

Analysis of Multi-GNSS Signal Visibility Throughout a Representative Ballistic Lunar Transfer Scenario

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Abstract

The increasing volume of space missions expected over the coming decades will drive demand for autonomous navigation methods that can reduce reliance on terrestrial tracking networks. Several research efforts have shown that global navigation satellite systems (GNSSs) can be used to navigate Earth-orbiting spacecraft at altitudes well beyond the GNSS constellations themselves and show great promise as a means of autonomous navigation for spacecraft in cislunar space and at the Moon. This work analyzes the GNSS signal visibility achievable by a high-sensitivity receiver throughout a ballistic lunar transfer (BLT), a highly efficient lunar transfer trajectory in which spacecraft fly to a maximum altitude of approximately four times the Earth–Moon distance over the course of roughly four months. The multi-GNSS signal visibility in the L1 and L5 bands across all currently operational constellations is analyzed throughout the BLT flown by NASA's Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission. Publicly available GNSS transmit antenna pattern data from the Global Positioning System, Galileo, BeiDou Navigation Satellite System, and Quasi-Zenith Satellite System are used.

Keywords

BLT, GNSS antenna patterns, GNSS simulation, high-altitude GNSS, lunar navigation, multi-GNSS

1 | INTRODUCTION

The coming decades are expected to see a substantial increase in the number of missions to the Moon and beyond (Cohen et al., 2021; Potter, 2025). This expected increase has inspired numerous research efforts to identify low-cost methods for autonomous navigation of spacecraft that can reduce the amount of ground-based tracking required by systems such as the National Aeronautics and Space Administration's (NASA) Deep Space Network (DSN). Two-way radiometric range and Doppler data have long been the predominant means for navigating spacecraft in deep space. Ground networks such as the DSN typically record these data over a span of hours and post-process them on the ground to estimate the trajectory of a spacecraft. The DSN and other similar ground tracking systems are currently used to operate numerous missions in deep space and at the Moon. The

cost of utilizing these systems can be prohibitive because of the need for observations to be scheduled on a limited number of ground stations, which are routinely oversubscribed (Foust, 2023; Johnston, 2020). Autonomous or semi-autonomous navigation methods that can reduce the amount of ground tracking needed to meet mission navigation requirements are highly beneficial and can serve to reduce the operational complexity and cost of deep space navigation (Turan et al., 2022).

1.1 | Background and Motivation

Several previous and ongoing research efforts have demonstrated the viability of autonomous navigation at and beyond geostationary orbit (GEO) altitudes using Earth-centric global navigation satellite systems (GNSSs) (Ashman et al., 2018; Bauer et al., 1998; Braasch & Uijt de Haag, 2006; Delépaut et al., 2020). NASA's Magnetic Multiscale (MMS) mission has achieved operational use of the Global Positioning System (GPS) at a distance of 29 Earth radii (RE) ($1 \text{ RE} \approx 6378.137 \text{ km}$), nearly half the distance to the Moon, using NASA's high-heritage Navigator receiver (Parker et al., 2022; Winternitz et al., 2017), which is capable of signal acquisition at a carrier-to-noise-density ratio (C/N_0) as low as 25 dB-Hz. A case study comparing DSN- and GPS-based navigation for NASA's planned lunar Gateway station (Winternitz et al., 2019) suggested that Navigator could provide autonomous navigation capability that meets or exceeds the performance of the DSN for the Gateway's near-rectilinear halo orbit (NRHO). These encouraging results have inspired projects such as the Lunar GNSS Receiver Experiment (LuGRE), which recently acquired GPS and Galileo signals in lunar orbit and on the surface of the Moon (Schauer, 2025) using a QN400 GPS/Galileo receiver developed by Qascom (Parker et al., 2022).

The use of GNSS to support the operation of lunar relay satellites that will provide dedicated lunar position, navigation, and timing (PNT) and communications services has also been investigated (Ashman et al., 2024; Bhamidipati et al., 2023; Small et al., 2022). NASA's Lunar Communications Relay and Navigation Systems (LCRNS) (NASA Goddard Space Flight Center, 2022), the European Space Agency's (ESA) Moonlight (Cozzens, 2021), and Japan Aerospace Exploration Agency's Lunar Navigation Satellite System (Khalil, 2024) are a few examples of such systems currently under development that are likely to leverage GNSS signals from Earth for real-time navigation and timing. The Lunar Pathfinder mission under development by ESA plans to utilize a NaviMoon GPS/Galileo receiver designed by SpacePNT (Pultarova, 2022), purpose-built for lunar operation with a tracking threshold as low as 15 dB-Hz (SpacePNT & European Engineering and Consultancy, 2024). Alongside NaviMoon and LuGRE, NASA's NavCube3-mini (NC3m) GNSS receiver (a modernized descendant of the Navigator receiver) is under continued development to add new signal types and improve sensitivity to support future lunar missions (Hassouneh et al., 2023; Petrick et al., 2015).

Recent studies indicate promising navigation performance using single/dual-constellation GNSS receivers for lunar applications. Iiyama et al. (2024) showed that by leveraging time-differenced carrier phase (TDCP) measurements in addition to pseudorange measurements, a GPS-only receiver in an elliptical lunar frozen orbit with a 15-dB-Hz acquisition/tracking threshold alone can nearly meet the strict signal-in-space error (SISE) requirements of 3σ position error $\leq 13.43 \text{ m}$ and 3σ velocity error (over a 10-s interval) $\leq 1.2 \text{ mm/s}$ put forth in the LCRNS requirements document (NASA Goddard Space Flight Center, 2022) despite dilution of precision (DOP) values > 1000 . Such favorable predictions of the capabilities

of GNSS receivers in lunar orbit further suggest that GNSSs could support missions operating beyond lunar distances.

A previous publication by the authors (Peters et al., 2023) identified ballistic lunar transfers (BLTs) as a potential use case for GNSS beyond lunar distance. BLTs are low-energy lunar transfers that span 2–4 months and reach a maximum altitude of 1.5–2 million km—roughly 4–5 times the distance of the Moon (Parker & Anderson, 2013)—making them an ideal case study for the use of GNSS beyond lunar distance. The key advantage of a BLT is efficiency, reducing the total fuel spent by the spacecraft to insert into its final orbit. In 2021, NASA's Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission used a BLT to enter an NRHO (Cheetham, 2021) over the course of approximately 4 months. In the case of CAPSTONE's transfer, the deterministic spacecraft ΔV needed for the BLT was only 20–60 m/s whereas a direct transfer would have required 350–550 m/s (Gardner et al., 2022). This advantage makes BLTs potentially likely candidates for the deployment of dedicated lunar assets in the future, as they can serve to extend the operational lifetime of lunar satellites by conserving their fuel. Additionally, relay satellites traversing BLTs equipped with high-sensitivity GNSS receivers for operation in lunar orbit could serve as ideal platforms for the evaluation of these capabilities.

1.2 | GNSS Receivers for Lunar Applications

The successful use of GNSS-based navigation by high-altitude space users has largely been driven by the development of high-sensitivity receiver architectures capable of acquiring and tracking the weak signals received from the sidelobes of GNSS antenna patterns (Winternitz et al., 2017). Given the Earth-pointing antenna patterns of GNSS satellites, receivers above these constellations must track either the small portion of the main lobe signals that cross the limb of the Earth or the weaker sidelobe signals transmitted at higher antenna off-boresight angles. Although the higher gain of the main lobe signals provides a clear advantage in terms of link margin for acquisition and tracking, these signals are generally less often in view of high-altitude users when compared with sidelobe signals. GNSS receivers commonly have separate and distinct acquisition, tracking, and data demodulation thresholds for a given signal (Bastide et al., 2002). The acquisition threshold is defined as the minimum C/N_0 needed to detect a signal with a certain false alarm probability P_{fa} and detection probability P_d . The acquisition threshold is generally higher than the tracking threshold. The data demodulation threshold is typically defined as the minimum C/N_0 needed to extract the navigation message bits with a defined error probability (Anghileri et al., 2013). Data demodulation thresholds vary by signal type as a function of symbol rate and a signal's error correction code performance.

Regarding acquisition thresholds achievable by high-sensitivity spaceborne GNSS receivers, several assumptions can be made based on current receiver development efforts for high-altitude GNSS, theorized performance for spaceborne receivers in literature, and the performance of high-sensitivity terrestrial GNSS receivers. In the case of NASA's NC3m receiver and the LuGRE receiver, unaided cold-start acquisition thresholds on the order of 23 dB-Hz are targeted for GPS and Galileo signals (Ashman et al., 2024; Hassouneh et al., 2023; Konitzer et al., 2022), although test results indicate that NC3m can track as low as 20 dB-Hz. This tracking is achieved without any coupling with a navigation filter or other sensors and without the use of any external aiding data or multi-hypothesis

acquisition/tracking, which could enable very long coherent integration across symbol boundaries. Sciacca et al. (2025) and Song et al. (2025) performed detailed and comprehensive analyses of multi-GNSS acquisition in a GEO using assumptions based on the stated acquisition and tracking thresholds of LuGRE, highlighting several challenges to achieving these thresholds across various signal types and providing valuable commentary on operational considerations.

Blunt et al. (2016) described a spaceborne receiver architecture (Spaceborne Autonomous Navigation based on GNSS (SANAG)) that possesses an acquisition engine capable of unaided acquisition of GPS L1 C/A at 18 dB-Hz and navigation filter-aided acquisition at 15 dB-Hz, with a tracking sensitivity as low as 12 dB-Hz. In its filter-aided mode, the receiver uses its converged filter solution to apply time, frequency, and frequency-rate aiding to perform long coherent integrations (440 ms) within the time-of-week word of the GPS navigation message, where several consecutive bits can be reliably predicted. To support this performance, the oscillator and navigation filter-aiding should support a maximum residual error on the Doppler rate of 2.6 Hz/s. In its unaided mode, the receiver uses a more traditional approach, where multiple short coherent integrations are non-coherently combined to achieve the 18-dB-Hz acquisition threshold. The NaviMoon GPS/Galileo receiver (SpacePNT & European Engineering and Consultancy, 2024) has evolved from this research effort and is currently under development to support future lunar missions.

Musumeci et al. (2016) described the design of a high-sensitivity GPS/Galileo receiver for lunar missions that is capable of acquisition as low as 8 dB-Hz. This threshold is achieved through navigation filter-aiding and long coherent integrations enabled by the assumption that the unknown symbols on each navigation signal are provided by a separate aiding source. This receiver design was intended to support navigation during the dynamically challenging lunar descent and landing phases of a mission, where Doppler shifts on the order of 25 kHz and Doppler rates on the order of 17 Hz/s are expected. The residual navigation filter errors were bounded to 0.0245 Hz and 4×10^{-3} Hz/s for Doppler and Doppler rate, respectively, in order to achieve the 8-dB-Hz acquisition threshold. Channel acquisition at 8 dB-Hz was demonstrated for Galileo E1C using a coherent integration time of 1.128 s. Table 1 summarizes the key features of the high-sensitivity spaceborne GNSS receivers discussed above.

