Navigation Performance of 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 Navigation Satellite Systems in spacecraft navigation. 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. He is a member of the Institute of Navigation, the Institute of Electrical and Electronics Engineers, and the American Physical Society.

ABSTRACT

This paper extends the results I reported at this year's ION International Technical Meeting [1] on multi-constellation GNSS coverage by showing how the use of multi-constellation GNSS improves Geometric Dilution of Precision (GDOP).

Originally developed to provide position, navigation, and timing for terrestrial users, GPS has found increasing use for in space for precision orbit determination, precise time synchronization, real-time spacecraft navigation, and three-axis attitude control of Earth orbiting satellites. With additional Global Navigation Satellite Systems (GNSS) coming into service (GLONASS, Galileo, and Beidou) and the development of Satellite Based Augmentation Services, it is possible to obtain improved precision by using evolving multi-constellation receiver.

The Space Service Volume (originally defined in [2]) is formally defined as the volume of space between three thousand kilometers altitude and geosynchronous altitude (~36,500 km), with the volume below three thousand kilometers defined as the Terrestrial Service Volume (TSV).

The USA has established signal requirements for the Space Service Volume (SSV) as part of the GPS Capability Development Documentation (CDD). Diplomatic efforts are underway to extend Space service Volume commitments to the other Position, Navigation, and Timing (PNT) service providers in an effort to assure that all space users will benefit from the enhanced capabilities of interoperating GNSS services in the space domain.

INTRODUCTION

GNSS use in the Space Service Volume has unique requirements. As the spacecraft's altitude increases, the number of signals received form above decreases, until it becomes zero when the spacecraft is above the GNSS constellations. However, it becomes possible to receive many signals that cross the Earth's limb, as shown in Figure A. Due to the increased range and reduced transmitter gain at the larger off-nadir angles, the signals received at the spacecraft will be much weaker than the signals available at the Earth's surface.

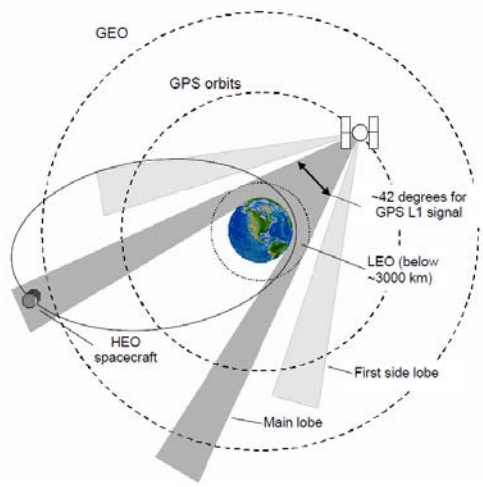

Figure A: Geometry for reception of GNSS signals by a HEO satellite [2].

However, specialized GPS receivers have demonstrated the increased acquisition and tracking sensitivity and integrate a navigation filter for state estimation when less than four satellite coverage is available. Multi-constellation GNSS receivers for satellites are currently under development, and are already a fixture in terrestrial signal monitoring systems such as the International GNSS Service (IGS) managed by the NASA Jet Propulsion Laboratory (JPL).

TERRESTRIAL AND SPACE SERVICE VOLUMES

Figure B show the Terrestrial and Space Service Volumes. The divisions are due to signal reception

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geometry. In the terrestrial service volume, GNSS signals largely come from satellites above the spacecraft. In the space service volume at medium altitudes, signals come both from satellites above the spacecraft and from those beyond the Earth's limb. Finally, in the high altitude space service volume signals largely come from beyond the Earth's limb.

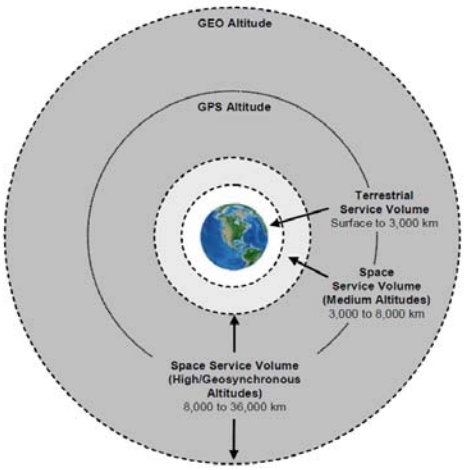

Figure B: Terrestrial and Space Service Volumes [2].

GNSS SATELLITES CONSIDERED

For the simulations reported in this paper, I considered the following GNSS:

1) Global Positioning System (GPS), the 24+3 configuration [2]
2) Galileo, the planned 27-satellite configuration [3]
3) Global Navigation Satellite System (GLONASS), the current 24-satellite configuration [4]
4) Beidou, the planned 27 MEO, 5 GEO, and 3 IGSO constellation [5]

I also included the following Satellite Based Augmentation Services (SBAS):

1) Wide Area Augmentation Service (WAAS) in the current three satellite configuration (USA) [6]
2) European Geostationary Navigation Overlay Service (EGNOS) in the current three satellite configuration [7]
3) System of Differential Correction and Monitoring (SDCM) in the planned three satellite configuration (Russia) [8]
4) Quasi Zenith Satellite System (QZSS) in the planned three satellite configuration (Japan) [9]
5) GPS Aided Geo Augmented Navigation system (GAGAN), first satellite only (India) [4]

I did not consider the Japanese MTSAT Satellite Augmentation System (MSAS) assuming that QZSS will replace it in the future.

