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Space Vehicle Orbital Determination Performance Analysis Considering GNSS Side Lobe Signals

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Abstract Global navigation satellite systems (GNSS), which were originally designed for terrestrial location service, are now developed for utility in space, which are called GNSS Space Service Volume (SSV). One major problem that SSV confronts is the poor satellite availability in high orital vehicles when main beam signals are soly used. Recently side lobe signals, the signals emitted sideways from transmitter antennas, have been proposed to improve the SSV performance. It is necessary to study the GNSS SSV with the presence of side lobe signals. In this paper, the system improvement owing to the side lobe signals in high orbital vehicles for specific missions are quantitatively evaluated. Different multi-constellation conditions and system setups are taken into account as factors. GPS and BDS III constellations are simulated, and the satellite availability and the maximum outage duration(MOD) are assessed in three scenarios, the GEO, HEO, and lunar trajectory, in different heights. The experimental results indicate that the side lobe signals can effectively improve satellite availability for space users, especially in the upper SSV. Moreover, it shows that the advantages of multi-constellation interoperability lie in improving signal availability and shortening the MOD.

Keywords Space service volume · side lobe signal · satellite availability · maximum outage duration · orbital determination

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1 Introduction

GNSS was originally designed to provide Position, Navigation and Timing (PNT) services for terrestrial users, but now it was increasingly utilized for autonomous navigation in space as well. Historically, most space users have been located at low altitudes, where GNSS signal reception is similar to that on the ground [1]. They have been used for Low Earth Orbit (LEO) space vehicles. However, it is usually difficult to provide reliable PNT services for space vehicles above 3,000 km altitude. The usual navigation systems are the GPS system in the United States the GLONASS system in Russia, China's BDS and Europe's Galileo system [2]. The availability and performance of GNSS signals at high altitude is documented as the SSV[1]. And the SSV is developed for the benefit of all high-altitude users, especially in GEO and HEO [3]. Space receivers in the SSV operate in an environment significantly different than the environment of a classical terrestrial receiver or GNSS receiver in low Earth orbit. SSV users span very dynamic and changing environments when traversing above and below the GNSS constellation.

