GNSS Performance Possibilities

Adam Gorski and Greg Gerten
Analytical Graphics, Inc. 220 Valley Creek Blvd.
Exton, PA 19341   610.981.8224
agorski@agi.com, ggerten@agi.com

Biography

Greg Gerten is the navigation and electronic warfare (EW) point of contact for Analytical Graphics, Inc. (AGI). He received his Master's Degree in electrical engineering from the University of Dayton, including graduate courses in GPS at the Air Force Institute of Technology. He has more than 10 years experience in constructive mission simulation development in the areas of communications, navigation warfare, EW tactics, and weapon effectiveness. He has been responsible for the design, development, and deployment of several NAVWAR simulations and has been involved in using these models to support numerous trades' analysis and campaign studies.

Adam Gorski is the lead systems engineer for AGI in the United Kingdom. He received his Bachelor's Degree in aeronautical and astronautical engineering from the University of Illinois at Urbana-Champaign with a focus on satellite trajectory/astrodynamic analysis and satellite system design. He has supported customer applications in the United States and across the world and trained engineers from numerous countries and backgrounds in the use of advanced AGI software tools.

Key Words

GNSS, Performance Analysis, Augmentation, Accuracy, PDOP, System Modeling

Abstract

There have been discussions over the past couple years of mission effectiveness and performance using multiple and interoperable Global Navigation Satellite Systems (GNSS). While each GNSS is making strides in even higher accuracy, availability, and continuity—there still exists concern over assured reliability and integrity when relying on one system, especially when factors such as interference are introduced.

This paper will discuss the advantages of using multiple systems and their added benefits on accuracy, availability, continuity, and integrity. Dr. Brad Parkinson will be the first to give you a list of GPS problems, but in this paper we will investigate such events as clock run off, interference, and loss of service (for several reasons) and determine the quantitative benefits that several different Global Navigation Satellite Systems will provide. To give each system its fair shot, we will also provide results on how the same events would be handled using updated constellations (GPS III, Galileo, and Glonass-K) and next-generation ground control segments (OCX, Galileo OCS, Glonass SCC).

Table of Contents

1. Introduction

GNSS have become a key utility in much of the world's infrastructure. GNSS are being used not only as a primary source for accurate position and velocity information, but also as a source of important precise timing. From safety-of-life operations to space vehicle launches, GNSS are being employed to help users perform tasks faster, cheaper, and more accurately than before. As our infrastructure becomes more reliant on GNSS, the accuracy and integrity of these systems becomes increasingly important. However, there are significant repercussions if this fragile system is interrupted or suffers from interference [1].

Currently, users will see a loss in data if such outages occur, and the system will act as though it is confused but will give no warning of GNSS anomalies. When a power grid, cellular telephone tower, communications link tower, or any other system using GNSS for accurate time loses GNSS, the effects are not instantly realized. The bandwidth and system performance degrade as the backup clock begins to drift. Eventually, the system will have such poor performance that the system will discontinue and shut down, reference [2] and [3]. Systems such as weather balloons, uninhabited aerial vehicles, and other GNSS-equipped platforms using position data may become unusable at the onset of the anomaly. While GNSS is free and easy to use, interference with low power signals—whether unintentional or intentional—may cause large area outages.

While the current GNSS are so vulnerable to various losses and reliance on them increases across the globe, it is crucial to understand the performance possibilities of the numerous systems and their interoperability with each other and the various augmentation systems that may be required for the myriad use cases from military navigation to safety of life and civilian operations in constrained environments.

2. Problem Statement

As more satellite-based navigation systems enter operation, the modeling of these systems becomes more and more complex. While it becomes increasingly difficult to accurately model the widely varying constellation geometries, the increased number of active broadcasting signals makes analysis of these systems even more daunting (Figures 1 and 2). In addition to the difficulties in modeling the satellite vehicle performance on orbit, it is just as crucial to analyze the specific requirements and environmental considerations of unique user applications.

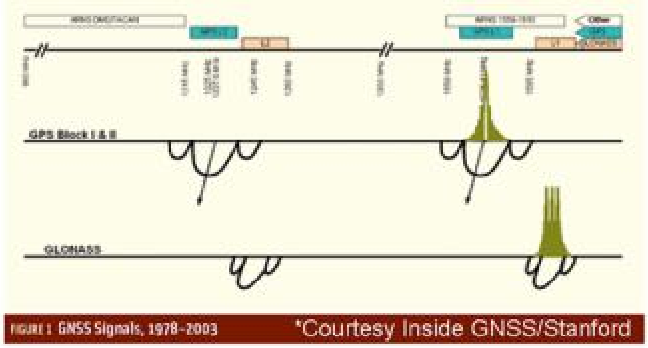

Figure 1. Today's GNSS Signals [4]

