Do We Need Augmentation Systems?

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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. Gerten 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, Augmentation, SBAS, Performance Analysis, GBAS

Abstract

There have been numerous debates over the past couple years whether we should maintain such costly augmentation systems if Global Navigation Satellite Systems (GNSS) are available, accurate, and "free." While GNSS are making strides in even higher accuracy, availability, and continuity—concerns still exist over assured reliability and integrity especially, when the concepts of interference and urban canyons are introduced.

This paper will discuss the advantages of augmentation 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 augmentation systems (LORAN-C, Pseudolites, and LAAS) provide. To give each GNSS 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).

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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 precision agriculture 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, what happens if the system is interrupted or is interfered with? Currently, users will see a loss in data 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 back-up 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.

Many question the use of augmentation systems because of their cost per coverage area. The argument is that global navigation systems give "good enough" accuracy, availability, integrity, etc. and that augmentation systems are only needed in extreme/precision events like aircraft landings. So the question do we need augmentation systems now becomes, "what use cases need augmentation systems," and what type?

2. Problem Statement

GNSS are purposely designed as a very low power system, using spread spectrum signal processing techniques to acquire and track the satellite signals. Because of this low power signal, GNSS are very vulnerable to interference, particularly the signal and code structure available to civilian users of the system. This interference may be intentional, such as deliberate jamming by an adversary military or terrorist threat, but in most cases it is due to unintentional sources, such as broadband noise from electrical equipment in the vicinity or spurious harmonics.

This vulnerability cannot be completely eliminated for a variety of reasons. For instance, signals are typically low power in an already crowded spectrum and multiple sources of noise exist due to the increasing use of radio-frequency emitters in our everyday lives. Figure 1 shows the range of a -41 dB (under the FCC limit) spurious effect (Green = above GNSS, Yellow = no acquisition, and Red = jammed, range rings in Km). Furthermore, currently there are only limited means for determining whether our operational systems are being affected by interference or jamming. Most users of GNSS simply assume the signal will be there and is usable and accurate.

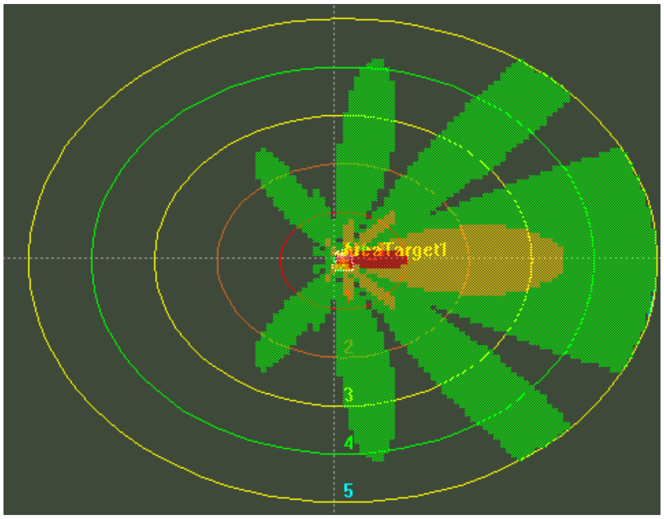


Figure 1: Jammed Region from 1 Source

At the same time, systems that were used in the past (Transit, Loran in Figure 2, and other now-called backups) are being decommissioned because of the observed capability of GNSS alone. We have reached the point where the mass market of GNSS has taken over and augmentation systems are very rarely enough included in the trade space. While needs for higher accuracy, availability, and integrity exist for particular use cases, we have lost the economy of scale (less users with these needs) and therefore less funding to pursue them. Even GNSS experts will state the need for a backup system—but none agree on just which backup/augmentation system that should be.

