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Multi-GNSS for Space Service Volume

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ABSTRACT

Global Navigation Satellite System (GNSS) play a crucial role in enabling the autonomous navigation capabilities for space vehicles. GNSS offers good coverage in terrestrial as well as in Low Earth Orbit (LEO) and in turn enables autonomous space vehicle operations. The extension of this service to Space Service Volume (SSV) is made feasible through tracking the signals available over the limb of the earth. But with a single constellation configuration, the receiver can experience significant outages at higher altitudes. This paper explores the possibility of multi-GNSS configurations to enable consistent positioning at higher altitudes. For this study, navigation systems considered include GPS, GLONASS, GALILEO, BEIDOU, QZSS, and SBAS. This paper also characterises the GNSS availability based on three main parameters: antenna pattern (transmitting and receiving antennas), synodic period (between user and GNSS), and user orbital parameters. The study is extended through MATLAB simulation to a wide array of altitude and inclination combinations in the SSV which is helpful in mapping the user orbit against GNSS service availability. It is evident from the simulation results that a multi-GNSS approach has a collective advantage in high orbits and thus future missions can effectively utilize the services available in the SSV to lower the overall cost of the mission.

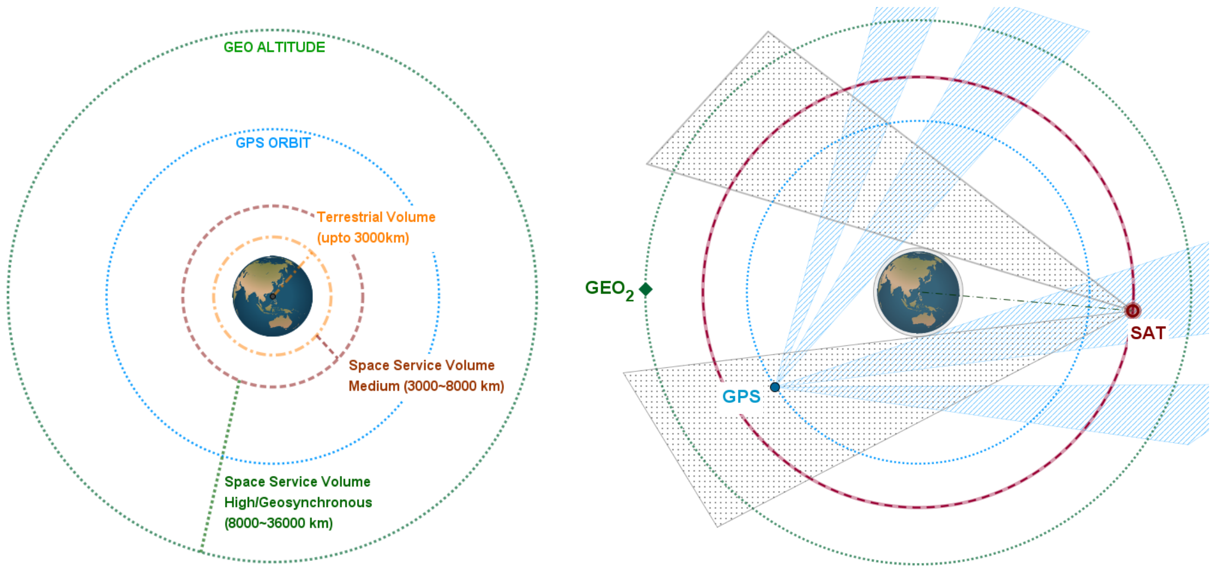
KEYWORDS: Space Service Volume, Multi-GNSS

1. INTRODUCTION

During the last two decades, GNSS has evolved into a robust system addressing extensive user requirements and offering high precision Position, Navigation, and Timing (PNT) services. GPS and GLONASS are the two fully operational global navigation systems, where others such as GALILEO and BEIDOU are under development. Regional support system such as QZSS (Quasi-Zenith Satellite System) is also expanding and the constellation was designed to augment GPS signals over the Japanese region to enable increased satellite visibility in urban canyons. Other stand-alone regional navigation system include IRNSS/NAVIC has seven satellites deployed in orbit and is ready for operation. Apart from

global and regional systems there are also Satellite Based Augmentation Systems (SBAS) which support wide-area or regional augmentation through geo-stationary satellites broadcasting augmentation information. The primary application of SBAS lies in the aviation sector, a highly critical application. Several countries have their own SBAS system, namely, Europe – EGNOS (European Geostationary Navigation Overlay Service) (3 sat), USA – WAAS (Wide Area Augmentation System) (3 sat), Japan – MSAS (Multi-functional Satellite Augmentation System) (2 sat), India – GAGAN (GPS and GEO Augmented Navigation) (2 sat) and Russian SDCM (System for Differential Corrections and Monitoring) (3 sat).