Soloviev et al. (2008) demonstrated 15-dB-Hz re-acquisition and tracking of GPS L1 C/A signals using a 1.2-s coherent integration time in a real-life aircraft flight test environment. This was achieved via ultra-tight coupling with a low-cost inertial measurement unit and an energy-based bit estimation algorithm that searches for the combination of bits that maximizes signal energy over the integration period. The use of such algorithms can enable bit wipe-off for long coherent integrations without the use of external aiding data, although the use of these methods may be computationally complex, particularly for signals with higher symbol rates, and has not been previously demonstrated in a spaceborne receiver. This receiver used an oven-controlled crystal oscillator with short-term (1-s) stability on the order of 10^{-11} s/s.

1.3 | Evaluation of GNSS Signal Visibility

Within the high-altitude GNSS context, signal availability can be characterized through different visibility metrics: geometric visibility (line-of-sight visibility

TABLE 1
Summary of High-Sensitivity Spaceborne GPS/Galileo Receiver Architectures

Receiver	Acquisition/Tracking Thresholds	Advantages	Limitations
NC3m & LuGRE	Acq: 23 dB-Hz Track: 20 dB-Hz	Flight heritage; no external aiding required	Higher acquisition threshold compared with aided architectures
SANAG	Unaided acq: 18 dB-Hz Filter-aided acq: 15 dB-Hz Track: 12 dB-Hz	Dual-mode operation (aided/unaided)	Filter-aided mode requires converged navigation solution; no flight heritage
Lunar Mission Receiver (Musumeci et al., 2016)	Acq/Track: 8 dB-Hz	Lowest acquisition threshold	Requires external aiding source for unknown navigation symbols; strict filter error bounds (0.0245 Hz, 4×10^{-3} Hz/s); No flight heritage

between satellite and receiver under free-space propagation), radiometric visibility (signal availability above a given C/N_0 threshold), and autonomous service availability (ability to decode navigation messages for autonomous position, velocity, and time (PVT) determination, which is ultimately tied to the demodulation threshold of a given signal). Geometric visibility and radiometric visibility are relatively straightforward to define: the former relies on line-of-sight visibility between the receiver and transmitter, and the latter can be taken as the receiver acquisition/tracking threshold for a given signal. Autonomous service availability is more complex to define, with no widely accepted signal C/N_0 thresholds defined in the GNSS literature. Anghileri et al. (2013) provided a useful framework for defining data message performance thresholds for GPS and Galileo signals based on the necessary C/N_0 required to achieve a clock and ephemeris data (CED) message error rate of 10^{-2} ; however, acceptable error rates may vary by mission and application. The present work focuses on radiometric visibility as the primary metric of interest.

Delépaut et al. (2020) characterized the radiometric visibility and autonomous service availability of GPS and Galileo for a receiver in an NRHO about the Moon using accurate transmit antenna patterns for GPS and Galileo space vehicles (SVs). Their analysis considered a threshold of 15 dB-Hz for radiometric visibility and found that less than 20% of received signals were from main lobe transmissions for both the L1 and L5 bands. Navigator, LuGRE, and NaviMoon are all either single- or dual-constellation receivers that use only GPS and/or Galileo and are designed to be capable of tracking the weaker sidelobe signals from these systems. Studies that consider the potential of a fully interoperable GNSS space service volume (SSV), such as those conducted by Enderle et al. (2018), Parker et al. (2018), and Ugazio et al. (2020), have shown strong visibility of main lobe signals when combining all available constellations, with four or more signals visible nearly 100% of the time throughout the high-altitude SSV. Naturally, receivers capable of tracking signals received from sidelobes (roughly 10 dB below the gain of the main lobes) at lunar distances could be capable of tracking main lobe signals at considerably greater distances.

1.4 | Objectives and Contributions

This work focuses on BLTs as a potential frontier for GNSS-assisted navigation. A previous work by the authors (Peters et al., 2023) developed a basic radiometric visibility simulation with the purpose of broadly surveying potentially viable mission scenarios for the use of GNSSs beyond lunar distance. This work builds upon the previous publication by providing a more detailed analysis of the BLT mission scenario. The simulation has been improved by including all currently available antenna pattern data for all GNSS constellations, performing Doppler and DOP analysis throughout the trajectory, and improving the modeling accuracy of parameters such as SV transmit power and attitude. The objective of this work is to provide a detailed characterization of the radiometric visibility of GNSS signals in BLT trajectories in the “L1 band” (L1/E1/B1) and “L5 band” (L5/E5a/L3/B2a), with a focus on acquisition thresholds, while quantifying the benefits of multi-constellation integration and analyzing parameters of interest for receiver design.

The key contributions of this work are summarized as follows:

- A software simulation is developed to model GNSS signal visibility, making use of all currently available GNSS antenna pattern data (for GPS, Galileo, BeiDou, and Quasi-Zenith Satellite System (QZSS) satellites) and inferred patterns for systems for which data have not been made publicly available (Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) and Navigation with Indian Constellation (NavIC)).
- The radiometric visibility of GNSS signals is quantified in the L1 and L5 bands using the BLT trajectory flown by the CAPSTONE mission as a case study, assessing multiple receiver acquisition thresholds with a notional radiofrequency (RF) front-end and receiving antenna pattern.

The remainder of this article is structured as follows: Section 2 describes the simulation design and methodology used to analyze GNSS visibility, including the trajectory of the CAPSTONE mission, GNSS constellation configurations, GNSS transmit antenna pattern data, and link budget assumptions. Section 3 presents the results of the simulation, which indicate significant radiometric signal visibility even at the apogee of the BLT, with multi-GNSS configurations showing particular promise for deep space navigation. Section 4 concludes with a discussion of the implications of these findings for future lunar missions and deep space navigation.

2 | SIMULATION DESIGN

This work conducts a GNSS visibility analysis using a simulation developed in MATLAB. The actual operational configurations of each GNSS constellation during the simulated time period are used. The analysis accounts for new SVs that enter service during the course of the simulation. Table 2 summarizes the configurations of the constellations at a representative point during the simulation. The GNSS satellite states are propagated using multi-GNSS broadcast ephemerides (Montenbruck & Steigenberger, 2022). A lookup table was created to map each specific satellite to its relevant attributes, such as which signals are transmitted by a particular satellite and its block/type. In line with past analyses of GNSS availability in the high-altitude SSV (Enderle et al., 2018; Parker et al., 2018), only

TABLE 2

GNSS Constellation Configurations (Considering Only Usable SVs) as of Late August 2024
MEO, GEO, IGSO, and QZO refer to medium Earth orbit, geostationary orbit, inclined geosynchronous orbit, and quasi-zenith orbit, respectively.

System	Num. of SVs per signal	Num. of SVs per orbit	Semi-major axis (km)	Inclination (°)
GPS	L1: 31 L5: 17	MEO: 31	26560	55
GLONASS	L1: 24 L3: 9	MEO: 24	25510	64.8
Galileo	E1: 25 E5a: 25	MEO: 25	29600	56
BDS	B1I: 46 B2a: 28	MEO: 28	27906	55
		GEO: 8	42164	0
		IGSO: 10	42164	55
QZSS	L1: 4	QZO: 3	42164	43
	L5: 4	GEO: 1	42164	0
NavIC	L5: 4	GEO: 2	42164	0
		IGSO: 2	42164	29

signals in the L1 and L5 bands are considered. The number of SVs transmitting in each band is also shown in Table 2 and is consistent with the actual operational constellations throughout the simulated time period. Table 3 summarizes the transmit power and antenna patterns of each constellation used in the simulation. For each system, one signal from each band is modeled in the simulation. The signal chosen for each system/band is selected based on which is the most common open signal broadcast by SVs in that band (e.g., GPS L1 C/A is currently broadcast by more SVs than L1C).

First, the simulation determines which GNSS satellites are geometrically visible to the user at each epoch using the methods described in Section 2.1. For each visible satellite, the effective isotropic radiated power (EIRP) in the direction of the user is computed as described in Section 2.2. The EIRP, receiving antenna gain, and total system noise temperature of the receiver are then used to estimate the C/N_0 . All assumptions made with regard to the user and the overall link budget are captured in Section 2.3. The trajectory of the CAPSTONE mission as used by the simulation is detailed in Section 2.4.

2.1 | Computing Geometric Visibility

After propagating the state vectors of both the user and the GNSS satellites over a time span, the simulation then determines which GNSS satellites are geometrically visible to the user at each time step. To do this, the simulation iterates over each GNSS SV and computes the coordinates of the user in a coordinate frame centered on the SV. This requires a knowledge of the SV orientation relative to the Earth, which changes over time as the SV maintains attitude control throughout its orbit to keep its transmit antenna pointed at the Earth and its solar panels pointed toward the Sun in accordance with its attitude control laws. Generally, the attitude of any GNSS SV can be described at a given epoch using its current body-to-Sun vector and its position vector relative to the center of the Earth, which together define the yaw-steering frame (YSF). The implementation of the YSF used in this

TABLE 3

GNSS RF Parameters for the Simulation

Signals for each system are chosen based on which signal is most commonly broadcast in each band. P_t is computed in each case using a reverse link budget calculation based on the minimum received power specifications of each signal.

Constellation	Signal	Frequency (MHz)	Antenna Pattern Data Source	P_t (dBW)
GPS	L1 C/A	1575.42	USCG NavCen ¹	BIIR: 12.6
				BIIRM: 12.9
				BIIF: 12.6
				BIII: 11.9
GPS	L5-Q	1176.45	USCG NavCen ²	BIIF: 11.4
				BIII: 12.3
Galileo	E1C	1575.42	GRAP	N/A ³
Galileo	E5a-Q	1176.45	GRAP	N/A ³
BDS MEO	B1I	1561.098	IAMCAS	N/A ³
BDS GEO-IGSO	B1I	1561.098	IAMCAS	N/A ³
BDS MEO	B2a-pilot	1176.45	IAMCAS	N/A ³
BDS GEO-IGSO	B2a-pilot	1176.45	IAMCAS	N/A ³
GLONASS	L1	1605.375	Offset GPS BIII L1 ⁴ (+2.5°)	7.1
GLONASS	L3	1201	Offset GPS BIII L5 ⁴ (+8°)	5.2 ⁵
QZSS	L1 C/A	1575.42	NSPS	13.9
QZSS	L5-Q	1176.45	NSPS	11.2
NavIC	L5	1176.45	Offset GPS BIII L5 ⁴ (−10°)	15.2

¹ NASA ACE data are used for BIIF L1 patterns and supplemented by data available through the USCG Navigation Center.