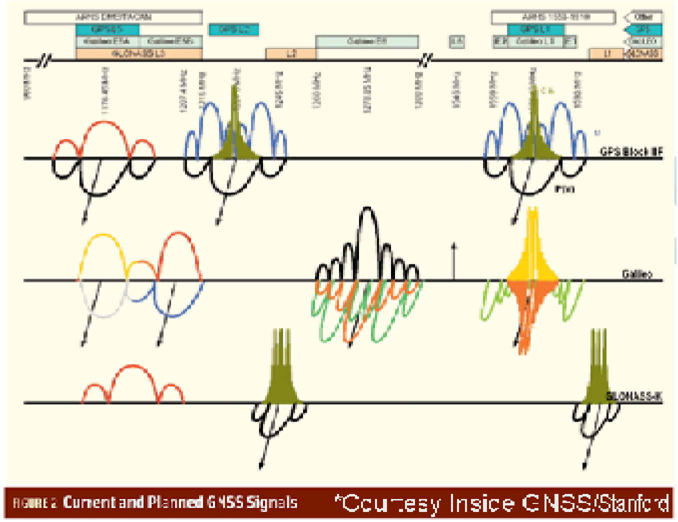

Figure 2. Future GNSS Signals [4]

In order to fully understand the current GNSS performance capabilities and determine efficient ways to improve upon them, it is necessary to quickly and comprehensively model the entire operational environment. Every GNSS provider or designer of user applications or equipment will need to be able to understand the effect of their component or service within the full system.

If every research institute, corporation, or performance assessment facility spent the time and resources to develop the necessary systems capable of modeling every aspect of the operational environment from ground control segment design to satellite engineering to user equipment performance, the loss of community-wide productivity would be devastating to the industry as a whole.

Fortunately, there exists commercially available off-the-shelf (COTS) simulation environments that have been validated and widely used for specifically this type of analysis. The rest of this paper will describe the methodology that we used to assess current and future performance possibilities of GNSS with the readily available Satellite Tool Kit (STK) software produced by Analytical Graphics, Inc. and how these tools can be used to asses system performance of not only the multitude of individual GNS Systems, but also the various augmentation systems and interoperability options that could be available.

3. System Modeling

In order to perform the complex performance assessment described above, the time-dynamic simulation environment of the STK geometry engine was implemented. At its core, STK uses a highly accurate model of the Earth and its dynamic position and orientation within the solar system as the basis for simulation. This allows for accurate computation of solar and celestial event modeling to be incorporated into the analyses being performed.

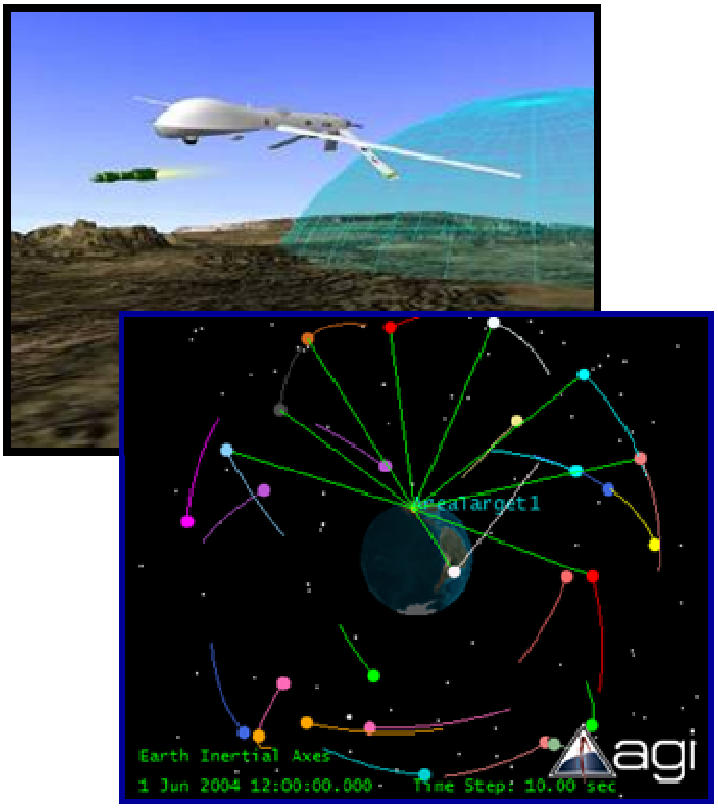

Figure 3. STK Analysis Environment

Around this dynamic model of the Earth ellipsoid, STK can model the position and orientation of satellites, facilities, and user platforms as they change over time. With performance-based methods of vehicle propagation, the movement of complex vehicles like jet aircraft and unmanned aerial vehicles can be quickly and easily modeled. Specifically, spacecraft can be propagated forward from ephemeris almanacs, Two Line Element sets (TLEs), real-time data, or custom orbital elements using analytical propagators or numerically integrated force models. This allows the analyst to answer the question, “Where are all the assets of the system over time?”

