Individual Global Navigation Satellite Systems in the Space Service Volume

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BIOGRAPHY

Dale A. Force is an electronics engineer at NASA Glenn Research Center studying the use of Global Satellite Navigation Systems for navigating satellites. He received the B.S. and M.S. degrees in Physics from Michigan State University and an M. E. degree in electrical engineering from the University of Utah.

ABSTRACT

Besides providing position, navigation, and timing (PNT) to terrestrial users, GPS is currently used to provide for precision orbit determination, precise time synchronization, real-time spacecraft navigation, and three-axis control of Earth orbiting satellites. With additional Global Navigation Satellite Systems (GNSS) coming into service (GLONASS, Beidou, and Galileo), it will be possible to provide these services by using other GNSS constellations.

The paper, "GPS in the Space Service Volume", presented at the ION GNSS 19th International Technical Meeting in 2006 [1], defined the Space Service Volume, and analyzed the performance of GPS out to seventy thousand kilometers. This paper will report a similar analysis of the performance of each of the additional GNSS and compare them with GPS alone.

The Space Service Volume, defined as the volume between three thousand kilometers altitude and geosynchronous altitude, as compared with the Terrestrial Service Volume between the surface and three thousand kilometers. In the Terrestrial Service Volume, GNSS performance will be similar to performance on the Earth's surface. The GPS system has established signal requirements for the Space Service Volume.

A separate paper presented at the conference covers the use of multiple GNSS in the Space Service Volume.

INTRODUCTION

Although GNSS were created to provide position, velocity and timing (PVT) for terrestrial applications, they can also provide PVT to Earth orbiting satellites. GPS is already being widely used for this purpose, having first flown onboard Landsat 4 in 1982 [2].

For satellites operating in low earth orbit (LEO), GNSS receivers will see signal that are similar to those seen by terrestrial users, apart from the high dynamic effects due to orbital velocity. They can receive signals through a zenith-pointing antenna because they are within the primary transmitted beam of the GNSS satellites. For GNSS use, LEO extends to beyond 3,000 km.

For satellites in higher orbits, a zenith-pointing antenna can receive fewer signals, since the satellite will be outside the main beam of many satellites. Above GNSS altitude, of course, the number of signals received from above the satellite will be zero. However, GNSS can still be used for PVT at these altitudes by taking advantage of tracking GNSS signals crossing the Earth's limb using a nadir-pointing antenna, as shown in Figure A, while satellites at intermediate altitudes can use a combination of zenith- and nadir- pointing antennas. Due to the increased range and reduced transmitter gain at the larger off-nadir angles, the signals will be much weaker than those available at the Earth's surface. However, specialized GPS receivers have demonstrated the increased acquisition and tracking sensitivity and integrated a navigation filter for state estimation when less than four satellites are available. Multi-constellation GNSS receivers for satellites are currently under development.

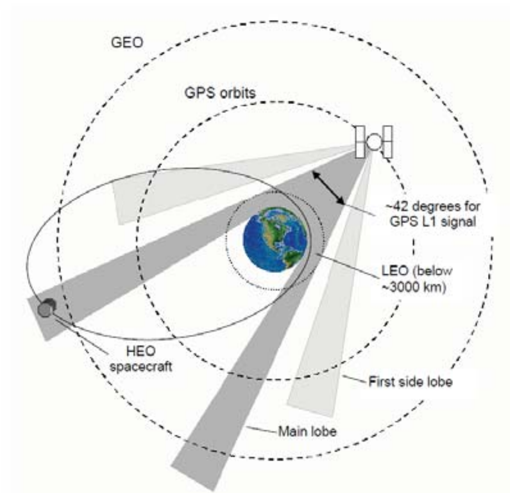

Figure A: Geometry for reception of GNSS signals by a HEO satellite [1].

SPACE SERVICE VOLUME

Based on the unique nature of GNSS signals as a function of altitude, requirements for GNSS spacecraft services can be allocated to two service volumes. The terrestrial service volume (TSV) includes all terrestrial and space GNSS users up to an altitude of 3,000 km, and the space service volume from 3,000 km to the approximate geostationary altitude of 36,000 km.

Terrestrial Service Volume: Users in the TSV enjoy uniform received powers and have fully overlapping coverage. The use of multiple GNSS will have some benefit due to the increased number of pseudoranges available although individual GNSS already provide very good coverage.

Space Service Volume: The SSV can be divided into two regions: (1) the medium earth orbit (MEO) SSV (3,000 km to 8,000 km), and (2) the HEO/GEO SSV (8,000 km to 36,000 km). Figure B illustrates the relationship between the three altitude regions described above. In the TSV, adequate coverage can be supplied by a zenith-pointing antenna; in the MEO region, a combination of zenith- and nadir- pointing antennas are needed, but even a single GNSS will often provide four-satellite coverage; in the HEO/GEO region nearly all GNSS signal will come from satellites transmitting across the Earth's limb.

Availability of GNSS services: Currently GPS provides promises of future signal strength and quality within guaranteed beamwidth out to GEO altitude [3].

Figure B: Terrestrial and Space Service Volumes [1].

SIGNAL AVAILABILITY

This section summarizes the analyses of multi-constellation GNSS availability for spacecraft navigation.

STK® simulations were used to evaluate the availability of GNSS signals for each of the new systems (GLONASS, Galileo, and Beidou) as well as GPS.