² BIII L5 patterns are used for BIIF L5.

³ EIRP patterns are available, so P_t is not needed. For these signals, the total EIRP on a given frequency is reduced to represent the power of the individual signal component shown in the table.

⁴ Antenna pattern data are not available, so elevation-offset GPS BIII patterns are used. The offset angle is defined in Equation (3).

⁵ GLONASS L3 currently has no minimum received power specification, so P_t was computed by assuming the same value as L1.

work is summarized in Appendix A. The position of the user is then expressed in the YSF of each GNSS satellite to determine its azimuth and elevation angles relative to the SV.

Geometric visibility for the case in which the user is above the GNSS constellations is determined by two conditions:

1. The elevation angle of the user in the YSF of the GNSS SV is greater than 10° (to avoid using signals that interact with the spacecraft body).
2. The line of sight from the SV to the user is not occluded by the Earth.

To determine whether a signal is occluded by the Earth, the angle α from the satellite's local horizontal to the edge of the Earth is computed:

$$\alpha = \cos^{-1} \left(\frac{R_E + h_{\text{mask}}}{|\mathbf{r}|} \right) \quad (1)$$

where $R_E = 6378.137$ km is the equatorial radius of the Earth (National Geospatial-Intelligence Agency, 2014) and h_{mask} is an atmospheric height mask. Here, we use $h_{\text{mask}} = 1000$ km, which corresponds to the approximate height of Earth's protonosphere (Klobuchar, 1996). This ionospheric mask height is commonly adopted in high-altitude GNSS applications (Estrada et al., 2024). If the elevation angle of the user in the YSF is greater than α , then the signal is considered to be occluded by the Earth. The chosen value for h_{mask} ensures that signals passing through large portions of the ionosphere will not be considered visible. It is also assumed that the receiving antenna is always pointed toward the Earth with an antenna pattern that fully covers all GNSS satellites; thus, no additional considerations are made regarding the orientation of the user. The user's azimuth angle ϕ , elevation angle θ , and distance from the GNSS satellite R expressed in the YSF of each GNSS satellite visible to the user at each epoch are stored and later used to compute the received power.

2.2 | GNSS Transmit Antenna Patterns

The simulation must next determine the EIRP of each geometrically visible GNSS satellite in the direction of the user. The EIRP can be computed as the sum of the transmit antenna gain $G_t(\phi, \theta)$ and the nominal transmit power P_t of the satellite:

$$\text{EIRP}(\phi, \theta) = P_t + G_t(\phi, \theta) \quad (2)$$

Table 3 summarizes the data used for each constellation in determining the EIRP of each signal. The simulation uses publicly available gain pattern data for GPS and QZSS satellites and EIRP data for Galileo and BeiDou. For each SV type with antenna pattern data available, the mean gain or EIRP pattern for the type was used rather than using the individual patterns for each SV. This approach was used for the sake of consistency and simplicity, as the individual patterns for each SV are not always available. For all SVs, it is assumed that the YSF and antenna frame are identical. For systems where EIRP patterns are not available, the nominal transmit power P_t was computed using the minimum received power specifications defined in the interface control document for each system, following the specific conventions described by each GNSS service provider (Cabinet Office, 2024; ISRO Satellite Centre, 2017; Russian Institute of Space Device Engineering, 2008; United States Coast Guard Navigation Center, 2022a, 2022b). For each signal, P_t was computed using the mean gain pattern assigned to that specific SV/signal such that the overall EIRP is consistent with the associated minimum received power specification. Note that throughout the following descriptions of antenna pattern data used, frequent reference will be made to the “off-boresight” angle, $\theta_{\text{OB}} = 90^\circ - \theta$ (where θ is the elevation angle with respect to the xy -plane of the YSF), which is commonly used when describing GNSS antenna patterns. Figure 1 illustrates the definition of θ_{OB} . The boresight direction is defined as the $+z$ axis (pointing toward Earth), and θ_{OB} is defined with respect to the $+z$ axis.

For GPS, full antenna pattern data for all currently active SV blocks are available through the U.S. Coast Guard (USCG) Navigation Center website (United States Coast Guard Navigation Center, n.d.). Figure 2 depicts the mean gain patterns for GPS BIII SVs used in the simulation and is intended to provide an intuitive visual reference for the shape of a representative GNSS transmit antenna pattern. For BIIF satellites, full patterns are available via the USCG NavCen, although they are only measured in increments of 45° in azimuth, which is insufficient to

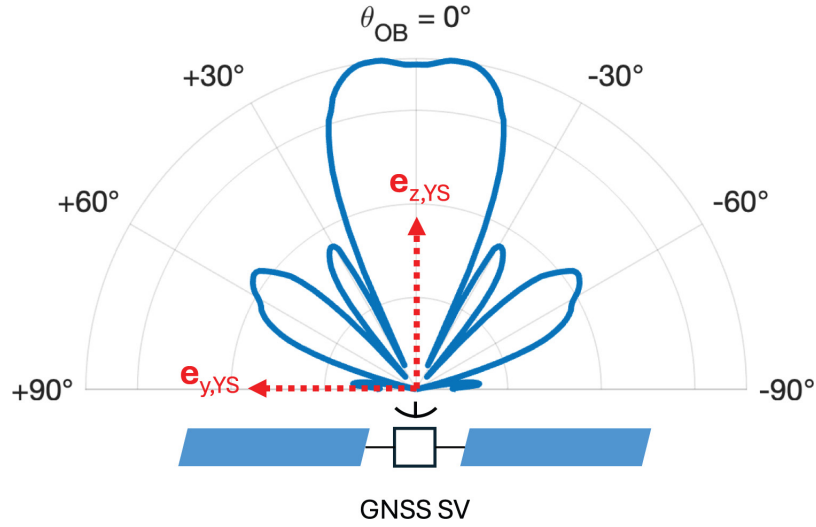


FIGURE 1 Illustration of the definition of θ_{OB} . The red overlaid axes represent the YSF, where $+z$ is the antenna boresight direction.

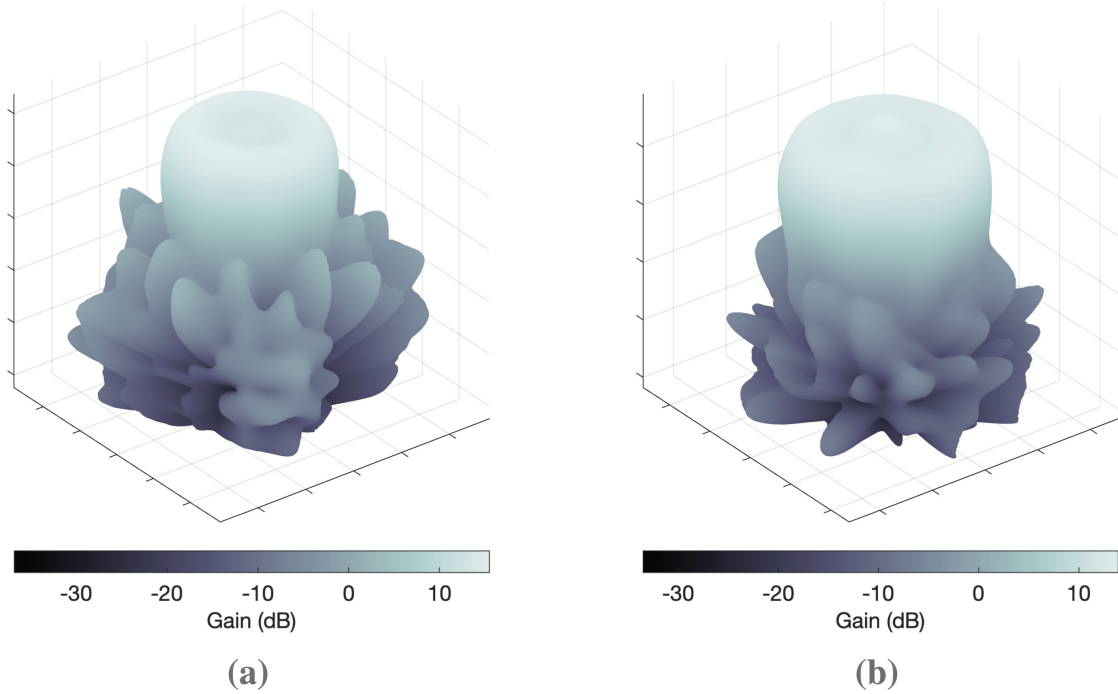


FIGURE 2 Mean GPS BIII antenna patterns: (a) BIII L1, (b) BIII L5

accurately interpolate across the full pattern. NASA's GPS Antenna Characterization Experiment (ACE) (Donaldson et al., 2020) provides higher-resolution data for BIIF L1 antenna patterns (in increments of 1° in both θ and ϕ), excluding the portion of patterns below off-boresight angles of 16° , which could not be accurately measured from a GEO platform. For this simulation, the low off-boresight angles missing in the ACE data set were filled in using BIIF data available through the USCG NavCen website. Azimuthal interpolation does not pose a significant error source for low off-boresight angles, as the patterns are nearly uniform across all azimuth angles within the main lobe. For BIIF L5 signals, which were not published in the NASA ACE data set, the simulation simply uses the BIII L5 pattern shown in Figure 2(b).

For GLONASS and NavIC satellites, the simulation uses GPS BIII antenna patterns, which are offset in elevation according to the difference in main beamwidths between each system and GPS, as specified in the United Nations Office for Outer Space Affairs Interoperable SSV booklet (United Nations Office for Outer Space Affairs, 2021). The difference in beamwidth is applied as an offset to the elevation angle of the GPS BIII antenna pattern of the corresponding frequency. The Interoperable SSV booklet defines the main beamwidth for each system in terms of reference off-boresight angles, such that the given angle (β) corresponds to half of the two-sided main beamwidth. Using these reference angles, the offset angle for each system is computed as follows:

$$\theta_{\text{offset}} = \beta_{[\text{GLO,NavIC}]} - \beta_{\text{GPS}} \quad (3)$$

For example, the main beamwidth angle given for GPS L1 is 23.5° , and for GLONASS L1, it is 26° . The offset angle θ_{offset} for GLONASS L1 is then 2.5° . Each elevation offset angle used by the simulation is provided in Table 3. Using this method, the gain directed at a given elevation angle θ is given by the following:

$$G_{\text{offset}}(\phi, \theta) = G_{\text{GPS}}(\phi, \theta + \theta_{\text{offset}}) \quad (4)$$

which simulates the effect of a wider or narrower antenna pattern, where negative values of θ_{offset} represent a pattern with a narrower main beamwidth than GPS and positive values represent a wider main beamwidth. Figure 3 depicts the offset pattern formed for NavIC L5 signals using this method. It must be acknowledged that this simplistic approach to offsetting the patterns in elevation is particularly likely to misrepresent the gain of the sidelobes, as the width of the main beam influences the gain of the sidelobes. A method similar to the one described here was applied by Delépaut et al. (2020), where GPS L5 patterns were simulated using GPS L1 patterns scaled to the wider beamwidth of L5. In their study, this approach was validated by applying the same scaling methodology to Galileo patterns and comparing against the true E5a patterns. The authors noted small inconsistencies between the approximated (scaled) pattern and the real pattern, particularly in the off-boresight angles and amplitudes of sidelobes, which were stated to have a small impact on their results.