Once all of the satellites, ground stations, augmentation systems, and user locations or paths have been populated within an STK scenario, the software uses verified algorithms for determining inter-visibility analysis called ‘access.’ These inter-visibility calculations are based not just on the position and attitude of the assets but also on other positioned elements (sensors, antennas, etc.) defined by the analyst.

Additionally, there exists the capability within the STK environment to specify, on the objects in question, RF devices such as transmitters, receivers, and even radar systems. STK has a complex RF communications package capable of handling numerous modeled modulations as well as external spectrums, power levels, polarizations, antennas, data rates, filtering, and bandwidths. Antennas can be modeled by specifying physical attributes to a number of antenna types (Gaussian, parabolic, dipole, etc.) or by applying measured gain data or custom data through a plug-in to understand the performance of specific devices in the overall system. (Figure 4). This capability answers the question, “When can all the assets ‘see’ or ‘talk’ to one another?”

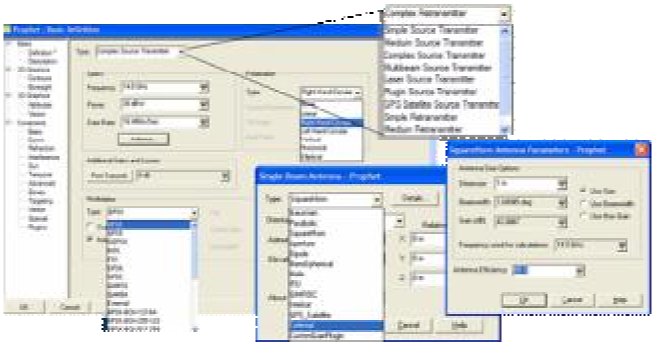

Figure 4: STK Transmitter Input Page

Finally, the software applies advanced constraints to the analysis environment to evaluate the quality of inter-object relationships. For instance, Digital Terrain Elevation Data (DTED) is used to compute terrain masking. Additionally, environmental effects can be added to the simulation. Atmospheric propagation models, rain models, cloud and fog models, tropospheric scintillation, effects of propagating over irregular terrain, and other plug-in models (custom attenuation models, for example) can all be added to understand the quality of signals between the numerous assets in a simulation. Recently, efforts to understand the effect of urban and indoor multipath effects have been embedded in STK with the Ray-Tracing Algorithms from Ergospace©. This allows us to model the effects/attenuation caused by the environment on the transmission path (Figure 5).

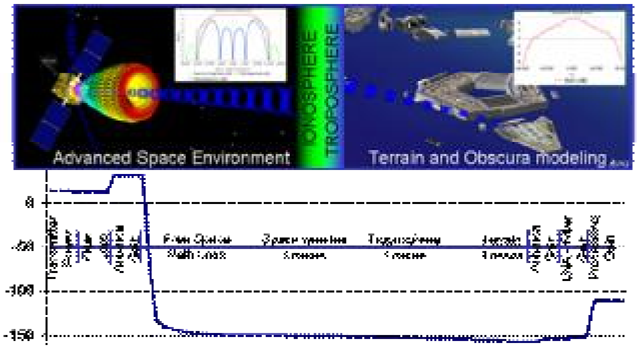

Figure 5: STK Path Loss Contributors

These effects could include any value from the complex link budget (EIRP, Path loss, Received Isotropic Power-RIP, power into the receiver, total RF power, J/S, power flux density, S/N, S/N+I, Eb/No, or even bit-error-rate BER). Any of these values can be put into a table, graphed, displayed dynamically in a strip-chart or on the 3D display as numerical data, or by coloring the route via a color contour (Figure 6).

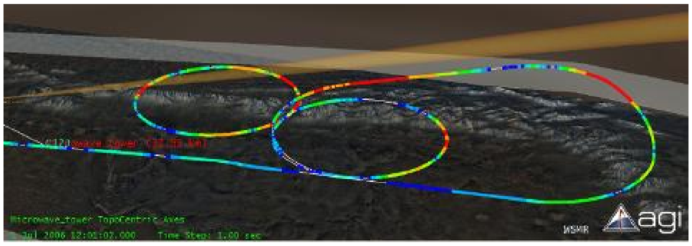

Figure 6: Power Received Route Coverage Contour

Another option would be to look at the interference impact over a region over time at altitude (3D) (Figure 7).

