satellites and no NavIC(IRNSS) spacecraft failures. Signal availability at 95% of the areas at a specific altitude within the specified SSV.

[c]The antenna for a user in lower SSV is considered to be omnidirectional.

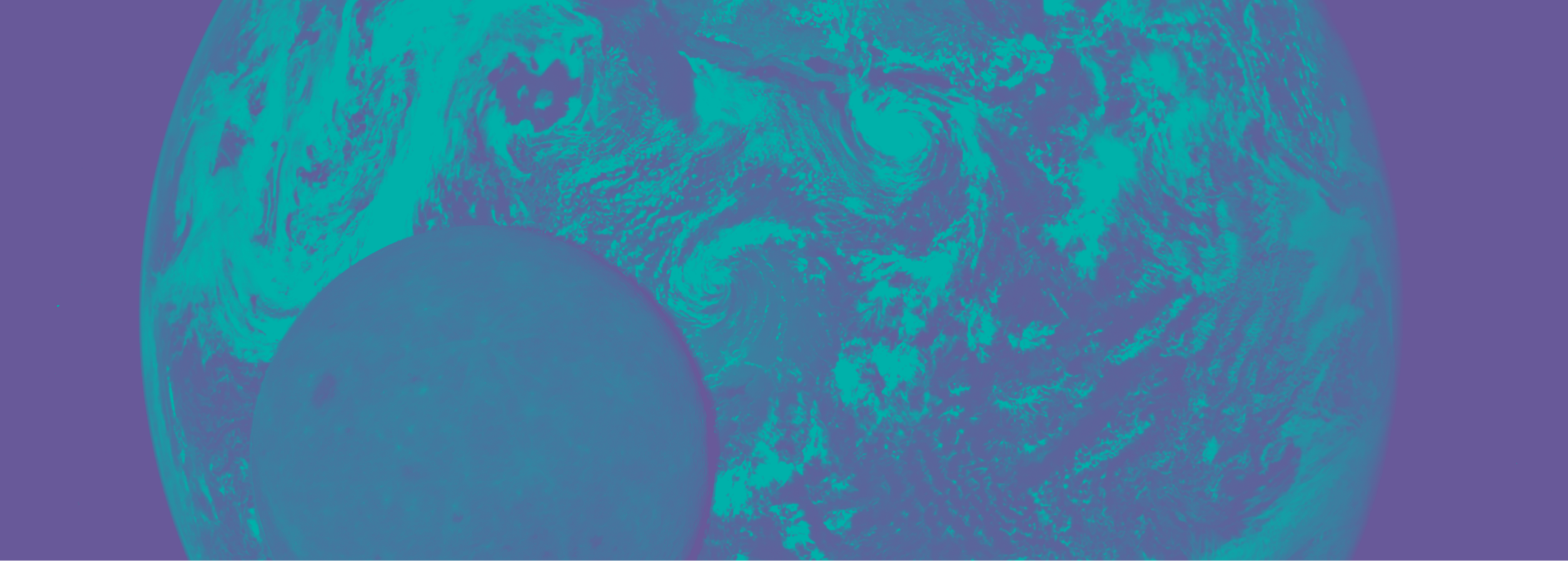
[d]Maximum continuous outage time of the constellation is 348 mins (scenario duration of 14 days).

[e]Maximum continuous outage time of the constellation is 20,160 mins (scenario duration of 14 days).

[f]The antenna for a user in the upper SSV is considered to be boresight at 83°E and 5°N.

[g]Maximum continuous outage time of the constellation is 20,160 mins in the upper SSV (scenario duration of 14 days).

[h]Maximum continuous outage time of the constellation is 20,160 mins in the upper SSV (scenario duration of 14 days).



Annex B. Recommendations

The recommendations in this annex were adopted by the International Committee on GNSS (ICG) via Working Group B (WG-B) to advance development and adoption of the interoperable GNSS space service volume by providers, users, and equipment manufacturers.

All official ICG documentation is available on the ICG Information Portal, www.unoosa.org/oosa/en/ourwork/icg/icg.html.

B1. Statement of interest in GNSS space service volume (ICG-7, 2012)

Background/brief description of the issue

WG-B has followed in the last year recommendation 6 of ICG-6 entitled "Interoperable GNSS Space Service Volume". WG-B has addressed this topic at a technical level at its interim meeting in June 2012 in Vienna and has identified the advantages of an interoperable GNSS SSV for the space user community.

Discussion/analyses

In order to progress further towards an interoperable GNSS SSV the contribution of the different system providers is an essential element. Only with their direct involvement in an SSV definition process it is possible to achieve a harmonization of the qualitative and quantitative characteristics of such an interoperable GNSS SSV.

Recommendation of Committee action

Recognizing the advantages of an interoperable GNSS SSV for the space user community, ICG is invited to take notice that WG-B encourages all system providers to identify their interest in contributing to a future interoperable GNSS SSV. The qualitative and quantitative specification of such a future, interoperable GNSS SSV is recommended to be coordinated through the ongoing GNSS SSV initiative within ICG WG-B. This process will need the involvement of the system providers in order to allow for a high level of interoperability in SSV.

The committee recommends that a definition of an interoperable GNSS SSV be introduced into the ICG glossary of terms.

B2. Specifying and characterizing an interoperable GNSS space service volume (ICG-8, 2013)

Background/brief description of the issue

WG-B has continued the efforts addressed in recommendation 6 of ICG-6 entitled "Interoperable GNSS Space Service Volume". Since ICG-6, WG-B has made excellent progress in specifying SSV and populating respective templates that will characterize the expected qualitative and quantitative characteristics of signals within an interoperable GNSS space service volume. SSV will open new science and technological opportunities through the use of robust, interoperable GNSS navigational signals in space, enabling missions that save lives, understand our Earth, and the universe, and provide economic advantages worldwide.

Discussion/analyses

WG-B has made significant progress in establishing an interoperable GNSS SSV during ICG-8 through significant pre-work, presentations at ICG-8 and additional robust contributions from the administrations of China and the Russian Federation. At ICG-8 several administrations presented their SSV signal templates and presented SSV performance expectations. During ICG-8, the WG-B team discussed the importance of common definitions and data needed from the GNSS constellations, in conjunction with the signal template data, to conduct consistent SSV performance analyses. We recommend that WG-B provide an additional template to develop these common definitions and data requirements, and gather this data from the appropriate administrations.

Recommendation of Committee action

Recognizing the advantages of an interoperable GNSS SSV for the space user community, ICG is invited to take notice that the WG-B team has taken several actions to compile definitions to support future analyses and gather template data approved by GNSS system providers. The SSV template data, coupled with the other requested data and definitions, will enable users to analyse GNSS signal availability and navigation performance expectations for space vehicles flying in SSV.

Providers are invited to send all action responses to the WG-B Co-chairs and Interagency Operations Advisory Group (IOAG) ICG representative. Until recommendation on the SSV template is approved by ICG, the members agreed to keep this information within ICG forum. WG-B action items include:

- *SSV template completion*
  - *WG-B team works with service providers to complete and formally submit the SSV templates to WG-B co-chairs prior to the second interim WG meeting.*
  - *Questions and discussion regarding the template will be addressed during a video conference to be held prior to the first interim WG meeting.*
  - *WG-B team members shall be prepared to discuss their template inputs at the first interim WG meeting.*
- *Maturity of definition*
  - *WG-B team to develop definitions of the minimal service capability of the GNSS constellations (i.e., satellite orbit, number of satellites and constellation geometry). This will be used in conjunction with template data to perform unified GNSS SSV performance analyses.*
- *Spaceborne GNSS receivers*
  - *WG-B encourages the development of interoperable multi-frequency space borne GNSS receivers that exploit the use of GNSS signals in space.*
- *Antenna/electronics characterization*

  Stable performance of the GNSS space segment over long time periods is crucial for the scientific community. The scientific community recommends:

  - *Minimizing phase and group delay variations of GNSS transmit antennas vs. angle during the design phase*
  - *Measure phase and group delay variations of GNSS transmit antennas vs. angle, and making this information available to the scientific community*
  - *Measure phase centre and group delay centre for GNSS transmit antennas vs. angle, and make this information available to the scientific community*
  - *Spacecraft electronics: Maintain strict coherence of phase and group delay between signals on the same spacecraft*

B3. Interoperable GNSS space service volume characterization outreach (ICG-9, 2014)

Background/brief description of the issue

WG-B has followed in the last period the recommendation to establish an "Interoperable GNSS Space Service Volume". WG-B has addressed this topic at the technical level at several meetings and has identified the advantages of an interoperable GNSS SSV for the space user community. So far several GNSS service providers have supported this initiative, either by providing their SSV characterization or by indicating their intention to do so in the near future.

Discussion/analyses

In order to communicate to the public domain the advantages of an interoperable GNSS SSV and the relevant support of every GNSS service provider, interested members of WG-B have agreed to elaborate a booklet identifying:

- The advantages of an interoperable GNSS SSV for space users
- The support of every GNSS service provider to an interoperable GNSS SSV based on an agreed comprehensive template
- An estimation of the capabilities of the identified interoperable GNSS SSV, given the individual SSV characteristics per service provider as input

This booklet is considered of particular interest to GNSS space-receiver manufacturers. The booklet is meant to characterize the contribution of the different GNSS to an interoperable GNSS SSV for the benefit of the users, but shall not induce commitments as they are handled by the individual GNSS providers in their respective performance commitment documents.

The booklet shall be worked out by WG-B members representing GPS, GLONASS, BeiDou, Galileo, QZSS and IRNSS, and they shall organize the necessary work to have a final version ready for commenting and approval within WG-B at ICG-10.

Recommendation of Committee action

GNSS providers are recommended to support SSV outreach by making the booklet on "Interoperable GNSS Space Service Volume" available to the public through their relevant websites once the booklet is available.

B4. Support to space service volume in future generations of satellites (ICG-11, 2016)

Background/brief description of the issue

The importance of establishing an interoperable GNSS SSV is acknowledged by space agencies and service providers. Important progress has been made in establishing the interoperable GNSS SSV based on data that was released by the service providers.

Discussion/analyses

Service providers have been actively contributing to the completion of the SSV templates that include SSV support for the different systems. Many GNSS provided data in the SSV template derived from measurement and characterization efforts conducted based on existing satellite designs.

Recommendation of Committee action

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 generation of satellites. Service providers and space agencies are invited to report back to WG-B on their progress on a regular basis.

B5. Additional data for space service volume (ICG-11, 2016)

Background/brief description of the issue

In order to exploit the interoperable GNSS SSV for space missions or to develop GNSS space receivers, information from service providers regarding the power emissions for wide off-boresight angles is essential. Initial information on this aspect is available from every service provider.

Discussion/analyses

Recognizing the success of WG-B in encouraging all providers to supply SSV service details in templates for their constellations, GNSS space users now have the data necessary to determine if the SSV service is applicable to their needs.