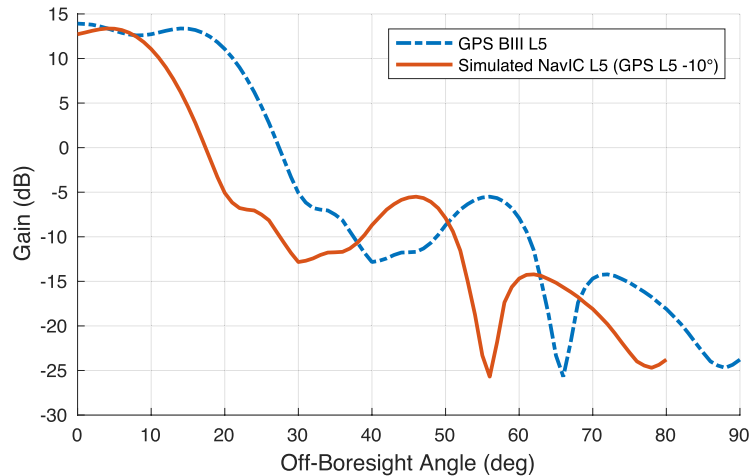


FIGURE 3 Approximation of NavIC L5 antenna pattern formed by offsetting GPS BIII L5 pattern in elevation by $\theta_{\text{offset}} = -10^\circ$, showing an azimuth = 0° cut

For Galileo, full EIRP patterns have been published by Menzione et al. (2024) and are provided to the public in a data set referred to as the Galileo Reference Antenna Patterns (GRAPs). The GRAP data are derived from all Galileo full-operational-capability SVs and are provided for each signal frequency in terms of the average, lower-bound, and upper-bound performance of the entire constellation. The average EIRP patterns for E1 and E5a are applied for all Galileo satellites in the simulation. The EIRP patterns for E1 and E5a represent the combined power of the in-phase data and quadrature pilot components of the signal. In each band, the power is split equally between the two components (European Union, 2023). As a conservative assumption, this simulation uses half of the total EIRP in each band (e.g., $\text{EIRP}_{\text{EIC}} = \text{EIRP}_{\text{EIBC}} - 3 \text{ dB}$), effectively assuming that the receiver only acquires/tracks the pilot component of the signal.

BeiDou-3 EIRP patterns were extracted from a study conducted by Lin et al. (2020) to analyze the use of BeiDou Navigation Satellite System (BDS) signals for high-altitude users. Lin et al. (2020) stated that the data used in their study were provided by the Innovation Academy for Microsatellites, Chinese Academy of Sciences (IAMCAS). As with the GRAP data, the BDS-3 EIRP patterns are defined in terms of the total power on each frequency. The B2a-pilot EIRP is given by subtracting 3 dB from the total B2a EIRP (China Satellite Navigation Office, 2017b). This simulation uses B1I as the reference L1-band signal for BDS instead of B1C owing to the higher number of satellites that broadcast this signal (46 for B1I versus 28 for B1C as of late August 2024). The B1I EIRP was estimated from the B1C EIRP using the difference between the minimum power specifications for B1C and B1I (−163 dBW for B1I, −159 dBW for B1C MEO, and −161 dBW for B1C IGSO) (China Satellite Navigation Office, 2017a, 2019). These adjusted EIRP patterns are used for all BDS satellites in the simulation (including BDS-2 satellites) owing to a lack of additional data.

Gain patterns for all active and planned QZSS satellites have been published by the Japanese National Space Policy Secretariat (NSPS) Cabinet Office (National Space Policy Secretariat, 2023). QZS-02 and QZS-04 are equipped with helical array transmit antennas, and all others use patch antennas (Nakajima & Yamamoto, 2024). Only four of the seven planned QZSS satellites are available (QZS-1R, 02, 03, 04) during the time period of this simulation. Published antenna pattern data for QZS-1R and QZS-03 are recorded only to 60° off-boresight, with all remaining patch-equipped satellites (05–07) measured to 90° off-boresight. The reference patterns used for QZS-1R and QZS-03 in the simulation are formed by averaging all patch-type patterns (QZS-1R, 03, 05–07) together and interpolating as with all other patterns. QZS-02 and QZS-04 are also measured to 90° off-boresight and are likewise averaged together and interpolated to form reference patterns for the helical-type antennas.

2.3 | Receiver Link Budget

At each epoch, the simulation iterates over every satellite with geometric visibility to the user and computes the received power and C/N_0 according to Equations (5) and (6) (Betz, 2017; Ward et al., 2017):

$$P_r = \text{EIRP}(\phi, \theta) + G_r + 20 \log_{10} \left(\frac{\lambda}{4\pi R} \right) \quad (5)$$

$$C/N_0 = P_r - 10 \log_{10}(kT_{\text{sys}}) \quad (6)$$

where the received power P_r in dBW is given by the sum of the EIRP directed at the user, the receiving antenna gain G_r , and the free-space path loss computed using the signal wavelength λ and the distance between the transmitter and receiver R , both in units of m. The receiving antenna is assumed to have a fixed gain of 16 dBi and a beamwidth wide enough to fully cover all GNSS satellites. This gain value was chosen because it matches the 16-dBi peak gain of the L1/L5-band antenna used by the LuGRE mission (Konitzer et al., 2022). The noise density, $N_0 = 10 \log_{10}(kT_{\text{sys}})$, is computed in units of dBW/Hz using the user's system noise temperature T_{sys} in K and Boltzmann's constant ($k = 1.38 \times 10^{-23}$ J/K).

T_{sys} is constant throughout the simulation and is defined as $T_{\text{sys}} = 290 \text{ K} \times 10^{\text{NF}/10-1} + T_{\text{ant}}$ (Ward et al., 2017), where the noise figure (NF) is assumed to be 1 dB and T_{ant} is assumed to be 100 K, resulting in a T_{sys} of 175 K. These assumptions are summarized in Table 4. As a point of reference, the total system noise temperature of the LuGRE receiver was determined through flight hardware testing to be 162 K (Konitzer et al., 2022), indicating that the assumptions applied in this simulation are reasonable. The effect of varying T_{sys} is mathematically equivalent to varying the receiver acquisition/tracking threshold using the mapping given in Figure 4.

In this simulation, the acquisition threshold is used as the primary metric to determine radiometric visibility. If the computed C/N_0 of a given signal is above the acquisition threshold, then that signal is considered to be radiometrically visible to the user. This assumption is made for simplicity, although it is conservative in that a receiver with a given acquisition threshold will generally be able to track signals at lower C/N_0 values.

In Section 3, the radiometric visibility is shown over a range of acquisition thresholds from 12 dB-Hz to 23 dB-Hz. Sections 3.1 and 3.2 conduct more detailed analyses around the most distant portion of the simulated trajectory, with a focus on acquisition thresholds of 15 dB-Hz and 23 dB-Hz, respectively, as these values are representative of the performance targets of current lunar GNSS receiver development efforts.

2.4 | User Trajectory

Ephemeris data for the NASA CAPSTONE mission were retrieved from the NASA Horizons System (Jet Propulsion Laboratory, 2023) for the time span of July 1, 2022, through December 1, 2022. CAPSTONE launched on June 28, 2022, and used a BLT (depicted in Figure 5) to enter an NRHO on November 13, 2022. Apogee was reached on August 26, 2022, at a maximum altitude of 1,531,949 km. The Earth-centered coordinates corresponding to the CAPSTONE trajectory were edited to be exactly 2 years later than their original epochs to conform with the time span used for simulating the GNSS constellations. Figure 5 depicts the simulated

TABLE 4
User RF Parameters

Parameter	Value
Noise figure	1 dB
Antenna noise temperature	100 K
System noise temperature	175 K
Antenna gain	16 dBi

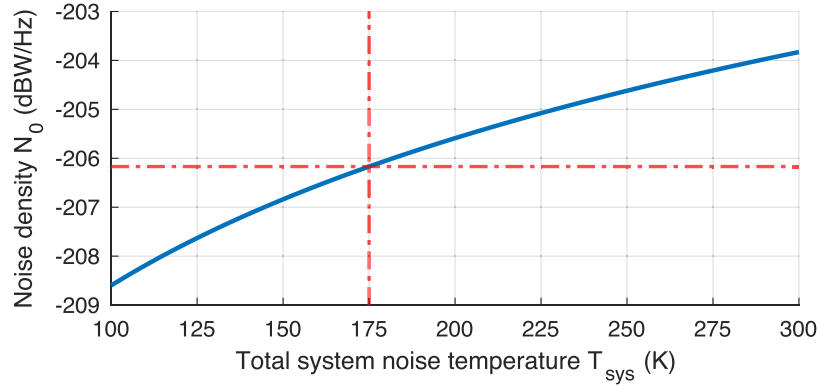


FIGURE 4 Noise density N_0 as a function of system noise temperature T_{sys} . The red dashed lines highlight the assumed $T_{\text{sys}} = 175$ K used in this simulation, which corresponds to $N_0 = -206.2$ dBW/Hz

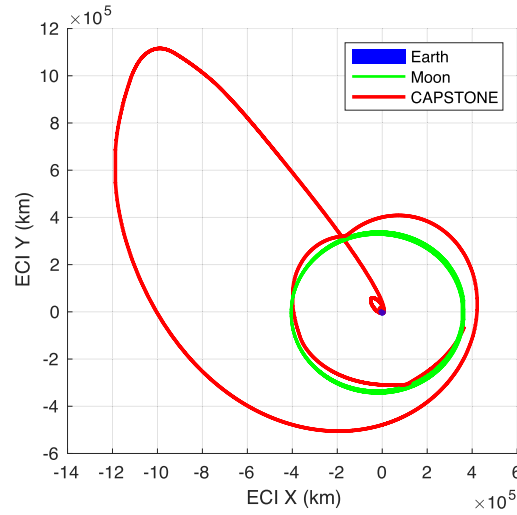


FIGURE 5 CAPSTONE's BLT trajectory viewed in an Earth-centered inertial (ECI) frame. The time span is July 1, 2024 (00:00), to December 1, 2024 (00:00) UTC.

trajectory from July 1, 2024 (shortly after launch), through December 1, 2024 (after the first few orbits in NRHO).