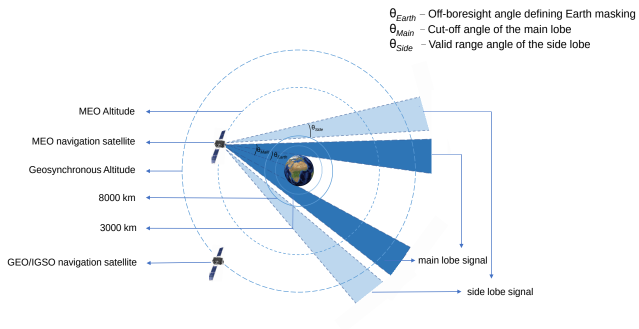


Fig. 1 SSV availability for BDS MEO satellite

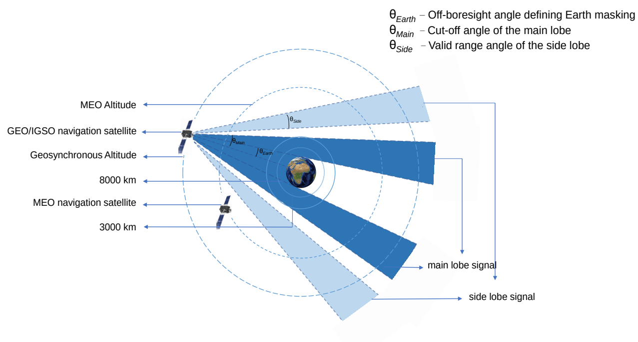


Fig. 2 SSV availability for BDS GEO/IGSO satellite

GNSS navigation technology suitable for spacecraft can provide real-time high-precision orbit data for LEO satellites and manned spacecraft [4], which greatly reduces the burden of ground tracking, telemetry and command (TT&C) network. However, because the antenna of GNSS navigation satellite is toward the earth and the angle of main lobe signal is limited [1], when the spacecraft orbital altitude exceeds GNSS constellation, only the navigation satellite signal from the other side of the earth can be received [6]. Therefore, in the high orbit environment, the availability and signal quality of GNSS navigation satellite will be limited by the earth occlusion and the increase of signal-free space loss [7]. At the same time, because the orbital altitude of the high-orbit spacecraft is very high and the received signal comes from the other side of the earth, the geometric configuration of the visible stars will be seriously affected, resulting in a sharp increase in the geometric accuracy factor [15]. Therefore, the application of GNSS is still mainly in low and medium orbit spacecraft [3]. In recent years, the research on GNSS positioning technology for high orbit aircraft has been gradually propelled, but the extant literature focuses on a research level. The main lobe signal reception of GNSS satellite limits the application scope [8]. Currently, the working group B of the United Nations International Committee on GNSS only takes the main beam signals into consideration, but the nature of the high-altitude positioning environments severely limits the GNSS accuracy and availability. Meanwhile, side lobe signals, the signals emitted sideways from transmitter antennas, have recently been proposed to assist GNSS in space. Therefore it is necessary to study the GNSS SSV service performance with the presence of side lobe signals. Side lobe signals, the signals emitted sideways from transmitter antennas, have recently been proposed to assist GNSS in space [5,9]. High-altitude applications of GNSS are more challenging due to reduced signal power levels and availability, potentially reduced pseudorange accuracy, less optimal geometric diversity, and in the case of elliptical orbits, highly dynamic motion [10]. In these environments, an increased number of available GNSS signals of sufficient power and accuracy would substantially improve the potential signal availability, and thus mission navigation performance [9]. In this paper, we study the effect of the side lobe signals to GNSS SSV performance. By taking side lobe signals into account, the performance improvement of the GNSS is quantitatively analyzed in multi-constellation conditions and system setups. We simulate the GPS, BDS III constellation, and evaluate the system performance in three scenarios, the GEO, HEO, and lunar trajectory, with different heights. The experimental results show that the side lobe signal, as a supplement to the main lobe signal, has potential in the future high altitude positioning. And we prove that in the multi-constellation GNSS, increasing the receiver sensitivity can greatly shorten MOD, improving the SSV service. Our results demonstrate that the side lobe signal is an important signal source to improve GNSS SSV service performance.

2 SSV Performance Assessment

2.1 Definition

The parameters used for SSV performance characterization are closely linked to the GNSS constellations and navigation satellite design including the transmitting power and gain pattern of the antenna. This section derives the models for the characterisation of each parameter for the shadowed areas as show in Figures 1 and 2 [10].

The GNSS performance will degrade with increasing altitude in the SSV. In order to allow for a more accurate reflection of the performance variations, the SSV itself is divided into two distinct areas [1]:

1) Lower SSV for medium Earth orbits: 3,000∼8,000 km altitude.
2) Upper SSV for geostationary and high Earth orbits: 8,000∼36,000 km altitude.

2.2 Characterization Metrics

1) **Minimum received power:** This is the minimum user-received signal power obtained by a space user in the relevant orbit, assuming a 0 dBic user antenna[1].
2) **Satellite 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 and four signals in view [1].
3) **Maximum outage duration:** A sub-metric to signal availability is maximum outage duration, defined as the maximum duration when a space user at a particular orbit will not obtain availability for at least one single or four signals simultaneously [1].

3 Availability Evaluation Index for Global SSV Performance

3.1 Geometric Constraints

The range of the effective main beam angle of SSV depends on the selection of the transmit antenna gain threshold. The lower the threshold is, the wider the available main beam is. On the contrary, the narrower the main beam is. [12].

BDS does not explicitly disclose the antenna gain modes of its third generation satellites, so we estimate the third generation situation based on the gain modes of the second generation satellites, and draw the variation curves of the antenna gain modes of MEO and GEO/IGSO satellites relative to the half-beam angle. Because the satellite orbital altitude is different from GPS, the Earth occlusion angle of MEO is 13.2°, and that of GEO and IGSO is 8.7°. If the gain threshold of the transmitting antenna is still 0 dB, the available angle range of the sub-beam of GPS L1 is 27.5∼33.0° and the sub-beam of L2/L5 is too weak to be used. Under the gain threshold of 0 dB transmitting antenna, the sub-beam availability angle of B1 frequency signal of BDS GEO/IGSO satellite is 25∼38° and the sub-beam of B2/B3 frequency signal is too weak to be used,the sub-beam availability angle of B1 frequency signal of BDS MEO satellite is 29∼37°, and the sub-beam of other two frequency signals of MEO satellite is not available [13,14], as listed in Table 1.