ASSUMPTIONS

I did the calculations for the L1 band, since this is the most commonly implemented and with its narrower beam is the most conservative choice.

The US has committed to minimum signal levels for the L1 signal within a 23.5° beam, so I use that for the GPS beam. I assume a 23.5° beam for the GLONASS and the Beidou MEO satellite beams as well. I use a 22° beam for the Galileo satellites based on published data. [10]

The WAAS and EGNOS systems use a 9° beam [], which I have also assumed for the SDCM, QZSS, GAGAN, and SDCM beams, with the SDCM beam tilted 7° toward the north [8]. I also assume a 9° beam for the Beidou GSO and IGSO satellites.

In considering interference, I assume that the GLONASS system maintains the current FDMA frequencies, which do not interfere with the other L1 systems due to the frequency offset. The calculations also treat the L1 CDMA signals as noise in the GNSS receivers.

PREVIOUS RESULTS

To provide context for the results from this study, I present a graph of GNSS coverage vs. altitude from my previous work [1] in Figure C.

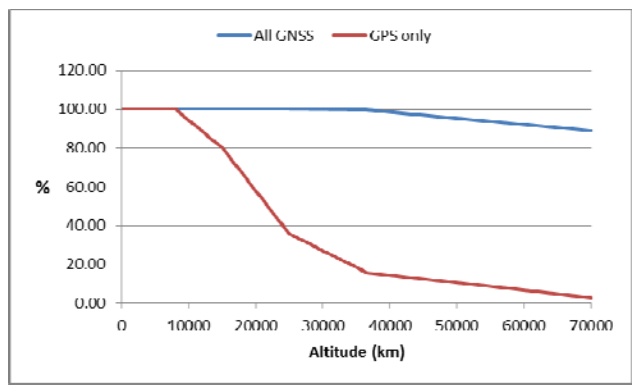

Figure C: Covereage by four or more satellite beams vs. altitude

CURRENT RESULTS

I calculated the Geometric Dilution Of Precision (GDOP) in Satellite ToolKit (STK) 9. The solutions were overdetermined, using all available satellites, which is why GDOP is below one at lower altitudes, where typically there are much more than four satellite signal available.

At each altitude, I generated a grid of approximately 2,000 evenly spaced points covering all latitudes and longitudes. For each grid point, the GNSS constellations were propagated forward in time for 24

hours (in 60-second increments) and the GDOP calculated for all points where at least four satellite signals were available.

The averages only include points where at least four satellite signals were available, so at higher altitudes the value of multi-constellation GNSS is greater than the graph show, since they do not include the increased number of points where an instantaneous solution is available.

I present the results for the altitudes of 300 km, 3000 km, 8000km, 15000 km, 25000 km, 36500 km (GEO), and 70000 km in Figures D-J.