Recommendation of Committee action

In order to fully support in-depth mission-specific navigation studies, WG-B invites providers to consider for the future, the provision of 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, also consider providing the following additional data (see also WG-D recommendations):

- *GNSS transmit antenna phase centre and group delay patterns for each frequency*

B6. GNSS space service volume – use of GNSS for exploration activities in cis-lunar space and beyond (ICG-12, 2017)

Background/brief description of the issue

During the WG-B GNSS SSV Working Group activities associated with the generation of the GNSS SSV booklet, it became clear that the use of GNSS signals in support of missions within and beyond cis-lunar space is possible and could contribute to improved on-board navigation capabilities.

Discussion/analyses

It is essential to understand user needs for missions to cis-lunar space and beyond, and to perform detailed analyses of GNSS SSV capabilities and potential augmentations related to the support of missions to cis-lunar space and beyond.

Recommendation of Committee action

WG-B will lead and service providers, space agencies and research institutions are invited to contribute to investigations/developments related to use of the full potential of the GNSS SSV, also considering the support of exploration activities in cis-lunar space and beyond.

B7. WG-B space applications subgroup (ICG-13, 2018)

Background/brief description of the issue

WG-B has an extensive work plan, including many facets such as performance enhancements, ionospheric modeling, new service concepts and augmentations, and SSV. The multi-GNSS SSV project, and other similar projects, benefit from a highly active and focused team, which otherwise may distract WG-B from its ability to focus on other activities within its work plan.

Discussion/analyses

The formation of a formal subgroup on space applications would allow for independent action by its voluntary membership and leadership. Its focus would be on the multi-GNSS SSV and other aspects specific to the space user community.

Recommendation of Committee action

WG-B will create a space applications subgroup, whose scope will include opportunities, issues, and challenges related to space applications of GNSS, as defined by the subgroup terms of reference. For these purposes, the subgroup will interact with the space user community and the service providers. The terms of reference will be adopted by WG-B and the need for modification will be reviewed annually.

B8. Release of GNSS transmit antenna patterns including side lobes (ICG-14, 2019)

Background/brief description of the issue

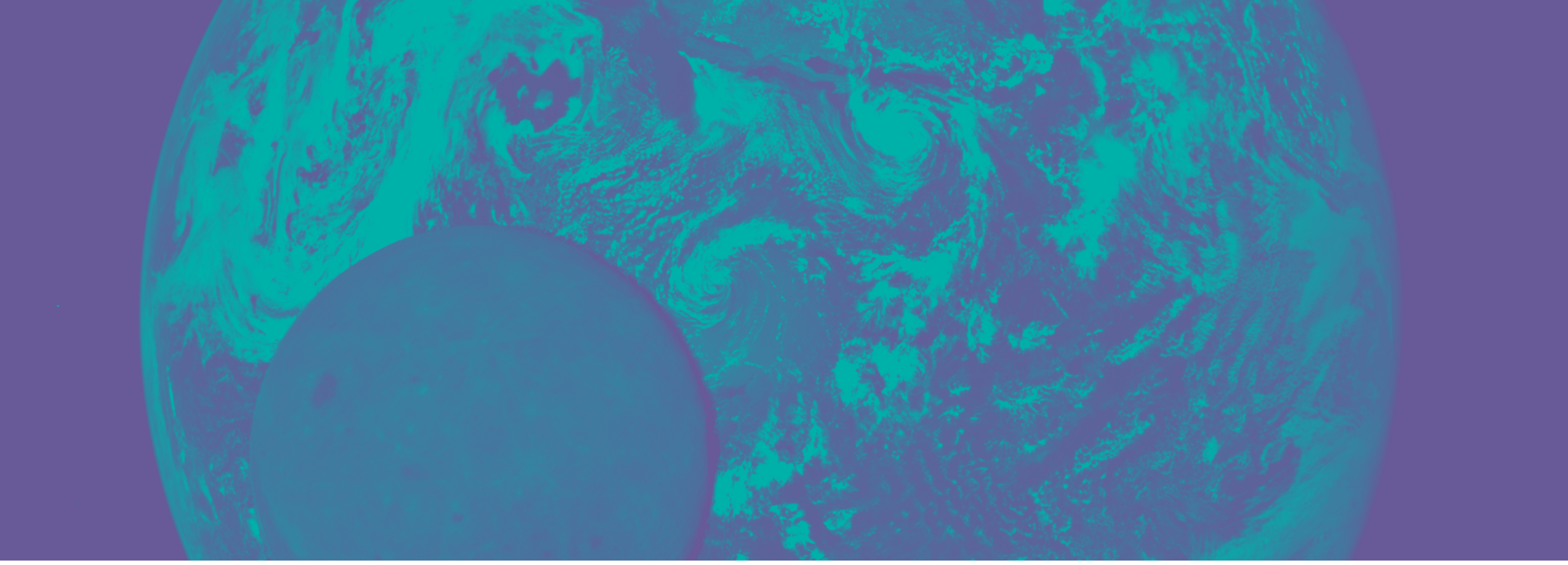
The use of GNSS for spacecraft navigation in general has increased over the last decade. In fact, navigation employing GNSS observations for spacecraft in low Earth orbit is considered routine. However, the situation is quite different for space missions that intend to employ GNSS in SSV (including MEO, GEO, HEO or missions to the Moon and beyond). For these space missions, the reception of signals from GNSS transmit antenna side lobes is essential to improve availability and performance. This recommendation extends recommendation #3 from Working Group-B "Additional Data for Space Service Volume", made on 10 November 2016, which addressed provision of antenna pattern data at least to the extent of the main lobe signal as outlined in the SSV booklet.

Discussion/analyses

The joint use of interoperable GNSS signals, especially the signals in the side lobes, will enable and/or improve the on-board navigation of spacecraft in SSV. In this context, knowledge of the full antenna pattern (main lobe and side lobes) from the transmitting antennas of each of the GNSS satellites in the various constellations is essential for missions in MEO, GEO, HEO or to the Moon and beyond, to allow mission analysis, mission design as well as for GNSS equipment (receiver and antennas) manufacturers and also for the spacecraft operators for the development of their respective operations concepts.

Recommendation of Committee action

WG-B recommends that GNSS service providers consider releasing the antenna gain patterns or equivalent representative modelling information (including both main lobe and side lobes for each frequency, for open services) for each of the transmit antennas of the GNSS satellites in the respective satellite constellations in order to enable and/or improve the use of GNSS in SSV. In addition, for future satellite developments, WG-B recommends that GNSS service providers consider conducting antenna gain measurements, testing and/or characterization, including both the main lobe and side lobes for each open service signal.



Annex C. 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.

C1. Global SSV simulations

This section will cover the globally averaged SSV simulations. These simulations analyse 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 C1, utilizing the orbital parameters specified for each constellation in annex D. Note that the effective Earth radius used when determining access is taken as the sum of the spherical Earth radius and the atmospheric radius. The rotation from the Earth-centred inertial frame to the Earth-fixed frame is performed using the Earth rotation angle only, as specified by Equation 5.15 of the International Earth Rotation and Reference Systems Service (IERS) Technical Note 36. UT1 is assumed to be equivalent to UTC for this simplified rotation.

Table C1. 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
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(1.00273781191135448)
Earth rotation angle at J2000 reference epoch (rad)	2π(0.7790572732640)

The GNSS constellation orbit parameters in annex C are provided in terms of mean anomaly. In many cases, it may be preferable to convert to true anomaly prior to analysis. There are many different approaches and sources for the relevant equations related to the transformation from mean anomaly to true anomaly. However, the following equations are valid for elliptical orbits. Please note that the implementation can be done in a variety of ways, but this aspect will not be addressed here.

From mean anomaly to true anomaly:

$$E(M) = M + e\,sin(E)$$ Kepler equation, to be solved iteratively (1)

$$v\,(E) = 2\,atan\left(\sqrt{\frac{1+e}{1-e}}\,tan\left(\frac{E}{2}\right)\right)$$ (2)

with

- M = mean anomaly (rad)
- e = orbital eccentricity
- E = eccentric anomaly (rad)
- v = true anomaly (rad).

From true anomaly to mean anomaly:

$$E(v) = 2\,atan\left(\sqrt{\frac{1-e}{1+e}}\,tan\left(\frac{v}{2}\right)\right)$$ (3)

$$M(E) = E - e\,sin(E)$$ (4)

The global analysis represents the SSV receiver locations using an equal-area grid of points, as illustrated in figure C1. 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 2,562 points.

Figure C1. User grid locations over Earth's surface

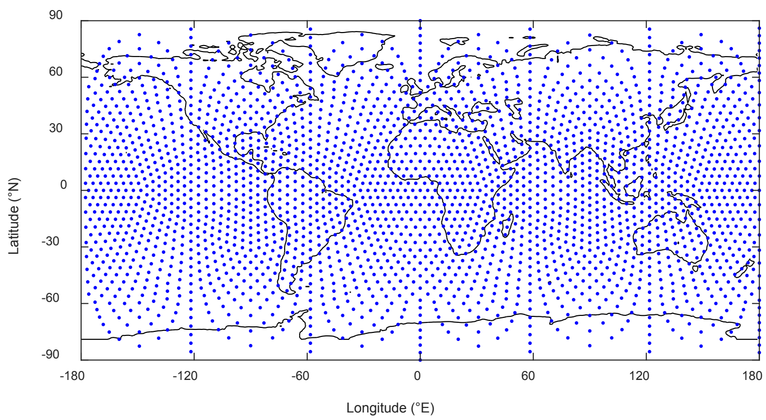


Table C2 summarizes the GNSS transmit beamwidths for both the L1 and L5 frequency bands that are studied in the simulations. Note that for the BDS constellation, the beamwidth is defined separately for the satellites in MEO and the satellites in GEO/IGSO. Also note that the NavIC L1 beamwidth is not 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 beam-width as a result of antenna physics, as that will directly impact performance results.

Table C2. 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	26	34
GPS	23.5	26
NavIC	N/A	16
QZSS	22	24

The attitude of each GNSS transmitting antenna is determined according to table C3, 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 C3. 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 C4 and table C5 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 C4. 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	97.2	45	19.6	*	100	0	100	0
	QZSS	39.8	*	6.6	*	100	0	95.6	*
	Combined	**99.9**	**26**	**98.2**	**93**	**100**	**0**	**100**	**0**
L5/L3/E5a/B2	GPS	96.9	77	15.6	1,180	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	32.7	644	100	0	100	0
	QZSS	44.4	*	9.5	*	100	0	95.6	*
	NavIC	36.9	*	0.6	*	98	348	51.4	*
	Combined	**100**	**0**	**99.9**	**15**	**100**	**100**	**0**	**0**

* No signal observed at the worst-case grid location for duration of simulation

Table C5. 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	97.0	181	28.2	*	100	0	99.5	31
	QZSS	65.4	*	31.7	*	93.4	*	63.8	*
	Combined	**99.9**	**18**	**92.3**	**1,412**	**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	12	47.2	*	100	0	100	0
	QZSS	65.4	*	31.7	*	93.4	*	63.8	*
	NavIC	25.5	*	15.3	*	92.8	*	33.5	*
	Combined	**100**	**0**	**99.9**	**9**	**100**	**0**	**100**	**0**

* No signal observed at the worst-case grid location for duration of simulation

Radio frequency 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). MRTP is constant for all off-boresight angles smaller than the reference off-boresight angle. All assumptions listed in table C1 also apply.