The GPS constellation used in the simulations is the 24+3 constellation currently planned for future availability. The GLONASS constellation is the current 24-satellite constellation. The Galileo constellation is the planned 24-satellite constellation. The Beidou constellation is the 24 MEO satellite portion.

The beamwidths used in the simulation are the committed GPS half-beamwidths of 23.5° for GPS L1 and 26° for GPS L2 and L5 [3]. Since beam data for Beidou and GLONASS are not available, we assume half-beamwidths of 23.5° for GLONASS L1 and Beidou B1; and 26° for GLONASS L2 and L3, Beidou B2 and B3, similar to GPS beamwidths. The published Galileo IOV antenna data show somewhat narrower beams (appropriate for their higher altitude) so we used 24° for the half-beamwidth of E5 and E6 and 20° for the half-beamwidth of E1 [4].

An earth atmosphere mask was applied requiring signals to pass at least 50 km above WGS84. While ionospheric effects can be important for signals passing less than 1,000 km above the earth's surface, all GNSS satellites transmit multiple frequency signals through this region allowing multi-frequency receivers to correct for ionospheric effects.

Table A – Simulated Altitudes

Altitude	Comment
300 km	Typical LEO Altitude
3,000 km	Border between TSV and SSV
8,000 km	Border between medium and high orbit service
15,000 km	Within high orbit service, below GNSS altitude
25,000 km	Within high orbit service, above GNSS altitude
36,500 km	Approximate GEO altitude
70,000 km	Approximately twice GEO altitude

At each altitude, a grid of approximately 2,000 evenly spaced points was generated covering all latitudes and longitudes, as shown in Figure C below. For each grid point, the GNSS constellations were propagated forward in time 48 hours (in 60-second steps) and line of sight vectors were evaluated for each step in time. The products of a run were time histories of GNSS satellites visible. From this availability, statistics were calculated, giving the following metrics:

- Availability of at least 1 and of at least 4 GNSS satellites, both for an average point and for the worst point
- Duration of longest single-fold outages (intervals when no satellite visible)
- Duration of longest four-fold outages (intervals when less than four satellites were visible)
- Minimum, average, and maximum number of satellites visible

Table B – 300 km Altitude

	GPS	GLONASS	Galileo	Beidou
1+ (%)	100	100	100	100
4+ (%)	100	100	100	100
<1 (s)	0	0	0	0
<4 (s)	0	0	0	0
Min. (#)	10	14	12	12
Ave. (#)	14.3	15.2	12.7	12.5
Max.(#)	19	18	17	17

Table C – 3,000 km Altitude

	GPS	GLONASS	Galileo	Beidou
1+ (%)	100	100	100	100
4+ (%)	100	100	100	100
<1 (s)	0	0	0	0
<4 (s)	0	0	0	0
Min. (#)	16	15	16	18
Ave. (#)	20.9	18.0	18.7	18.7
Max.(#)	24	22	20	20

Table D – 8,000 km Altitude

	GPS	GLONASS	Galileo	Beidou
1+ (%)	100	100	100	100
4+ (%)	99.9+	99.9	100	100
<1 (s)	0	0	0	0
<4 (s)	595	706	0	0
Min. (#)	3	3	4	5
Ave. (#)	9.6	7.5	9034	9.9
Max.(#)	15	12	12	12

Table E – 15,000 km Altitude

	GPS	GLONASS	Galileo	Beidou
1+ (%)	99.9+	97.3	98.8	98.6
4+ (%)	80.0	61.6	68.7	75.2
<1 (s)	604	2,395	2,502	2,083
<4 (s)	8,289	7,247	7,581	5,405
Min. (#)	0	0	0	0
Ave. (#)	4.7	3.8	3.6	4.6
Max.(#)	10	9	8	9

Table F – 25,000 km Altitude

	GPS	GLONASS	Galileo	Beidou
1+ (%)	99.4	98.7	99.9	99.98
4+ (%)	36.0	19.6	15.8	24.6
<1 (s)	3,158	1,069	414	262
<4 (s)	30,166	28,692	79,839	25,283
Min. (#)	0	0	0	0
Ave. (#)	3.1	2.6	2.7	3.0
Max.(#)	8	6	6	6

Table G – 36,500 km Altitude Low Frequency Signals

	GPS	GLONASS	Galileo	Beidou
1+ (%)	97.0	94.0	94.9	90.2
4+ (%)	15.6	9.6	5.4	8.0
<1 (s)	9,763	2,194	3,024	1,649
<4 (s)	72,272	Never	Never	Never
Min. (#)	0	0	0	0
Ave. (#)	2.4	2.1	2.0	2.3
Max.(#)	6	6	4	5

Table H – 70,000 km Altitude

	GPS	GLONASS	Galileo	Beidou
1+ (%)	89.6	79.9	79.2	85.1
4+ (%)	2.8	4.7	2.4	3.2
<1 (s)	Never	4,013	Never	4,763
<4 (s)	Never	Never	Never	Never
Min. (#)	0	0	0	0
Ave. (#)	1.7	1.4	1.4	1.6
Max.(#)	6	4	4	4

CONCLUSIONS AND SUMMARY

The results clearly show the increased availability and reduced outage durations from using multiple GNSS for spacecraft PVT at the higher altitudes. At lower altitudes, the increase in number of GNSS satellites in view will allow more accurate PVT, even though the use of multiple GNSS constellations is not necessary to prevent outages.

