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Signal Strength-Based Global Navigation Satellite System Performance Assessment in the Space Service Volume

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Abstract

NASA is participating in the International Committee on Global Navigation Satellite Systems (GNSS) (ICG)'s efforts towards demonstrating the benefits to the space user in the Space Service Volume (SSV) when a multi-GNSS solution space approach is utilized. The ICG Working Group: Enhancement of GNSS Performance, New Services and Capabilities has started a three phase analysis initiative as an outcome of recommendations at the ICG-10 meeting, in preparation for the ICG-11 meeting. The second phase of that increasing complexity and fidelity analysis initiative is based on augmenting the Phase 1 pure geometrical approach with signal strength-based limitations to determine if access is valid. The second phase of analysis has been completed, and the results are documented in this paper.

Introduction

The region of space nearby the Earth is divided into two specific regions, defined as the Terrestrial Service Volume (TSV) and the Space Service Volume (SSV) (Ref. 1). The TSV is defined from the Earth's surface up to an altitude of 3,000 km, while the SSV is defined from the altitude of 3,000 km to the geostationary altitude of roughly 36,000 km. These two regions of space are illustrated in Figure 1.

Navigation system performance is vastly different in these two regions of space, as many of the GNSS constellations operate in Medium Earth Orbit (MEO) at an altitude around 20,000 km. Space users in the SSV will observe dramatically different numbers of GNSS satellites, as compared to what is available to users on the Earth's surface or in the TSV, which has already been studied from a purely geometrical standpoint (Ref. 2) to determine that the services required to meet the minimum of 4 satellites in view can be provided when multiple GNSS constellations are utilized together. At the maximum altitude within the SSV at 36,000 km, space users will not be able to observe GNSS satellites with a zenith-facing antenna, but rather, will be required to observe GNSS satellites with a nadir-facing antenna which have signals crossing over the Earth's limb (Ref. 3). At that maximum altitude, signal power levels that cross the Earth's limb will have undergone a much larger free space path loss compared to typical users much closer to the Earth's surface, and thus the receiver capabilities and antenna requirements play a much more important role to determine if a signal is useable than strictly geometry. However, it should be noted that geometry is still a fundamental aspect to determine if visibility exists, and that this work is augmenting the previous efforts for these additional signal strength restrictions.

Navigation system performance is vastly different in these two regions of space, as many of the GNSS constellations operate in Medium Earth Orbit (MEO) at an altitude around 20,000 km. Space users in the SSV will observe dramatically different numbers of GNSS satellites, as compared to what is available to users on the Earth's surface or in the TSV, which has already been studied from a purely geometrical standpoint (Ref. 2) to determine that the services required to meet the minimum of 4 satellites in view can be provided when multiple GNSS constellations are utilized together. At the maximum altitude within the SSV at 36,000 km, space users will not be able to observe GNSS satellites with a