Table C6 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 to those in GEO or IGSO. Table C7 provides additional parameters pertaining to general radio frequency (RF) assumptions used for these calculations and the simulations performed in this analysis.

Table C6. GNSS radio frequency parameters

GNSS constellation	Signal name	Frequency (MHz)	Max beam-width (°)	Minimum received power (dBW)	MRTP (dBW)
GPS	L1 C/A	1,575.42	23.5	-184	9.1
Galileo	E1 B/C	1,575.42	20.5	-182.5	10.9
GLONASS	L1	1,605.375	26	-179	14.1
BDS MEO	B1	1,575.42	25	-184.2	9
BDS GEO/IGSO	B1	1,575.42	19	-185.9	9
QZSS	L1 C/A	1,575.42	22	-186.1	9.0
GPS	L5	1,176.45	26	-182	8.5
Galileo	E5a	1,176.45	23.5	-182.5	8.4
GLONASS	L3	1,201	34	-178	12.6
BDS MEO	B2	1,191.795	28	-182.8	8
BDS GEO/IGSO	B2	1,191.795	22	-184.4	8.1
QZSS	L5	1,176.45	24	-183.4	9.2
NavIC	L5	1,176.45	16	-184.54	7.8

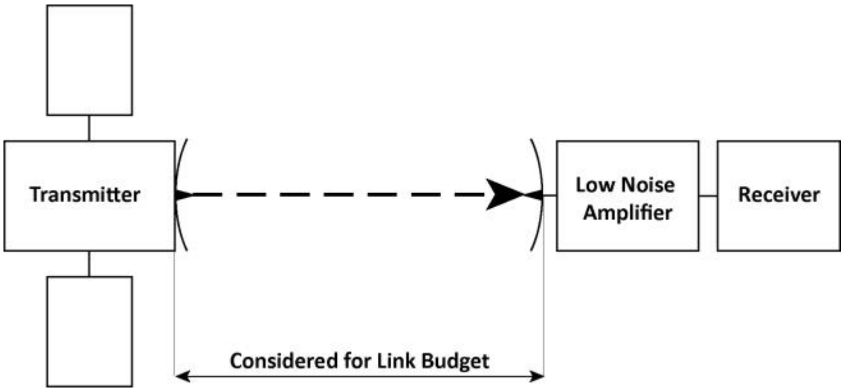
Table C7. General radio frequency simulation assumptions

Parameter	Value
Speed of light (m/s)	299,792,458
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

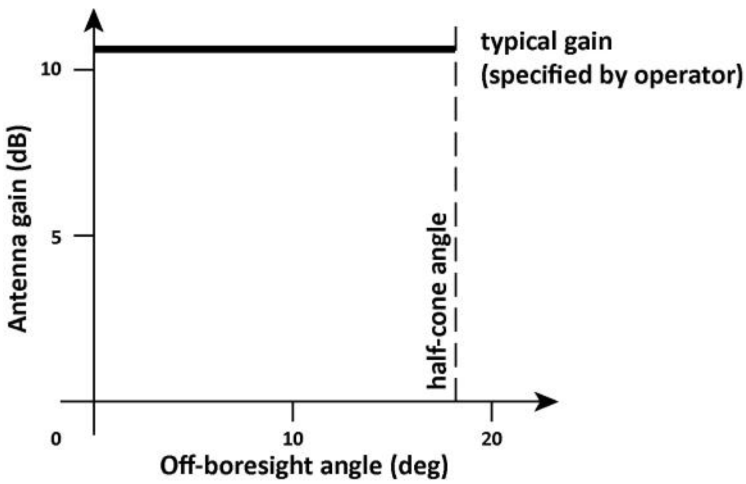
Because MRTP is not included in the SSV template completed by the GNSS service providers, this value must be derived for each constellation using an inverse link budget calculation with the constellation's specified minimum received power. The overall situation for the link budget calculation and the terms taken into account is outlined in figure C2.

Figure C2. 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 C3 visualizes the basic assumption.

Figure C3. Simplified GNSS satellite antenna pattern, as used in the simulations for GNSS space service volume 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 is the free space path loss at the worst-case Earth-limb distance:

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

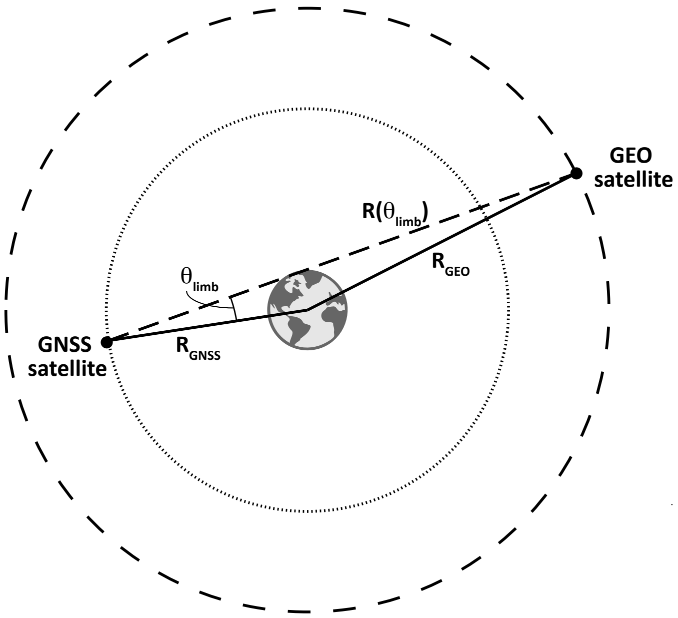
In this equation, *f* is the centre frequency of the signal from table C6, *c* is the speed of light from table C7 and $R(\theta_{limb})$ is the distance from the worst-case apogee altitude of the GNSS constellation (see table C8) to a GEO user at 36,000 km altitude, along the line that intersects the Earth's limb.

Table C8. Worst-case apogee altitude used for each constellation in MRTP calculation

GNSS constellation	Signal name	Altitude (km)
GPS	L1 C/A	20,181.80
Galileo	E1 B/C	23,221.80
GLONASS	L1	19,140.33
BDS MEO	B1	21,611.86
BDS GEO/IGSO	B1	35,912.69
QZSS	L1 C/A	38,948.48
GPS	L5	20,181.80
Galileo	E5a	23,221.80
GLONASS	L3	19,140.33
BDS MEO	B2	21,611.86
BDS GEO/IGSO	B2	35,912.69
QZSS	L5	38,948.48
NavIC	L5	35,815.71

The geometry used in calculating $R(\theta_{limb})$ is shown figure C4. Note that the Earth's radius from table C1 should be added to the GNSS and GEO altitudes to obtain R_{GNSS} and R_{GEO} respectively.

Figure C4. 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 C6 for each GNSS constellation.

Radio frequency 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.

Radio frequency access analysis results

Results in table C9 provide the average globalized upper SSV expected system performance when RF-based signal strength constraints are applied to geometrical-only 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 of the simulations performed at one-minute intervals. The lower SSV was only simulated under geometric conditions; see table 5.2 for details.

Table C9. Upper space service volume performance with radio frequency constraints, for various C/N_0 thresholds

Band	Constellation	$C/N_{0_{min}}$ = 15 dB-Hz				$C/N_{0_{min}}$ = 20 dB-Hz				$C/N_{0_{min}}$ = 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	97.2	45	19.6	*	69.8	70	0.6	*	0.0	*	0	*
	QZSS	39.8	*	6.6	*	0.0	*	0	*	0.0	*	0	*
	Combined	**99.9**	**26**	**98.2**	**93**	**99.9**	**33**	**89.8**	**117**	**93.9**	**48**	**7**	*****
L5/L3/E5a/B2	GPS	96.9	77	15.6	1,180	96.9	77	15.6	1,180	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	32.7	644	99.9	7	27.2	644	0.0	*	0	*
	QZSS	44.4	*	9.5	*	44.4	*	9.5	*	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**

General observations concerning the availability estimates given in table C9 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/N_0 threshold.
- 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/N_0thresholds of 15 and 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 C/N_0 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, availability for the multi-constellation case is nearly 90% or better and MOD is limited to less than 120 minutes. Not until you get to the L1 band with four-signal coverage with a C/N_0 threshold of 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/N_0 threshold of 20 dB-Hz). For the global constellations (GPS, GLONASS, Galileo and BDS) a one-signal availability is indicated at greater than 90% for the L5 band and C/N_0 threshold of 15 dB-Hz. However, only multi-constellation allows very high availability (> 99.5%) for four-signal coverage.

C2. Mission-specific space service volume 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 C1. 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 C10 and correspond to characteristics of readily available antennas available on the open market.

Table C10. 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.

Geometric dilution indicator

The mission-specific simulations expand on the signal availability analysis to include analysis of geometric diversity through calculation of a geometric dilution indicator (GDI). GDI provides an indication of the effects of GNSS vehicle geometry relative to the user. Geometric effects are especially important for users in SSV, as their altitude results in GNSS signals being collected from one hemisphere, or in the case of lunar-vicinity users, an area just a few degrees across. The familiar dilution of precision (DOP) property quantifies the impact of several factors, including residual error in receiver clock bias estimation, and relates URE to PVT errors. For the purposes of these simulations, however, only the relative geometry between the user and the GNSS satellites was considered. This is summarized by GDI, which provides an illustration of general geometric effects. As with DOP, lower values of GDI indicate generally better geometric diversity.

The calculation of GDI proceeds as follows. At each instant of time, for m GNSS constellations and n_j available SVs within each constellation, define the user position as $\vec{x}$ and the positions of the visible GNSS SVs as $\left\{\overrightarrow{r_i^j} \middle| 1 \le i \le n_j, 1 \le j \le m\right\}$, where the superscript, j, indicates constellation and the subscript i indexes SV location within a particular constellation. Thus the total number of visible SVs is $n = \sum_{j=1}^{m} n_j$. The corresponding Line of Sight (LoS) ranges from the user to the available SVs are:

$$\left\{\left|\overrightarrow{R_i^j}\right| \middle| 1 \le i \le n_j, 1 \le j \le m\right\}$$

$$\left|\overrightarrow{R_i^j}\right| = \left|\vec{x} - \overrightarrow{r_i^j}\right|$$

where $|\cdot|$ indicates the L2 norm of the vector.

Define the transpose of the design matrix, H^T, as the horizontal concatenation of the gradient vectors of the ranges with respect to each of the ECEF coordinate axes:

$$H^T = \left[\nabla\left|\overrightarrow{R_1^1}\right|, \nabla\left|\overrightarrow{R_2^1}\right|, \ldots, \nabla\left|\overrightarrow{R_{n_1}^1}\right|, \nabla\left|\overrightarrow{R_1^2}\right|, \nabla\left|\overrightarrow{R_2^2}\right|, \ldots, \nabla\left|\overrightarrow{R_{n_2}^2}\right|, \ldots, \nabla\left|\overrightarrow{R_1^m}\right|, \nabla\left|\overrightarrow{R_2^m}\right|, \ldots, \nabla\left|\overrightarrow{R_{n_m}^m}\right|\right]_{3xn}$$

where:

$$\nabla\left|\overrightarrow{R_i^j}\right| = \frac{\vec{x} - \overrightarrow{r_i^j}}{\left|\overrightarrow{R_i^j}\right|}.$$

The covariance matrix is then defined as:

$$V = (H^T H)^{-1}$$

where $(\cdot)^{-1}$ refers to the matrix inverse. The GDI at the current time is finally calculated as:

$$\mathrm{GDI} = \sqrt{\mathrm{tr} V}$$

where tr indicates the matrix trace.