ACKNOWLEDGMENT

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ACRONYMS

AGI	Analytical Graphics, Inc.
GEO	Geosynchronous Earth Orbit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HEO	Highly Elliptical Orbit
IOV	In Orbit Validation
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
NASA	National Aeronautics & Space Administration
PNT	Position, Navigation, and Timing
PVT	Position, Velocity, and Timing
SCaN	Space Communication and Navigation
SSV	Space Service Volume
STK®	Satellite ToolKit
TSV	Terrestrial Service Volume

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[1] Bauer, F. H., et. al., "The GPS Space Service Volume', Proceedings of the ION GNSS-2006, Fort Worth, TX, Sept. 2006.

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[3] Anon., Global Positioning System Directorate Systems Engineering & Integration Interface Specification, IS-GPS-200 Revision F, Sept. 21, 2011.

[4] Monjas, Fernando, et. al., "Test Campaign of the IOV (In Orbit Validation) Galileo System Navigation Antenna for Global Positioning", 2010 Proceedings of the Fourth European Conference on Antennas and Propagation (EuCAP).

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Besides providing position, velocity, and timing (PVT) for terrestrial users, the Global Positioning System (GPS) is also being used to provide PVT information for earth orbiting satellites. In 2006, F. H. Bauer, et. al., defined the Space Service Volume in the paper “GPS in the Space Service Volume”, presented at ION’s 19th international Technical Meeting of the Satellite Division, and looked at GPS coverage for orbiting satellites. With GLONASS already operational, and the first satellites of the Galileo and Beidou/COMPASS constellations already in orbit, it is time to look at the use of the new Global Navigation Satellite Systems (GNSS) coming into service to provide PVT information for earth orbiting satellites. This presentation extends “GPS in the Space Service Volume” by examining the individual coverage capability of each of the new constellations, as well as updating the original paper for the current GPS constellation.

GPS was first explored as a system for refining the position, velocity, and timing of other spacecraft equipped with GPS receivers in the early eighties. Because of this, a new GPS utility developed beyond the original purpose of providing position, velocity, and timing services for land, maritime, and aerial applications. GPS signals are now received and processed by spacecraft both above and below the GPS constellation, including signals that spill over the limb of the earth. Support of GPS space applications is now part of the system plan for GPS, and support of the Space Service Volume by other GNSS providers has been proposed to the UN International Committee on GNSS (ICG). GPS has been demonstrated to provide decimeter level position accuracy in real-time for satellites in low Earth orbit (centimeter level in non-real-time applications). GPS has been proven useful for satellites in geosynchronous orbit, and also for satellites in highly elliptical orbits.

Depending on how many satellites are in view, one can keep time locked to the GNSS standard, and through that to Universal Time as long as at least one satellite is in view (the longest duration with no satellites in view is important in determining the maximum clock drift from GNSS time). Instantaneous position requires four satellites in view, but because orbital motion is predictable, it is possible to build up knowledge of the orbital position gradually through time without a need for constant four satellite coverage. However, it is desirable to have four satellite coverage when performing satellite maneuvers, since there can be significant changes in velocity, leading to large changes in orbit parameter, causing substantial divergence in position over time.

The Space Service Volume has been defined as the volume between three thousand km altitude and geosynchronous altitude, and can be divided into medium orbit services between three thousand km altitude and eight thousand km altitude, and high orbit services above eight thousand km. The Terrestrial Service Volume includes the Earth’s surface, the atmosphere, and space below the altitude of three thousand km. The Terrestrial Service Volume is the volume within which the GNSS systems will have very similar performance to the Earth surface, and satellites need only use the signals specified to provide terrestrial performance. Above three thousand km the use of signals passing by the Earth’s limb becomes important, so it is desirable to have additional information on signal strength, phase delay, and group delay covering wider beam angles than are needed for terrestrial service (and which can be obtained by monitoring GNSS signals from the Earth's surface).

The presentation will largely follow the format of "GPS in the Space Service Volume", presenting data on the availability of one, two, three, or four of the particular GNSS constellation satellites at approximately two thousand grid points evenly spaced and fixed in longitude and latitude, the duration of the longest single-fold outages (intervals when no satellites are available), and the duration of the longest four-fold outages (intervals when fewer than four satellites are available) at several altitudes. Following the original paper, we will use the altitudes of three hundred km (typical LEO satellite, and within the Terrestrial Service Volume), at three thousand km (border between Terrestrial Service Volume and Space Service Volume), at eight thousand km (the border between medium and high orbit service within the Space Service Volume), at fifteen thousand km (just below the GNSS constellations), at twenty five thousand km (just above the GNSS constellations), at thirty six thousand, five hundred km (limit of Space Service Volume definition, geosynchronous altitude), and at seventy thousand km (to show the potential usefulness of GNSS beyond geosynchronous altitude).