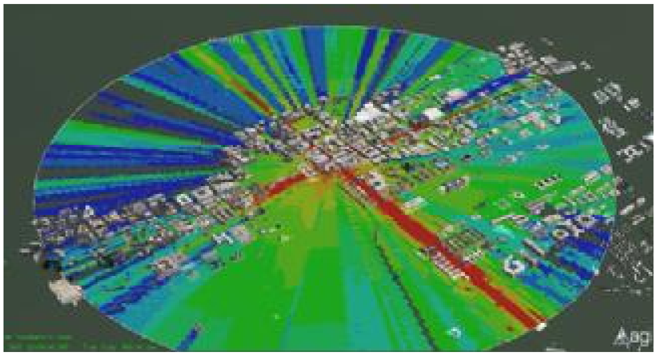

Figure 7: Urban Dynamic Coverage Contour

4. Event Modeling

With a comprehensive model of a system's operational environment, effects of events like system outages, interference, and augmentation can be rapidly analyzed. Figure 8 depicts the power received by a ground user over time as simulated in an STK scenario modeling the GPS transmitters. Notice the max power received is not directly at nadir, but rather at 40 degrees elevation. This antenna pattern has been created purposefully to give added power in the case where the signal will be traveling through more ionosphere and troposphere.

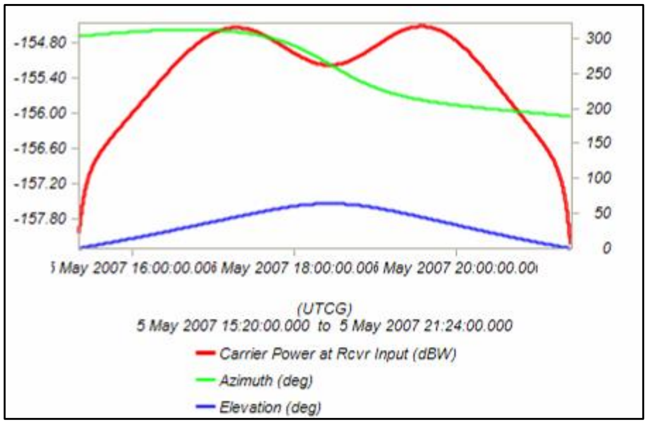

Figure 8: GPS Signal Strength versus Elevation/Azimuth

This weak received power creates the vulnerability with seemingly small interference sources, even if the interference sources are 120 db watts, resulting in a 40 dB jammer to signal (J/S) ratio, a ratio too high for civilian users to track. Without some means of backup the user would not have any information (Position, Velocity, or Time). Since STK is modeling the quality of the signals collected by the receiver and the location of any of the satellites or augmenting transmitters, it is possible to determine which signals are available and the navigational performance afforded by the resulting geometry. Navigational Accuracy and Dilution of Precision (PDOP, HDOP, VDOP, etc). can be easily calculated and used to determine true positional error and predicted covariance. This can be done on an individual receiver basis or as a global coverage by modeling the receivers at points across the globe or just custom regions of interest. Everything discussed so far has laid the groundwork for analysis that can be conducted on the host of systems to determine the best mix of GNSS and augmentation systems.

5. GNSS Modeling

The purpose of this study was to use a COTS tool to analyze the current performance of GNSS and the potential performance of GPS, Glonass, and Galileo once they have all achieved Full Operational Capability (FOC). Figure 9 depicts the current configurations of GPS-blue (30), Galileo-green (1), and Glonass-red (11) constellations as they were modeled on May 5, 2007.

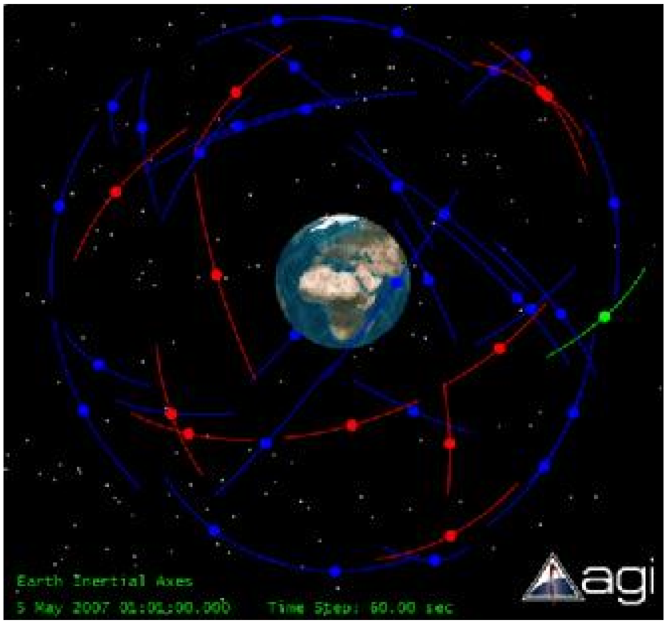

Figure 9: GPS/Galileo/Glonass Constellations in Current Configuration on 5 May 2007

The satellite's position and attitude change according to the propagation models (ICD-GPS-200d for GPS and similar ICDs for Glonass and Galileo). One easy analysis to investigate is that the better the geometry of the satellites, called dilution of precision (DOP), the better accuracy of the users. STK can compute these DOP plots across the globe and provide the max, min, average over time, and grid points (Figure 10) using fixed or variable elevation masks using a variable time step over hours, days, or even weeks.