3 | RESULTS AND ANALYSIS

The trajectory shown in Figure 5 was simulated over its full duration, July 1, 2024 (00:00), through December 1, 2024 (00:00) Coordinated Universal Time (UTC), at 5-s time steps. Figure 6 shows the number of radiometrically visible signals above a given acquisition threshold from unique SVs. Figure 6 includes a range of acquisition thresholds from 12 dB-Hz to 23 dB-Hz to provide a more complete picture of radiometric visibility trends. The user altitude throughout the trajectory is overlaid in blue, and its scale is shown on the right-hand axis. Table 5 summarizes the mean number of visible signals as well as the minimum number of signals visible at least 68% and 95% of the time for each acquisition threshold, with a focus on two regions of the overall trajectory: one week in the NRHO toward the end of the trajectory (from hours 3000 to 3168) and one week surrounding the apogee of the BLT (from hours 1272 to 1440). The NRHO region

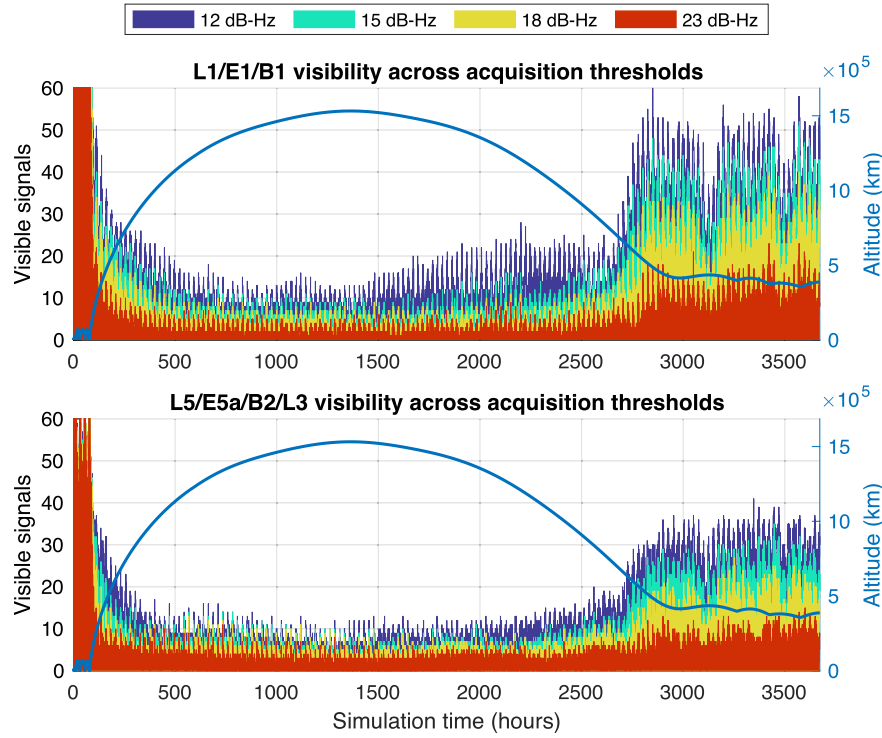


FIGURE 6 Number of signals above a given acquisition threshold during the entire trajectory, July 1, 2024, through December 1, 2024

The user altitude throughout this period is overlaid (in blue) and shown on the right-hand axis.

is included to illustrate the expected radiometric visibility once the spacecraft reaches its final orbit. The BLT apogee region is included because it is the furthest extent of the trajectory from the Earth. It is expected that the results in this region will be indicative of the worst radiometric visibility encountered throughout the entire mission.

Figure 7 shows the DOP throughout the full trajectory for all signals visible in the L1 band, assuming a radiometric visibility threshold of 15 dB-Hz. The DOP is computed with the assumption that the receiver must solve for its three spatial coordinates (x, y, z) and a single receiver-to-GNSS time offset Δt_{GNSS} (Parkinson, 1996); thus, at least four satellites must be visible to compute the DOP at a given epoch. For the sake of this DOP computation, it is assumed that all inter-system time biases are known. The covariance matrix is defined in the body frame of the receiving spacecraft (i.e., a radial, in-track, cross-track (RIC) frame, where x is the radial direction, z points in the direction normal to the orbit plane along the angular momentum vector, and y is the “in-track” direction) such that the vertical DOP (VDOP) is the DOP component in the radial direction and the horizontal DOP (HDOP) is defined in the plane perpendicular to the radial axis. The VDOP remains over 100 times larger than the HDOP throughout the trajectory and constitutes the majority of the overall geometric DOP (GDOP) magnitude. A mean GDOP of 613 was computed over one orbit in NRHO at the end of the trajectory. The high DOP values throughout the most distant portion of the trajectory ($>10^4$) are indicative of the need for a navigation filter and/or coupling with additional sensors to achieve suitable navigation performance.

The magnitude of the Doppler shift is of practical interest because it determines the frequency search space necessary for the acquisition process. The Doppler shift envelopes throughout the trajectory are shown in Figure 8, assuming the same

TABLE 5

Mean Number of Visible GNSS Signals and Minimum Counts at 68% and 95% Availability Levels for Different Acquisition Thresholds

Visibility here refers to radiometric visibility and represents the number of unique SVs visible in each band.

Region	Band	12 dB-Hz	15 dB-Hz	18 dB-Hz	23 dB-Hz
<i>Mean - Min 68% - Min 95%</i>					
NRHO	L1/E1/B1	31.1 - 26 - 20	23.2 - 19 - 13	15.9 - 13 - 8	6.3 - 5 - 2
	L5/E5a/L3/B2	23.9 - 21 - 17	17.1 - 15 - 11	10.9 - 9 - 6	4.9 - 4 - 2
BLT Apogee	L1/E1/B1	6.1 - 5 - 2	3.8 - 3 - 1	2.4 - 1 - 0	1.1 - 0 - 0
	L5/E5a/L3/B2	4.5 - 3 - 1	3.2 - 2 - 1	2.4 - 1 - 0	1.3 - 1 - 0

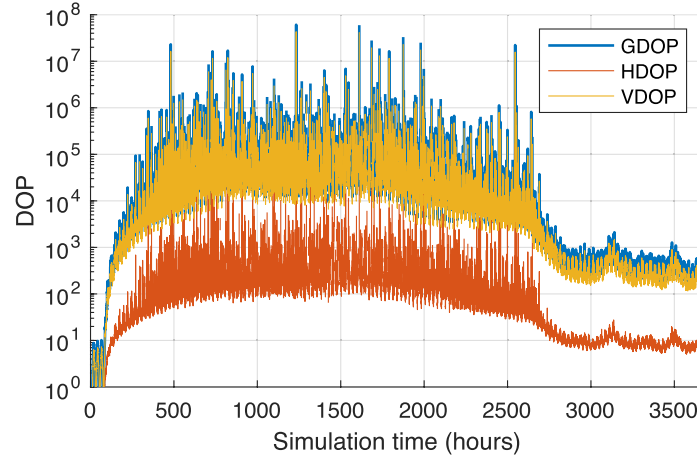


FIGURE 7 DOP throughout the BLT trajectory for signals in the L1 band, assuming a 15-dB-Hz acquisition/tracking threshold

The DOP is defined in the body frame of the receiving spacecraft, with the VDOP in the Earth-pointing direction (x axis) and the HDOP in the yz plane. The DOP was computed once per 10 min of simulation time.

15-dB-Hz threshold as used for the DOP calculation in Figure 7. The Doppler shift (in Hz) is computed as follows (Axelrad & Brown, 1996):

$$f_D = - \left(\frac{\mathbf{v}_i - \mathbf{v}_u}{c} \cdot \frac{\mathbf{r}_i - \mathbf{r}_u}{|\mathbf{r}_i - \mathbf{r}_u|} \right) f_c \quad (7)$$

where $\mathbf{v}_i$ and $\mathbf{v}_u$ are the SV and user velocities, respectively, $\mathbf{r}_i$ and $\mathbf{r}_u$ are the SV and user positions, c is the speed of light, and f_c is the signal carrier frequency. Once the receiver enters the high-altitude SSV (approximately 100 h into the simulation), the maximum L1-band Doppler shift for all medium Earth orbit (MEO) GNSS satellites is contained within a range of ± 25 kHz. Because of their longer orbital periods and lower orbital velocities, the geosynchronous GNSS satellites fit within a narrower range of approximately ± 20 kHz. The Doppler shift minima and maxima in Figure 8 are computed over each 12-h period for the MEO satellites and over each 24-h period for the geosynchronous satellites, in order to match the approximate orbital periods of the SVs.

In the following two sections, a more detailed analysis of visibility trends around the apogee of the BLT is presented, focusing on 15-dB-Hz and 23-dB-Hz acquisition/tracking thresholds. A duration of one week surrounding the apogee of the

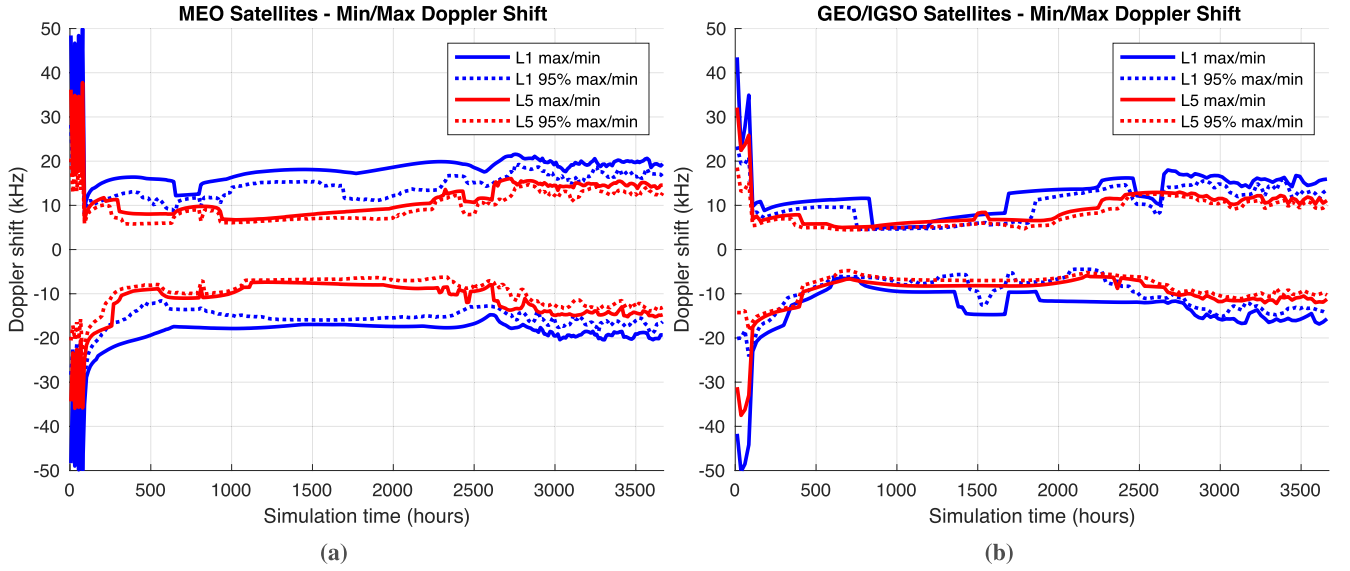


FIGURE 8 Maximum/minimum Doppler shift envelopes throughout the BLT trajectory for (a) MEO satellites and (b) GEO/IGSO/QZO satellites, assuming a 15-dB-Hz acquisition/tracking threshold