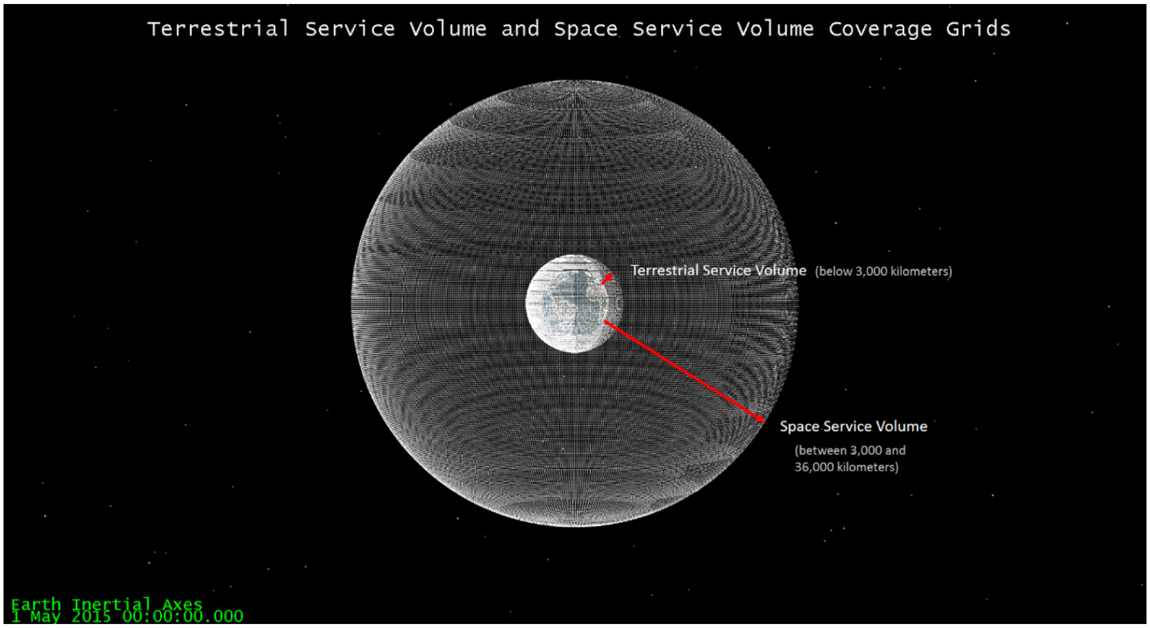

Figure 1.—Earth Terrestrial and Space Service Volume Regions

zenith-facing antenna, but rather, will be required to observe GNSS satellites with a nadir-facing antenna which have signals crossing over the Earth's limb (Ref. 3). At that maximum altitude, signal power levels that cross the Earth's limb will have undergone a much larger free space path loss compared to typical users much closer to the Earth's surface, and thus the receiver capabilities and antenna requirements play a much more important role to determine if a signal is useable than strictly geometry. However, it should be noted that geometry is still a fundamental aspect to determine if visibility exists, and that this work is augmenting the previous efforts for these additional signal strength restrictions.

Analysis (Ref. 2) previously reported the geometrical coverage performance of four global and two regional GNSS constellations, solely using a nadir-facing antenna at the altitude of 36,000 km altitude. The trade space of the global GNSS constellation includes the United States' Global Position System (GPS) (Refs. 4 and 5), European Galileo (Ref. 6), Russian Global Navigation Satellite System (GLONASS) (Ref. 7), and Chinese BeiDou (Ref. 8). The trade space of the regional GNSS constellations include Indian Regional Navigation Satellite System (IRNSS) (Ref. 9) and the Japanese Quasi-Zenith Satellite System (QZSS) (Ref. 10). Due to the nature of the main antenna beam of those GNSS constellations being directed nadir, along with the fact that side-lobe antenna performance is unspecified, geometrical visibility is restricted to the portion of the antenna beam that extends beyond the Earth blockage, as seen in Figure 2.

That ultimately limits the maximum number of visible GNSS spacecraft that can be in view of the space users at all altitudes. The results of this paper utilize previously developed analytical techniques (Ref. 2) for deriving the visibility Figures of Merit with the concept of analyzing individual GNSS constellations separate from the combined multi-GNSS system. However, this work extends that capability by incorporating additional constraints to the access determination routine pertaining to the received signal being of a minimum carrier to noise density ratio, thereby allowing the examination of minimum receiver acquisition thresholds to be included for consideration, with a methodology of using an omnidirectional gain antenna limited to the nadir-facing hemispherical coverage as studied previously (Ref. 2).