The GNSS service regions can be classified into two major categories: the *Terrestrial service volume* (TSV) and the *Space Service Volume* (SSV) (Bauer et al. 2006). The TSV encloses the region that comprises the Earth's surface and LEO altitudes up to 3000 km. Terrestrial users have ready access to the requisite four satellites from a single constellation and signal strength is relatively uniform in this region. The LEO users also enjoy a similar environment with only small modifications required to their receivers to accommodate the dynamic effects of the orbit.



(a) (b)

Figure 1: a) GNSS Service Regions b) Orbit and Antenna pattern of satellites

Though every navigational system was primarily designed and developed for terrestrial applications, the use of GNSS service in space vehicles has becomes common. With the number of missions based on high earth orbit and geostationary orbit set to increase, GNSS based positioning is challenged to work at those heights. GNSS positioning at higher altitudes increases the spacecraft autonomy and lowers mission operation cost. Also, there are other expected performance improvements such as achieving metre class positioning rather than the current level of kilometre class and also reducing the trajectory manoeuvre recovery time to minutes (Parker 2016).

The space service volume encloses the region with altitudes extending from 3000 to 36000 km. This region is sub-divided in to two categories, MEO SSV and HEO/GEO SSV. The MEO SSV encloses the altitudes from 3000 to 8000 km and has access to satellites from either the GNSS constellation directly above or the signal available over the Earth's limb. The user in the HEO/GEO SSV only has GNSS signals available over the limb of the earth's

surface. This restricts the number of satellites visible to the HEO/GEO user and in turn the positioning service available from a single constellation. GPS based navigation in the SSV was previously studied in (Davis et al. 2002), (Ruiz and Frey 2005) and multi-GNSS based navigation for highly elliptical orbits in (Kahr 2013). SBAS signal reception in space is studied by (Kahr et al. 2016), though the study was based on LEO orbit, such a study can be extended to multi-GNSS based positioning in SSV. From previous studies, it is evident that offering continuous positioning service at higher altitudes is difficult with a single constellation and the user suffers extended outages at geostationary altitudes.

This paper investigates multi-GNSS based positioning and possible combinations to enable consistent positioning in HEO/GEO SSV. For this study, navigation systems considered includes GPS, GLONASS, Galileo and BEIDOU. It also includes QZSS and SBAS, which are above platforms in the HEO/GEO SSV. The paper characterises GNSS availability based on three main parameters: antenna pattern (transmitting and receiving antennas), synodic period (between user and GNSS), and user orbital parameters. The study is extended through a MATLAB simulation to a wide array of altitude and inclination combinations in HEO/GEO SSV and is thus helpful in mapping the percentage of mission duration that GNSS service is available. The design trade-offs considered to make the simulation more robust are discussed in detail in sections 2 and section 3. In section 4, the simulation results are discussed in detail for different cases, i.e. combinations of two or more navigational systems.

2. MULTI-GNSS

2.1 Parameters

The availability of the signals is assessed based on the three primary parameters (Parker 2016). They are

- Minimum received power level
- Satellite availability
- Pseudo range accuracy

Minimum received power level: The signals reaching the higher altitudes from the far side of the earth are significantly weaker than those available on the earth surface, because these signals travel larger distance to reach higher altitudes than earth's surface. The power loss will be dominated by the free space path loss in the link budget, and the transmit antenna roll-off. The link budget equation describing the Carrier-to-Noise density ratio (C/N_0) at a GNSS receiver is provided below (Van Dierendonck 1996).

$$C/N_0 \text{ (dB-Hz)} = EIRP + G_t + G_r - L_f - L_{atm} - K_B - T_{sys}$$

EIRP is the equivalent isotropic radiated power in dB-W, G_t and G_r are gain of transmission and receiver antennas in dB, L_f and L_{atm} – free space loss and atmospheric loss in dB, K_B is Boltzmann constant in dBW/K-Hz and T_{sys} is the system noise temperature in dB-K. The received signal strength can be increased through adjusting the receiving antenna gain by having a directional antenna with significant gain pointing at nadir to receive the signals from the main lobe and side lobes of GNSS antennas. Based on previous studies in the SSV, the theoretical available minimum received signal power (for different GNSS constellations) to a 0dBi antenna located at geo-stationary orbit is listed in the Table 1.

Satellite availability: The availability of the GNSS satellites for positioning is dominated by the beam pattern of both the transmitting and receiving antennas. The GNSS main lobe signals available on either side of the earth are too narrow to have continuous availability of the satellite at higher altitudes. The GNSS side lobe signals are vital for positioning at geostationary altitudes. The antenna pattern specifications of the GNSS constellation are not publically available, except for the block IIR and IIR-M of GPS satellites released by Lockheed martin (Marquis and Reigh 2015).

For the GPS constellation, earth service uses a 13.5° half-beam width in the main lobe. After considering the dense atmospheric region of 50 km and 0dB directivity level for the main lobe, only 14°-22° of the main lobe signal is available for positioning in the SSV. The reference off boresight angles of other GNSS constellations are highlighted in Table 1.

Geometric Dilution of Precision: GDOP is one of the secondary parameters considered to analyse GNSS positioning at higher altitudes. It primarily depends on the distribution of the satellites which in turn boresight angles of the transmitting and the receiving antennas.