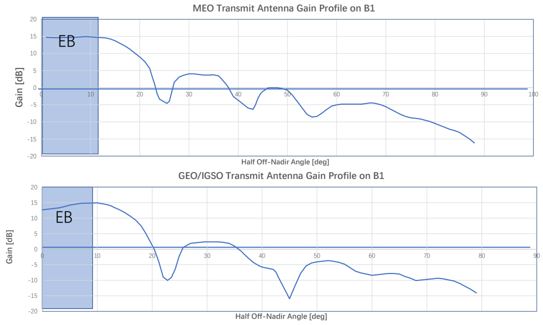


Fig. 3 Assumed BDS III transmitting gain for B1 vs. off-nadir angle. (EB represents Blocked by Earth)

Table 1 Overall off-nadir angles of available signals

Constell.	Sig.	Orb.	EBA[a] (°)	MLA[b] (°)	RSLVA[c] (°)
BD	B1	MEO	13.2	22	29-37
		GEO/IGSO	8.7	21	25-38
GPS	L1	MEO	13.8	23.5	27.5-33

[a] Earth Blocked Angle
[b] Main Lobe Cut-off Angle
[c] Range of Side Lobe Valid Angles

Each SSV user is assumed to mount two 0 dBic receiving antennas on board, one faces the Earth and the other is directed towards the zenith. This will enable a user to capture all available signals from satellites both upward and downward.

So in this paper, we only consider the performance of BDS on B1 and GPS on L1 signal.

3.2 Radio Frequency Access Constraints

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. The MRTP is constant for all off-boresight angles smaller than the reference off-boresight angle.

It is known that the signal received power of the GNSS receiver onboard an aircraft is directly determined by the signal power transmitted by the satellite, the gain of the transmitting antenna, the space propagation loss and the gain of the antenna [16]. The received power Pr can be expressed as:

$$P_r = P_t + G_t + L_s + G_r \quad (1)$$

where G_t is the gain of transmitting antenna, G_r is the gain of the antenna, P_t is the transmission power of sig-

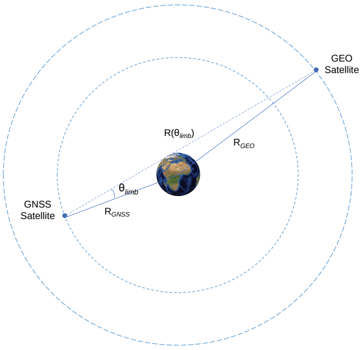


Fig. 4 Geometry used in MRTP calculation

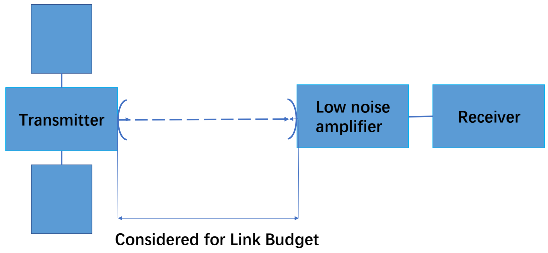


Fig. 5 Link Budget calculation scenario, where T_x is transmitter onboard the GNSS satellite, LNA is the low noise amplifier and R_x is the user receiver.

nal, and L_s is the loss of space propagation path. Their units are dB. If the ambient temperature is T which is assumed to be $290K$ under normal circumstances, we can get the noise power spectrum density:

$$No = 10 \log kT = -203.98 dBW/Hz \tag{2}$$

where k is the Boltzmann constant and equals $1.38106505 \times 10^{-23} J/K$. Based on the minimum received power P_r, the carrier-noise ratio is:

$$C/No = P_r - No - L_{proc} \tag{3}$$

The space propagation loss L_s in free space is related to the signal transmission distance. The minimum received power is at the maximum distance.

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

Therefore, the maximum signal transmission distance must be determined. Using this geometry, the Earth-limb angle can first be calculated with

$$\theta_{limb} = \arcsin(R_{earth}/R_{GNSS}). \tag{5}$$

According to Figure 4 [1], this angle can then be used to calculate the Earth-limb distance using the following formula:

$$R(\theta_{limb}) = R_{GNSS} \cos(\theta_{limb} + \sqrt{R_{GEO}^2 - R_{GNSS}^2 \sin^2(\theta_{limb})}. \tag{6}$$

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

MRTP can be derived for each constellation using an inverse link budget calculation with the constellations specified minimum received power. The overall situation for the link budget calculation and the terms taken into account [1] is outlined in Figure 5.