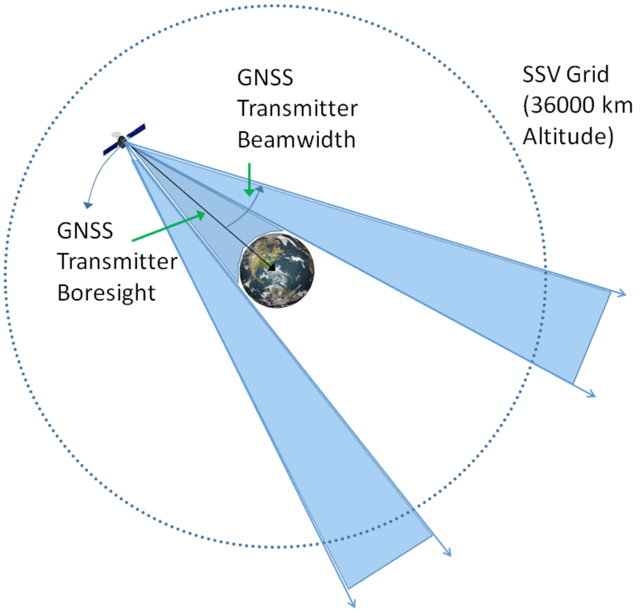

Figure 2.—GNSS Visibility Limitations

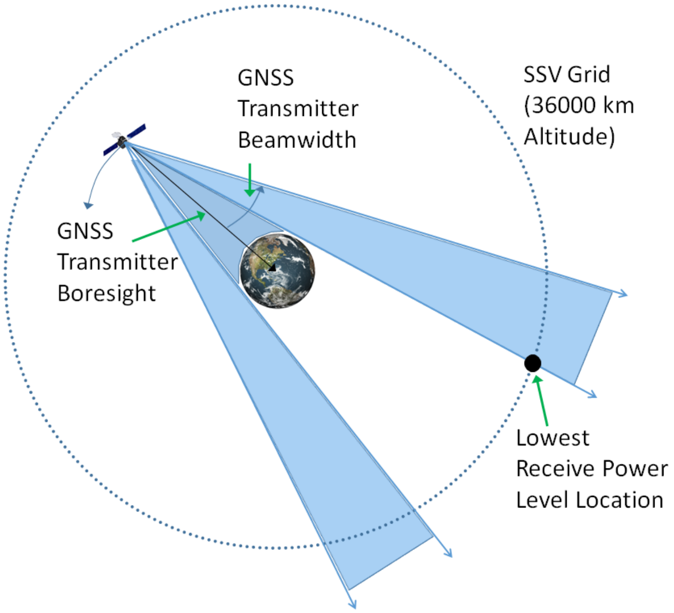

Figure 3.—GNSS Visibility Limitations

Analysis Methodology and Assumptions

This paper describes the methodology and results of an expanded effort to analyze the performance of GNSS constellations in the SSV, compared to the results reported previously (Ref. 2), where the coverage considerations were purely geometrical. These efforts build on those same Keplarian orbital simulation assumptions, equal area-based grid of points and maximum beamwidths by determining the minimum Equivalent Isotropic Radiated Power (EIRP) for each GNSS to be used over that maximum beamwidth, and using that value to derive the signal to noise ratio at grid points at the SSV altitude of 36,000 km, as illustrated in Figure 3.

All orbital simulation assumptions and orbital Keplarian parameters can be found in Reference 2. Table 1 provides the minimum received power level per GNSS constellation, along with maximum beamwidth and specific center frequency, used to derive the minimum EIRP to be considered over the beamwidth, per Equations (1) through (4). Note that for the BeiDou constellation, the beamwidth is defined separately for satellites in MEO than for those in Geostationary (GEO) / Inclined Geosynchronous Orbit (IGSO). Table 2 provides additional parameters pertaining to general Radio Frequency (RF) assumptions used for these calculations and the simulations performed in this analysis.

Similarly to the previous study (Ref. 2), access is initially derived and limited from purely geometrical limitations from two perspectives, but now is additionally limited by the minimum carrier to noise density threshold of interest. The space user in the SSV grid needs to be within the specified beamwidth angle of the GNSS transmitter beam, which may preclude access due to Earth blockage, as seen in Figure 4. Also, the GNSS transmitter needs to be within the space user’s antenna field of view, which is defined to be nadir-facing hemispherical, which is illustrated in Figure 5. Previous specialized definitions for the IRNSS pointing vector (Ref. 2) also apply in this analysis effort, as that is an artifact of that constellation design and implementation.