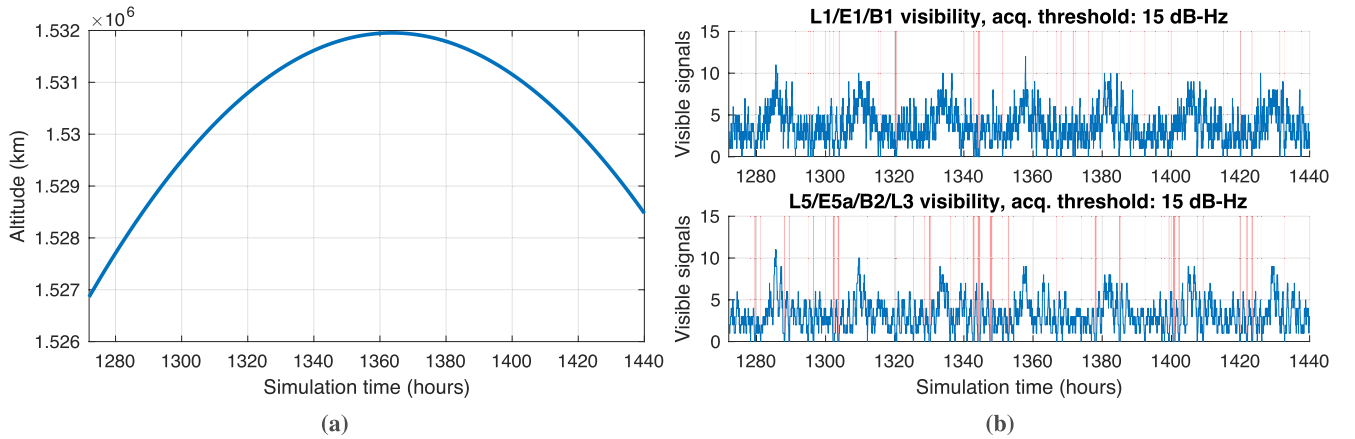


FIGURE 9 (a) User altitude and (b) number of visible signals around the apogee of the BLT with a 15-dB-Hz receiver threshold for August 23, 2024, through August 30, 2024

BLT from August 23 (00:00) UTC to August 30 (00:00) (from hours 1272 to 1440 of simulation time) is analyzed for each threshold.

3.1 | BLT Apogee: 15-dB-Hz Acquisition Threshold

Figure 9(a) shows the altitude of the user throughout this period, and Figure 9(b) shows the total number of visible signals in each band from unique SVs. The red shaded regions in Figure 9(b) denote periods of time when the number of visible signals in a particular band is zero. Statistics for this period are summarized in Table 5.

Spikes in visibility with a period of 24 h are shown in Figure 9(b). These spikes occur when the geosynchronous GNSS satellites—which all orbit over the eastern hemisphere of the Earth—are oriented to be in view of the user. As evidenced

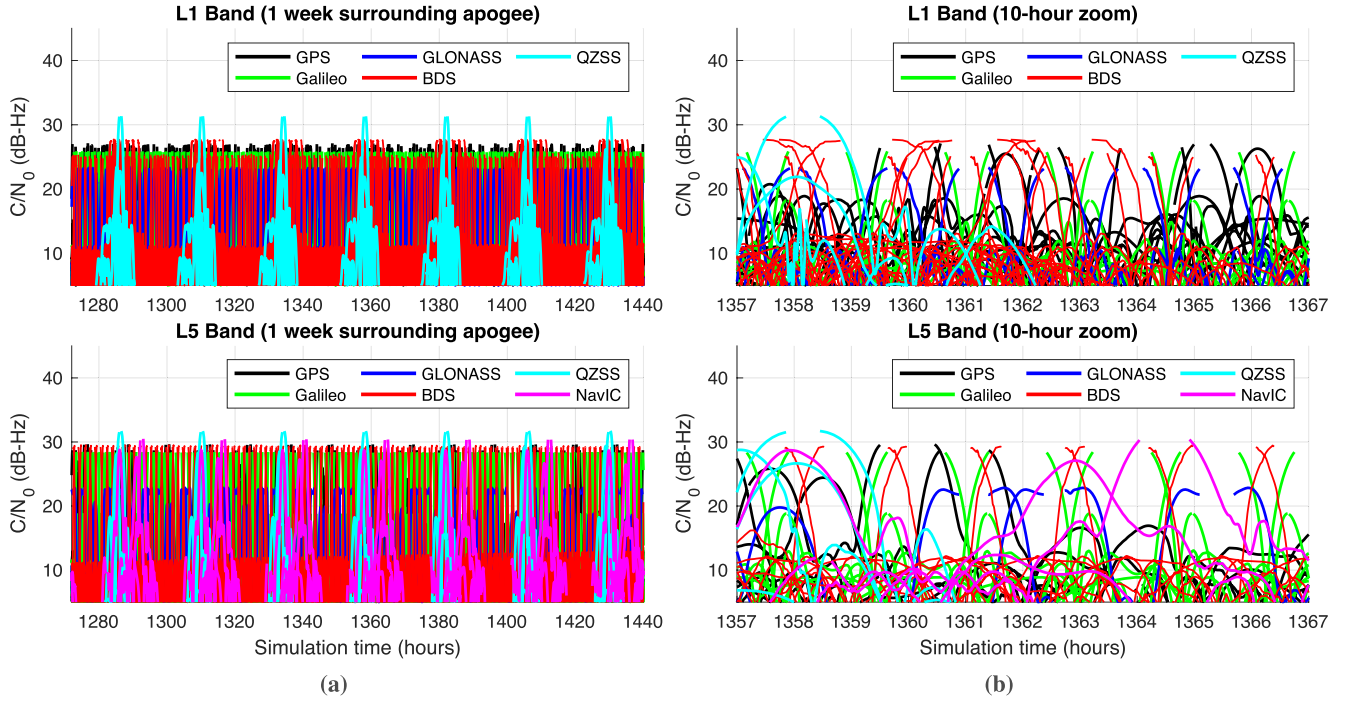


FIGURE 10 (a) L1/L5-band C/N_0 observed by the user throughout the full one-week segment surrounding apogee; (b) L1/L5-band C/N_0 observed by the user during a 10-h span surrounding apogee

by Figure 9(b), periods when the number of visible satellites drops to zero vary between bands and are somewhat irregular. These outage periods may operationally be challenging to anticipate, as they may only be predicted by modeling the current GNSS SV/user geometry and link parameters. Figure 10 shows the received C/N_0 values by constellation for both bands. Figure 10(b) shows only a 10-h span around the user's apogee for the sake of legibility. Delépaut et al. (2020) observed apparent phasing effects in received C/N_0 values throughout the NRHO, which appeared to relate to the precession of the GNSS orbit planes relative to the lunar observer. Such phasing effects are not distinctly observable throughout the BLT trajectory; instead, the dominant visibility trend here appears to relate to the daily visibility cycles of the geosynchronous GNSS satellites. It is also apparent in Figure 10 that the majority of signals received above the 15-dB-Hz threshold come from main lobe transmissions, with a dense cluster of sidelobe signals falling just below the threshold.

To confirm that the received signals in this case are mostly from main lobes, the histograms shown in Figure 11 were formed by binning every signal above the visibility threshold at each epoch according to the off-boresight angle from which they were received. Figures 11(a) and 11(b) show histograms for L1 and L5 signals, respectively. The red lines denote the approximate average main beamwidth of all satellites in a given band and are drawn at 22° for L1 and 25° for L5. These histograms indicate that main lobe signals are visible more often than sidelobe signals at this distance.

Figure 12(a) shows the Doppler shift of all signals observed by the user in both bands over the same 10-h span shown in Figure 10. Signals observed from main lobe transmissions will exhibit smaller Doppler shifts than sidelobe observations because the orbital velocity of the GNSS satellites is closer to perpendicular to the line of sight when these regions of the antenna pattern are directed

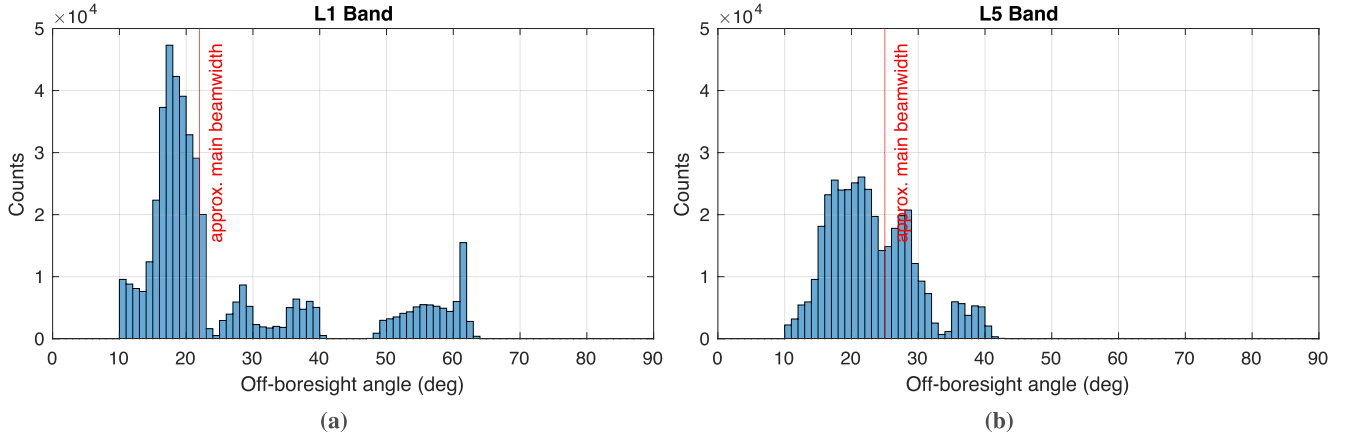


FIGURE 11 (a) L1-band and (b) L5-band off-boresight angle histogram for visible signals with a 15-dB-Hz receiver threshold for August 23, 2024, through August 30, 2024. Red lines denote the approximate average main beamwidth of all satellites in a given band and are drawn at (a) 22° and (b) 25°.