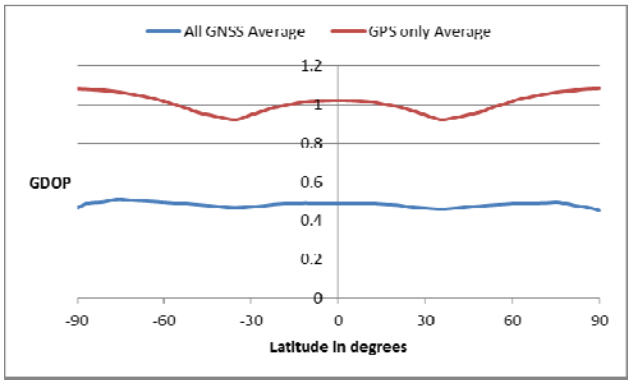

Figure D: average GDOP vs. latitude 300 km altitude

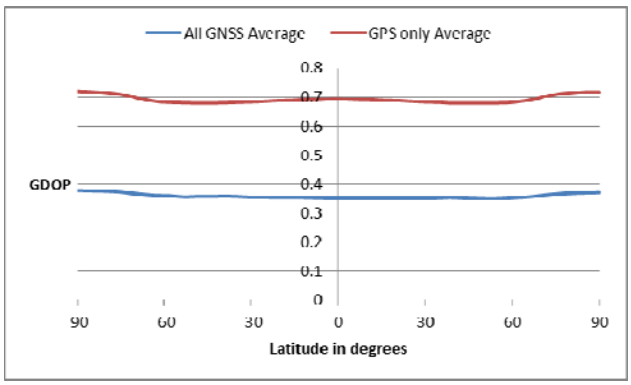

Figure E: average GDOP vs. latitude 3,000 km altitude

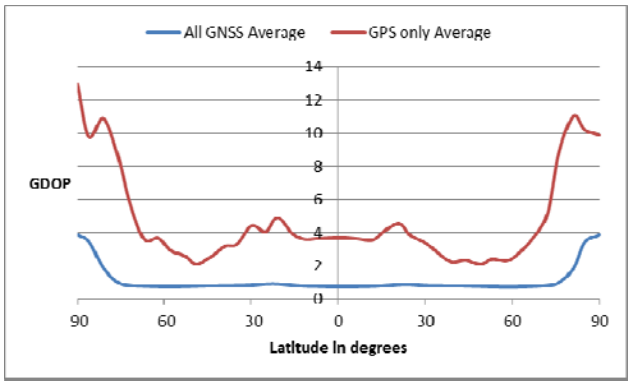

Figure F: average GDOP vs. latitude 8,000 km altitude

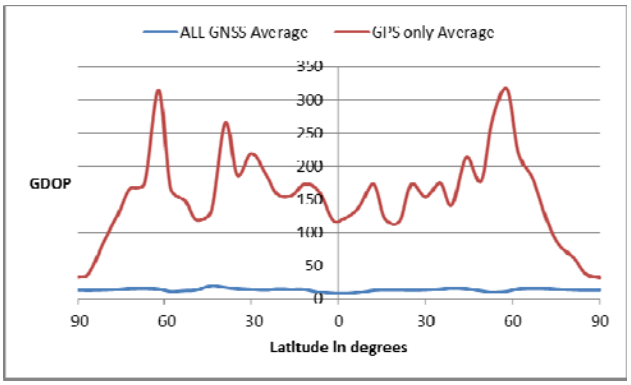

Figure G: average GDOP vs. latitude 15,000 km altitude

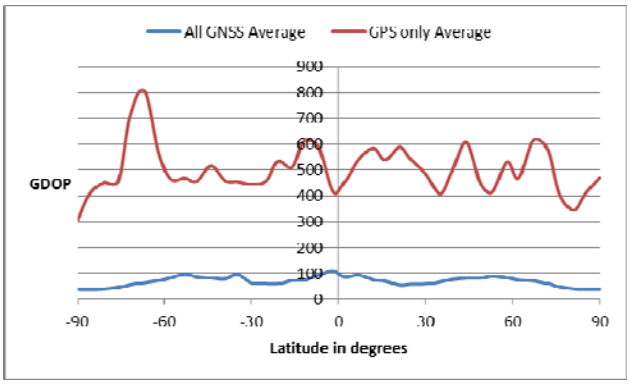

Figure H: average GDOP vs. latitude 25,000 km altitude

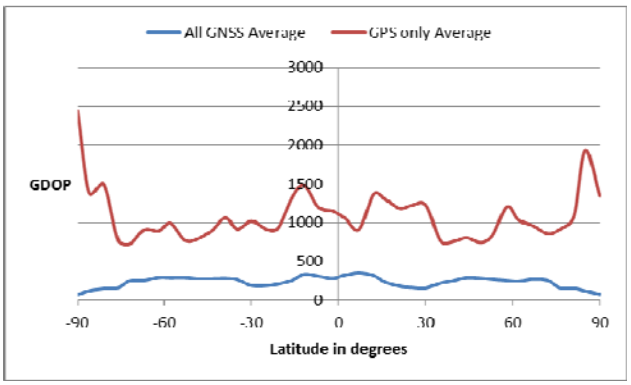

Figure I: average GDOP vs. latitude 36,500 km altitdue (GSO)

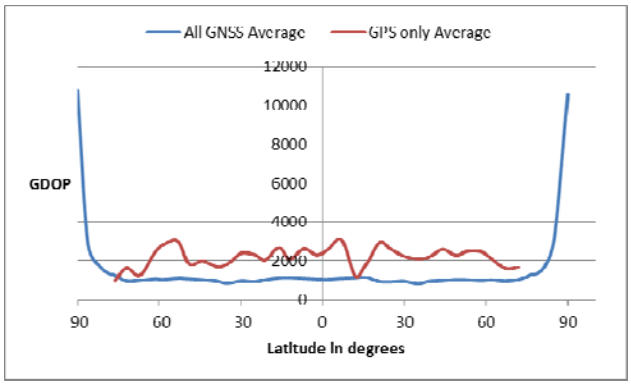

Figure J: average GDOP vs. latitude 70,000 km altitude

CONCLUSIONS

The graphs show that typically the use of multi-constellation GNSS navigation improves GDOP by a factor of two or more over GPS alone. In addition, at higher altitudes, obtaining four satellite solutions is much more common. Indeed, at 70,000 km altitude GPS alone never provides four-satellite coverage at high latitudes.

However, mission planning requires a commitment that sufficiently strong signals will be available in the future, such as the US has made and is seeking form other providers.

For actual navigation use, besides the commitment to provide adequate signal strength, it is valuable to provide data on the variation of group and phase delay over the beam, allowing improved navigation solutions. I hope the data presented here encourages other providers to provide beam data on their current satellites and commitments for future satellites.

ACKNOWLEDGMENTS

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