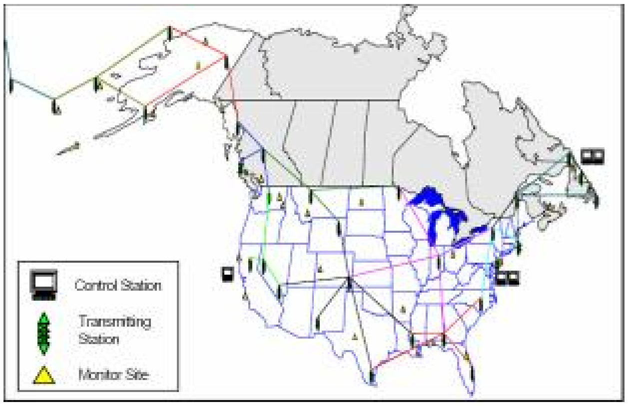


Figure 2: Loran-C System Architecture [4]

3. Augmentation Systems

An augmentation system is any system that aids the primary (GNSS) system by increasing accuracy, availability, and integrity. The system can be a space-based augmentation system (SBAS) or ground-based augmentation system (GBAS). The system can act as a single source of ranging much like a single satellite, which, if exhibiting characteristics of GNSS but on the ground, are named Pseudolites. Or the system may help to remove errors in those signals being transmitted from GNSS through differential processing (removing common errors between the reference and those users in close proximity to the reference), see Figure 3.

Figure 3: Example GBAS

These corrections can also be computed for each GNSS signal at each moment in time and communicated to the users whereby removing these errors over a much larger area. These include such systems as:

- Wide Area Augmentation System (WAAS)
- European Geostationary Navigation Overlay System (EGNOS)
- Multifunction Satellite Augmentation System (MSAS)
- GPS Aided GEO Augmented Navigation (GAGAN)

These systems are regional by nature and only aid those users they cover (Figure 4 shows the WAAS coverage).

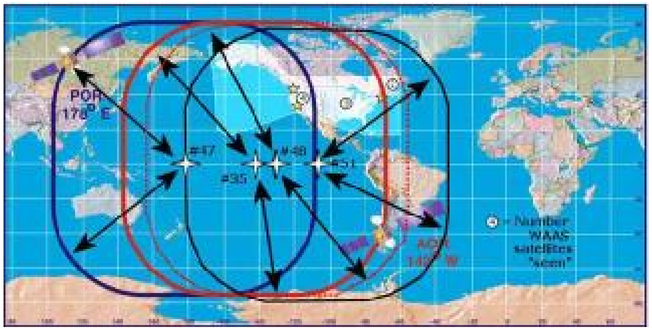


Figure 4: WAAS Coverage

Other augmentation systems could include:

- Compass (heading aiding)
- Inertial navigation systems (INS)
- High-stability clocks
- Terrain mapping/correlation
- Celestial/star tracking
- VHF omni-directional ranging (VOR)

Each system has its pros and cons and may need to work in concert to provide the level of reliability needed in particular use cases. Therefore, each and all need to be investigated and modeled on what capability they provide for each use case in question.

4. Augmentation Modeling

Several modeling efforts have been completed to analyze augmentation systems and their benefits to GNSS. But each tool has been designed under a particular program to investigate one application or system. In this case, we needed to use a tool that was built to model any system and capable of reading in the actual spectrums and parameters as well as predicted spectrums, transmission effects, environmental effects, and receiver types.

Satellite Tool Kit (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 (Figure 5).

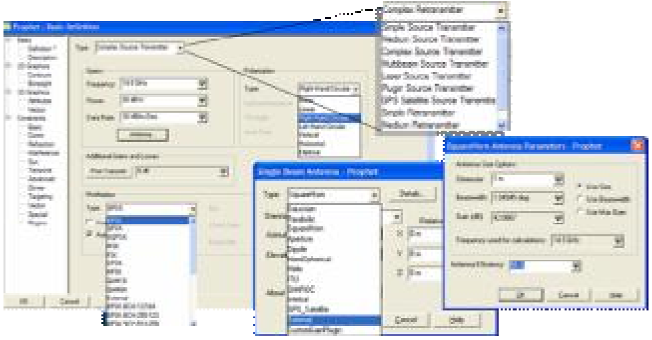


Figure 5: STK Transmitter Input Page

STK also models the environment to include terrain effects using numerous different propagation models, rain models, cloud and fog models, tropospheric scintillation, and other plug-in models (custom attenuation models for example). This allowed us to model the effects/attenuation caused by the environment on the transmission path (Figure 6).