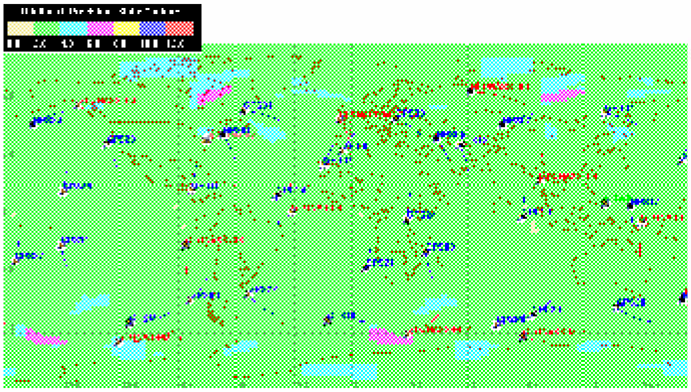

Figure 10: STK DOP Global Plot

For this analysis, STK was used to quickly (literally, in minutes) calculate the global min, avg, and max PDOP for a 24-hour-period (2x2 degree grid). PDOP was calculated with over-determined (all visible satellites) geometry, but it is just as simple to calculate based on the 'Best-4' solution, 'Best-N' solution based on user parameters, or one could apply custom algorithms to the STK geometry to perform this analysis on their own via access plug-ins.

Within each measurement over time, we also found the positional min, avg, and max to determine the best, worst, and most common case scenarios for GPS, Glonass, and a combination of the two on the day in question (Figs 11-13).