TABLE 1.—GNSS RF PARAMETERS

GNSS constellation	Signal name	Frequency, MHz	Maximum beamwidth, degrees	Minimum received power, dBW	EIRP, dBW
GPS	L1 C/A	1575.42	23.5	–184	9.1
Galileo	E1 B/C	1575.42	20.5	–182.5	10.9
GLONASS	L1	1605.375	20	–185	8.1
BeiDou MEO	B1	1575.42	25	–184.2	9
BeiDou GEO/IGSO	B1	1575.42	19	–185.9	9
QZSS	L1 C/A	1575.42	22	–186.1	9.1
GPS	L5	1176.45	26	–182	8.5
Galileo	E5a	1176.45	23.5	–182.5	8.4
GLONASS	L3	1201	28	–184	6.6
BeiDou MEO	B2	1191.795	28	–182.8	8
BeiDou GEO/IGSO	B2	1191.795	22	–184.4	8.1
QZSS	L5	1176.45	24	–183.4	9.3
IRNSS	L5	1176.45	16	–184.54	7.8

$$EIRP = \left\lceil P_{r,\min} + 20\log\left(\frac{4\pi f}{c} D_{\max}\right)\right\rceil \tag{1}$$

$$D_{\max} = R_{Sat,\max}\cos\left(\theta_{EarthEdge}\right) + \sqrt{R_{Grid}^2 - \left(R_{Sat,\max}\sin\left(\theta_{EarthEdge}\right)\right)^2} \tag{2}$$

$$\theta_{\mathrm{EarthEdge}} = \arcsin\left(\frac{R_E}{R_{Sat,\max}}\right) \tag{3}$$

$$R_{Sat,\max} = SMA\left(1+e\right) \tag{4}$$

TABLE 2.—GENERAL RF SIMULATION ASSUMPTIONS

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

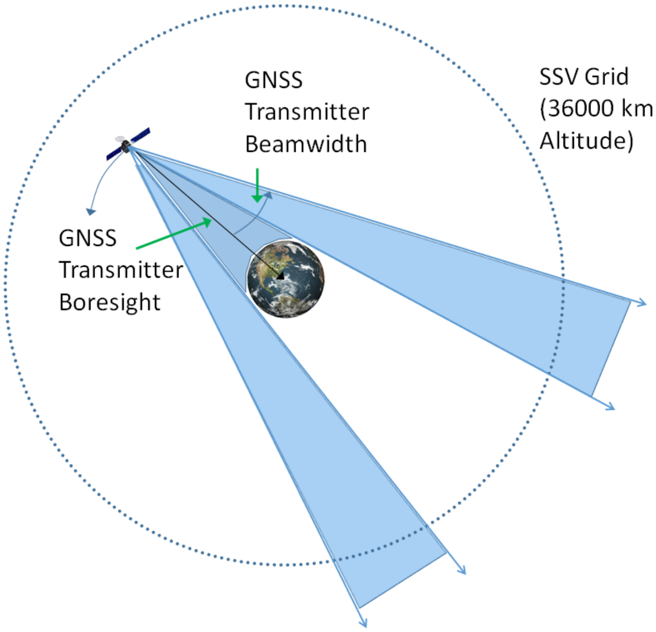

Figure 4.—GNSS Transmitter Geometrical Access Considerations

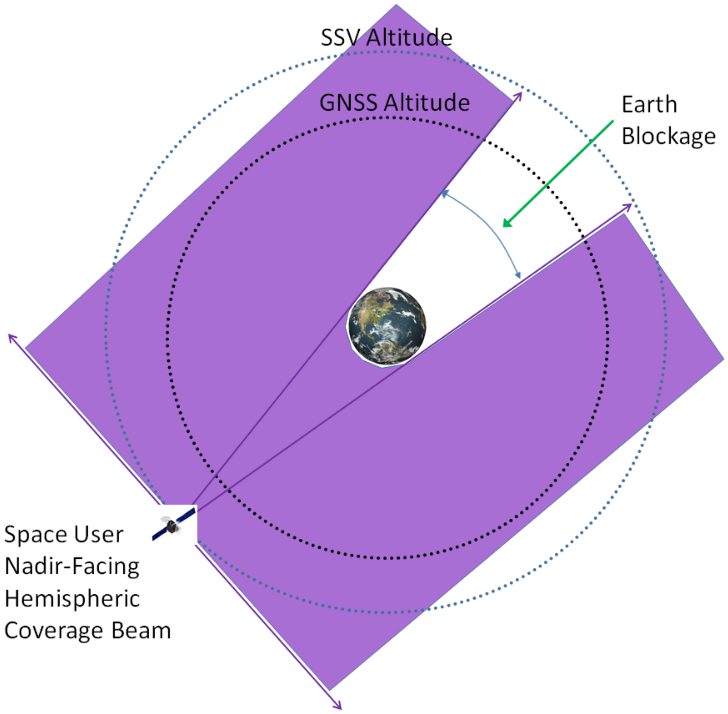

Figure 5.—Space User Nadir-Facing Antenna Geometrical Access Considerations

The overall simulation methodology is performed in multiple steps, which now adds additional steps to include constraints for the RF considerations of this study, which are listed below:

1. Propagate orbit position vectors into Earth-Centered Earth-Fixed frame coordinates over scenario time instances.
2. Calculate angle off GNSS boresight vector to all SSV grid points over scenario time instances.
3. Calculate angle off SSV nadir boresight vector to all GNSS orbit positions over scenario time instances.
4. Determine yes/no access using maximum GNSS beamwidth consideration, Earth blockage consideration, and SSV hemispherical beamwidth consideration over scenario time instances for all SSV grid points.
5. Calculate received signal to noise ratio to all SSV grid points from all GNSS transmitters, where geometrical access is available, over scenario time instances.
6. Determine yes/no access comparing received signal to noise ratio with minimum threshold signal to noise ratio.
7. Calculate Figures of Merit from RF-augmented access determination over scenario time instances over all SSV grid points.

The System Availability (SA) metric is defined over a matrix of data X that spans the range of time instants N_T by the range of grid points N_P containing the number of available satellites in view meeting the required signal to noise threshold at individual grid-time points, as shown in Equations (5) and (6).

$$SA(N_{\min}) = \frac{1}{N_T N_P} \sum_{i=1}^{N_T} \sum_{j=1}^{N_P} Y(i, j, N_{\min}) \tag{5}$$

$$Y(i, j, N_{\min}) = \begin{cases} 1, & X(i, j) \geq N_{\min} \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

Access Results

The simulation results that are presented here are the various Figures of Merit calculated in the analysis effort. For this simulation effort, the Figures of Merit are defined as System Availability and Maximum Outage time, with the minimum number of satellites under consideration being either one or four satellites. Since the grid points are defined as having equal area pertaining to each grid point, averaging of performance over the grid points can be done using a pure mean calculation, without the need for additional scale factors to de-weight the grid point contributions. As stated, the constellations being considered are the six individual constellations, as well as a combined multi-GNSS constellation consisting of all individual constellations, at either the L1 or L5 frequency bands, independently. Therefore, a system performance assessment is not, for example, of using the L1 frequency band performance of BeiDou, Galileo, GLONASS, GPS and QZSS combined with the L5 frequency band performance of IRNSS. Finally, for the purpose of IRNSS, which does not support the L1 frequency band, tabulated results are shown as “Not Applicable” (N/A). Maximum Outage times that are the duration of the scenario, which is the result if the criteria is never met within the scenario duration, are denoted as “Max Scenario Duration (SD).” Carrier to noise density thresholds that were examined under this study ranged from 15 dB/Hz to 25 dB/Hz in increments of 1 dB. Table 3 and Table 4 reports the various 1 satellite System Availability Figures of Merit for the L1 frequency band and L5 frequency band, respectively, while Table 5 through Table 10 in the Appendix provide the remaining Figures of Merit.

Results in Table 3 and Table 4 provided the averaged globalized 1 satellite System Availability performance. Results in the Appendix provide the 4 satellite System Availability performance as well as the Maximum Outage Time performance. All system availability metrics that were provided were values that were rounded down to the next lowest tenths decimal place, so as to not overstate performance. Maximum outage time is limited to integer numbers of minutes, due to the nature that the simulations were performed on one minute intervals.