The minimum radiated transmit power resulting from the inverse link budget calculation is based on the user minimum received civilian signal power as established[1]. The inverse link budget is defined as

$$MRTP = P_{min} + L_s \tag{7}$$

where P_{min} is the specified minimum received power at GEO and L_s is the free space path loss at the worst-case Earth-limb distance The resulting MRTPs calculated with this method are shown in Table 2 [1] for each GNSS constellation.

Table 2 GNSS Radio Frequency (RF) parameters

Constell.	Sig.	Orb.	Freq.	MCP[a] (dBW)	MRTP
BD	B1	MEO	1575.42	-184.2	9
		GEO/IGSO	1575.42	-185.9	9
GPS	L1	MEO	1575.42	-184	9.1

[a] Minimum Received Power

4 Simulations

Navigation performance in the SSV is primarily characterized by three properties: user range error (URE), received signal power, and signal availability. The focus of these simulations is on signal availability, which serves as a proxy for navigation capability [1].

In order to fully understand the influence of side lobe signals on SSV service performance, we synthetically evaluated single and multi-GNSS constellations. By considering side lobe signals, the performance improvement of GNSS under Multi-constellation conditions and system settings is quantitatively analyzed. The evaluation of multiple constellations is based on

Table 3 Basic orbit parameters of BDS III and GPS constellation

Constell.	Orb.	NS[a]	NP[b]	Hgt[c] (km)	Ic.[d] (°)	Ec.[e]
BDS	MEO	27	3	21528	55	0
	GEO	5	1	35786	0	0
	IGSO	3	3	35786	55	0
GPS		24	6	26561.75	55	0

[a] Number of Satellites
[b] Number of Planes
[c] Height
[d] Inclination
[e] Eccentricity

BDS III and GPS [11]. Their informations are attached in Table 3.

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. Mission-specific performance estimates are obtained by estimating signal availability for a spacecraft on a particular trajectory within the SSV.

In the simulation, the provided data derives from the main lobe and side lobe of the transmit antenna patterns and captures the only minimum transmit power and worst-case pseudorange accuracy. The transmit beam width 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 in the simulation. Only the L1/B1 bands are used in the simulation.

4.1 Global Space Service Volume Performance

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

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

The attitude of each GNSS transmitting antenna is determined depending on which constellation the spacecraft belongs to, and the transmitting antenna of

Signal	Constellation	Signal availability (%)		Max Outage Duration(min)	
		At least 1 signal	4 or more signals	At least 1 signal	4 or more signals
Main lobe	BD	76.59	12.26	994	6700
	GPS	57.86	0	712	1432
	Combined	88.76	24.81	705	783
Main lobe and Side lobe	BD	97.70	60.97	51	545
	GPS	83.77	0.84	106	1004
	Combined	99.64	82.02	46	383

Fig. 6 Global performance estimates of availability and maximum outage duration for each constellation and all constellations together. Results for omni pointing antenna (nadir and zenith) in the lower SSV

Signal	Constellation	Signal availability (%)		Max Outage Duration(min)	
		At least 1 signal	4 or more signals	At least 1 signal	4 or more signals
Main lobe	BD	64.93	0.33	422	1905
	GPS	57.75	0	717	2433
	Combined	83.92	4.78	717	935
Main lobe and Side lobe	BD	96.01	26.89	64	850
	GPS	83.69	0.83	106	647
	Combined	99.40	62.33	46	514

Fig. 7 Global performance estimates of availability and maximum outage duration for each constellation and constellations together. Results for nadir-pointing antenna in the upper SSV

the BDS and GPS is nadir (Earths centre). Additionally, depending on the simulation, the receiving antennas boresight is pointed either nadir or zenith relative to the center of the Earth, and its field of view is defined as either hemispherical or omnidirectional.

4.1.1 Geometrical analysis methodology

Figure 6 and 7 show available performance at 8,000 km and 36,000 km altitudes considering a zero-gain user antenna when considering only geometrical access constraints.

No matter in the lower SSV or upper SSV, the participation of the side lobe signals improves the service performance of BDS and GPS dramatically, and one-signal availability significantly exceeds four-signal availability.