Relation to dilution of process

The definition of GDI adopted here is identical to a DOP measure developed for true range multilateration (TRM) systems that do not estimate receiver clock bias. As such, GDI indicates the ratio of the root sum square (RSS) of 3-D positional errors to ranging error. Examples of TRM systems include aircraft navigation systems that employ multilateration processing together with distance measuring equipment, transceiver measurements and systems in which fully synchronized clocks can be assumed (such as combined Loran-C/GPS with a rubidium clock).

Using the matrix inversion lemma, it can be shown that the usual, single-constellation, pseudoranging, position dilution of precision (PDOP) measure is related to GDI through the following equation:

$$\mathrm{PDOP} = \sqrt{\mathrm{tr}V'}$$

where:

$$V' = \left(H^T H - \frac{\overrightarrow{L_S}\overrightarrow{L_S}^T}{n} \right)^{-1} \tag{1}$$

is the upper 3x3 portion of the PDOP covariance matrix and:

$$\overrightarrow{L_s} = \sum_{j=1}^{m} \sum_{i=1}^{n_m} \nabla \left| \overrightarrow{R_i^j} \right|$$

is the vector sum of the normalized (unit length) LoS vectors connecting the user location to the SV locations. Note that, to the extent that the user is evenly surrounded by GNSS SVs, the magnitude of the vector diminishes. Thus, the second term inside the parenthesis of equation (1) will diminish to zero as symmetry of the user coverage by GNSS SVs improves, leading GDI and conventional single-constellation PDOP to converge. This is typically not the case, however, in the challenging environment of the upper SSV and beyond.

GEO mission

The GEO mission scenario examines 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 L1/E1/B1 and L5/L3/E5a/B2 signals.

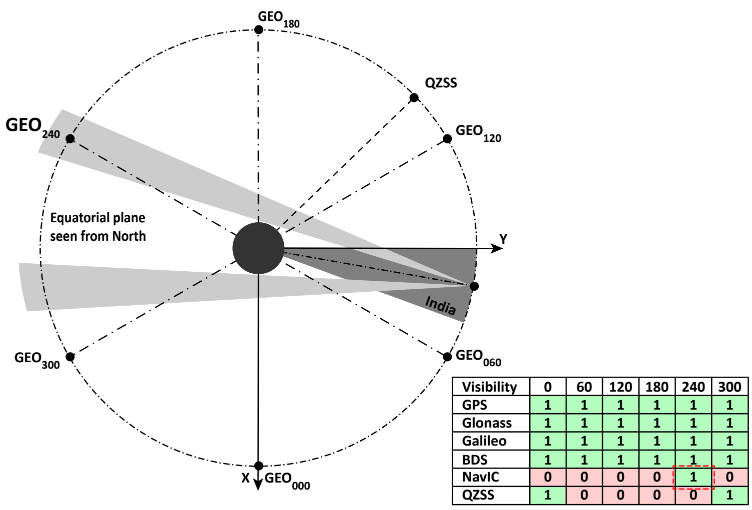
Spacecraft trajectory

Six GEO satellites are simulated and share the same orbital plane apart from a 60-degree separation in longitude (see table C11). 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 C5).

Table C11. GEO osculating Keplerian orbital elements

Epoch	1 Jan 2016 12:00:00 UTC		
Semi-major axis	42,164.0 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

Figure C5. Example for visibility of NavIC satellite from the GEO at 240-degree longitude



Spacecraft attitude and antenna configuration

The user antenna on board the user spacecraft is configured as 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 C10. The assumed acquisition threshold of the space user receiver is 20 dB-Hz.

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 the number of visible MEO signals are very similar to all six GEO receivers.

The situation is different for the geostationary and inclined geosynchronous GNSS satellites of the BDS, QZSS and NavIC 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 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 L5/L3/E5a/B2 signal).

For all six GEO receivers, and at L1 and L5 frequencies, the satellite visibility is shown in the figure C6, figure C7, figure C8 and figure C9 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 no 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, up to fifteen and more. 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 C6. L1/E1/B1 visibility for GEO at 0 deg, 60 deg and 120 deg