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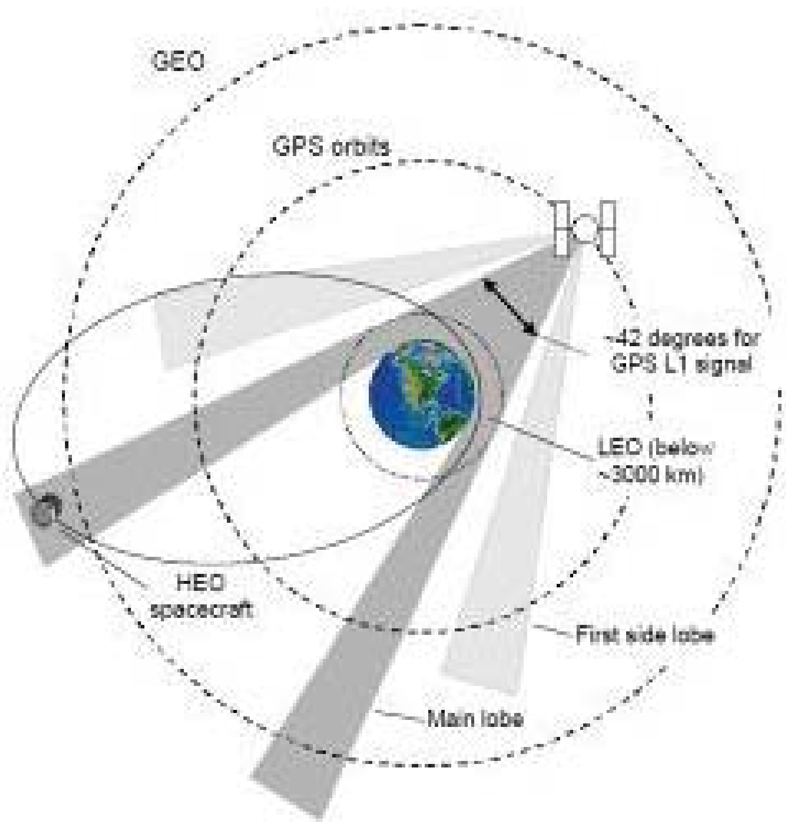
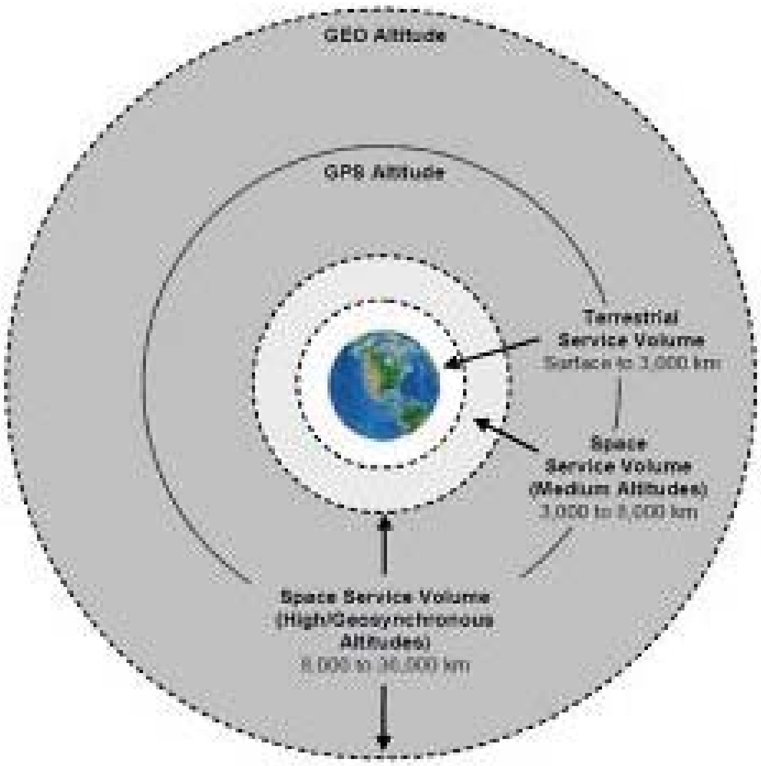
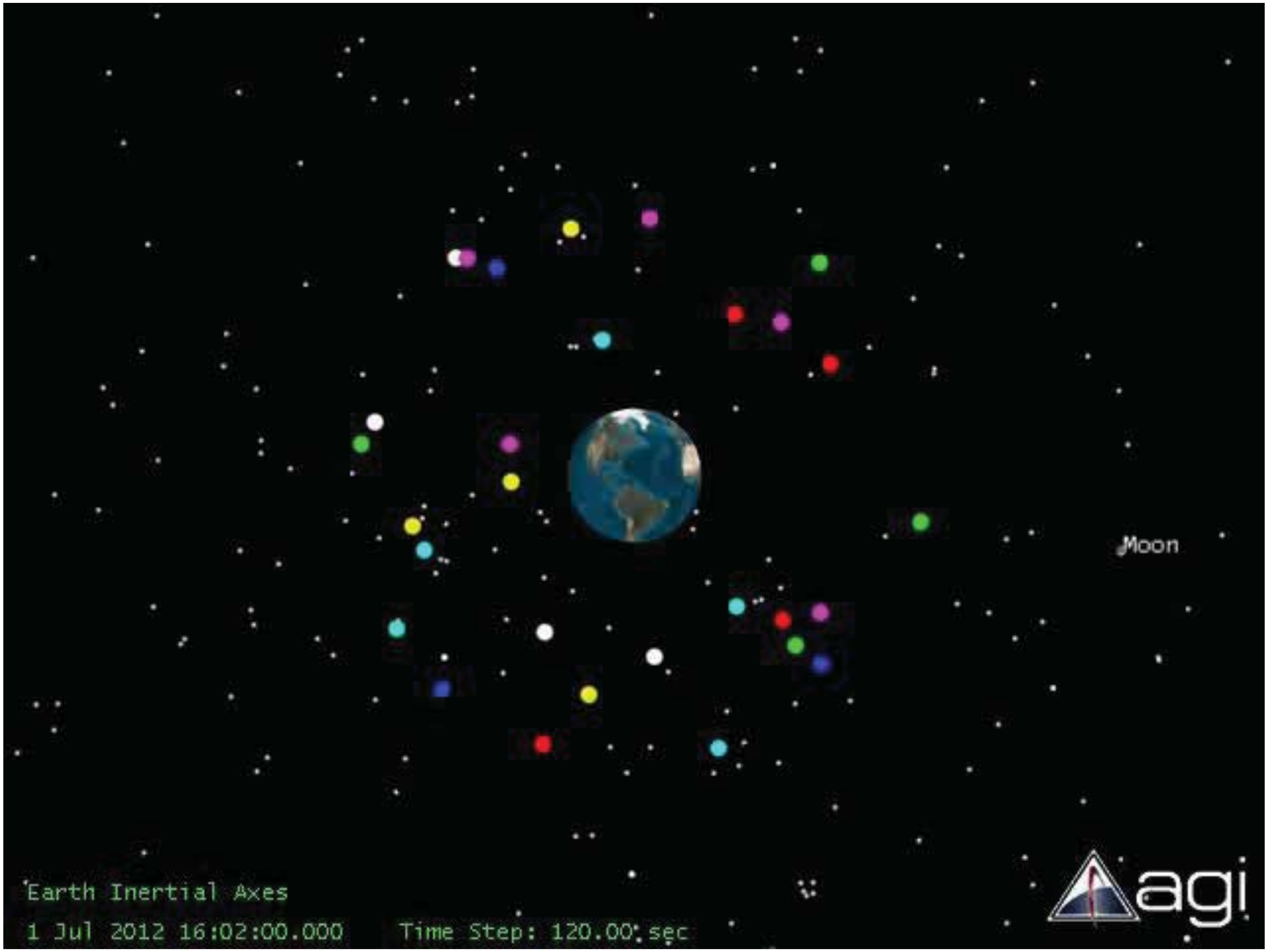
Geometry of reception of GNSS signals by satellites