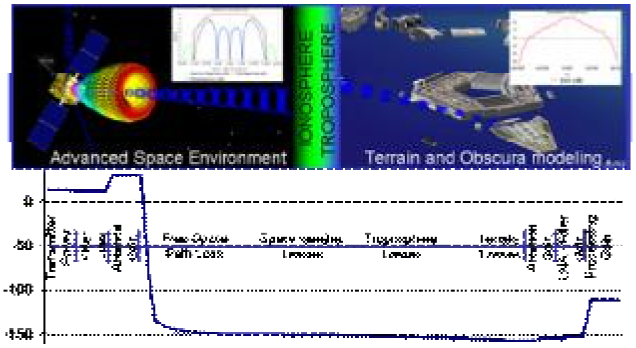


Figure 6: STK Path Loss Contributors

The final component is the user receiver. Whether GPS or a spectrum analyzer, STK can model the RF front end to include the center frequency, bandwidth, antenna, polarization, processing gains, and calculate system temperature (Figure 7).

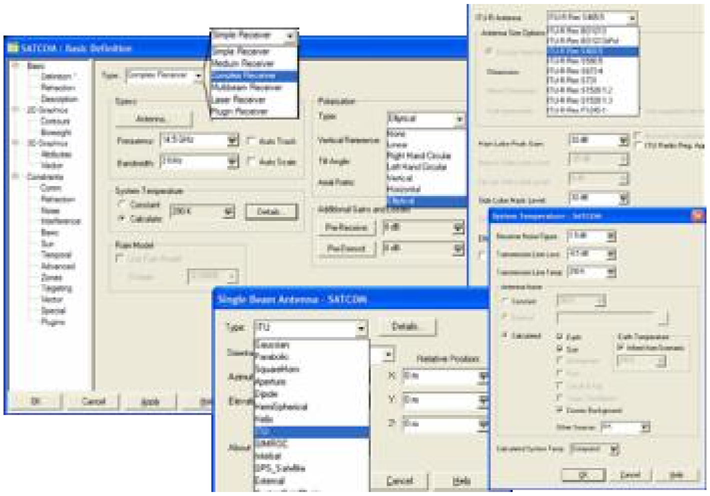


Figure 7: STK Receiver Input Page

These transmitters can be placed at static locations pointing in fixed locations or in more realistic cases be attached to an object (land, sea, air, space) that is dynamic in nature including attitude (targeting) or temporal (on/off times) (Figure 8).

Figure 8: Dynamic Transmitters

The effects can then be modeled for land, sea, air, or space platforms and numerous use cases. 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 coloring the route via a color contour (Figure 9).

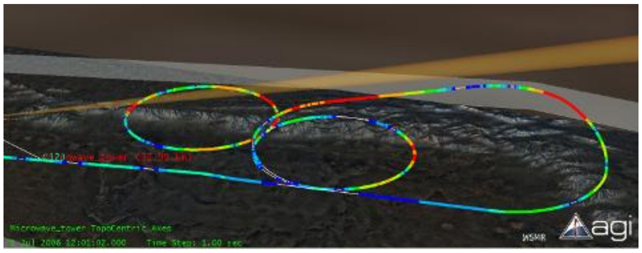


Figure 9: Power Received Route Coverage Contour

Another option would be to look at the interference impact over a region over time at altitude (3D) (Figure 10).

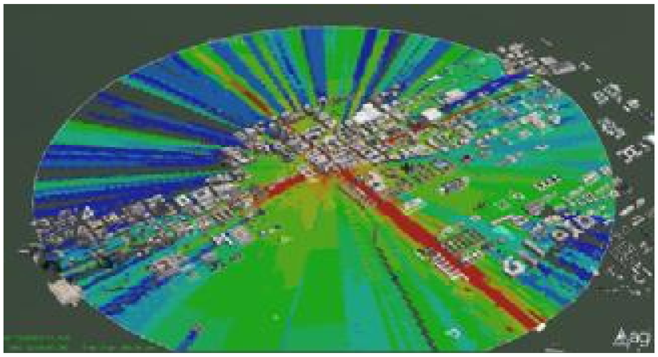


Figure 10: Urban Dynamic Coverage Contour

This same principle can also be used to model the desired signals (communication, radar, or in our case, augmentation systems).