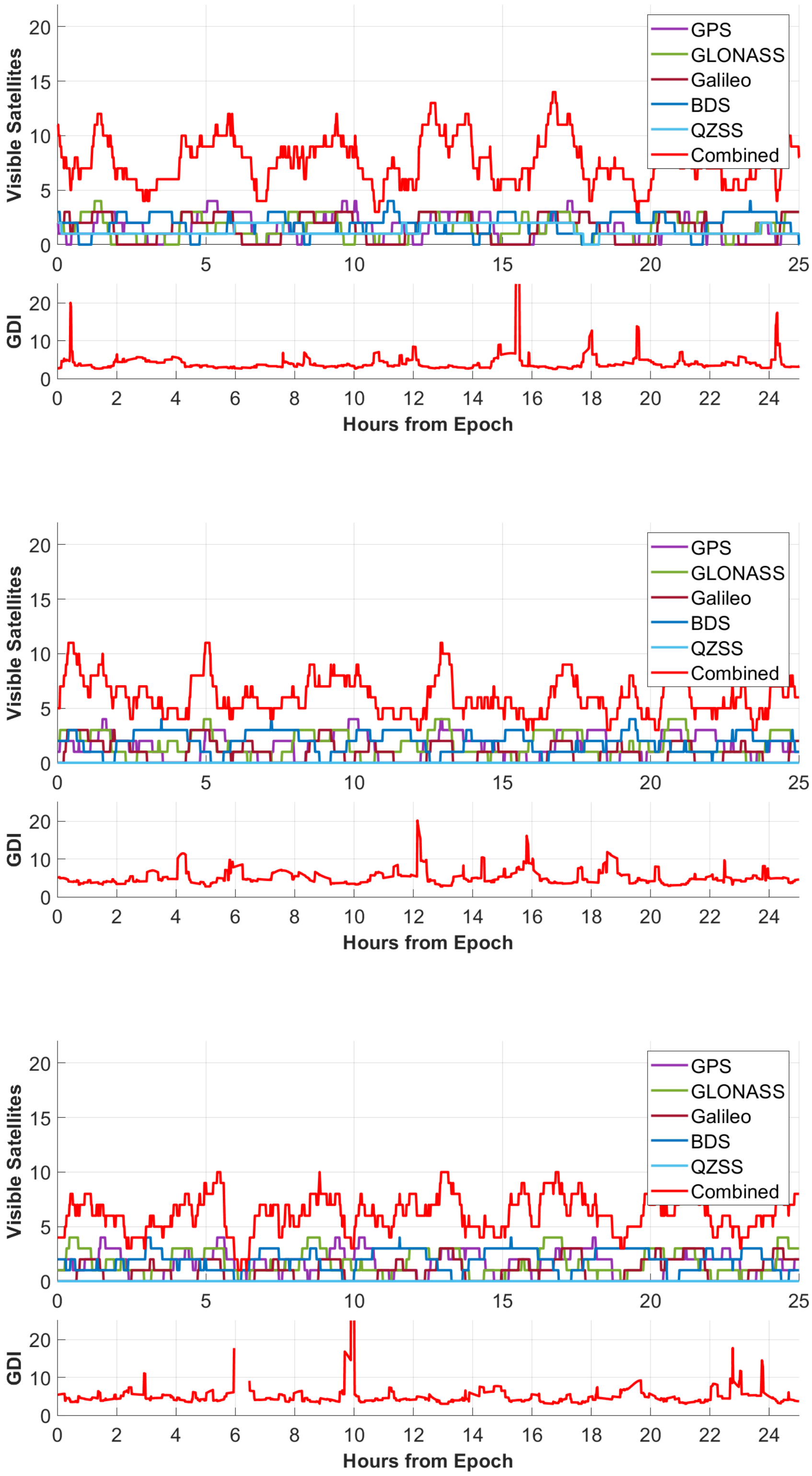


Figure C7. L1/E1/B1 visibility for GEO at 180 deg, 240 deg and 300 deg

Figure C8. L5/L3/E5a/B2 visibility for GEO at 0 deg, 60 deg and 120 deg

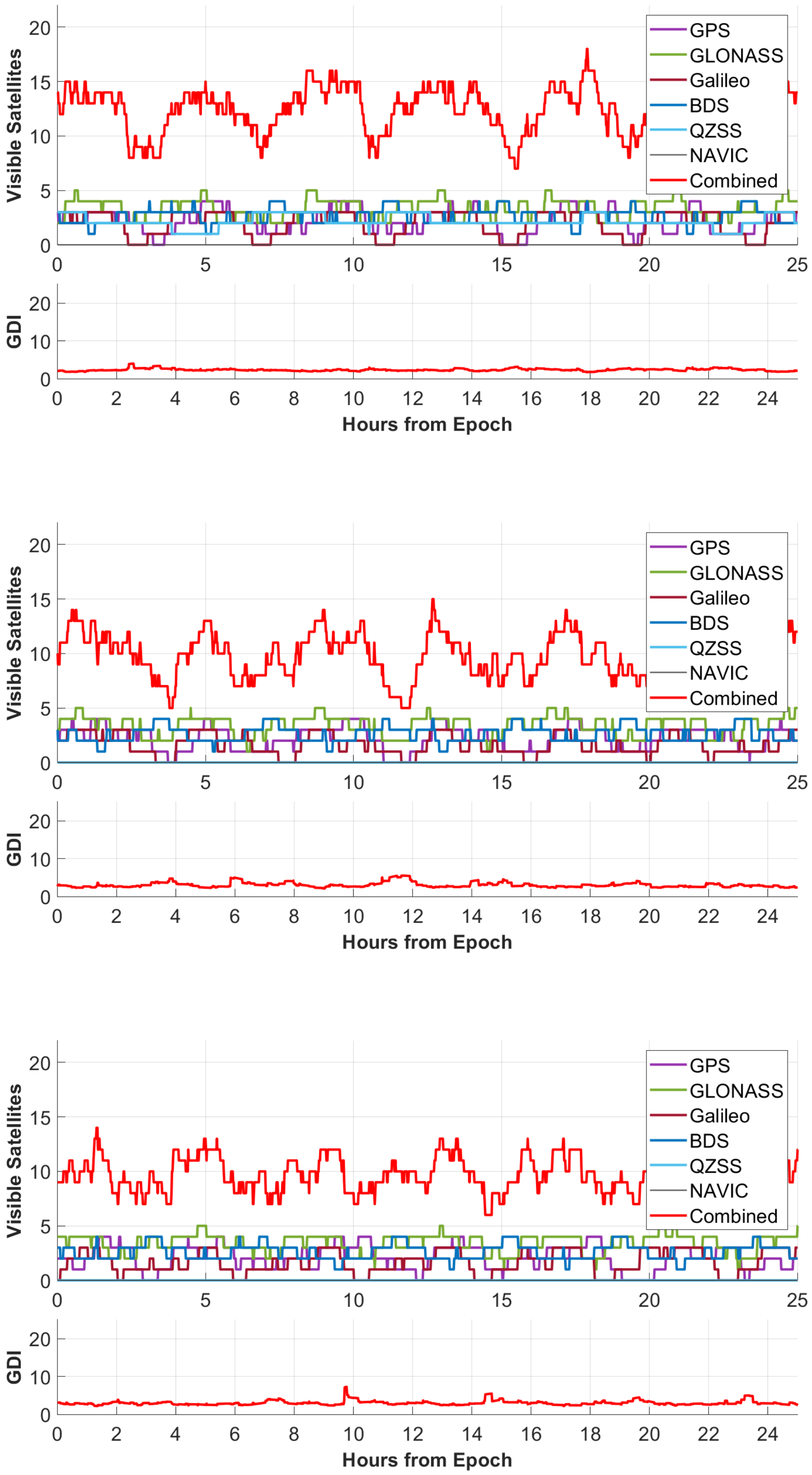
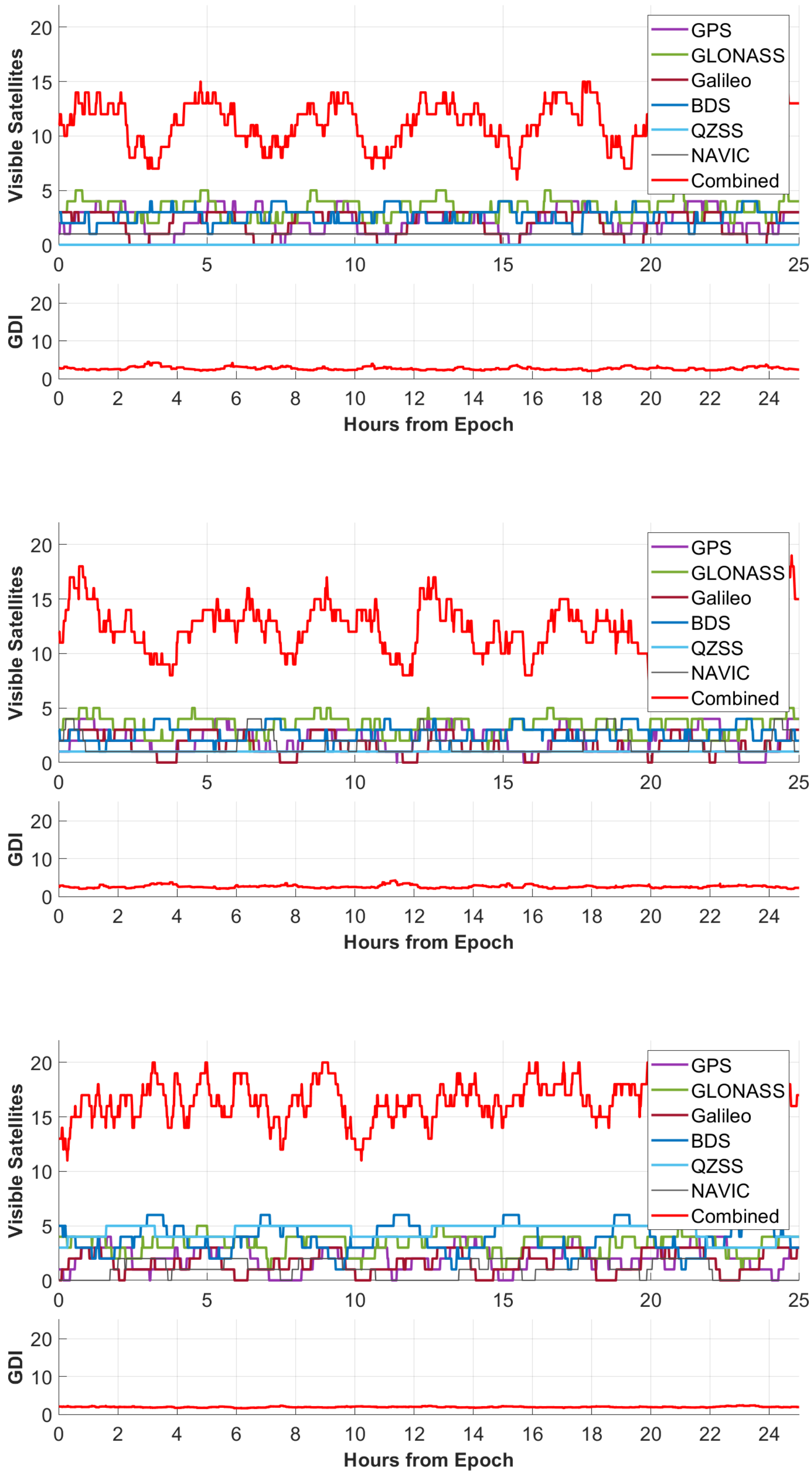


Figure C9. L5/L3/E5a/B2 visibility for GEO at 180 deg, 240 deg and 300 deg



C3. 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 11 km/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.

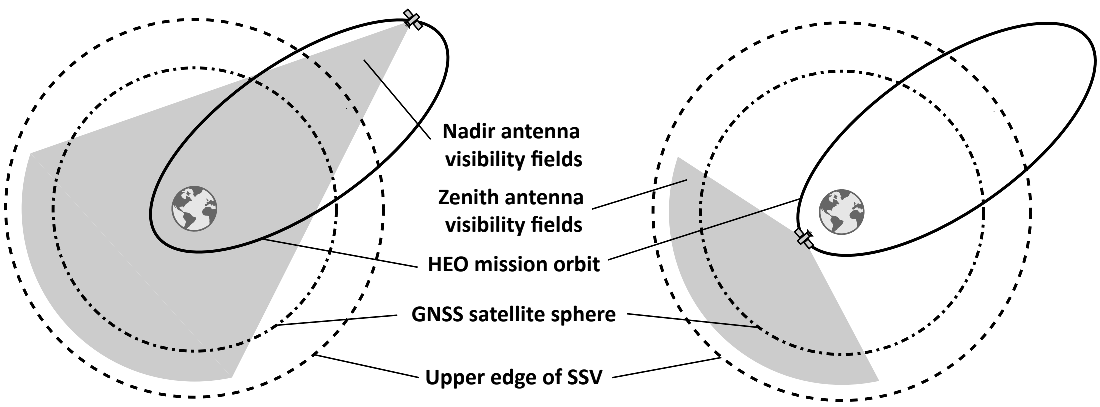
Table C12. Osculating Keplerian HEO orbital elements

Epoch	1 Jan 2016 12:00:00 UTC		
Semi-major axis	35,937.5 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 C10, 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 types of antennas are given in table C10. 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 C10. Schematic of the HEO mission with nadir- and zenith-pointing antennas



Results

Figure C11 and figure C12 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 C11. Visible GNSS satellites over 1.5 orbital periods of HEO (L1/E1/B1)

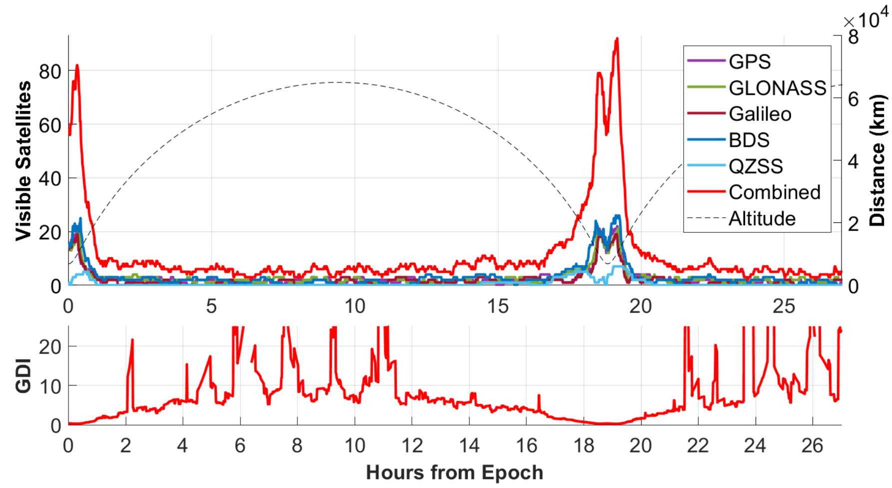


Figure C12. Visible GNSS satellites over 1.5 orbital periods of HEO (L5/L3/E5a/B2)

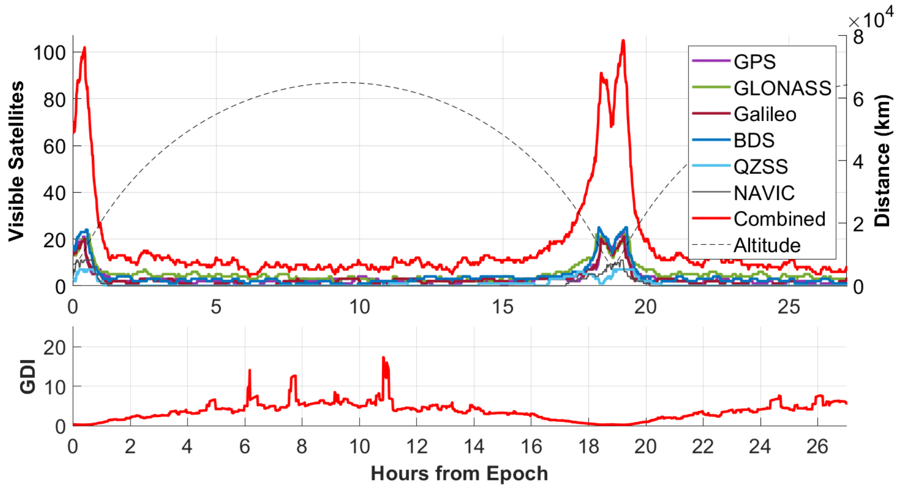


Figure C13. Visible satellites over HEO mission altitude (14 days)