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. In

Signal	Constellation	C/NO_{min}=15dBHz				C/NO_{min}=20dBHz				C/NO_{min}=25dBHz			
		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)
Main lobe	BD	91.04	109	5.09	10325	14.14	133	0	10051	*	*	*	*
	GPS	91.04	109	5.09	10325	91.04	109	5.09	10325	*	*	*	*
	Combination	99.50	58	66.42	348	92.40	92	8.20	1216	*	*	*	*
Combined	BD	99.22	27	45.26	309	97.31	41	53.97	322	*	*	*	*
	GPS	99.22	27	45.26	309	99.22	27	45.26	309	*	*	*	*
	Combination	100	0	99.94	23	99.97	22	94.53	69	*	*	*	*

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

Fig. 8 Upper SSV performance with RF constraints, for various C/No thresholds

the lower SSV, single satellite availability is high for all individual systems and combined-signal availability is 97.70% in BD system. Obviously, SSV performance can be dramatically improved when combining BD and GPS. The availability of at least one satellites increases from 88.76% to 99.64% with the presence of side lobe signals.

The addition of side lobe signals is especially effective in the upper SSV. The availability of more than one satellite of the reaches 96.01% while considering side lobe signals, and the availability of four or more satellites increases to 62.33% when multiple systems are interoperable.

On the basis of the availability of side lobe signals, MOD can be effectively reduced under interoperability of satellites systems, and the service performance will be better when multiple systems are interoperable.

4.1.2 RF Access Analysis Methodology

Results in figure 8 provide the average globalized upper SSV expected system performance when RF-based signal strength constraints are applied to geometrical-only access calculations. Simulations were performed using three different thresholds of C/No of 15, 20, and 25 dB-Hz.

Figure 8 shows the signal availability and the MOD for a user in the upper SSV as a function of different C/No thresholds for each individual constellation and for all constellations combined. One-signal availability significantly exceeds four-signal availability. When side lobe signals are considered, one-signal availability is nearly 100% for 15 dB-Hz threshold. The abundance of signals available in an interoperable multi-GNSS SSV greatly reduces constraints imposed by navigation in the upper SSV. At the highest threshold of 25 dB/Hz, availability is nearly 0.0% in the upper SSV shown. This indicates the challenge of extremely low GNSS signal levels for missions, and the importance of using specialized high-altitude receivers and high-gain antennas. With the increase of altitude, the availability of satellite decreases obviously. Nevertheless, in an interoperable multi-GNSS SSV, the availability of satellite increases obviously and the MOD becomes shorter. While side lobe signals are considered, the availability of signals increased dramatically, especially for the more than four signals at the 20 dB/Hz threshold, where the availability of four signals reaches 94.53% from 8.20%, which also reflects the great potential of side lobe signals for deep space orbit determination in the future.

4.2 Mission-Specific Performance

Mission-specific simulated usage scenarios are considered as actual use cases for GNSS spatial users. Three representative mission scenarios were selected for simulation, a geostationary orbit mission, a highly elliptical orbit mission, and a lunar mission. The contribution of side lobe signals to space service and the influence of Individual constellation to multi-GNSS in SSV are simulated and analyzed.

4.2.1 Common Assumptions and Methods

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 a gain of approximately 2 dBi, and a "high-gain" antenna with a gain of 8 to 9 dBi.

4.2.2 Geostationary orbit mission

The GEO mission scenario analyses multi-GNSS signal reception for six geostationary satellites. The objective is to obtain more representative signal strength values than in the global analysis by using realistic user antenna patterns onboard the space users for receiving the B1/L1 signals with the presence of side lobe signals. The user antenna onboard the user spacecraft is a high-gain antenna that permanently points towards the nadir (center of the Earth). The assumed acquisition threshold of the space user receiver is 20 dB-Hz.

The six GEO satellites are all in the equatorial orbital plane but phased by 60° 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.

For all six GEO receivers at L1 frequencies, the satellite availability is shown from the Figure 9(a,b,c,d).