Terrestrial and Space Service Volumes

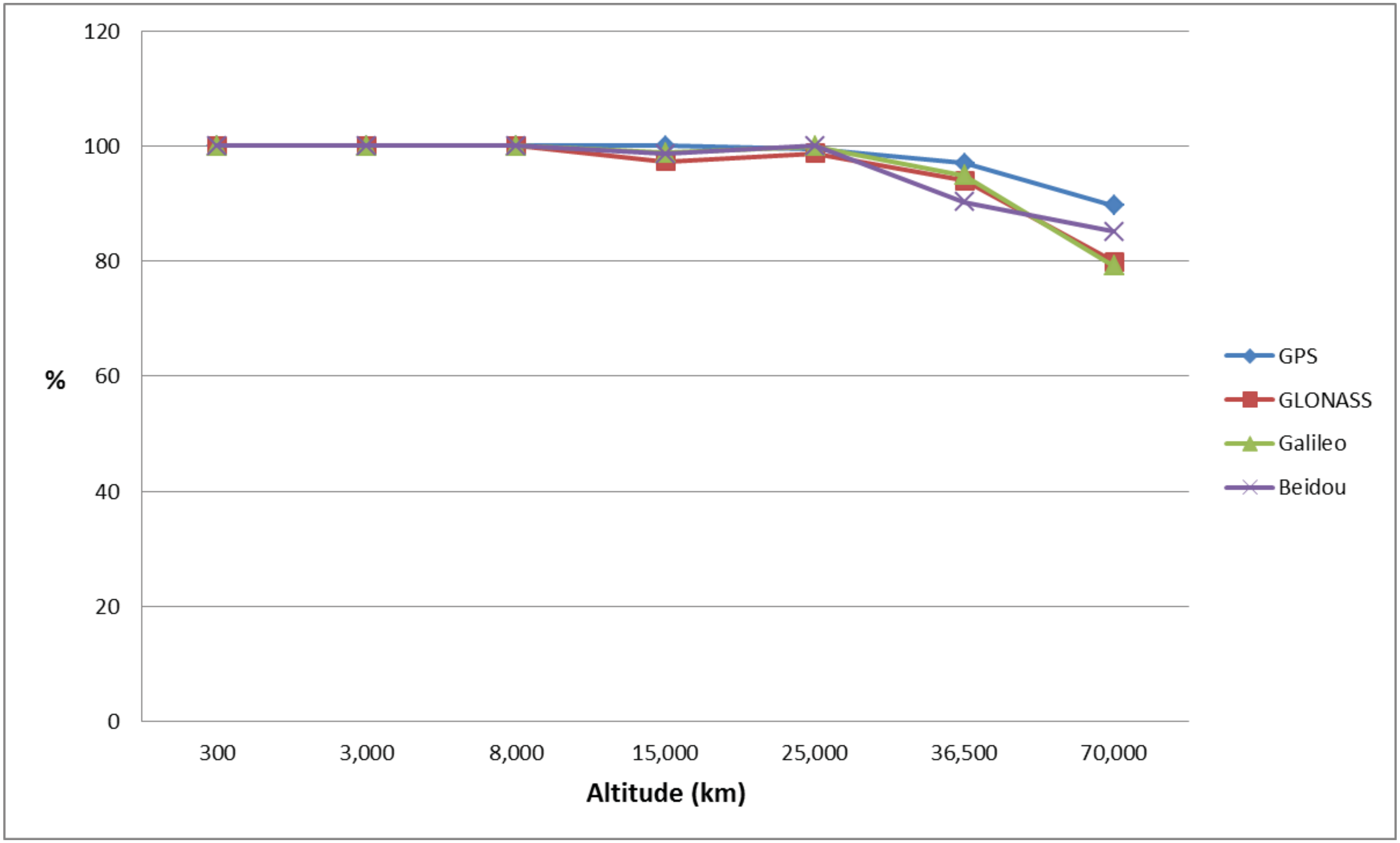


GPS Constellation

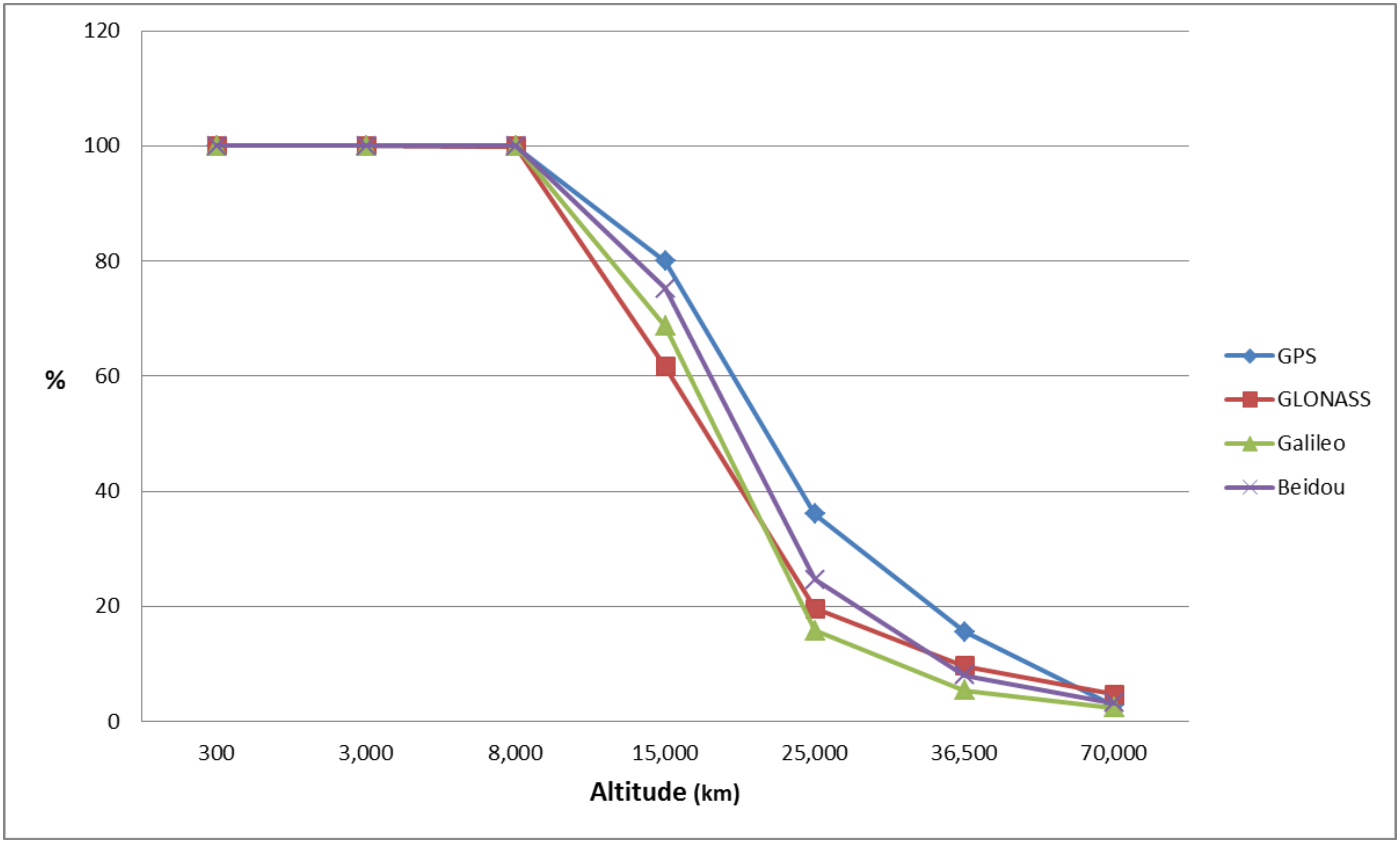