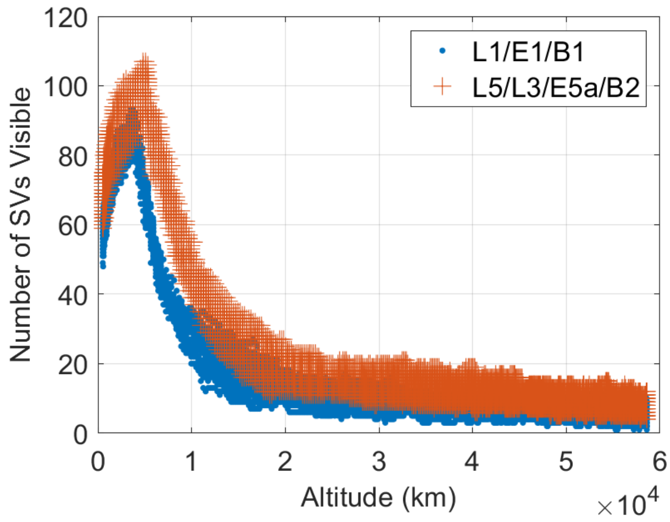


Table C13. HEO mission simulated performance result

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	69	12	1,036
	GLONASS	98	12	13	991
	Galileo	74	85	9	1,026
	BDS	87	51	14	1,032
	QZSS	26	1,076	3	2,340
L5/L3/E5a/B2	GPS	94	53	17	911
	GLONASS	100	0	55	134
	Galileo	87	64	11	990
	BDS	96	30	23	925
	QZSS	33	1,020	6	1,150
	NavIC	32	1,023	3	1,099
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	1,066	4	1,085
	GLONASS	7	1,059	4	1,081
	Galileo	7	1,059	4	1,085
	BDS	10	1,031	5	1,076
	QZSS	7	1,136	2	2,275
L5/L3/E5a/B2	GPS	7	1,059	4	1,079
	GLONASS	8	1,046	6	1,061
	Galileo	7	1,051	4	1,075
	BDS	10	1,027	6	1,068
	QZSS	8	1,132	3	2,269
	NavIC	5	2,255	3	2,266
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	69	12	1,036
	GLONASS	98	12	14	986
	Galileo	74	85	9	1,025
	BDS	88	51	15	1,013
	QZSS	31	1,009	7	1,066
	Combined	**100**	**0**	**94**	**47**
L5/L3/E5a/B2	GPS	94	53	17	911
	GLONASS	100	0	55	134
	Galileo	87	64	11	980
	BDS	96	30	24	925
	QZSS	36	998	10	1,032
	NavIC	35	990	5	1,091
	Combined	**100**	**0**	**100**	**0**

Figure C13 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 C13, 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 C13. The signal availability was evaluated with 20 dB-Hz C/N_0 threshold for each individual constellation and all constellations combined.

For both L1/E1/B1 and L5/L3/E5/B2 the one-signal availability reaches 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. It also shows in the table that signal availability for the L5 case is better than the L1 case.

Lunar mission

A lunar scenario was considered in order to explore the practical boundary of the GNSS SSV beyond Earth orbit.

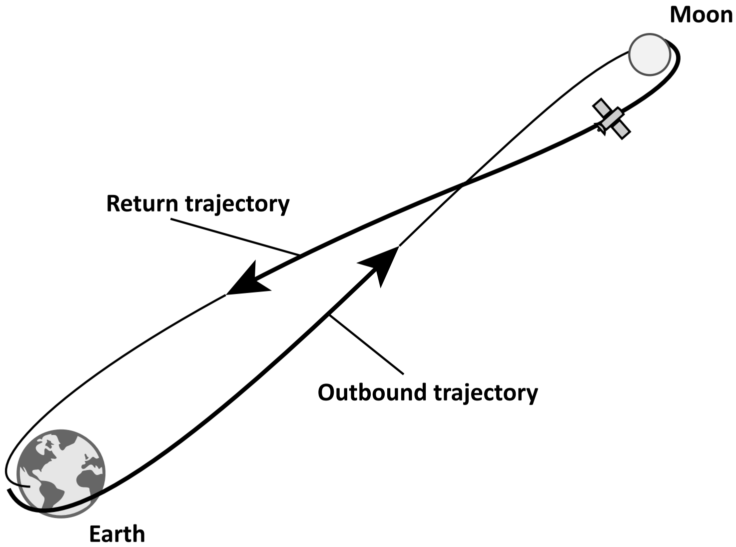
Spacecraft trajectory

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 C14.

Figure C14. 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 C14. 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 C14 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 with peak gain of 4.5 dBi that is permanently zenith-pointing (spacecraft -Z direction) and therefore relevant during the low-altitude portion of the mission, and one high-gain antenna with peak gain of 9 dBi 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 C10. 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

Figure C15 shows the general structure of the GNSS signal availability, using the L5 band as an example to capture the contributions of all constellations. Availability is highly dependent on distance from Earth and user equipment assumptions for the C/N_0 tracking threshold and the antenna gain. As the distance from Earth increases, the availability drops quickly and reaches zero beyond 30 RE, which is approximately 50% of the distance to the moon. When using all constellations combined, the single-satellite availability is nearly 100% to a distance of 30 RE, and zero thereafter. The benefit of the combined multi-GNSS case is best seen above 10 RE, where signal availability is consistently higher than any individual constellation, and often nearly double. Notably, combining constellations does not increase the altitude at which such signals are available; rather, it increases the number of signals available at a given altitude. These results show that navigation with the combined multi-GNSS SSV is conservatively feasible for nearly half the duration of a lunar outbound trajectory, well beyond the upper limit of SSV, and is possibly a solution for navigation for the outbound trans-lunar injection manoeuvre and return trajectory correction manoeuvres.

Figure C15. Signal visibility by trajectory altitude, to the limit of available signals at 30 RE (approx. 50% of lunar distance)

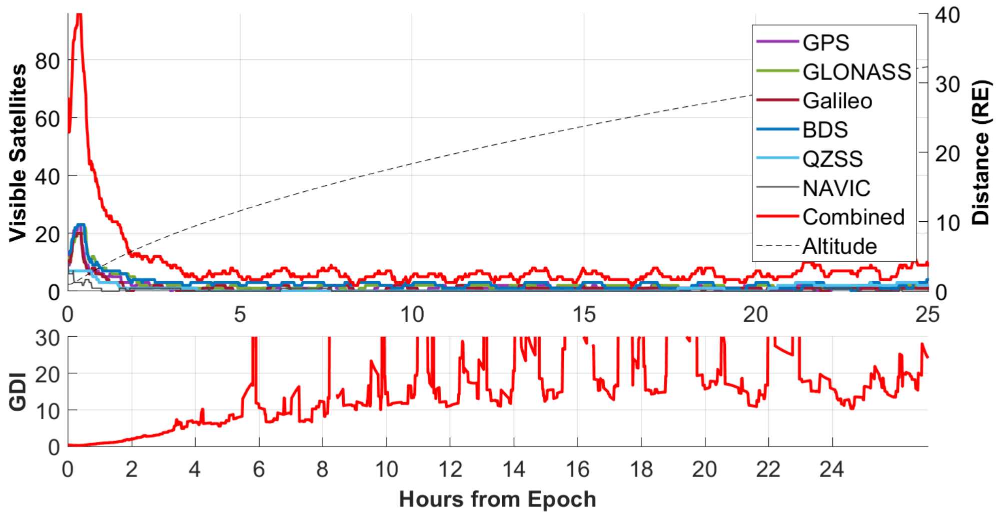
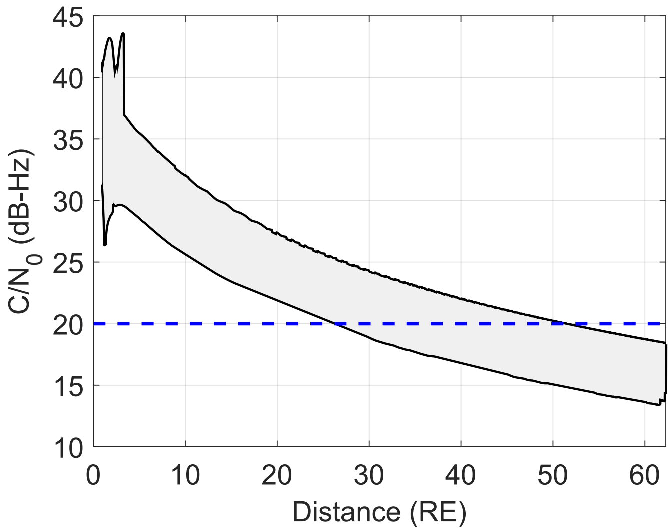
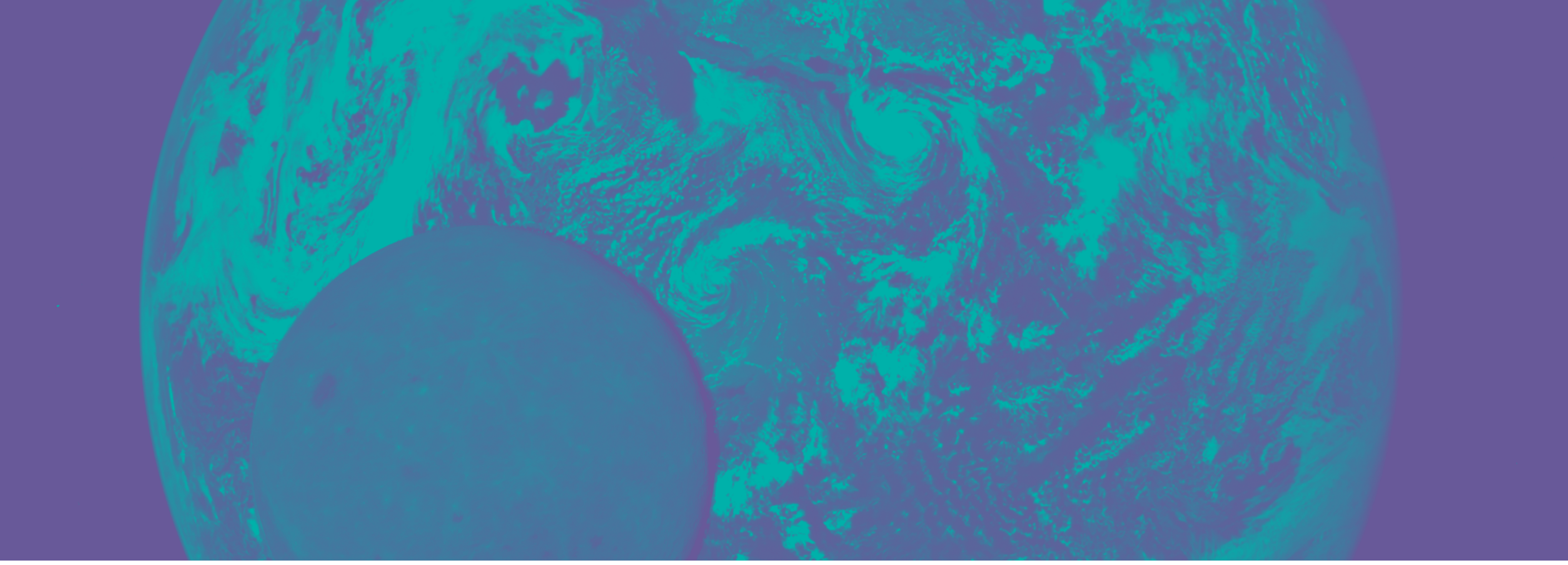


Figure C16. shows the simulated C/N_0 received by the example spacecraft as a range encompassing all individual GNSS constellations for the entire trajectory to lunar distance (60 RE). It shows the reason for the availability drop-off near 30 RE shown in figure C15. The C/N_0 of most GNSS signals at the user antenna drops below the 20 dB-Hz minimum threshold beyond 30 RE. If a moderately more sensitive receiver or higher-gain antenna were employed the signal availability would be achievable up to the lunar distance. A simple improvement in antenna gain has been proposed to support lunar vicinity missions such as Gateway.

Figure C16. Simulated C/N_0 range for lunar trajectory with 20 dB-Hz analysis threshold marked





Annex D. 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, 1 January 2016 12:00:00 UTC.

