Interoperation and Integration of Satellite Based Augmentation Systems

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ABSTRACT

In recent years there has been widespread growth in the independent development of Satellite Based Augmentation Systems (SBASs). The Federal Aviation Administration's Wide Area Augmentation System (WAAS) will be the first of multiple systems to become operational in the near future. Of current interest is interoperability of these physically separate, independent SBASs. In particular, designers are investigating the type, amount, and methodology of information shared between systems.

There are interface issues related to a user passing from one SBAS to another. Among these is the degradation of the ephemeris and clock integrity bounds for users operating outside of the SBAS network of reference stations. While some degradation in performance and integrity limits can be expected, it is shown that the ability to verify the quantity of error can deteriorate very rapidly. Both geometric and dynamic ephemeris estimates will suffer this increase in uncertainty due to dramatic decreases in GPS satellite observability. The effect of adding periphery stations to reduce this degradation is demonstrated through use of the National Satellite Test Bed (NSTB) network.

Distributed systems have the ability to provide complementary and cooperative data while retaining specific levels of independence. This extends as well to worldwide interoperability of continuous navigation services and in the standardization of international aviation navigation aids. A risk/benefit analysis of SBAS interoperability is presented. The analysis presents strategies of information integration that optimizes overall user integrity for the typical SBAS architecture by monitoring data sent from systems external to the SBAS. The performance of this integrity monitoring is characterized. The conceptual distributed design is supported by results from the NSTB network.

INTRODUCTION

To improve the accuracy, availability and integrity of GPS the FAA is currently developing the Wide-Area Augmentation System (WAAS) which is an example of a Space Based Augmentation System (SBAS) as depicted in Figure 1. This will be accomplished by utilizing measurements from a network of GPS wide-area reference stations located throughout the coverage region. These measurements will be gathered by a wide-area master station through a communications network to compute corrections to GPS errors that are common at each reference station (or a subset of reference stations). Among these errors are ionospheric delay, satellite clock and broadcast satellite ephemeris (position) uncertainties. These corrections will be transmitted through an uplink center to one or more geosynchronous spacecraft which will broadcast the messages to users at the GPS L1 frequency using Pseudo-Random Noise (PRN) codes not in use by and orthogonal to GPS codes.

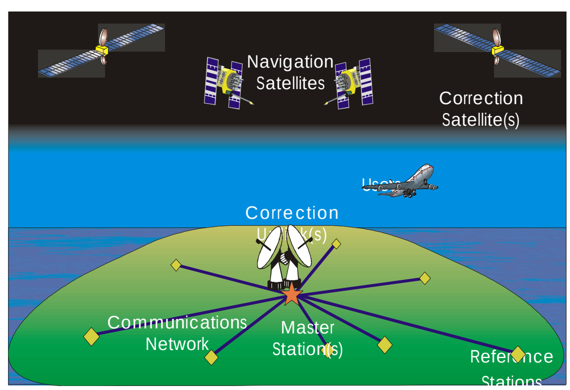

Figure 1. SBAS Architecture.

The users operating within a SBAS can be in one of four modes: 1) Precision approach (three-dimensional guidance in close proximity to an airport); 2) Non-precision approach (navigation in close proximity to an airport); 3) Terminal (navigation at an airport); and 4) En-Route (navigation between departure and arrival airports). Each of these modes has prescribed integrity and availability limits that are specified by the SBAS within its primary design area or *service volume*.

Different groups around the world are currently implementing SBASs. Currently these are the European Geostationary Navigation Overlay System (EGNOS) [1], the Japanese MTSAT Satellite Augmentation System (MSAS) [2] and the Wide Area Augmentation System (WAAS) [3] in the United States.

Stanford University is part of the National Satellite Test Bed (NSTB) [4]. The NSTB is a network of GPS reference receivers located throughout the United States with additional sites in Canada and Europe. The NSTB is being used as a research and development system to test concepts and algorithms for WAAS. We collect data through the NSTB network and process the measurements for corrections for both passive reference stations (not used for corrections) as well as being able to transmit this data to independent users. Processing can either be applied to users in real-time or stored for post-processing.

This paper will study the benefits of integrated space based augmentation systems of the GPS constellation. First an overview of each of the major SBASs under development today will be given. A risk/benefit analysis of the different types of SBAS interoperation will be presented. The paper will then proceed to show the correction availability of users in the individual systems versus the combined cases. Since the NSTB has wide geographic coverage it is possible to study the effects of distributed SBAS architectures by breaking the NSTB into parts and treating each part as a separate system. The last part of the paper will break the NSTB into two major groups of stations to compare the results for both UDRE and border-case user accuracy for both the distributed and combined systems.

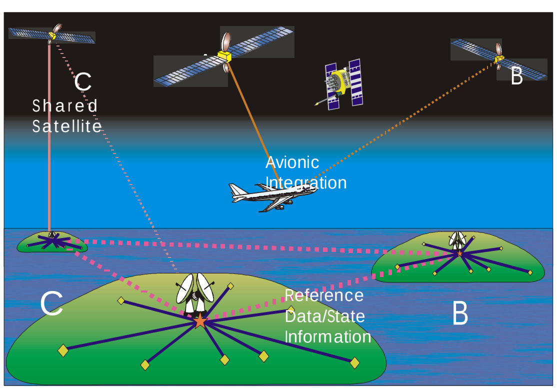

Figure 2. SBAS Interoperability Options.