Pseudo range accuracy: The User Range Error (URE) is an error bound on the GNSS range measurements. It is a function of different parameters such as accuracy of GNSS orbit, clock solutions generated by control segment, validity of the solution since the last broadcast ephemeris upload from control segment and also physical and modeling parameters of the GNSS satellites (Bauer et al. 2006). Pseudorange accuracy is also affected by the uncertainty in the measurement difference between the electrical phase centres of the antennas and the user geometry with respect to the GNSS satellites, delays through the ionosphere and troposphere, receiver noise and multipath. For the main lobe signal the phase centre differences are correlated to the greater extent to minimise the errors. However, the non-availability of phase variations at larger beam width angles also affects the pseudo range accuracy.

	Signal	Ref. off boresight angle (Main lobe)	Approx. minimum received power (0 dBi RCP antenna at GEO) dBW	References
GPS	L1	23.5°	-184	(Bauer et al. 2006)
	L2	26°	-183	
	L5	26°	-182	
GLONASS	L1	20°	-185	(Kosenko, Grechkoseev and Sanzharov 2014)
	L2	28°	-184.4	
	L3	28°	-184	
GALILEO	E1	20.5°	-182.5	(Wallner 2015)
	E5	23.5°	-182.5	
	E6	21.5°	-182.5	
BEIDOU	B1	24° & 18°	-184.1 & -185.8	(Chang, Mei and Yang 2015)
	B2	26° & 21°	-182.7 & -184.4	
	B3	26° & 21°	-184.5 & -186.2	
QZSS	L1	22°	-185.3	(Kogure and Kishimoto 2012)
	L2	24°	-188.7	
	L5	24°	-180.7	

Table 1: Boresight angles and minimum received power of different GNSS constellations

3. SIMULATION

3.1 General

The previous SSV studies are focussed on single constellation (especially GPS). The simulation involves distributed gridded points with uniform equatorial spacing around the globe and the visibility analysis was performed over a certain time period for a defined set of SSV altitudes, which includes only one intermittent altitude between GPS and GEO orbit.

In the current approach, the GNSS availability is studied through a combination of the orbital altitude and inclination especially between MEO constellation and geostationary altitude. In our simulation, we assume line of sight visibility i.e. the GNSS satellite is considered available for positioning when both the GNSS and receiving satellite are in the field of view of each other. Also, assuming the signal satisfies the minimum power requirement for the geostationary altitude. This allows us to plot the signal availability characteristics based on the three major parameters, altitude (receiver), inclination and mission duration. Mission duration is simulated through the synodic period measurement between the orbital period of the receiver at certain altitudes and the GNSS constellation at the highest altitude.

We simulated an array of combinations between user orbital altitude and inclination. The altitudes varied from 25,000 to 35,800 km with intervals of 450 km and the inclination of the user orbit varied from 0° to 60° with intervals of 2.5°. This arrangement provides an array of 25x25 points with each point simulated for the respective synodic period between the user and the GNSS constellation. We carried out for different multi-GNSS combinations and the different cases are listed in the Table 2.

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
GPS	●	●	●	●	●
GLONASS		●	●		
GALILEO				●	
BEIDOU					●
QZSS	●	●			
SBAS	●	●			

Table 2: Multi-GNSS Simulation: Study cases

From a theoretical perspective, the combination of GNSS constellations orbiting at higher altitudes and having wider antenna beam width angles should maximise the GNSS positioning availability for any given receiver satellite orbit and the time period.

3.2 Attributes

Though a large number of attributes influence the GNSS positioning at higher altitudes, our study is based on the nadir-pointed directional antenna with nominal gain over a limited half-beam width angle (32.5°). The signals reaching the HEO/GEO SSV pass through the intense regions of ionosphere, so considering delay mitigation as well as to eliminate the ionospheric mask requirement, the receiver/user satellites are presumed to be equipped with dual frequency receivers. The half beam width angles used for the simulation of the GNSS constellation are based on their respective primary signal.

3.3 Single Constellation Visibility

Before discussing multi-GNSS results, for comparison, we provide the results considering only the GPS constellation (Rathinam and Dempster 2016). As shown in Figure 2, if a user is orbiting at equatorial Geo-stationary orbit, the visibility (4 or more satellites) using only the GPS main lobe is around 5 percent of the mission period. With inclined geo-synchronous orbit the percentage can drop to nearly less than 1 percent. With the inclusion of the first side lobe signal from the GPS satellites, the percentage increases to 60 ~ 80 percent. This result highlights the importance of the availability of side lobe signals of GPS constellation.