TABLE 3.—L1 1 SATELLITE SYSTEM AVAILABILITY PERFORMANCE

Carrier to noise density, dB/Hz	BeiDou	Galileo	GLONASS	GPS	IRNSS	QZSS	All
15	97.4	78.5	59.1	90.5	N/A	26.7	99.9
16	97.4	78.5	59.1	90.5	N/A	26.7	99.9
17	97.4	78.5	59.1	90.5	N/A	26.7	99.9
18	97.4	78.5	59.1	90.5	N/A	26.3	99.9
19	96.1	78.5	59.1	90.5	N/A	0.6	99.9
20	69.8	78.5	0	90.5	N/A	0	99.1
21	0	78.5	0	0	N/A	0	78.5
22	0	0	0	0	N/A	0	0
23	0	0	0	0	N/A	0	0
24	0	0	0	0	N/A	0	0
25	0	0	0	0	N/A	0	0

TABLE 4.—L5 1 SATELLITE SYSTEM AVAILABILITY PERFORMANCE

Carrier to noise density, dB/Hz	BeiDou	Galileo	GLONASS	GPS	IRNSS	QZSS	All
15	99.9	93.4	98.3	96.9	36.9	30.5	100
16	99.9	93.4	98.3	96.9	36.9	30.5	100
17	99.9	93.4	98.3	96.9	36.9	30.5	100
18	99.9	93.4	98.3	96.9	36.9	30.5	100
19	99.9	93.4	98.3	96.9	36.9	30.5	100
20	99.9	93.4	98.3	96.9	1	30.5	100
21	99.9	93.4	0	96.9	0	28.3	99.9
22	0	0	0	96.9	0	0	96.9
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0

For any metric provided, the smaller minimum carrier to noise density thresholds provide the optimum performance. Also, it should be noted that at the smallest thresholds of nominally 15 through 18 dB/Hz, the performance is the exact same as was found previously (Ref. 2). This means for those cases that the limiting factor in system performance is the underlying geometrical constraints. For slightly higher minimum carrier to noise density thresholds of 19 through 22 dB/Hz, performance degrades due to the actual signal levels being too low to be received by those space users. Finally, at thresholds of 23 dB/Hz and above, performance drops to 0% System Availability. This shows that the required receiver capabilities are quite complex in order to be able to utilize the extremely low signal levels that show promising results, as well as the fact that antenna gain will directly scale with the capabilities illustrated in the data, such that a receiver that has a 20 dB/Hz minimum threshold with a 0 dB gain antenna will perform the same if the threshold were 23 dB/Hz with a 3 dB gain antenna in the same hemispherical coverage.

Conclusions and Next Steps

The analysis presented in this paper extends the previously published geometrical-only assessments of navigation performance at the maximum altitude in the SSV. Results are calculated at both L1 and L5 frequency bands for the 6 unique GNSS constellations, as well as the combined GNSS constellation. The results show minimum carrier to noise density thresholds where performance is equivalent to the geometrical-only assessment, as well as thresholds where performance is degraded or non-existent at higher thresholds. The results are very promising towards meeting the needs of space users in the SSV, given that the receivers have very capable hardware onboard.

While this study augments previous efforts to include RF based considerations to access calculations, it does so in only a limited fashion that does not include all real-world considerations. Future efforts to augment this analysis would be to consider a gain profile of the antenna, instead of a fixed value gain in only a hemispherical region of space, as well as to ascertain the performance of the system using different carrier to noise density thresholds for initial acquisition than for ongoing tracking of the signal. Future work should also be cognizant of the realistic variations in acquisition and tracking thresholds that would apply to the different GNSS constellations, due to the variations in modulation and coding schemes implemented on their navigation signals. Finally, additional analysis should extend the work beyond that of a grid of points and apply these concepts to specific mission cases. Finally, it is important to note that the methodologies created and reported in this document can be utilized beyond the scope of navigation system coverage analysis, such as for space communication architecture analysis, though for that particular application, the metric of consideration may likely be augmented to be signal to noise ratio or bit error rate, which are direct parameters that can be calculated from carrier to noise density ratio, and are more appropriate in the space communication architecture analysis field, with the caveat that the minimum number of satellites required would likely be left to 1 satellite in view, aside from analyzing the performance for launch vehicle tracking.