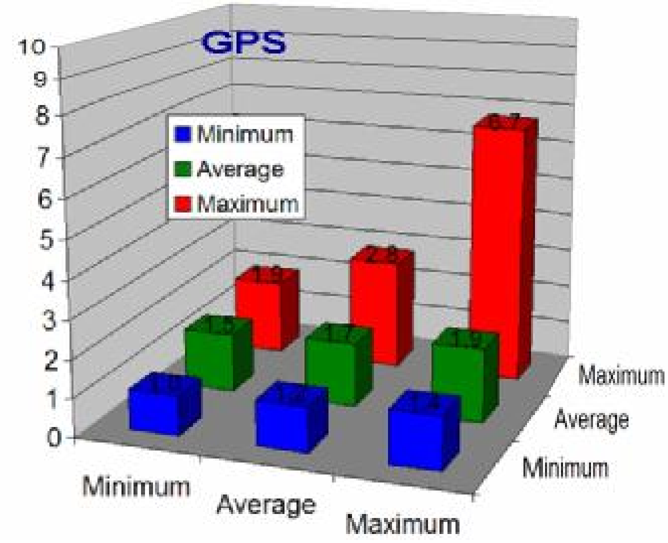

Figure 11. GPS PDOP Analysis – 5 May 2007

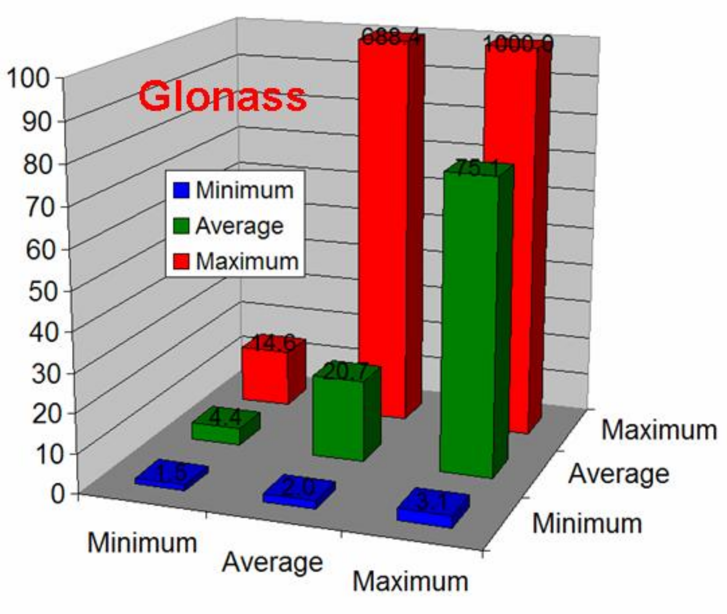

Figure 12. Glonass PDOP Analysis – 5 May 2007

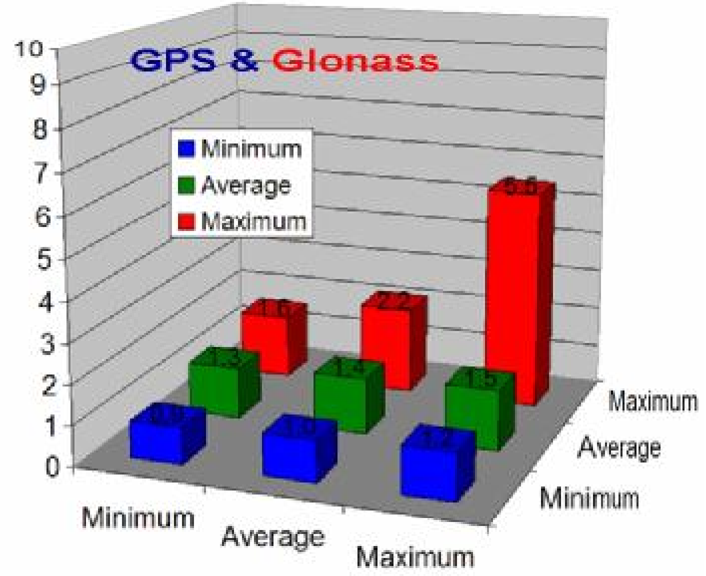

Figure 13. Combined GPS and Glonass PDOP Analysis – 5 May 2007

It is easy to see from this analysis that the incomplete Glonass constellation is nowhere near the performance level of GPS. In fact, it was necessary to cap the PDOP measurements for Glonass as there were actually some locations in the analysis period where no navigational solution was available. However, even in an incomplete state, the addition of Glonass to GPS signals results in a much improved navigational performance over either system alone.

For the second part of our GNSS analysis, we again used STK to quickly simulate all three constellations in their Fully Operational Capability (FOC) depicted in Figure 14: GPS-III-blue (30), Glonass-red (24), and Galileo-green (30). Once more, global PDOP was calculated for each individual GNSS as well as comparisons using both GPS/Galileo signals and GPS/Glonass signals. The constellation designs are all depicted as Walker constellations. GPS was modeled using a 30-satellite constellation in six equal planes, Galileo as 30 satellites in three planes, and Glonass as 24 satellites in three planes.

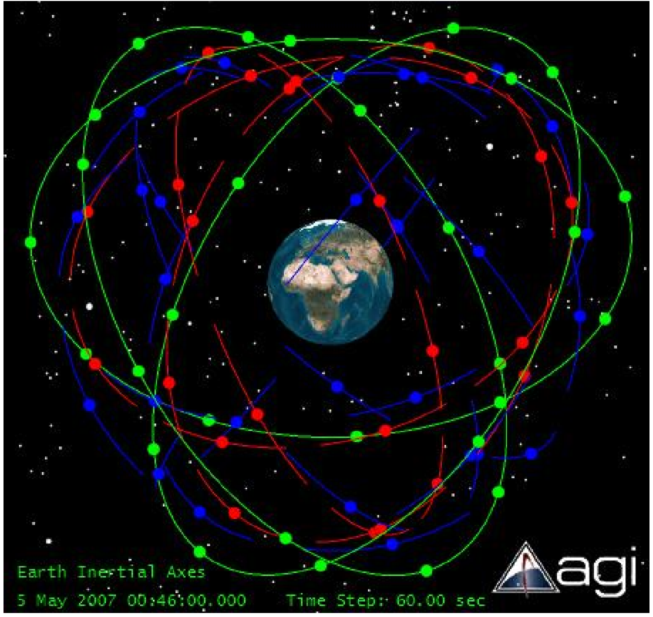

Figure 14. Depiction of GPS/Galileo/Glonass Constellations in Fully Operational Capability

Though this analysis is simple and quick to perform in the STK simulation environment, it sheds great light on the performance capabilities of the various GNSS. Notice in figures 15-17 the improvement we will see in the individual system performance compared to current capability. Finally, note the vast improvement by allowing signals to be received from GPS/Glonass and GPS/Galileo in Figures 18 and 19.

This highlights the ease in which interoperability, augmentation, and reliability studies can be performed. By modeling the full operational environment, it is possible to achieve assessment of full system performance on a global scale or within specific user environments and use cases. With so many new applications for GNSS technology, understanding how these systems will perform is increasingly important. COTS tools like STK allow for rapid modeling and analysis of these systems.