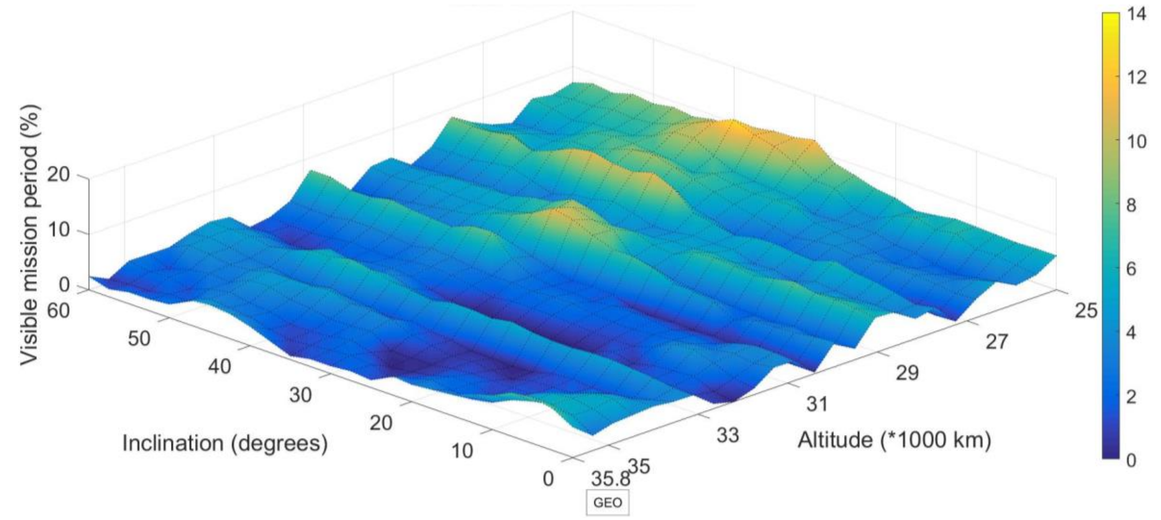


Figure 2: Visibility of GPS Constellation (Main lobe)

The visibility of GPS satellites with both main and side lobe is plotted in the Figure 3. The multi-GNSS simulations include the results of GPS side lobe signals along with other constellations. For the remaining constellations detailed antenna patterns are not available, hence the simulations will be restricted to main lobe signals.

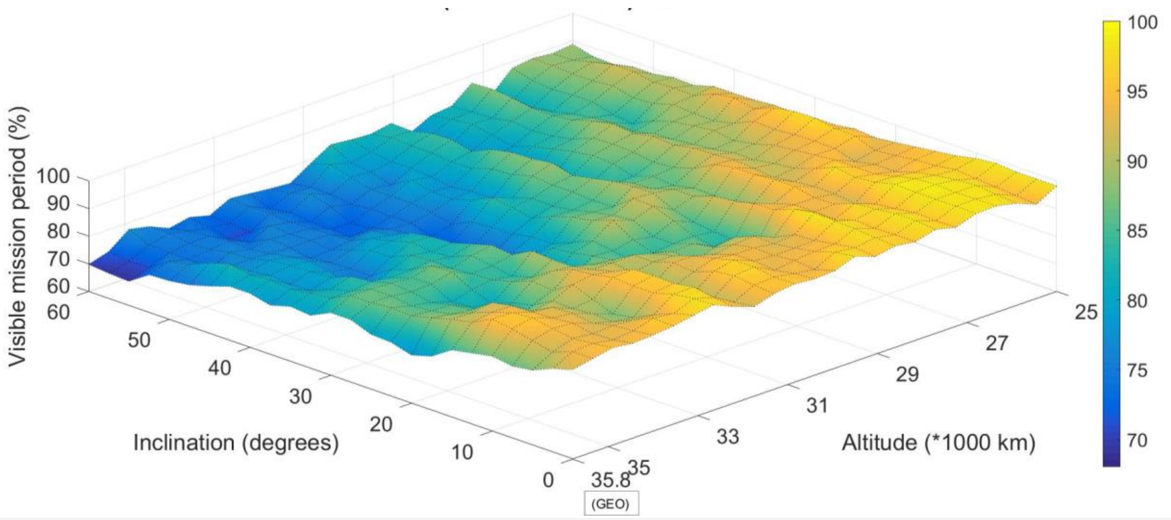


Figure 3: Visibility of GPS Constellation (Main lobe and Side lobe)

4. RESULTS

The simulations were performed for different multi-GNSS combinations listed in **Table 2** and the results are presented below.

Case 1: GPS + QZSS + SBAS

The GPS constellation along with the QZSS and SBAS satellites is simulated in this case. With the GPS main and side lobe already providing good visibility, the addition of SBAS and QZSS satellites expected to boost the availability. From Figure 4, it is evident that the additional GNSS satellites help to achieve 100% percentage at lower altitudes/inclinations.