GLONASS Constellation

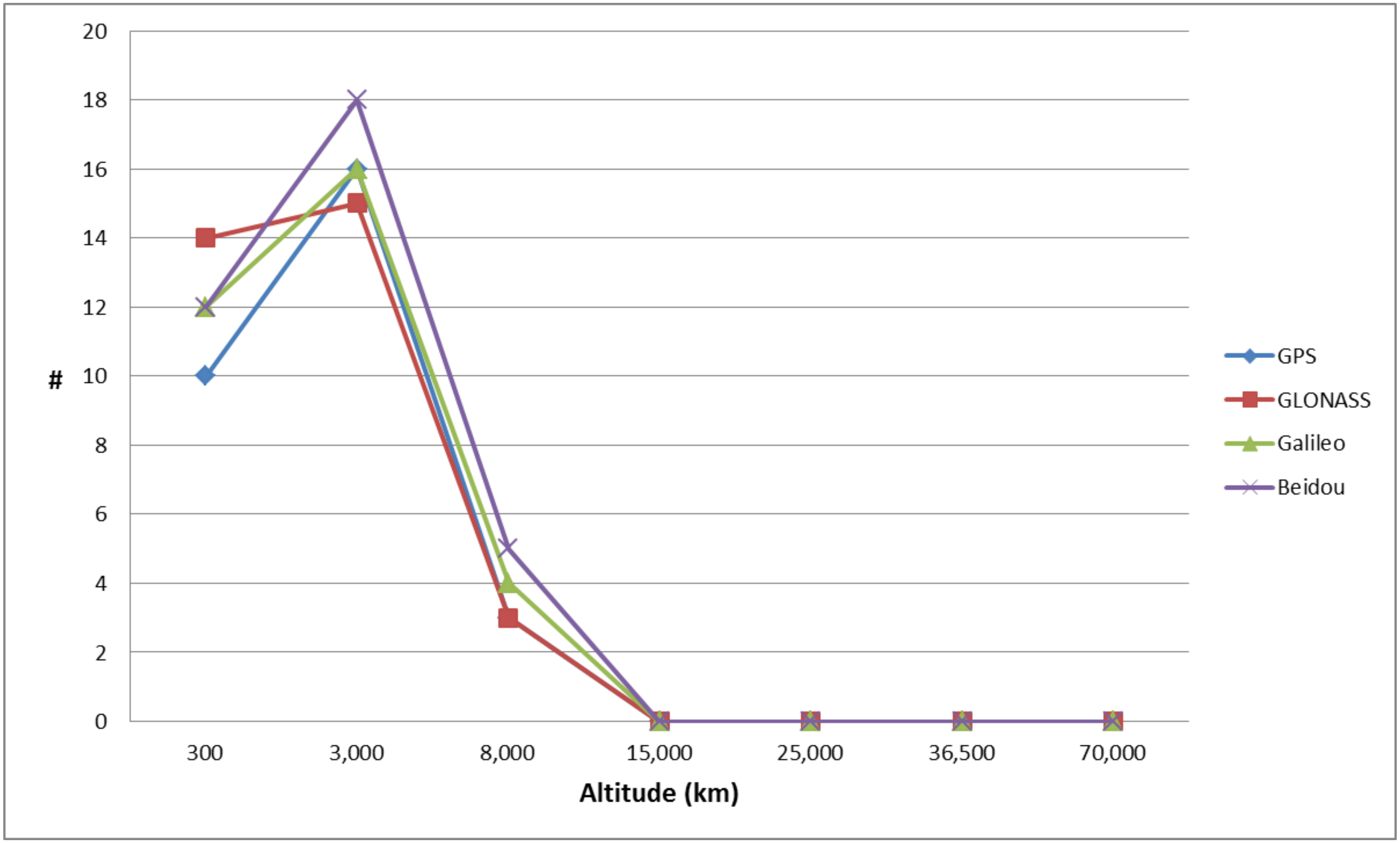
Single-fold GNSS coverage



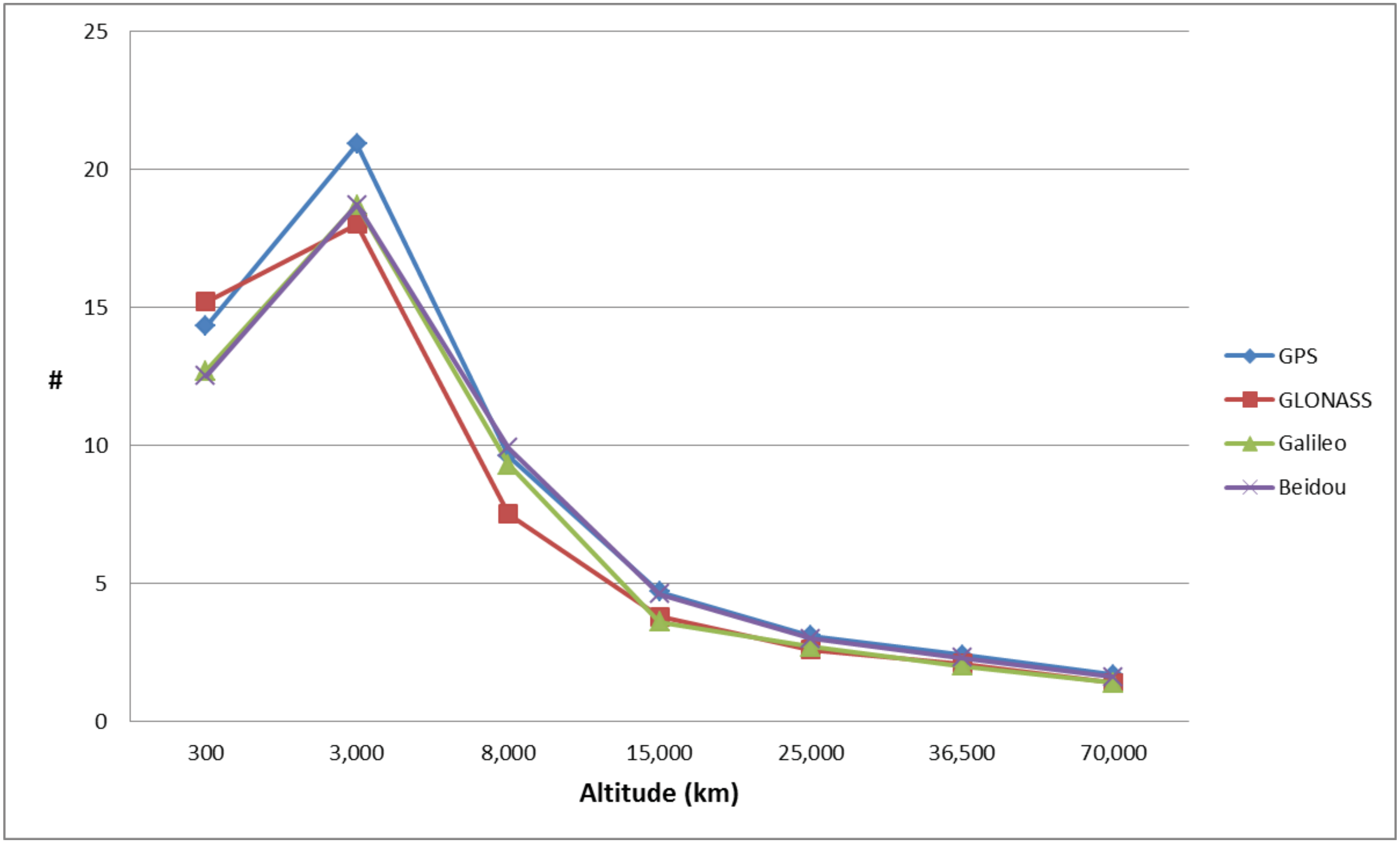