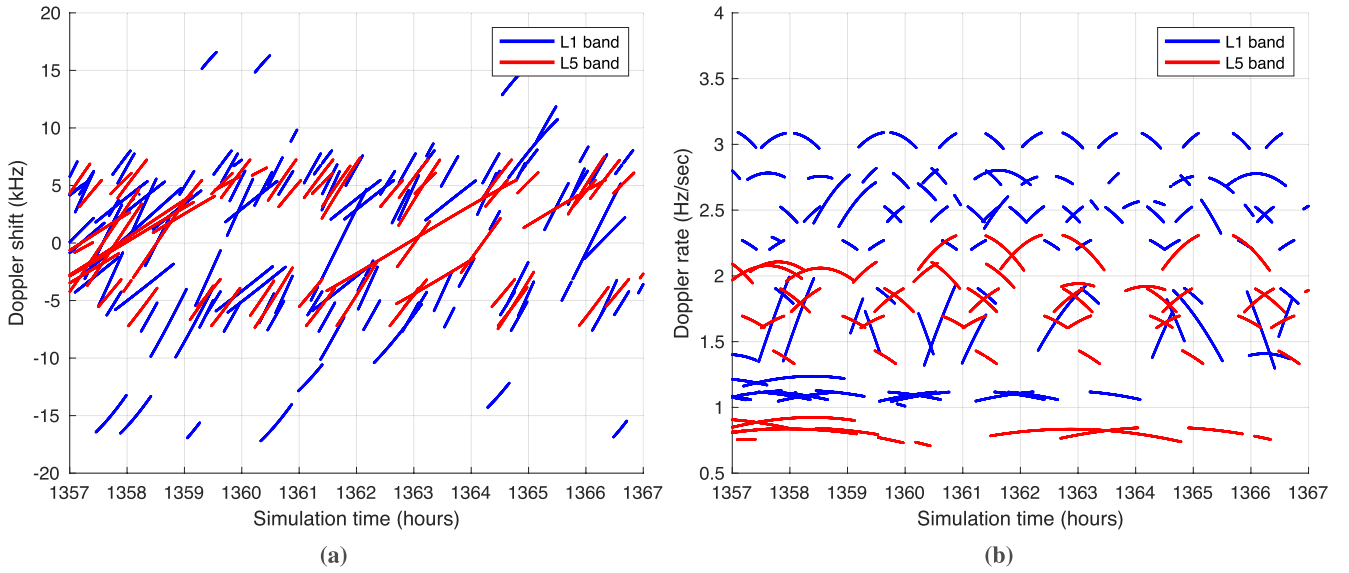


FIGURE 12 (a) Doppler shifts and (b) Doppler rates for all visible signals over 10 h surrounding apogee with a 15-dB-Hz acquisition threshold

toward a distant user (Wang et al., 2024). Short and sporadic streaks with higher Doppler shifts can be observed in Figure 12(a), which result from some brief periods when sidelobe signals with high off-boresight angles are above the 15-dB-Hz threshold. Figure 12(b) also reveals a cluster of lower Doppler rates observed in the range of 0.5 Hz/s to 1.5 Hz/s, which correspond to the geosynchronous satellites.

Table 6 summarizes the visibility statistics computed throughout the apogee of the BLT across all systems in each band. It is shown that at least one signal is visible more than 95% of the time for both the L1 and L5 bands when all constellations are combined, illustrating the benefits of full multi-GNSS capability. A case showing the combined performance of only GPS and Galileo is included as an indication of the visibility attainable by existing dual-constellation receivers such as SANAG/NaviMoon. The average track length and maximum outage durations (MODs) for

TABLE 6

Detailed Visibility Statistics Between Simulation Epochs August 23, 2024, and August 30, 2024, with a 15-dB-Hz Receiver Threshold

Note that GLONASS and NavIC patterns are approximated by offsetting GPS patterns in elevation as described in Section 2.2; thus, their statistics may be less accurate.

Band	Constellation	Avg. track len. (min)	At least 1 signal		4 or more signals	
			Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	20.4	81.3	44.2	2.9	450.2
	Galileo	12.0	43.7	57.4	0.0	-
	GLONASS	22.0	48.7	47.2	0.0	-
	BeiDou (MEO)	17.3	37.8	67.1	0.0	-
	BeiDou (GEO-IGSO)	58.0	32.2	862.2	0.5	1431.3
	QZSS	35.2	15.1	1141.4	0.0	-
	GPS + Galileo	-	89.3	40.2	11.0	286.1
	All Combined	-	98.0	20.9	51.4	95.1
L5/E5a/L3/B2	GPS	32.3	51.0	164.2	0.0	-
	Galileo	17.0	58.9	56.2	0.0	-
	GLONASS	45.6	49.5	121.6	0.0	-
	BeiDou (MEO)	30.2	40.4	67.1	0.0	-
	BeiDou (GEO-IGSO)	34.5	1.7	3525.2	0.0	-
	QZSS	70.0	19.9	1087.6	0.0	-
	NavIC	89.7	32.7	834.8	0.0	-
	GPS + Galileo	-	79.2	55.5	0.9	1379.2
	All Combined	-	95.0	39.7	38.6	208.7

≥ 1 and ≥ 4 signals are shown for both bands. The geosynchronous satellites are observed to generally have longer average track lengths than those computed for MEO satellites, likely owing to their longer orbital periods (approximately 24 h for geosynchronous satellites and 12 h for MEO).

3.2 | BLT Apogee: 23-dB-Hz Acquisition Threshold

Here, we consider the case of a 23-dB-Hz acquisition/tracking threshold, achievable by receivers such as NC3m. Figure 13 shows the total number of visible signals per band throughout the same period considered in Section 3.1. Given that the results in the 15-dB-Hz case were indicative of a dependence on strong main lobe signals, it is expected that a loss of 8 dB of link margin in moving to a 23-dB-Hz threshold will significantly reduce radiometric visibility. As shown in Table 5, the average number of visible signals was decreased from 3.78 to 1.11 in the L1 band and from 3.18 to 1.33 in the L5 band as compared with the 15-dB-Hz case. The off-boresight angle histograms shown in Figure 14 confirm that only the strongest main lobe signals at low off-boresight angles are visible. Table 7 summarizes the overall visibility statistics, where it is noted that the overall visibility in the L5 band exceeds that of the L1 band despite there being significantly fewer satellites broadcasting L5 signals. This trend can be primarily attributed to the wider main beamwidths of the L5 signals, as suggested by Figure 14(b).

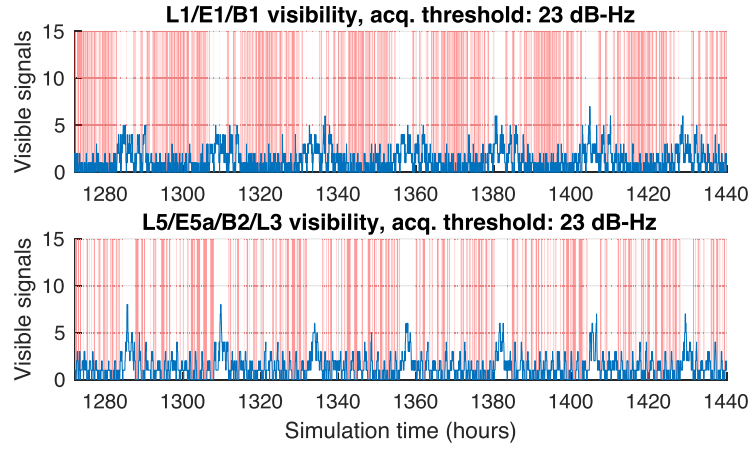


FIGURE 13 Number of visible signals around the apogee of the BLT with a 23-dB-Hz receiver threshold for August 23, 2024, through August 30, 2024
Red shaded regions in (b) denote periods of time when the number of visible signals in a particular band is zero.

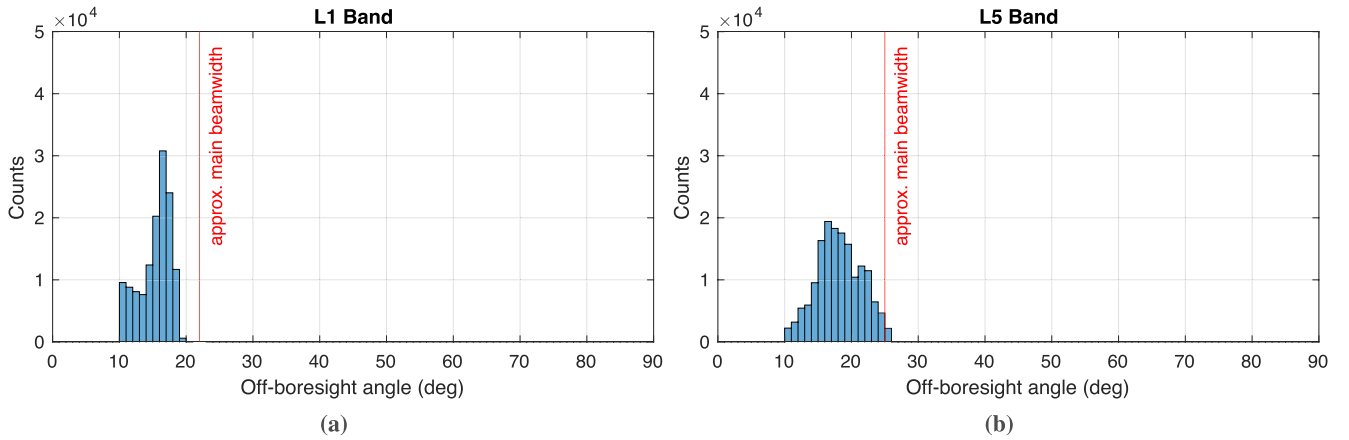


FIGURE 14 (a) L1-band and (b) L5-band off-boresight angle histograms for visible signals with a 23-dB-Hz receiver threshold for August 23, 2024, through August 30, 2024
Red lines denote the approximate average main beamwidth of all satellites in a given band and are drawn at (a) 22° and (b) 25°.