Appendix.—Figures of Merit

TABLE 5.—L1 4 SATELLITE SYSTEM AVAILABILITY PERFORMANCE

Carrier to noise density, dB/Hz	BeiDou	Galileo	GLONASS	GPS	IRNSS	QZSS	All
15	24.1	1.2	0.5	4.8	N/A	0.8	94.4
16	24.1	1.2	0.5	4.8	N/A	0.8	94.4
17	24.1	1.2	0.5	4.8	N/A	0.8	94.4
18	24.1	1.2	0.5	4.8	N/A	0.7	94.4
19	5	1.2	0.5	4.8	N/A	0	91.3
20	0.6	1.2	0	4.8	N/A	0	62.8
21	0	1.2	0	0	N/A	0	1.2
22	0	0	0	0	N/A	0	0
23	0	0	0	0	N/A	0	0
24	0	0	0	0	N/A	0	0
25	0	0	0	0	N/A	0	0

TABLE 6.—L5 4 SATELLITE SYSTEM AVAILABILITY PERFORMANCE

Carrier to noise density, dB/Hz	BeiDou	Galileo	GLONASS	GPS	IRNSS	QZSS	All
15	45.4	4.2	14.5	15.6	0.6	1.5	99.9
16	45.4	4.2	14.5	15.6	0.6	1.5	99.9
17	45.4	4.2	14.5	15.6	0.6	1.5	99.9
18	45.4	4.2	14.5	15.6	0.6	1.5	99.9
19	45.4	4.2	14.5	15.6	0.6	1.5	99.9
20	32.4	4.2	14.5	15.6	0	1.5	99.9
21	18.9	4.2	0	15.6	0	0.8	99
22	0	0	0	15.6	0	0	15.6
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0

TABLE 7.—L1 1 SATELLITE MAXIMUM OUTAGE TIME PERFORMANCE

Carrier to noise density, dB/Hz	BeiDou	Galileo	GLONASS	GPS	IRNSS	QZSS	All
15	45	98	134	111	N/A	Max SD	39
16	45	98	134	111	N/A	Max SD	39
17	45	98	134	111	N/A	Max SD	39
18	45	98	134	111	N/A	Max SD	39
19	45	98	134	111	N/A	Max SD	39
20	70	98	Max SD	111	N/A	Max SD	49
21	Max SD	98	Max SD	Max SD	N/A	Max SD	98
22	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	Max SD
23	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	Max SD
24	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	Max SD
25	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	Max SD

TABLE 8.—L5 1 SATELLITE MAXIMUM OUTAGE TIME PERFORMANCE

Carrier to noise density, dB/Hz	BeiDou	Galileo	GLONASS	GPS	IRNSS	QZSS	All
15	7	55	35	77	Max SD	Max SD	0
16	7	55	35	77	Max SD	Max SD	0
17	7	55	35	77	Max SD	Max SD	0
18	7	55	35	77	Max SD	Max SD	0
19	7	55	35	77	Max SD	Max SD	0
20	7	55	35	77	Max SD	Max SD	0
21	7	55	Max SD	77	Max SD	Max SD	1
22	Max SD	Max SD	Max SD	77	Max SD	Max SD	77
23	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD
24	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD
25	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD

TABLE 9.—L1 4 SATELLITE MAXIMUM OUTAGE TIME PERFORMANCE

Carrier to noise density, dB/Hz	BeiDou	Galileo	GLONASS	GPS	IRNSS	QZSS	All
15	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	97
16	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	97
17	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	97
18	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	97
19	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	99
20	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	223
21	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	Max SD
22	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	Max SD
23	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	Max SD
24	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	Max SD
25	Max SD	Max SD	Max SD	Max SD	N/A	Max SD	Max SD

TABLE 10.—L5 4 SATELLITE MAXIMUM OUTAGE TIME PERFORMANCE

Carrier to noise density, dB/Hz	BeiDou	Galileo	GLONASS	GPS	IRNSS	QZSS	All
15	644	Max SD	2252	1180	Max SD	Max SD	35
16	644	Max SD	2252	1180	Max SD	Max SD	35
17	644	Max SD	2252	1180	Max SD	Max SD	35
18	644	Max SD	2252	1180	Max SD	Max SD	35
19	644	Max SD	2252	1180	Max SD	Max SD	35
20	644	Max SD	2252	1180	Max SD	Max SD	35
21	644	Max SD	Max SD	1180	Max SD	Max SD	62
22	Max SD	Max SD	Max SD	1180	Max SD	Max SD	1180
23	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD
24	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD
25	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD	Max SD

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