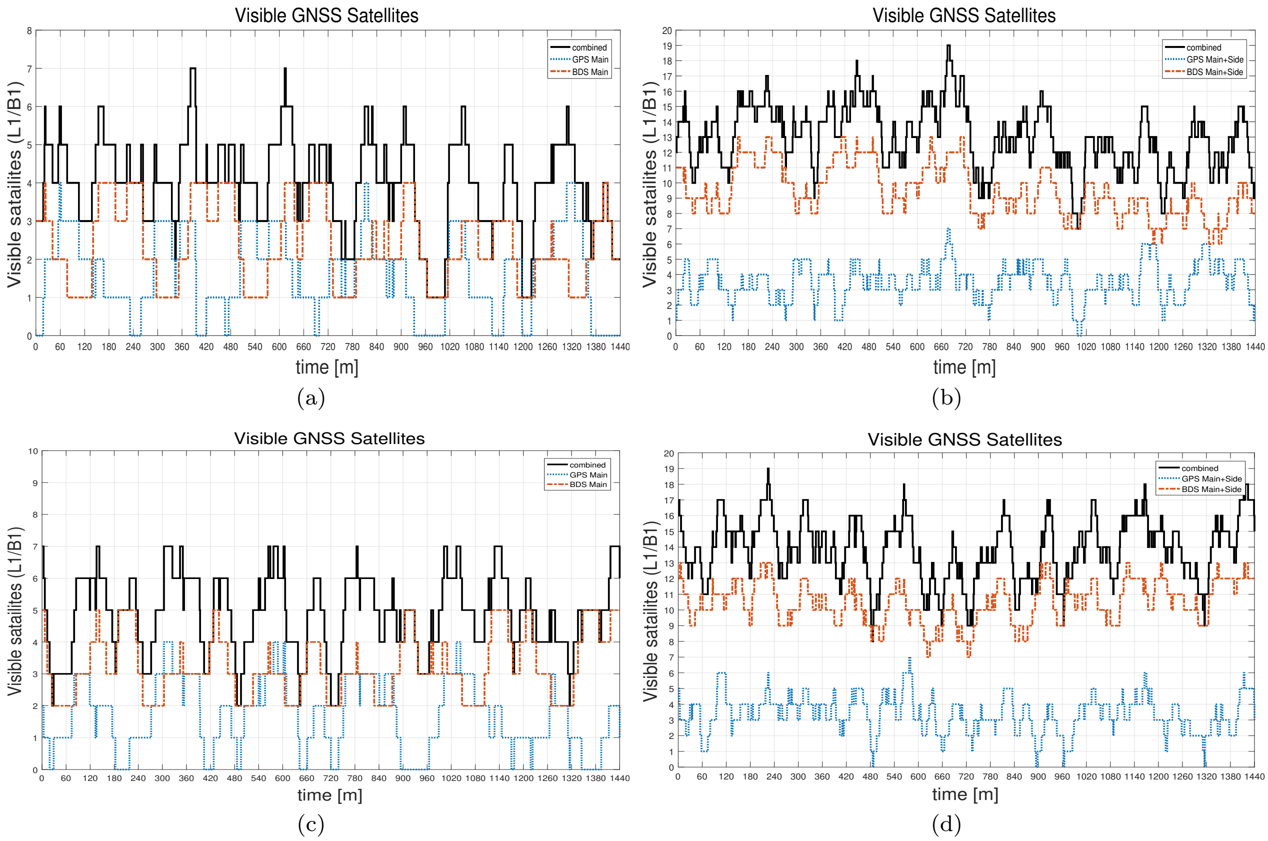


Fig. 9 (a) L1/B1 availability for GEO at 60° with main lobe signal. (b) L1/B1 availability for GEO at 60° with main lobe signal and side lobe signal. (c) L1/B1 availability for GEO at 180° with main lobe signal. (d) L1/B1 availability for GEO at 180° with main lobe signal and side lobe signal.

Obviously, when only the main lobe signal is available, the availability of satellite is low, but when the side lobe signal is added, the availability increases obviously. Especially when multiple systems are user-operated, the availability of side lobe signals makes the number of visible satellites almost always four or more, and even 19 in some areas.The service performance of BDS is better than that of GPS. At 180 deg, the availability of four satellites of BDS is from 30.0% to 100.0% when side lobe signal is added.

4.2.3 Scientific highly elliptical orbit mission

An HEO mission scenario with an apogee altitude of about 58,600 km and perigee altitude of 500 km is used to demonstrate the GNSS availability performance through all the GNSS SSV altitudes, both below and above the GNSS constellations.

The onboard GNSS antennas are configured in both nadir and zenith-facing sides of the spacecraft showed in Figure 10 [1]. 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.