5. GNSS Modeling

In a similar manner we need to model the desired signals. These transmitters may be from the ground in terms of ground-based augmentation systems (GBAS) or from space (GPS, Galileo, Glonass, Compass, QZSS, IRNSS, GAGAN, WAAS, EGNOS, etc). Figure 11 depicts the expected GPSIII-blue, Galileo-green, and GlonassK-red constellations.

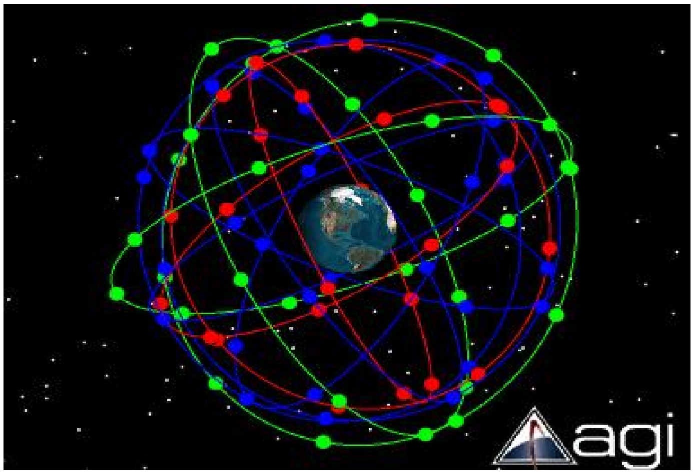


Figure 11: GPS/Galileo/Glonass Constellations

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 12) using fixed or variable elevation masks using a variable time step over hours, days, or even weeks (completed in only minutes).

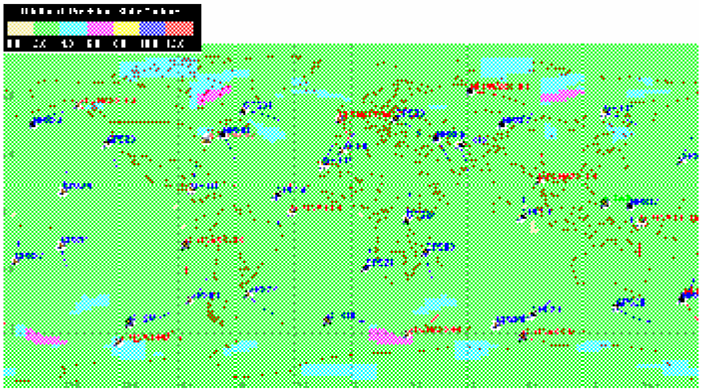


Figure 12: STK DOP Global Plot

The GPS satellites are 10,900 nmi from the Earth's surface, making the 100 watt transmitted signal (see antenna pattern in Figure 6 above) approximately 0.0000000000000001 watts (-160 dBW) by the time it reaches your GPS receiver. Figure 13 depicts the power received by a ground user over time. 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.