Four-fold GNSS Coverage



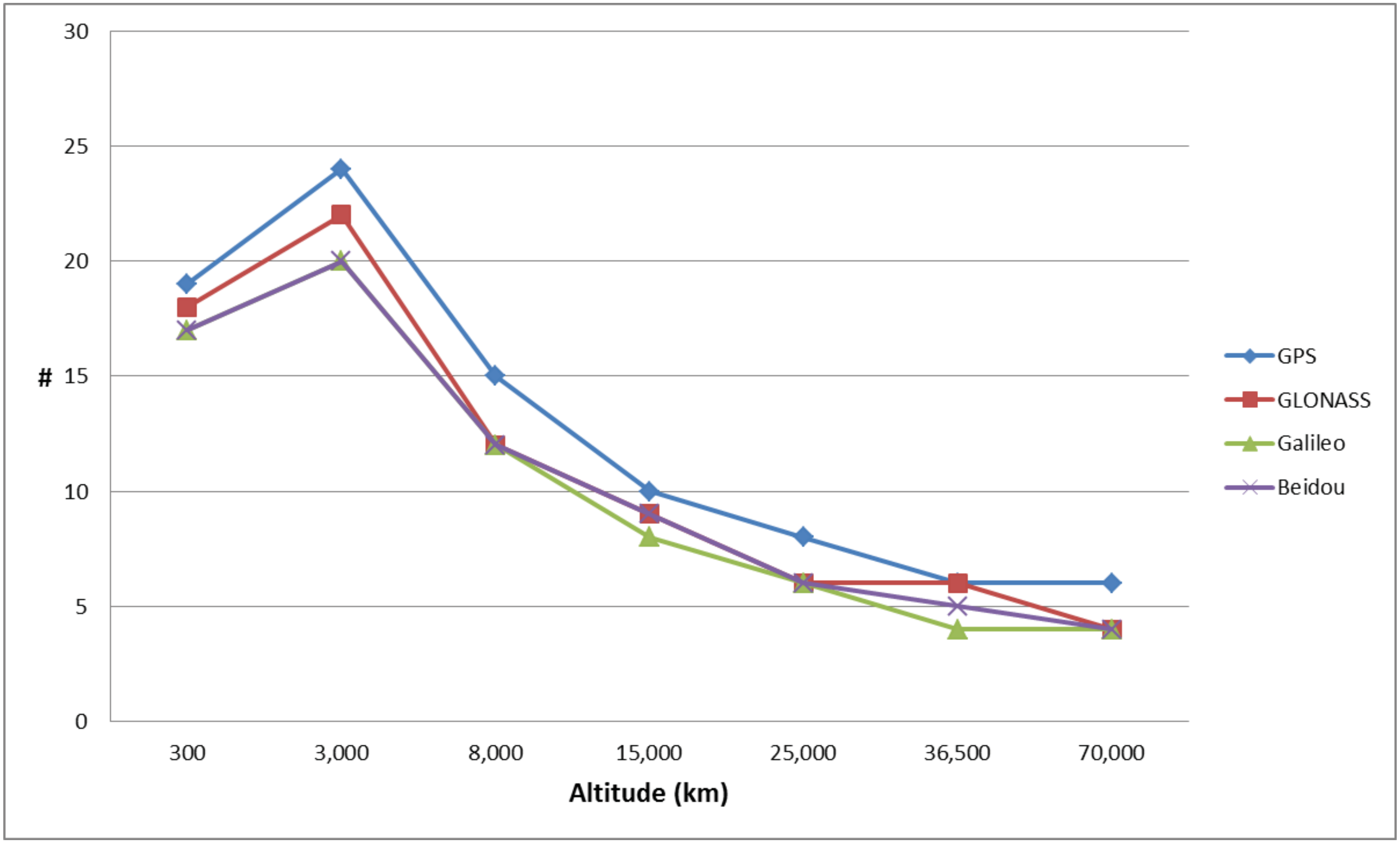
Minimum Number of GNSS Satellites Providing Coverage



Average Number of GNSS Satellites Providing Coverage



Maximum Number of GNSS Satellites Providing Coverage



GPS Coverage at GEO Level