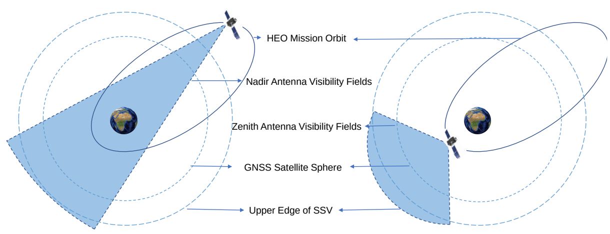
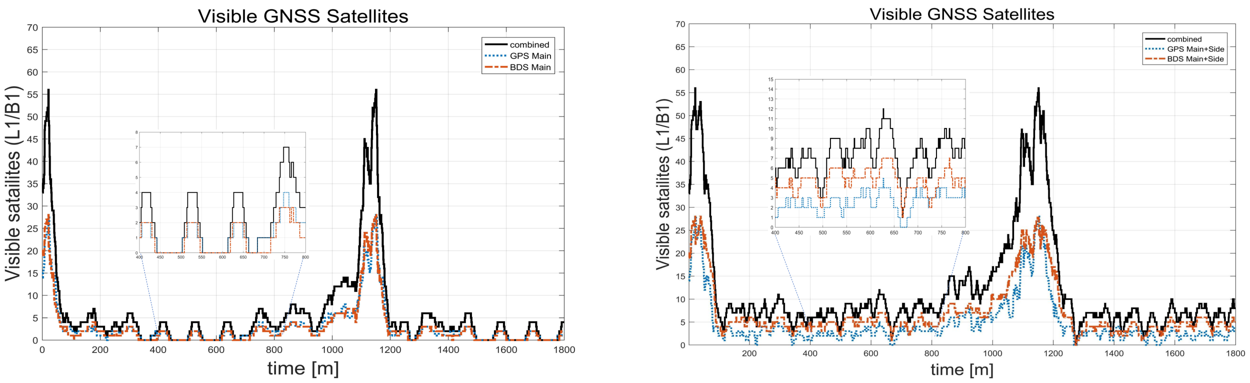


Fig. 10 Schematic of the HEO mission with nadir and zenith-pointing antennas

Figure 12 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.

The simulated results for the signal availability and MOD of the HEO mission are shown in Figure 11(a,b). The signal availability was evaluated with 20 dB-Hz



(a) (b)

Fig. 11 (a) Visible GNSS satellites over 1.5 orbital periods of HEO with main lobe signal. (b) Visible GNSS satellites over 1.5 orbital periods of HEO with the main lobe signal and side lobe signal.

Signal	Constellation	Signal availability (%)		Max Outage Duration(min)	
		At least 1 signal	4 or more signals	At least 1 signal	4 or more signals
Main lobe	BD	76.84	16.89	73	1020
	GPS	82.41	19.60	62	1006
	Combination	84.81	51.80	62	91
Combined	BD	99.89	84.56	11	74
	GPS	98.14	43.84	15	276
	Combination	99.96	96.67	5	19

Fig. 12 HEO mission simulated performance result

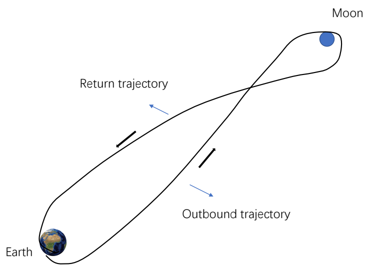


Fig. 13 Lunar trajectory phases

C/No threshold for each individual constellation and all constellations combined.

For L1/B1, the one-signal availability can reach 84.81% with all constellations combined only with the presence of main lobe signals, while 99.96% with the use of main lobe and side lobe signals. In the case of L1, four-signal availability is below 20.0% 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% when considering side lobe signals.

4.2.4 Lunar Mission

Many aerospace applications will be developed aiming at formation flying, rendezvous and docking, innovative scientific exploration, and so on. The interest will be lied in how GNSS supports the whole process of specific space missions.