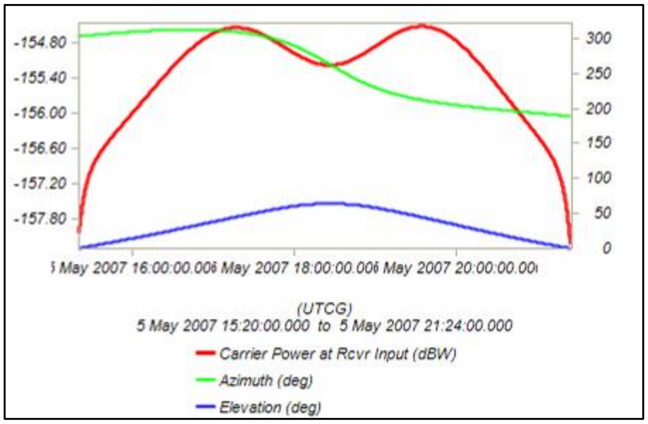


Figure 13: GPS Signal Strength versus Elevation/Az

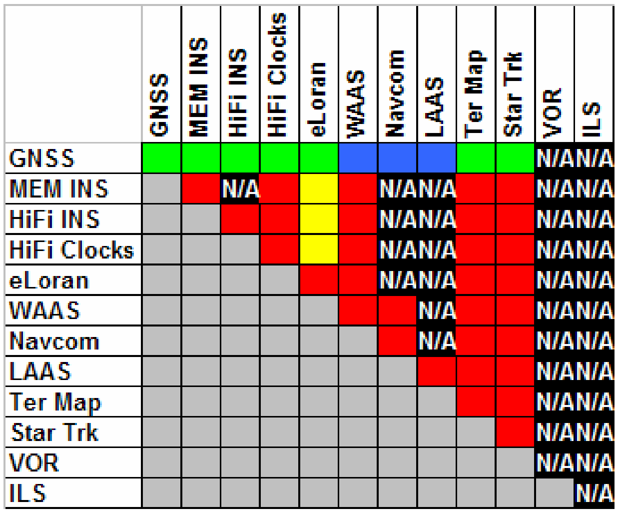
This weak received power creates the vulnerability with seemingly small interference sources even if the interference sources are 120 db watts, resulting in a 40 dB jammer-to-signal (J/S) ratio—a ratio too high for civilian users to track. Without some means of backup, the user would not have any information (position, velocity, or time). Even with some backup systems the user may have greatly reduced accuracy, as it may degrade with time or movement or the backup system might be jammed as well. Therefore, analysis must be conducted on the system of systems to determine the best mix of GNSS and augmentation systems.

6. Augmentation analysis

GNSS systems alone meet many users' needs but there are several use cases (FAA, precision farming, surveyors, etc.) that benefit from augmentation systems.

Each use case needs to be analyzed individually for its needed accuracy (<X.X meters), availability (>XX.XXX%), and integrity (X.X RNP). One of the challenges in this paper was to get actual requirements for these metrics—they appeared to be different in each document we read. Therefore, a simplified approach was conducted until these numbers could be agreed upon and the analysis re-run.

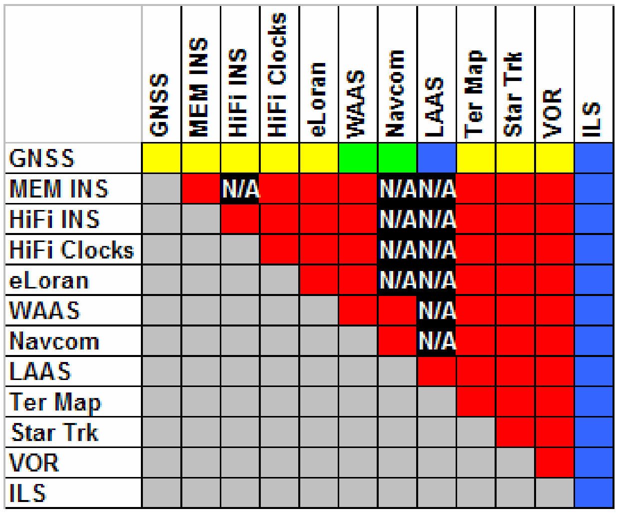
In the use case of precision agriculture, the accuracy must be better than 15 centimeters threshold and 5 centimeters objective and must be available 99.99% of the time with an integrity flag to alert of accuracy or availability beyond these bounds. In this case, GNSS alone will not meet either threshold or objective so some type of augmentation system needs to be employed. In Figure 14, the augmentation trade space is evaluated and the outcome demonstrates three potentials to meet objective (Blue) and several others that will help meet threshold (Green). Many others are not applicable (NA), may help but not enough (Yellow), or they don't work at all (Red).