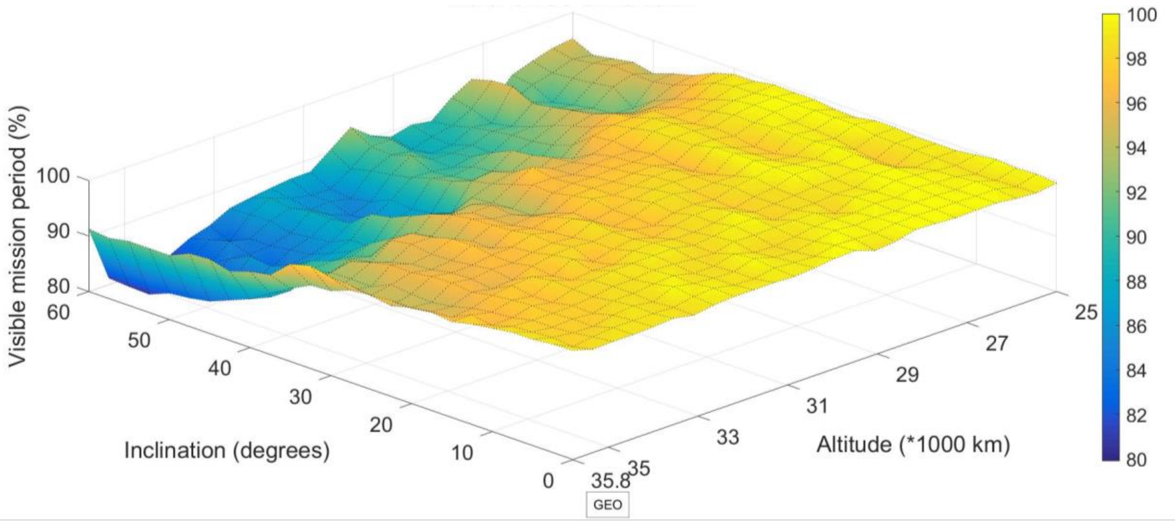


Figure 4: Multi-GNSS (GPS + QZSS + SBAS) visibility

As we move towards geostationary altitude, both GNSS and receiver satellite will be in same orbit and hence the synodic period becomes infinity. Thus, the availability at the final geostationary altitude line in Figure 4 represents only a small portion of the result. So, to better understand the GNSS positioning at geostationary altitude, we simulated the availability of four or more available navigational satellites for every latitude/longitude combination and plotted in Figure 5.

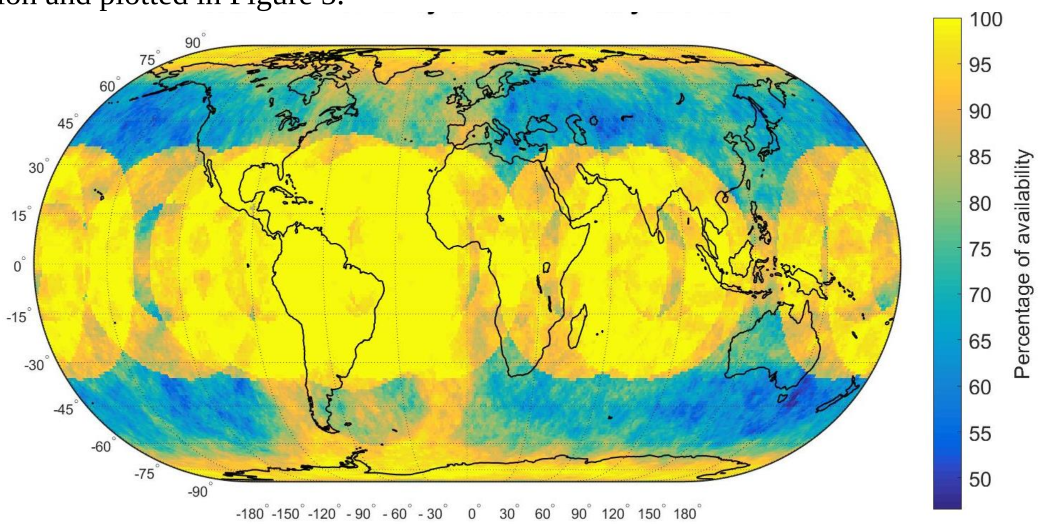


Figure 5: Multi-GNSS (GPS + QZSS + SBAS) visibility at geostationary altitude

The results shows with above combination we can achieve nearly above 90% availability within 35° latitudes, but at higher latitudes, the percentage drops to nearly 50% at certain regions, but considering the orbital conditions the average percentage of availability is above 80%.

Case 2: GPS + GLONASS + QZSS + SBAS

In case 2, we simulated the GPS, GLONASS, SBAS and QZSS and the result conveys the advantage of having a second MEO constellation. As seen in Figure 6, the increase in percentage of availability up to 10% is visible at higher inclinations and the lower altitude/inclinations are reaching saturation. Similar to case 1, we have geostationary GNSS satellites and the synodic period becomes infinity. To assess the GNSS availability at geostationary altitude, we have done a second simulation and plotted in Figure 7. The effect of having the GLONASS (second MEO constellation) is clearly visible in Figure 7 with the 15% increase in minimum percentage in comparison to Figure 5. But after considering the orbital conditions the average percentage of availability is nearly 90%.