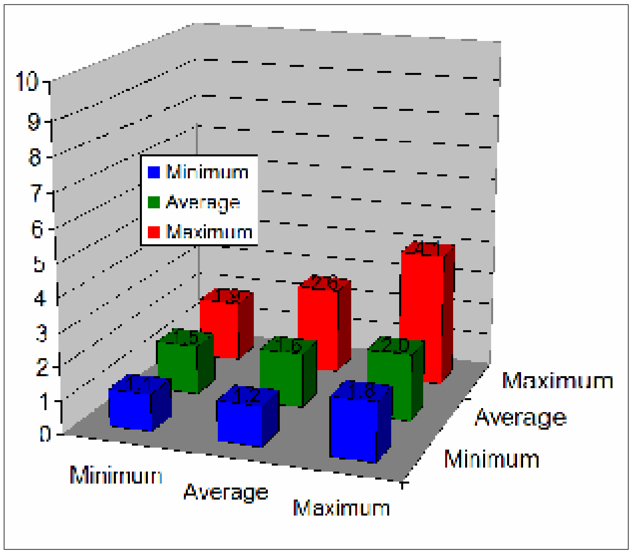

Figure 15. GPS PDOP Analysis – FOC

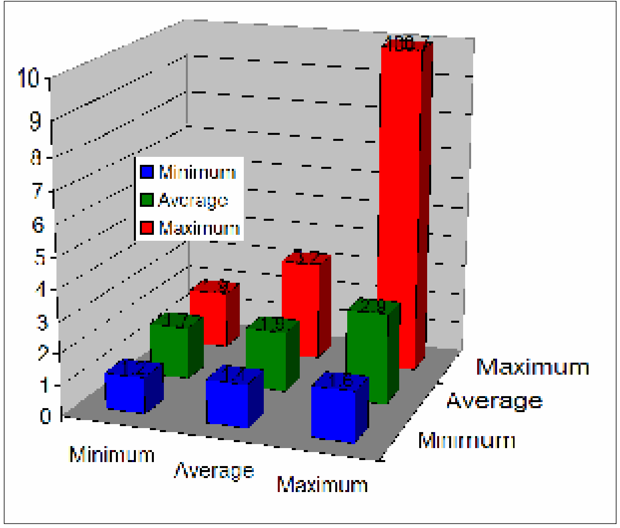

Figure 16. Glonass PDOP Analysis – FOC

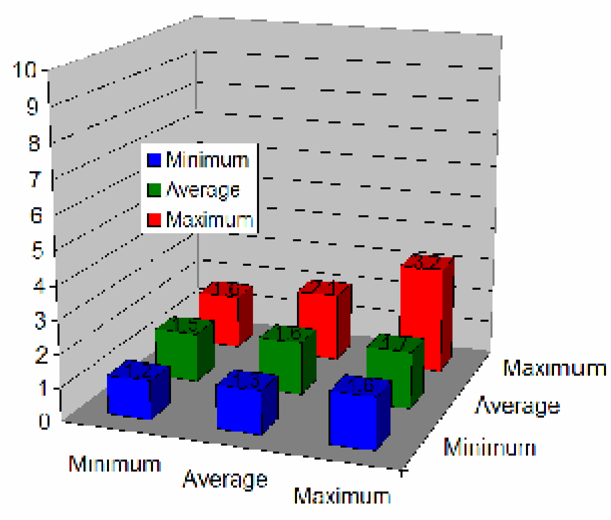

Figure 17. Galileo PDOP Analysis – FOC

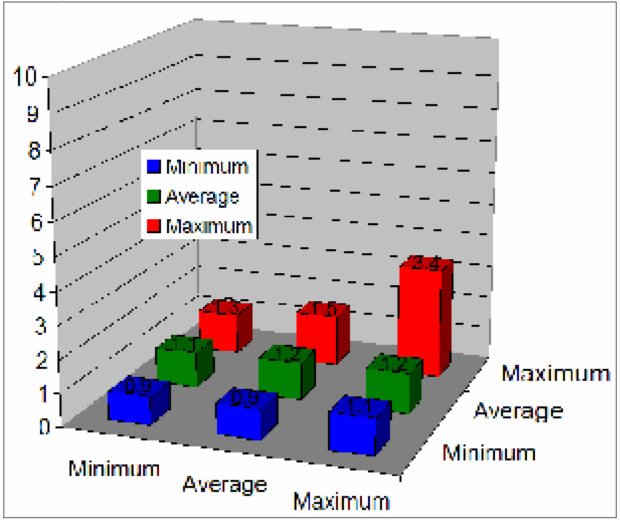

Figure 18. Combined GPS/Glonass PDOP Analysis – FOC

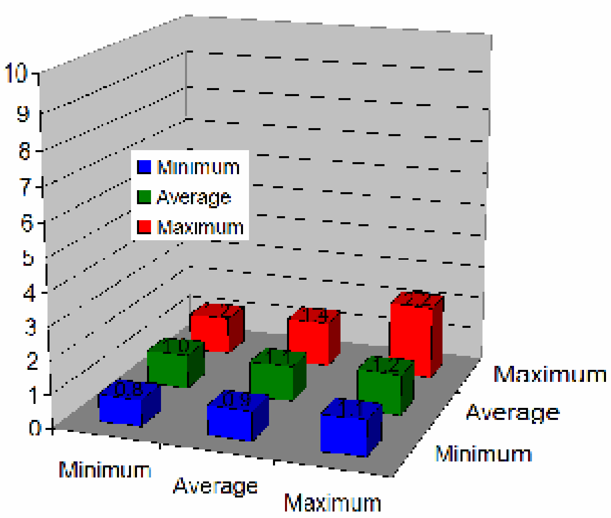

Figure 19. Combined GPS/Galileo PDOP Analysis – FOC

7. Validation and Verification

Validation and verification (V&V) by a third party is crucial to trusting a model or simulation and understanding the limits on the accuracy of its results. The geometry engine and satellite propagation algorithms used by STK have been independently validated and verified by the Aerospace Corporation [5]. The Air Force Operational Test and Evaluation Center (AFOTEC) has also conducted an independent evaluation on STK's communication models quantifying the RF performance of different propagation models [6]. The GPS Operations Center (GPSOC) has performed validation runs versus truth data collected from AMC2 reference system above Shriever Air Force Base, and Figure 20 shows the calculated error from the reference site (blue line) and the predicted error using AGI's software (yellow line).

The results of these studies, in addition to the more than 500 organizations currently using AGI software in 32,000 installations worldwide, provides strong evidence into the trusted nature and extensive testing that has gone into the development of the software. AGI and its technology have been in existence since 1989, and have continued to expand on expertise in dynamic system modeling ever since.

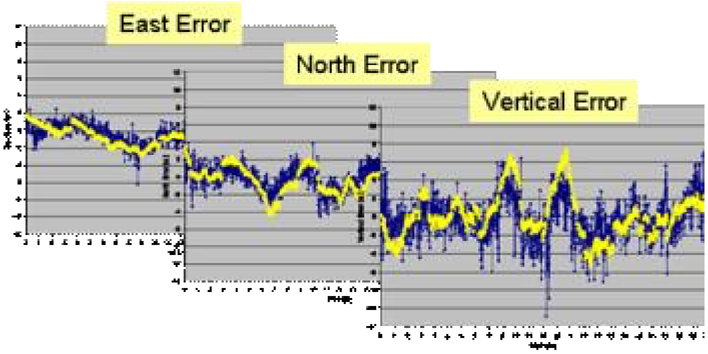

Figure 20 Error Prediction Validation

8. Summary