D1. GPS orbital parameters

Table D1. GPS orbital state definition

Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
1	26,559,800	0	55	273.056	0	11.676
2	26,559,800	0	55	273.056	0	41.806
3	26,559,800	0	55	273.056	0	161.786
4	26,559,800	0	55	273.056	0	268.126
5	26,559,800	0	55	333.056	0	66.356
6	26,559,800	0	55	333.056	0	94.916
7	26,559,800	0	55	333.056	0	173.336
8	26,559,800	0	55	333.056	0	204.376
9	26,559,800	0	55	333.056	0	309.976
10	26,559,800	0	55	33.056	0	111.876
11	26,559,800	0	55	33.056	0	241.556
12	26,559,800	0	55	33.056	0	339.666
13	26,559,800	0	55	33.056	0	11.796
14	26,559,800	0	55	93.056	0	135.226
15	26,559,800	0	55	93.056	0	167.356
16	26,559,800	0	55	93.056	0	257.976
17	26,559,800	0	55	93.056	0	282.676
18	26,559,800	0	55	93.056	0	35.156
19	26,559,800	0	55	153.056	0	197.046
20	26,559,800	0	55	153.056	0	302.596
21	26,559,800	0	55	153.056	0	333.686
22	26,559,800	0	55	153.056	0	66.066
23	26,559,800	0	55	213.056	0	238.886
24	26,559,800	0	55	213.056	0	334.016
25	26,559,800	0	55	213.056	0	0.456
26	26,559,800	0	55	213.056	0	105.206
27	26,559,800	0	55	213.056	0	135.346

D2. GLONASS orbital parameters

Table D2. GLONASS orbital state definition

Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
1	25,508,200	0.000397	64.16	201.81	28.75	295.76
2	25,505,500	0.001181	64.64	202.16	229.92	47.69
3	25,507,000	0.001152	64.47	202.24	242.46	349.96
4	25,509,600	0.000341	64.49	202.16	229.04	317.62
5	25,508,200	0.000593	64.15	201.75	71.12	71.67
6	25,505,600	0.000838	64.14	201.75	134.53	321.03
7	25,507,100	0.001027	64.48	202.28	239.38	172.44
8	25,509,600	0.00154	64.48	202.27	282.44	85.43
9	25,509,000	0.002309	64.93	322.43	13.68	322.87
10	25,506,000	0.001662	65.73	322.85	160.86	131.88
11	25,506,000	0.001846	65.34	322.22	357.58	250.24
12	25,509,100	0.003395	64.93	322.44	167.5	34.48
13	25,509,000	0.000449	65.33	322.18	95.45	60.38
14	25,505,900	0.001493	65.71	322.79	163.14	306.41
15	25,505,700	0.002211	65.71	322.78	345.48	85.17
16	25,509,300	0.001967	64.91	322.37	149.58	229.88
17	25,509,600	0.000831	64.79	82.98	220.69	132.36
18	25,507,100	0.001346	65.06	82.75	338.33	331.94
19	25,505,300	0.000102	65.28	83.61	167.08	95.28
20	25,508,100	0.00106	65.29	83.67	344.69	231.89
21	25,509,600	0.000685	65	82.79	185.84	348.48
22	25,507,200	0.002793	65.19	82.78	356.75	132.46
23	25,505,600	0.000142	65.17	82.74	135.86	306.03
24	25,508,000	0.000779	65.18	82.77	84.59	315.17

D3. Galileo orbital parameters

Table D3. Galileo orbital state definition

Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
1	29,599,801.224	0.0000001	56	326.60209225	0	107.1899147499
2	29,599,801.224	0.0000001	56	326.60209225	0	152.1899147499
3	29,599,801.224	0.0000001	56	326.60209225	0	197.1899147499
4	29,599,801.224	0.0000001	56	326.60209225	0	242.1899147499
5	29,599,801.224	0.0000001	56	326.60209225	0	287.1899147499
6	29,599,801.224	0.0000001	56	326.60209225	0	332.1899147499
7	29,599,801.224	0.0000001	56	326.60209225	0	17.1899147499
8	29,599,801.224	0.0000001	56	326.60209225	0	62.1899147499
9	29,599,801.224	0.0000001	56	86.60209225	0	122.1899147499
10	29,599,801.224	0.0000001	56	86.60209225	0	167.1899147499
11	29,599,801.224	0.0000001	56	86.60209225	0	212.1899147499
12	29,599,801.224	0.0000001	56	86.60209225	0	257.1899147499
13	29,599,801.224	0.0000001	56	86.60209225	0	302.1899147499
14	29,599,801.224	0.0000001	56	86.60209225	0	347.1899147499
15	29,599,801.224	0.0000001	56	86.60209225	0	32.1899147499
16	29,599,801.224	0.0000001	56	86.60209225	0	77.1899147499
17	29,599,801.224	0.0000001	56	206.60209225	0	137.1899147499
18	29,599,801.224	0.0000001	56	206.60209225	0	182.1899147499
19	29,599,801.224	0.0000001	56	206.60209225	0	227.1899147499
20	29,599,801.224	0.0000001	56	206.60209225	0	272.1899147499
21	29,599,801.224	0.0000001	56	206.60209225	0	317.1899147499
22	29,599,801.224	0.0000001	56	206.60209225	0	2.1899147499
23	29,599,801.224	0.0000001	56	206.60209225	0	47.1899147499
24	29,599,801.224	0.0000001	56	206.60209225	0	92.1890000000

D4. BDS orbital parameters

Table D4. BDS orbital state definition

Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
1	27,906,137	0.003	55	0	0	225.631
2	27,906,137	0.003	55	0	0	270.631
3	27,906,137	0.003	55	0	0	315.631
4	27,906,137	0.003	55	0	0	0.631
5	27,906,137	0.003	55	0	0	45.631
6	27,906,137	0.003	55	0	0	90.631
7	27,906,137	0.003	55	0	0	135.631
8	27,906,137	0.003	55	0	0	180.631
9	27,906,137	0.003	55	120	0	240.631
10	27,906,137	0.003	55	120	0	285.631
11	27,906,137	0.003	55	120	0	330.631
12	27,906,137	0.003	55	120	0	15.631
13	27,906,137	0.003	55	120	0	60.631
14	27,906,137	0.003	55	120	0	105.631
15	27,906,137	0.003	55	120	0	150.631
16	27,906,137	0.003	55	120	0	195.631
17	27,906,137	0.003	55	240	0	255.631
18	27,906,137	0.003	55	240	0	300.631
19	27,906,137	0.003	55	240	0	345.631
20	27,906,137	0.003	55	240	0	30.631
21	27,906,137	0.003	55	240	0	75.631
22	27,906,137	0.003	55	240	0	120.631
23	27,906,137	0.003	55	240	0	165.631
24	27,906,137	0.003	55	240	0	210.631
25	42,164,200	0.003	0	0	23.459	336.229
26	42,164,200	0.003	0	0	54.082	336.229
27	42,164,200	0.003	0	0	83.582	336.229
28	42,164,200	0.003	55	61.445	0	336.229
29	42,164,200	0.003	55	301.445	0	96.229
30	42,164,200	0.003	55	181.445	0	216.229

D5. QZSS orbital parameters

Table D5. QZSS orbital state definition

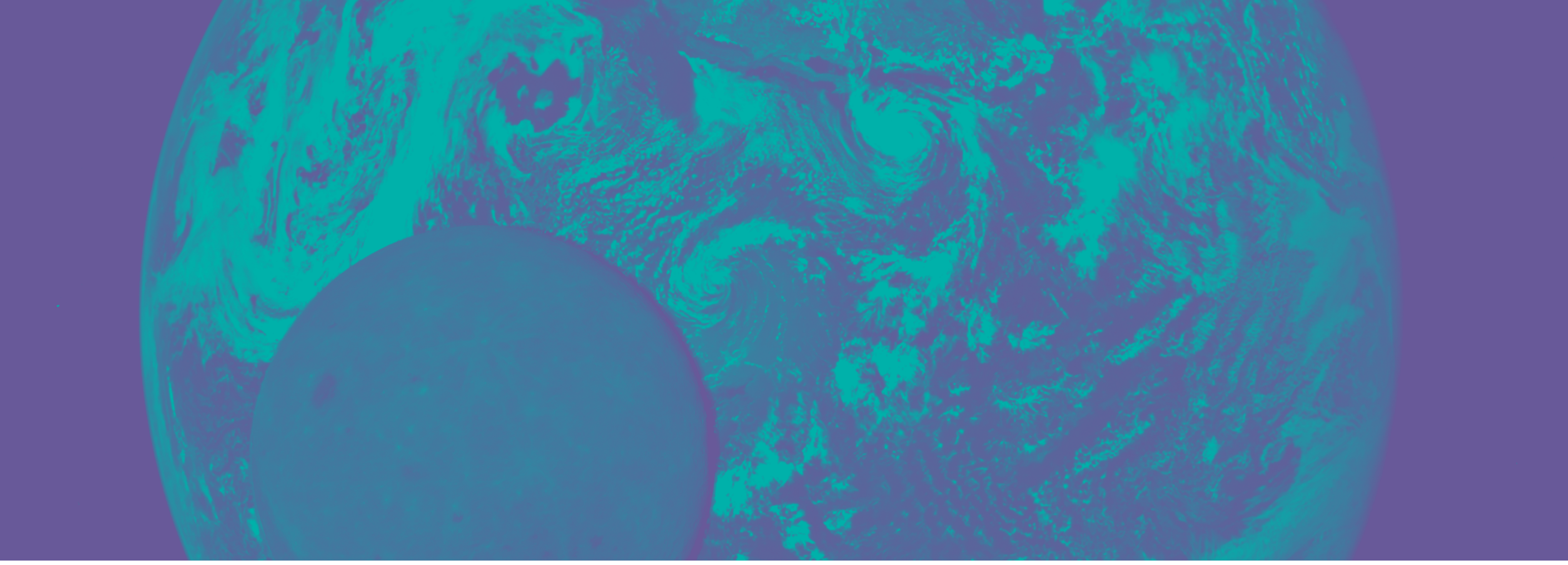
Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
1	42,164,169.45	0.075	41	135	270	23.58
2	42,164,169.45	0.075	41	295	270	214.58
3	42,164,169.45	0	0	0	0	47.58
4	42,164,169.45	0.075	41	35	270	114.58
5	42,164,169.45	0.075	41	210	270	299.58
6	42,164,169.45	0	0	0	0	11.08
7	42,164,169.45	0.008	3	320	0	145.58

D6. NavIC orbital parameters

Table D6. NavIC orbital state definition

Satellite	Semi-major axis (m)	Eccentricity	Inclination (°)	Right ascension (°)	Argument of perigee (°)	Mean anomaly (°)
1	42,164,200	0.0007	28.1	124.08	0	211.3
2	42,164,200	0.0007	29.97	303.04	0	32.32
3	42,164,200	0.0007	4.01	264.62	0	98.963
4	42,164,200	0.0007	29.98	303.19	0	88.964
5	42,164,200	0.0007	28.1	124.08	0	267.8
6	42,164,200	0.0007	5	270	0	42.663
7	42,164,200	0.0007	5	270	0	139.568
8*	42,164,200	0.0007	42	318.5	0	8.7629
9*	42,164,200	0.0007	42	110	0	235.5129
10*	42,164,200	0.0007	42	290	0	84.5129
11*	42,164,200	0.0007	42	279	0	121.2629

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



Annex E. Resources

E1. Interface control documents/interface specifications

GPS interface specifications: www.gps.gov/technical/icwg/

- IS-GPS-200: Defines the requirements related to the interface between the GPS space and user segments for radio frequency L1 (L1 C/A) and L2 (L2C).
- IS-GPS-705: Defines the requirements related to the interface between the GPS space and user segments for radio frequency L5.
- IS-GPS-800: Defines the characteristics of GPS signal denoted L1 Civil (L1C).