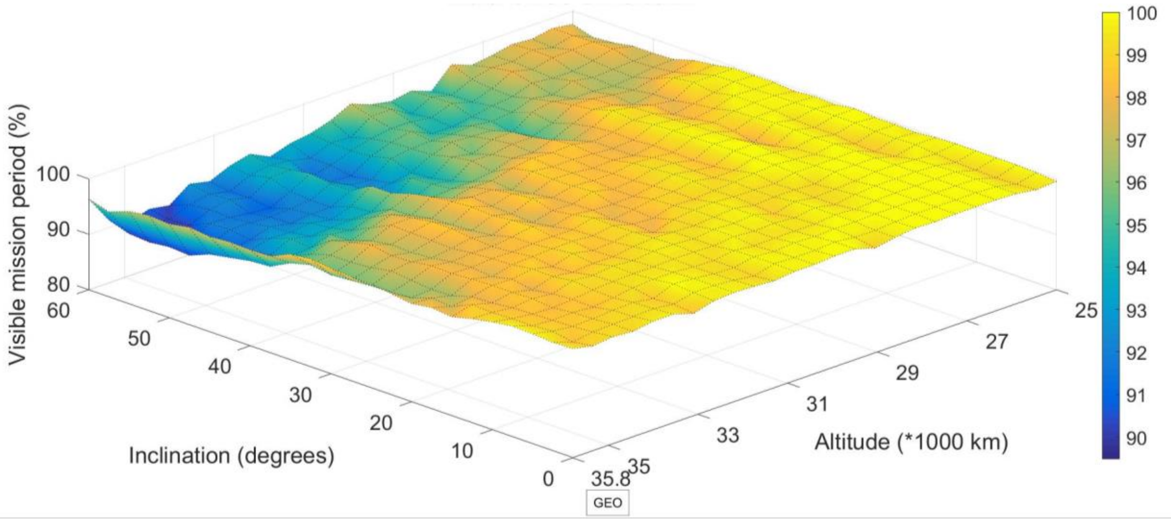


Figure 6: Multi-GNSS (GPS + GLO + QZSS + SBAS) availability

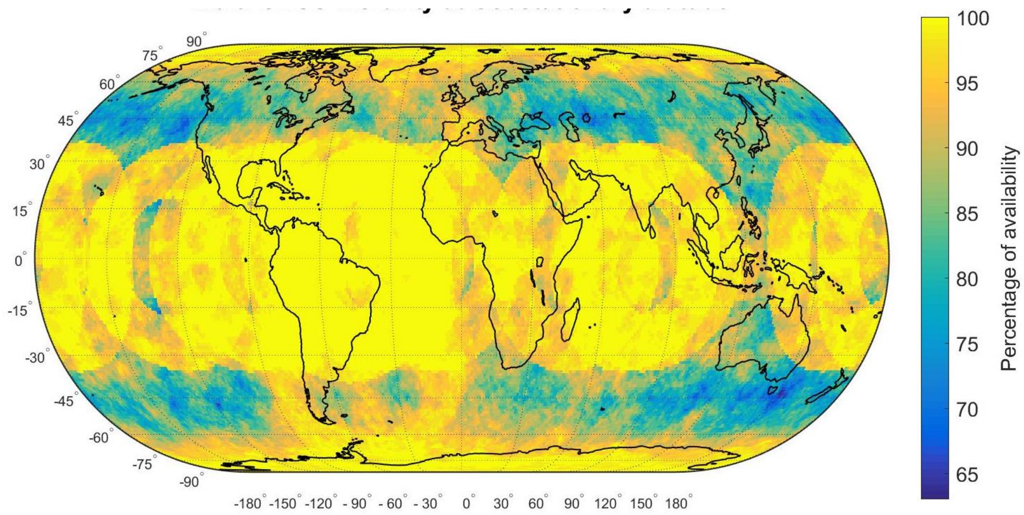


Figure 7: Multi-GNSS (GPS + GLO + QZSS + SBAS) availability at geostationary altitude

Case 3: GPS + GLONASS

In this case we simulated the two primary GNSS constellations GPS and GLONASS. Even though we simulated the GLONASS along with SBAS and QZSS, the primary motivation here is to evaluate whether we can achieve similar performance without the geostationary satellites. We achieved nearly 100 percent visibilities at lower altitudes though the surface of the plot is not as smooth as in Figure 6. The visibility at near equatorial geostationary orbits is nearly 96% and as we move towards the other orbit combinations (i.e. higher altitude/inclination) the visibility drops to 85%. This shows that having SBAS and QZSS as in case 2, have significant effect (8~10%) on the multi-GNSS positioning at higher altitudes and the results helps to choose a reliable system with significant advantage.