3.3 | Discussion

The C/N_0 threshold at which CED messages can be decoded varies by signal. For example, according to Anghileri et al. (2013), GPS L1 C/A CED messages can be reliably decoded at a threshold of 26.5 dB-Hz. For Galileo E5a, a threshold of 20.7 dB-Hz is needed. The use of advanced processing techniques that sum the energy of successive data frames can serve to reduce these thresholds. For example, Soloviev et al. (2009) showed that the GPS L1 C/A CED message can be reliably decoded as low as 15 dB-Hz after 20 min of tracking. The use of an assisted-GNSS receiver architecture (van Diggelen, 2009) would allow for estimation of the receiver's PVT without the need to decode these data. The availability of assistance data via a side channel could also be leveraged to achieve even lower receiver acquisition thresholds than those considered in this simulation, for example, the 8-dB-Hz acquisition threshold considered by Musumeci et al. (2016). These assistance data could be provided in a one-way data uplink via a terrestrial ground station without

TABLE 7

Detailed Visibility Statistics Between Simulation Epochs August 23, 2024, and August 30, 2024, with a 23-dB-Hz Receiver Threshold

Note that GLONASS and NavIC patterns are approximated by offsetting GPS patterns in elevation as described in Section 2.2; thus, their statistics may be less accurate.

Band	Constellation	Avg. track len. (min)	At least 1 signal		4 or more signals	
			Avail. (%)	MOD (min)	Avail. (%)	MOD (min)
L1/E1/B1	GPS	10.7	20.1	146.6	0.0	-
	Galileo	-	0.0	-	0.0	-
	GLONASS	-	0.0	-	0.0	-
	BeiDou (MEO)	6.1	16.1	67.1	0.0	-
	BeiDou (GEO-IGSO)	41.6	26.2	892.5	0.5	1431.3
	QZSS	-	0.0	-	0.0	-
	All Combined	-	61.1	42.1	5.0	1078.0
L5/E5a/L3/B2	GPS	20.0	22.9	364.9	0.0	-
	Galileo	-	0.0	-	0.0	-
	GLONASS	-	0.0	-	0.0	-
	BeiDou (MEO)	21.8	32.1	67.1	0.0	-
	BeiDou (GEO-IGSO)	-	0.0	-	0.0	-
	QZSS	-	0.0	-	0.0	-
	NavIC	-	0.0	-	0.0	-
	All Combined	-	71.6	58.8	6.0	1052.5

depending on the full capabilities of a deep space radiometric tracking system such as the DSN.

As shown in both the 15- and 23-dB-Hz cases at the apogee of the BLT, a multi-constellation receiver would achieve a significant visibility improvement over a single-constellation receiver. The results for the GPS/Galileo-only case in Table 6 show that even a two-constellation solution provides a significant visibility improvement over any one constellation. In practice, a dual-frequency receiver architecture may also provide the capability to perform dual-frequency ionospheric error corrections, which could enhance overall signal visibility, although further research is required to evaluate the effectiveness of these corrections for users at these altitudes.

3.3.1 | Ionospheric Effects and Masking

The simulation applies a 1000-km atmospheric height mask to exclude signals that pass through the Earth's ionosphere. Using a mask of $h_{\text{mask}} = 50$ km (i.e., the approximate height of the troposphere) instead results in an improvement to the visibility statistics. For example, for a 15-dB-Hz receiver threshold, the combined availability percentage for four or more signals in the L1 band in the week surrounding apogee increases from 51.39% to 65.27% when $h_{\text{mask}} = 50$ km is used. To the authors' knowledge, no previous studies have characterized the effectiveness of commonly used ionospheric error correction algorithms (e.g., dual-frequency corrections) in a high-altitude GNSS scenario. Flight data from previous missions using single-frequency GNSS receivers have been used to characterize the ionospheric delay observed by users in GEO, where significant delays on the order of

hundreds of meters are incurred (Estrada et al., 2024). Given this error magnitude and the difficulty of accurately performing real-time single-frequency ionospheric corrections in the high-altitude SSV, it is common practice to simply exclude these signals. For particularly low-passing signals crossing deep through the ionosphere, bending effects can introduce additional error to a dual-frequency total electron content (TEC) estimate. The magnitude of this residual bending error varies with solar flux, local time, and the vertical TEC gradient, although Chang et al. (2024) showed that the residual bending error typically falls below 3 TEC units (TECU) by using estimates produced by GPS radio occultation measurements on the COSMIC-2 satellite. A value of 3 TECU corresponds to approximately 0.5 m of delay at 1575.42 MHz (Parkinson, 1996). Reducing the height mask below 1000 km may be feasible (depending on current ionospheric conditions, mission requirements, and the capability of the receiver to simultaneously track multiple signals from a specific SV), although it has been shown that the added signal availability may only improve by $\sim 14\%$ at maximum. Additional studies using dual-frequency measurements from a high-altitude receiver are necessary to investigate the feasibility of dual-frequency ionospheric corrections at or beyond lunar distance.

4 | CONCLUSIONS

The visibility statistics computed by the simulations presented herein show that there is strong potential for GNSS-assisted navigation throughout a BLT. The results show that a multi-constellation receiver would provide a significant improvement in visibility compared with a single-constellation receiver. At the apogee of the BLT, it was shown that at least one GNSS signal was above the 15-dB-Hz threshold more than 96% of the time in the L1 band and more than 91% of the time in L5, both significantly exceeding the performance of any single constellation. Signals received at this distance are shown to be predominantly from main lobe transmissions. Sidelobe signals are less often visible and typically have shorter track lengths. The results also indicate some unique advantages introduced by geosynchronous GNSS satellites, such as the ability to provide signals with longer average track lengths and reduced Doppler shift and Doppler shift rates as compared with MEO satellites, owing to their longer orbital periods. The longer average track lengths of geosynchronous satellites may provide better opportunities for the autonomous reception of almanac data or augmentations. The results shown in Section 3.2 for a 23-dB-Hz threshold indicate highly limited visibility throughout the apogee of the BLT, although at least one signal was still visible more than 63% of the time in the L5 band. This result exceeds the minimum availability of 57% found in the L1 band despite there being significantly fewer satellites broadcasting L5 signals at the time of the simulation.

Future work will involve modeling the range and range-rate measurement accuracy that could be achieved by GNSS receivers during a BLT, along with a more comprehensive analysis of the level of navigation accuracy that could be achieved using GNSS receivers with various measurement types and aiding sources. As expected, this work shows that the overall DOP is the largest in the range (vertical) direction. Winternitz et al. (2019) highlighted a potentially complementary relationship between two-way ranging measurements and GNSS measurements in lunar orbit, where two-way systems exhibit much larger lateral errors than GNSS but are comparatively more accurate in the range direction. Follow-on studies can explore the potential for reducing or eliminating the need for two-way ranging by using GNSS measurements during a BLT. Additionally, further study is required

to determine the effectiveness of dual-frequency ionospheric correction models in high-altitude GNSS scenarios and to characterize the effects on signal tracking introduced by the ionosphere.

ACKNOWLEDGMENTS

The authors would like to pay their respects and gratitude to Dr. Michael Braasch, who passed away in September 2024. Dr. Braasch was a mentor, collaborator, and colleague who provided invaluable guidance and advice throughout the course of this work and will be greatly missed. The authors would also like to thank the reviewers for their thoughtful comments and suggestions, which helped to improve the quality of this work.

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How to cite this article: Peters, B.C., McKnight, R., & Ugazio, S. (2026). Analysis of multi-GNSS signal visibility throughout a representative ballistic lunar transfer scenario. *NAVIGATION*, 73. <https://doi.org/10.33012/navi.765>

A | SUMMARY OF THE YAW-STEERING FRAME DEFINITION

The YSF describes the orientation of a nadir-pointing spacecraft that yaws about its boresight axis to face its solar panels toward the sun. Montenbruck et al. (2015) described the attitude control laws for all GNSS constellations and defined the nominal YSF as follows:

$$\begin{aligned}
 \mathbf{e}_{x,YS} &= \mathbf{e}_{y,YS} \times \mathbf{e}_{z,YS} \\
 \mathbf{e}_{y,YS} &= \frac{\mathbf{e}_{\text{sun}} \times \mathbf{r}}{|\mathbf{e}_{\text{sun}} \times \mathbf{r}|} \\
 \mathbf{e}_{z,YS} &= -\frac{\mathbf{r}}{|\mathbf{r}|}
 \end{aligned} \tag{8}$$

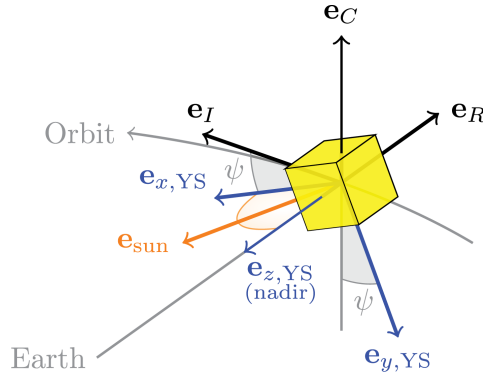


FIGURE 15 YSF used to describe the attitude of GNSS satellites
The YSF is defined by the Sun vector, the satellite position vector, and the cross product of these two vectors. This figure is inspired by Figure 1 in the work of Montenbruck et al. (2015) and depicts an example $\mathbf{e}_{\text{sun}}$ vector that defines the orientation of the YSF.

where $\mathbf{e}_{x, \text{YS}}, \mathbf{e}_{y, \text{YS}}, \mathbf{e}_{z, \text{YS}}$ are the unit vectors that define the frame, $\mathbf{r}$ is the SV position vector referenced to the center of the Earth, and $\mathbf{e}_{\text{sun}}$ is a unit vector that points from the SV to the Sun. Figure 15 illustrates an example of the YSF with respect to the body-fixed RIC frame. The yaw angle ψ defines a rotation about the $\mathbf{e}_{z, \text{YS}}$ direction, which is defined by the direction to the Sun.

Each constellation employs slightly varied attitude control laws based on the YSF, which handle certain special cases in different ways (e.g., when the Sun vector nearly intersects the orbit plane, which would result in rapid yaw slews). Typically, GNSS SVs will switch to a different attitude mode when the angle between the Sun vector and orbit plane falls below a specific threshold, which differs between service providers. For most GNSS satellites, including all GPS, Galileo, GLONASS, and MEO/IGSO BeiDou SVs, this Sun angle threshold is sufficiently small such that the nominal YSF can be considered the reference orientation for each of these satellite types (Montenbruck et al., 2015). Among all GNSS constellations, QZSS represents the most significant departure from the nominal YSF behavior, transitioning to a yaw-fixed attitude mode when the Sun angle falls below 20° . Under the overly conservative assumption that the Sun vector remains constantly aligned with each satellite's orbit plane, QZSS satellites would deviate from the nominal YSF for approximately 18% of their orbital period. Because this scenario represents the upper bound of deviation among all GNSS satellites and given that such deviations affect a minority of satellites for a limited fraction of time, for simplicity, this simulation models each SV using the nominal YSF described by Equation (8). The geocentric coordinates of the Sun are computed using a method given by Michalsky (1988) and are used to form the YSF of each SV.