With the ever-increasing reliance on GNSS, comprehensive understanding of these systems is essential. Moreover, with the political difficulties facing programs like Galileo, it is even more important than ever before to be able to quickly prove the benefits and performance enhancements made by the individual system in a clear and easy-to-understand manner. The simulation environment of STK is specifically tuned for exactly this type of quick and thorough analysis, and the graphical nature of the analysis output makes it an excellent choice for presenting important findings to customers and political leaders alike.

It is obvious that the proven nature of AGI technology makes it a trusted choice throughout the GNSS industry, and that the ability to rapidly model these systems and capabilities will enhance program performance across the board. Weak desired signals (still in the new GNSS design specification), exponentially more users of GNSS equipment, reliance on it, and a growing number of competing noise sources create the need to evaluate the future of GNS systems and future augmentation system and signal/receiver performance.

These trades need to be conducted using high-fidelity RF models that include all sources of potential augmentation. Furthermore, each new system needs to be analyzed per use case to determine the best overall system providing the most capability while minimizing cost. Some of the systems being looked at for decommission or those not being funded may be the best solution, but no one knows. Without proper analysis and investigation into the future of navigation, we will continue to be reactive instead of proactive in establishing the systems needed for tomorrow.

9. References

1. Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System. (29 August 2001) http://www.volpe.dot.gov/gps/gpsvuln.html
2. In Sync with GPS, Peter Kuykendall, Dr. Peter Loomis, http://www.galaxyfareast.com.tw/english/service/content/gps_ec.htm
3. BIENNIAL REPORT TO CONGRESS ON THE GLOBAL POSITIONING SYSTEM 1998
4. Inside GNSS – Standford GNSS article
5. Aerospace validation report on AGI’s Satellite Tool Kit
6. AFOTEC memorandum for review (MFR) of GPS /RF modeling, 2007