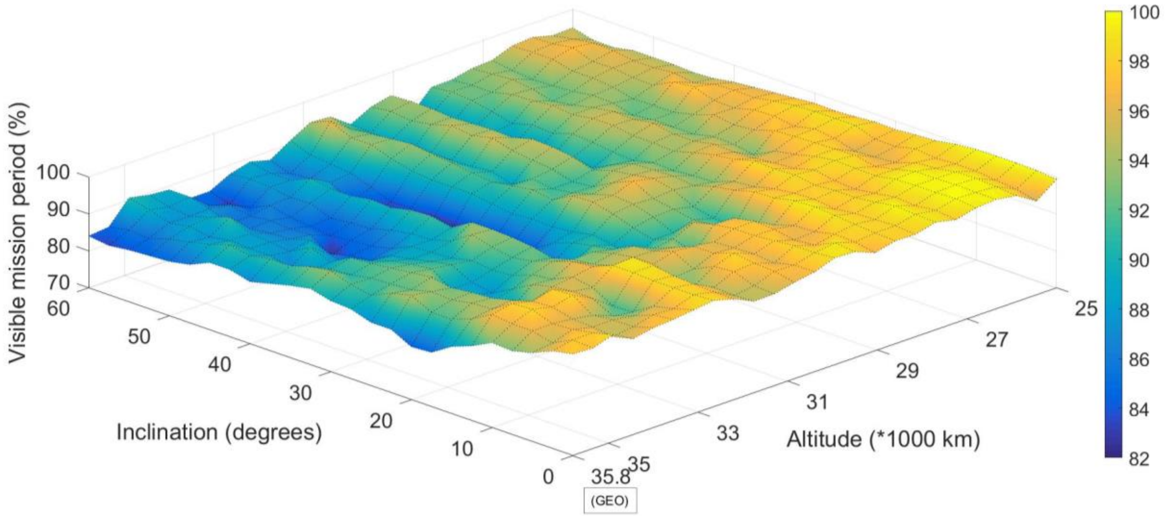


Figure 8: Multi-GNSS (GPS + GLO) visibility

Case 4: GPS + GALILEO

In this case GPS constellation is simulated along with ideal GALILEO configuration (since it is under development).

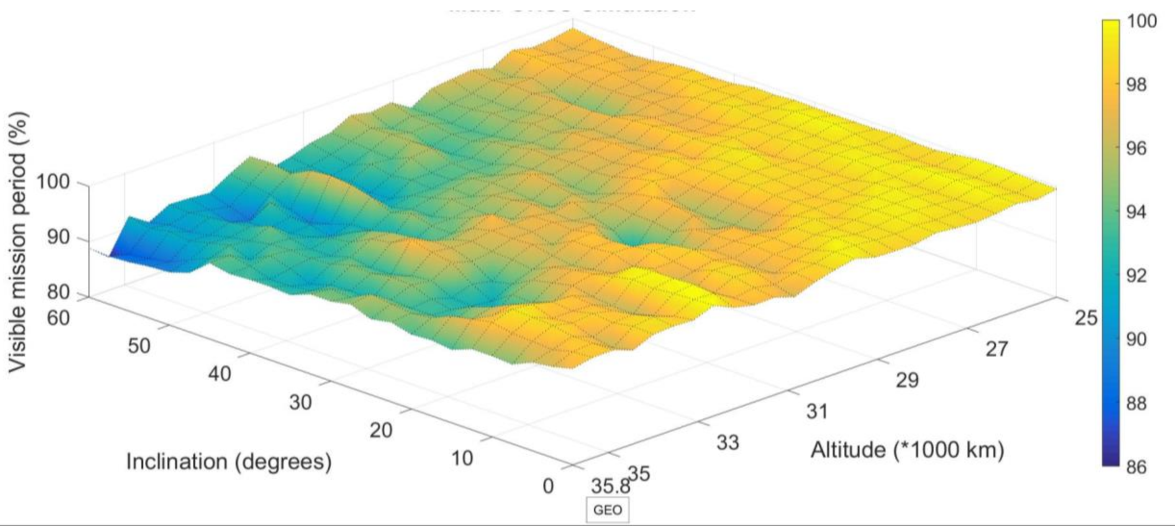


Figure 9: Multi-GNSS (GPS + GAL) visibility

The result shows that the visibility is increased as expected because the GALILEO orbits being at higher altitude and with the same half-beam width angle as GLONASS it covers a much larger area and in turn improves the GNSS signal availability. In Figure 9, the satellite availability reach above 86% at higher altitudes and inclination combinations and achieved near saturation (near 100%) visibilities at lower altitude/inclination orbit combinations.

Case 5: GPS + BEIDOU

In this case, we simulated GPS constellation along with an ideal configuration of BEIDOU constellation. As, BEIDOU also contains MEO, GEO and IGSO satellites, we experience a similar synodic period difficulty as in case 1 and 2. So, we carried out a separate simulation for geostationary altitude and plotted it in Figure 11. Even though BEIDOU MEO constellation orbits are below Galileo, the wider beam width angle enables much improved visibility over all the above cases. As shown in Figure 10, this configuration offers saturation coverage at lower altitude/inclinations and improved coverage at higher altitudes; at geostationary altitude (considering higher inclinations) the average percentage of availability equals nearly 86%.