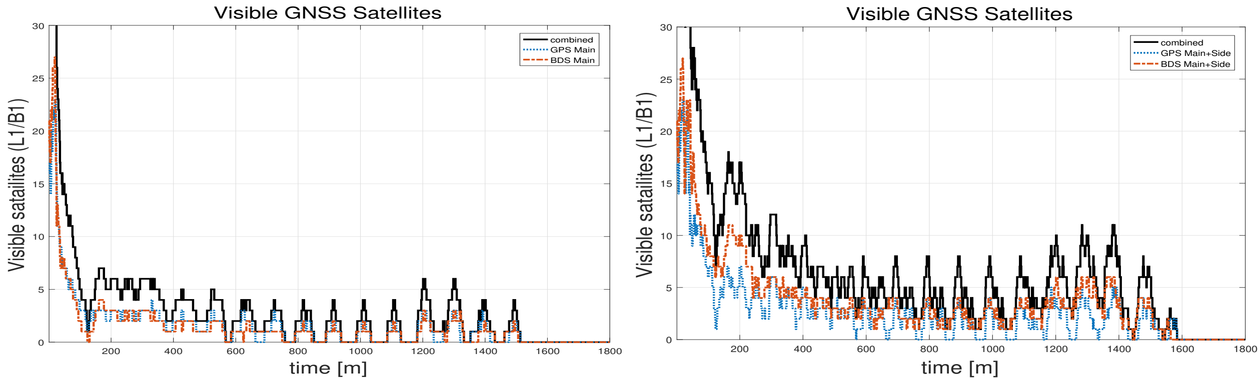
A full lunar mission trajectory contains four phases, as showcased in Figure 13 [1]:

1) **Earth parking orbit**
2) **Outbound trajectory**
3) **Lunar orbit**
4) **Return trajectory**

For the purposes of this analysis, only the outbound trajectory is modeled to illustrate the GNSS signal availability with increasing altitude. The assumed acquisition threshold of the receiver is 20 dB-Hz.

Figure 14(a,b) contains the full simulated performance results for this mission. In the case of L1 band, the availability of four simultaneous signals is nearly zero for any individual constellation, though in the combined case there is coverage to approximately 36 Earth Radius (RE) (approximately half the distance to the Moon) near 10.0∼15.0%. If a more sensitive receiver or higher-gain antenna were used such that signals at a C/No of 15 dB-Hz were usable, signal availability would be achievable for the entire trajectory to lunar distance.

It can be seen that when side lobe signal is added, the availability of satellite is generally improved, and the availability of four satellites has increased from less than 50.0% to nearly 80.0% in the multi-constellation



(a) (b)

Fig. 14 (a) Signal availability by trajectory altitude, to the limit of available signals at 36 RE with main lobe signal. (b) Signal availability by trajectory altitude, to the limit of available signals at 36 RE with the main lobe signal and side lobe signal.

GNSS, which fully illustrates the application potential of side lobe signal in deep space navigation.These results strongly confirm that side lobe signals will have more prominent potential in future orbit determination.

5 Conclusion

In this paper, the range of the main lobe and side lobe, and carrier-to-noise ratio threshold of the downlink antenna of BDS III and GPS are used as evaluation indicators to simulate and establish various GNSS constellations in the way of approaching the real state as far as possible. Sample points and specific missions at different orbital altitudes are added to the constellations, and the interoperability between the single constellation and multi-constellation is carried out. It is pointed out that the advantages of multi-constellation interoperability lie in improving signal availability and shortening MOD.

On this basis, as a supplement to The Interoperable Global Navigation Satellite Systems Space Service Volume published by the working group B of ICG in October 2018. The side lobe signal is presented, and its impact on improving satellite availability and shortening MOD is evaluated by simulation, which fully proves the potential of side lobe signals in orbit determination.

Taking BDS III, GPS single constellation and their interoperability as examples, the performances of the main lobe and side lobe signals are simulated and compared. Dual-frequency main lobe signal or dual-frequency main lobe signal enhanced by the side lobe signal can provide 100% potential navigation service for MEO spacecraft (more than four visible satellites). In the upper SSV, the addition of side lobe signals reflect its potential for orbit determination, significantly improves the availability of satellites and shortens the MOD.

In the global average service performance evaluation, the availability of satellites under different receiver sensitivities is considered. For C/No_{min} = 15 dB-Hz or 20 dB-Hz, one-signal availability exceeds fourfold availability. And the availability of the satellite is obviously improved when the side lobe signal is introduced. However, when the carrier-to-noise ratio threshold of the receiver is 25 dB/Hz, performance drops to 0.0% availability for all. The results show that in order to make use of these very weak GNSS signal levels, the required reception capability is quite harsh, that is, the receiver sensitivity needs to be improved to achieve.

In the case of high orbit, the availability of navigation satellites can be greatly improved by using interoperable GNSS constellations. This paper only discusses the status of interoperability between BDS and GPS, but on the basis of experimental simulation and existing knowledge, it can be concluded by analogy that when Galileo and GLONASS are added to the multi-constellation GNSS, the availability of satellites can be improved more significantly.

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