SBAS INTEROPERATION OVERVIEW

Interoperation implies that existing SBASs provide coverage within their service volumes. As users pass from one SBAS to another there will likely be a disruption in coverage since no current systems overlap. The assumption that continuous coverage will not be guaranteed by either SBAS drives to the heart of the interoperability issue. The primary goal of interoperability research is to reach seamless coverage between SBASs. Secondarily, the incorporation of data over a wider geographical region will increase the strength of an individual SBAS improving the performance of user on the periphery of SBAS coverage. As delineated in Figure 2 interoperation can take place at three different levels of the SBAS:

1) Reference Data/State Information
2) Avionics Integration
3) Shared Satellite

Reference Data/State Information

This exchange mode suggests some connection between SBASs to allow for the information transfer. In this mode SBASs A, B and C of Figure 2 are connected through some data link through which reference station measurements and status messages or the high-level state information from the master station process are transmitted. As it will be discussed below the high-level state information (i.e. states of dynamic ephemeris estimator, grid ionospheric delay, etc.) offers the best economy of data transfer however the low level reference data represents the highest possible integrity protection.

Avionics Integration

This type of exchange assumes that the user hardware is the primary medium for SBAS data sharing. Figure 2 shows the user employing corrections from both SBAS A and B. Coordinating interoperation at the user level requires knowledge of the difference in the master clock terms between SBAS A and B if pseudorange correction data is to be combined.

Shared Satellite

A shared satellite may be supposed in the case where two (or more) SBASs distribute the cost of a geosynchronous satellite for use as a backup to a primary satellite failure. Similarly, two SBASs could share an active satellite by transmitting signals on mutually orthogonal codes or at a frequency other than L1. Since this option is more sensitive to implementation issues, it was not considered in the balance of this paper.

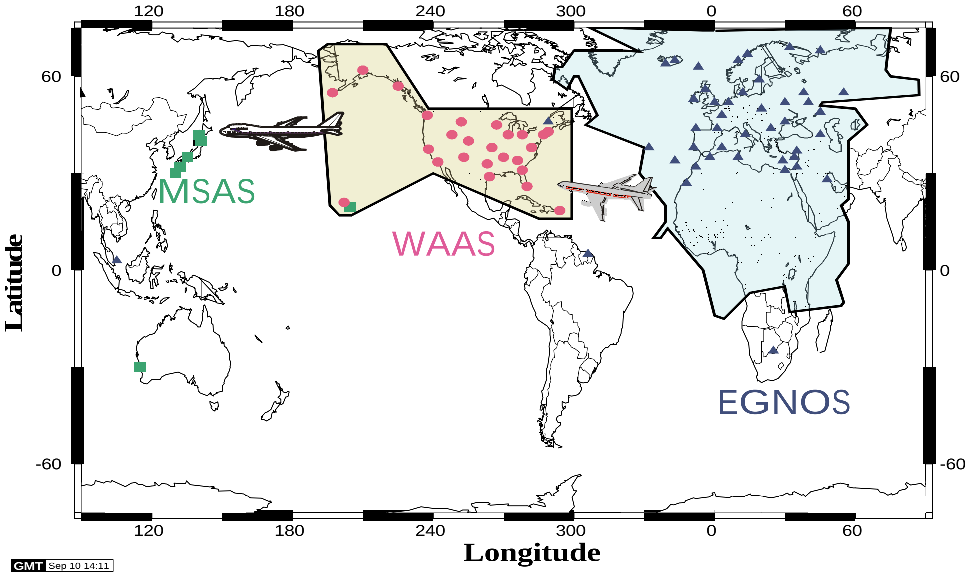

Figure 3. Current SBAS Development Examples.

CURRENT SBAS DEVELOPMENT

At the time of the writing of this paper, three SBASs are under development. Figure 3 shows the three systems, EGNOS, MSAS and WAAS.

EGNOS

The 44 stations that are denoted by triangles in Figure 3 represent the largest geographical distribution of all of the development SBASs. Most of the stations are located in Europe with periphery stations located in Africa, Malaysia, South and North America. Also indicated in the figure is the Non-Precision Approach (NPA) region as it is currently defined.

MSAS

The squares in Figure 3 indicate the locations of the stations that form the MSAS network. There are 8 stations in total with 6 in Japan itself and one each in Hawaii and Australia. Currently there are no Precision Approach (PA) or NPA regions defined for MSAS.

WAAS

Figure 3 designates the 24 WAAS reference stations located across the United States and Canada. These reference stations have all been installed and tested in anticipation of Phase I WAAS being operational in mid-1999.

RISK/BENEFIT ANALYSIS

In assessing the risks and benefits of interoperation, certain assumptions must be made regarding the structure of the underlying systems. By using linear systems theory it is possible to formulate a quantitative evaluation of the positive gains of interoperation through optimal fusion of distributed information.