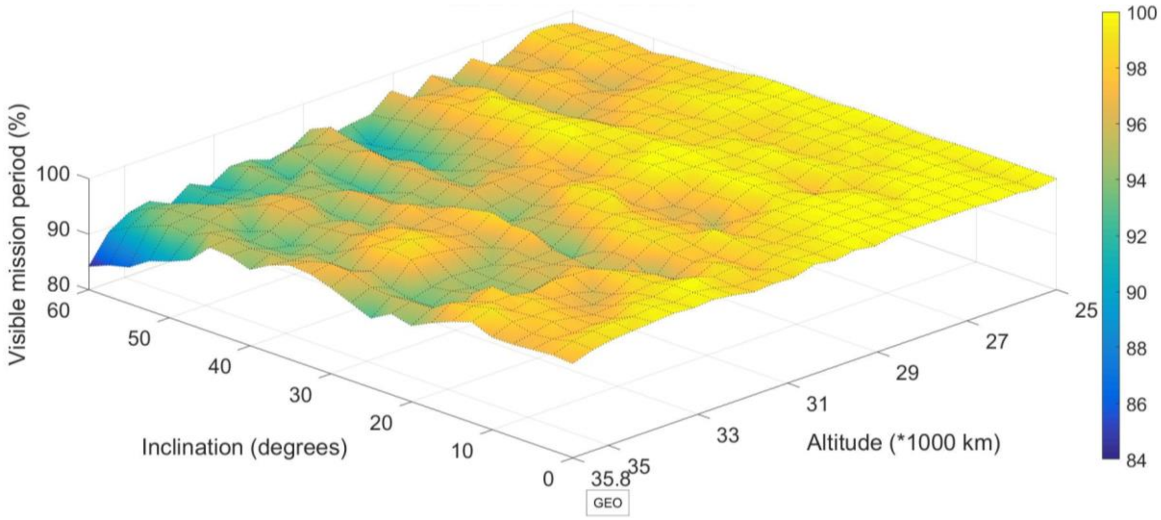


Figure 10: Multi-GNSS (GPS + BEI) visibility

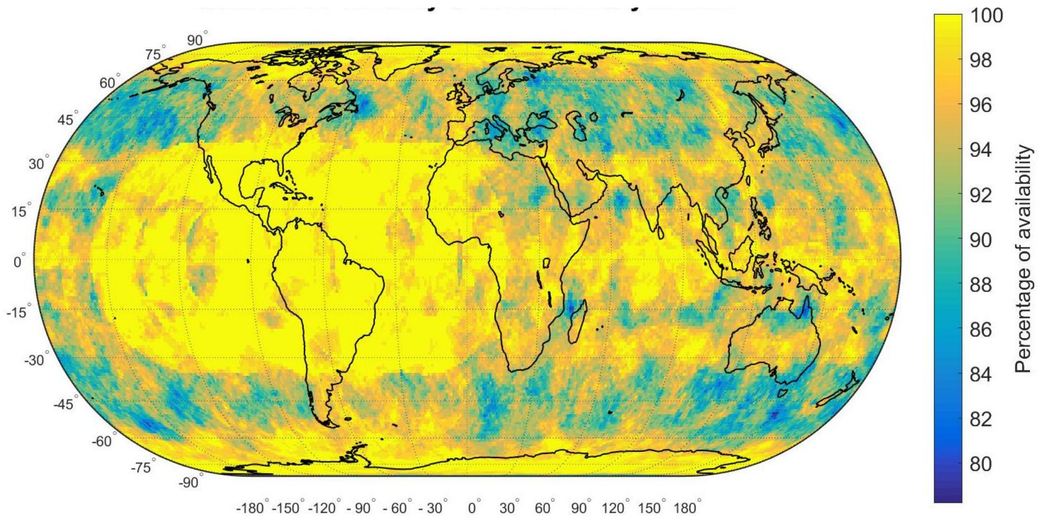


Figure 11: Multi-GNSS (GPS + BEI) visibility at geostationary altitude

5. CONCLUSIONS

This paper presents an assessment of multi-GNSS service in the space service volume. Multi-GNSS availability is studied based on three main parameters: antenna pattern (transmitting and receiving antennas), synodic period (between user and GNSS), and user orbital parameters. The simulations are performed for combinations of user orbital altitude and inclination and repeated for specific cases of multi-GNSS combinations. The results suggest that the combination of GPS, GLONASS, SBAS and QZSS offers maximum chances of positioning in Space Service Volume. It is also evident that all combinations offer near 100% visibility at lower altitudes (25~30,000 km), while the availability at higher altitudes (31~36,000 km), can be classified into lower inclinations (with 5~6% variation) and higher inclinations (with 70 ~ 90% variation). This suggests that the number of GNSS signals available over the limb of earth is sensitive to the GNSS orbit altitude and antenna half beam width angles.

Multi-GNSS based system will help to attain robust navigation performance in the space service volume. This ensures low mission operation cost and increased spacecraft autonomy. It also opens opportunities for low cost science missions targeting high earth orbits, formation flying operations, transfer orbit scenarios and future exploration missions. Future multi-GNSS receivers should implement effective weak signal acquisition and tracking, and a novel algorithm for the satellite selection. Also SSV-based missions must include better on-board orbital models and navigational filters to overcome any GNSS outage.

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