GLONASS Interface Control Document Navigational Radio Signal in Bands L1, L2 (Edition 5.1) http://russianspacesystems.ru/wp-content/uploads/2016/08/ ICD_GLONASS_eng_v5.1.pdf

GLONASS Interface Control Document General Description of Code Division Multiple Access Signal System (Edition 1.0) http://russianspacesystems.ru/wp-content/uploads/2016/08/ICD-GLONASS-CDMA-General.-Edition-1.0-2016.pdf

GLONASS Interface Control Document Code Division Multiple Access Open Service Navigation Signal in L1 Frequency Band (Edition 1.0) http://russianspacesystems.ru/wp-content/uploads/2016/08/ICD-GLONASS-CDMA-L1.-Edition-1.0-2016.pdf

GLONASS Interface Control Document Code Division Multiple Access Open Service Navigation Signal in L2 Frequency Band (Edition 1.0) http://russianspacesystems.ru/wp-content/uploads/2016/08/ICD-GLONASS-CDMA-L2.-Edition-1.0-2016.pdf

GLONASS Interface Control Document Code Division Multiple Access Open Service Navigation Signal in L3 Frequency Band (Edition 1.0) http://russianspacesystems.ru/wp-content/uploads/2016/08/ICD-GLONASS-CDMA-L3.-Edition-1.0-2016.pdf

European GNSS (Galileo) Open Service Signal in Space Interface Control Document
www.gsc-europa.eu/electronic-library/programme-reference-documents

BeiDou Navigation Satellite System Signal In Space Interface Control Document
http://en.beidou.gov.cn/SYSTEMS/Officialdocument/

NavIC(IRNSS) Signal-in-Space ICD for SPS (Standard Position Service).
www.isro.gov.in/sites/default/files/irnss_sps_icd_version1.1-2017.pdf

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James J. Miller, Michael Moreau, "Space Service Volume", Ninth Meeting of the GNSS Providers' Forum, Beijing, November 2012. www.unoosa.org/pdf/icg/2012/pf9/pf-2.pdf

Badri Younes, "ICG: Achieving GNSS Interoperability and Robustness", International Committee for GNSS Eighth Meeting, Dubai, United Arab Emirates, November 2013. www.unoosa.org/pdf/icg/2013/icg-8/1a.pdf

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E3. Database of GNSS-utilizing missions

The International Operations Advisory Group (IOAG) is working to identify current and future space missions relying on GNSS signals for PNT and science applications. The IOAG provides a forum for space agencies to identify common needs across multiple international agencies and to coordinate space communications policy, high-level procedures, technical interfaces and other matters related to interoperability and space communications.

IOAG members include:

- Agenzia Spaziale Italiana
- Canadian Space Agency
- Centre National d'Etudes Spatiales
- Deutsches Zentrum für Luft- und Raumfahrt
- European Space Agency
- Japan Aerospace Exploration Agency
- National Aeronautics and Space Administration

Observer members include:

- China National Space Administration
- Indian Space Research Organization
- Korea Aerospace Research Institute
- Russian Federal Space Agency
- South African National Space Agency
- UK Space Agency
- United Arab Emirates Space Agency

The GNSS missions reference tables are updated annually and are used by the ICG in its work to develop interoperable capabilities to support space users.

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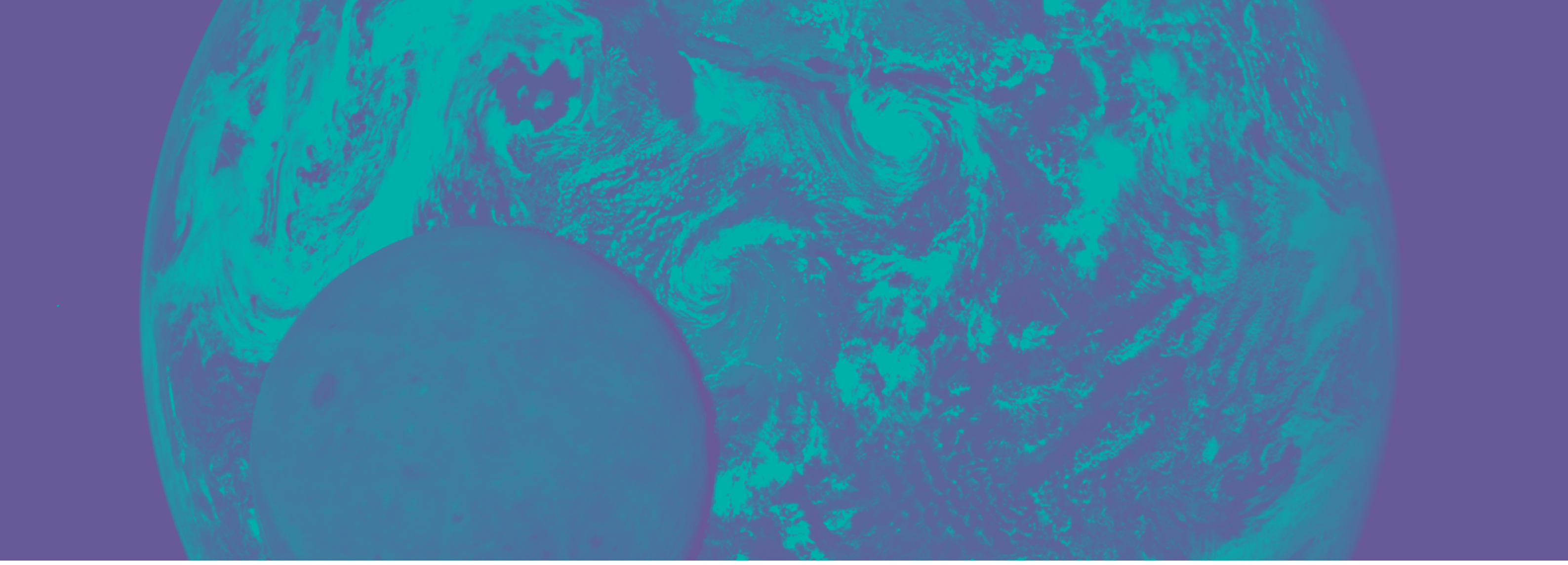
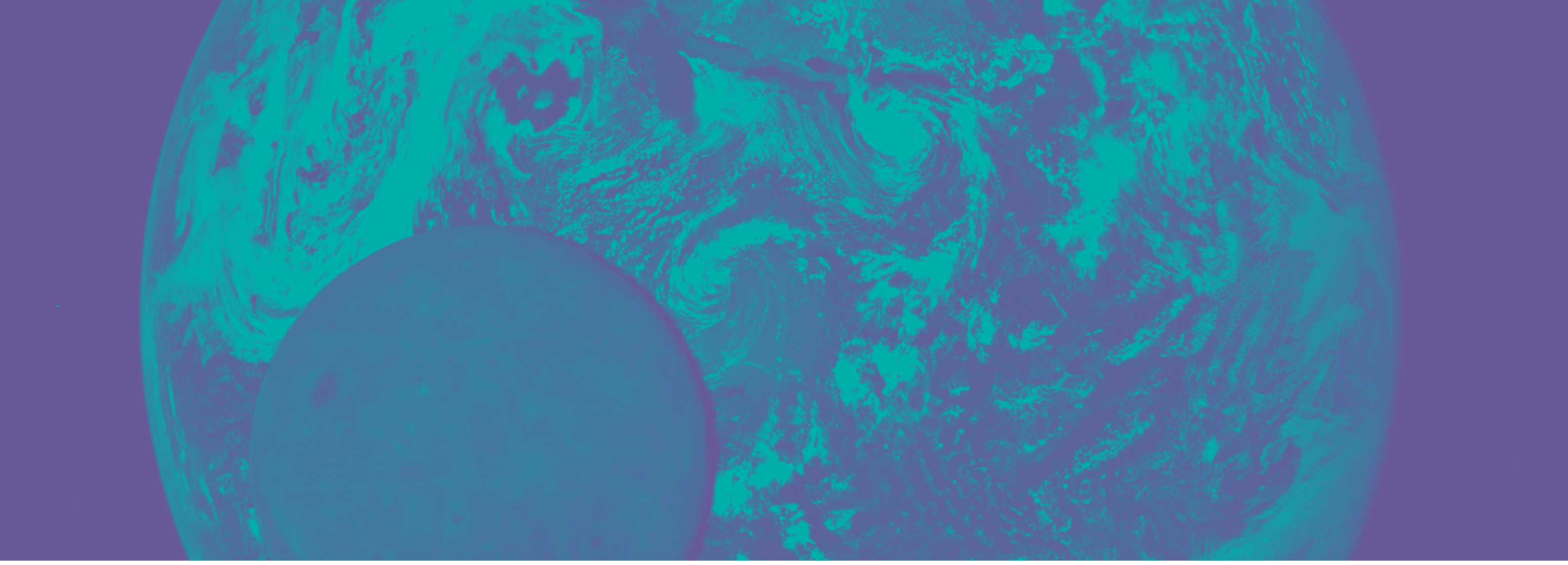


Annex F. Abbreviations and acronyms

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/N_o	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
DOP	Dilution of Precision
EC	European Commission
ESA	European Space Agency
FDMA	Frequency Division Multiple Access
FOC	Full Operational Capability
GCS	Ground Control Segment
GDI	Geometric Dilution Indicator
GEO	Geostationary Orbit
GEONS	GPS-Enhanced Onboard Navigation System

GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GOES-R	The Geostationary Operational Environmental Satellite - R Series
GPS	Global Positioning System
GRC	NASA Glenn Research Center
GSA	European GNSS Agency
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
ISRO	Indian Space Research Organisation
ISS	International Space Station
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 Multiscale Mission
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
OS	Open Service
PDOP	Position Dilution of Precision
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
RSS	Root Sum Square
S/C	Spacecraft
SIS	Signal in Space
SJTU	Shanghai Jiao Tong University
SMC	Space and Missile Systems Center
SPS	Standard Positioning Service
SSV	Space Service Volume
SUSG	ICG WG B Space Use Subgroup
SV	Space Vehicle
TCM	Trajectory Correction Manoeuvres
TLI	Trans-Lunar Injection
TRM	True Range Multilateration
TTC	Telemetry, Tracking and Command station
URE	User Range Error
URSC	U R Rao Satellite Center
UTC	Universal Time (Coordinated)
WG-B	ICG Working Group B



Annex G. Acknowledgements

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