	GNSS	MEM INS	HiFi INS	HiFi Clocks	eLoran	WAAS	Navcom	LAAS	Ter Map	Star Trk	VOR	ILS
GNSS	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟩	🟩	N/A	N/A
MEM INS		🟥	N/A	🟥	🟨	🟥	N/A	N/A	🟥	🟥	N/A	N/A
HiFi INS			🟥	🟥	🟨	🟥	N/A	N/A	🟥	🟥	N/A	N/A
HiFi Clocks				🟥	🟨	🟥	N/A	N/A	🟥	🟥	N/A	N/A
eLoran					🟥	🟥	N/A	N/A	🟥	🟥	N/A	N/A
WAAS						🟥	🟥	N/A	🟥	🟥	N/A	N/A
Navcom							🟥	N/A	🟥	🟥	N/A	N/A
LAAS								🟥	🟥	🟥	N/A	N/A
Ter Map									🟥	🟥	N/A	N/A
Star Trk										🟥	N/A	N/A
VOR											N/A	N/A
ILS												N/A

Figure 14: Precision Agriculture Trade Space

In a similar fashion, category I landing limits where investigated and the trade space is shown in Figure 15 on the following page.



	GNSS	MEM INS	HiFi INS	HiFi Clocks	eLoran	WAAS	Navcom	LAAS	Ter Map	Star Trk	VOR	ILS
GNSS	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟦	🟨	🟨	🟨	🟦
MEM INS	⬜	🟥	N/A	🟥	🟥	🟥	N/A	N/A	🟥	🟥	🟥	🟦
HiFi INS	⬜	⬜	🟥	🟥	🟥	🟥	N/A	N/A	🟥	🟥	🟥	🟦
HiFi Clocks	⬜	⬜	⬜	🟥	🟥	🟥	N/A	N/A	🟥	🟥	🟥	🟦
eLoran	⬜	⬜	⬜	⬜	🟥	🟥	N/A	N/A	🟥	🟥	🟥	🟦
WAAS	⬜	⬜	⬜	⬜	⬜	🟥	🟥	N/A	🟥	🟥	🟥	🟦
Navcom	⬜	⬜	⬜	⬜	⬜	⬜	🟥	N/A	🟥	🟥	🟥	🟦
LAAS	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟥	🟥	🟥	🟦
Ter Map	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟥	🟥	🟦
Star Trk	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟥	🟦
VOR	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟦
ILS	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦

Figure 15: Cat I Landing Trade Space

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. STK has 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 also performed validation runs versus truth data collected from AMC2 reference system above Shriever Air Force Base. Figure 16 shows the calculated error from the reference site (blue line) and the predicted error using AGI's software (yellow line).

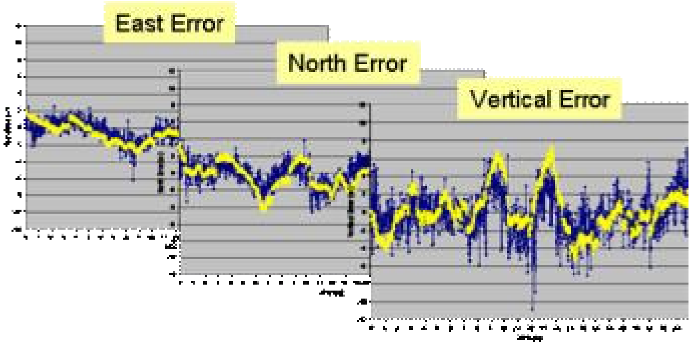


Figure 16: Error Prediction Validation

8. Summary

Weak desired signals (still in the new GNSS design specification), exponential users of GNSS equipment, reliance upon it, and a growing number of competing noise sources create the need to evaluate the future of augmentation systems and GNSS signal/receiver performance. These trades need to be conducted using high-fidelity RF models that include all sources of potential augmentation. These systems need to be analyzed per use case to determine the best augmentation systems providing the most capability while minimizing cost. Some of the systems being looked at for decommission may be the best solution, but no one knows. Without proper analysis and investigation into the future of navigation, whether with augmentation systems or without, we will continue to be reactive instead of proactive in establishing the systems needed for tomorrow.

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