DISTRIBUTED INFORMATION FUSION THEORY

Worst Case Distribution

Bayesian probabilistic information fusion scheme is the general optimal solution. Therefore, a probability distribution is needed for this type of analysis. For integrity considerations, we prefer a plausible worst-case probability distribution. From the *maximum entropy principle* suggests that for a *linear* system the worst-case probability distribution is normal [5]. This conclusion suggests that each master station can achieve global optimality by sharing a minimum of high level data such as state estimates, their error covariances and some prior information. While this is optimal the final integrity may be compromised by the non-linearities discussed below.

INTEGRITY AND PRACTICAL CONSIDERATIONS

Despite aspects of national security, economic, communication and implementation considerations the technical approaches prefer straightforward implementation schemes that share a minimum amount of high level information. By avoiding the overwhelming processing load by communicating a huge amount of raw measurements across SBAS implementations the problem can seem more tractable. However, to share data at a high level the assumption of a SBAS as a linear system must be applied for the power of Information Fusion Theory, outlined above, to be applied. While the assumption of linear system analysis for the case of augmenting system accuracy is not extraordinary it is marginal at best to rely on this for integrity issues.

Security Issues

Potential spoofing and other political issues cannot be ignored. Consistency validation before information fusion is required for integrity (by nature a non-linear operator). Remotely located *integrity monitoring stations* can also provide certain level of integrity guards (possibly outside of time-to-alarm constraints). Sufficient conditions for positive information fusion can be adopted to trade some optimality gain for guaranteed interoperation full integrity.

Implementation Options

All of the considered SBASs will broadcast information to the users through geosynchronous satellites. Therefore, equal optimality also suggests that information fusion by each information control center or by each individual user can be equally optimal as well. Furthermore, information fusion at raw measurement levels, correction, range, and position domains are equally optimal under the *linear* system assumption.

System Compatibility and Consistency

System incompatibility might reduce the degrees of freedom in implementation options. Fortunately, the constraint can be readily overcome by the above inherent flexibility of information fusion theory. For example, correction domain fusion for tomographic ionosphere estimators and kinematic orbit estimators are difficult. User range domain fusion can always be applied instead. Specific concerns for user-level (avionics) integration is lost data that might impact a manufacturer's liability. Meanwhile, information fusion at a lower level has more degrees of freedom in the fault detection/isolation sense and therefore degrades more gracefully in the case of inconsistency or failures at control centers.

Other Considerations

In an implementation, practical nonlinear effects can degrade information fusion optimality. These effects include, but are not limited to, latency, aging, quantization, partial information, and message dropouts. Fortunately the above information fusion scheme can still be applied as an approximate strategy.

Table 1 below summarizes the qualitative summary of the risk/benefit analysis in light of information fusion theory with the non-linear limitations superimposed.

Exchange Type	**Pro**	**Con**
Reference Data	Best integrity	Worst data bandwidth
State Information	Best data bandwidth	Soft on integrity
User Integration	User controlled	Hard to standardize

Table 1. Risk/Benefit Summary.

USER AVAILABILITY

The first step of achieving seamless coverage between independent SBAS will be to ensure an adequate number of corrections for users. To achieve this simulations were run to estimate the number of corrections available to users across the globe based on the following conditions:

1) There must be at least four (4) reference stations tracking the satellite to be considered valid;
2) The current GPS almanac of 27 SVs were used;
3) No GLONASS satellites were included;
4) No satellite failures were included;
5) Geostationary satellites were used for data transmission but not as a ranging source;
6) Both the reference stations and user had elevation masks of 5 degrees.

Item (1) above was a compromise position between the WAAS specification, which does not specify a lower bound on the number of stations tracking a valid SV (two assumed) and EGNOS which specifies a minimum of 5 reference stations tracking a SV before being considered valid.

The simulations produced probability distributions of the number of SVs available as a function of user position on the Earth. The cases presented in this paper represent the 99.9% bounds or the number of satellites that are available for *at least* 99.9% of the time.

Of concern in any simulation is representing a statistically significant number of samples to approximate the probability distribution. The ground tracks of the satellites will repeat themselves about every 2.55 years due to the equatorial bulge of the Earth (J2 gravitational term).

Since the goal is to achieve an even distribution of satellites over time total duration of the simulations presented here was chosen as 2.55 years representing one precessional rotation. However, the sampling period of this rotation is not obvious from any physical properties of the system. From statistical analysis, the number of samples required to achieve a certain level of confidence when the second moment (variance) of the distribution is given by the Chebychev inequality:

$$P\left\{\left|S_n - EX\right| \geq e\right\} \leq \frac{VarX}{ne^2} \quad (1)$$

where S_n is the sample mean if the random variable X. If the number of corrected SVs is the variable X we wish to establish the number of samples, n, necessary to bound the probability P. Given that we want to establish the unique integer satellite number; a fractional value of $\varepsilon=0.25\sigma_x$ was chosen. The value of σ_x was evaluated at around 1 giving an ε of 0.25. For a P greater than 0.999 the value of n should equal or exceed 16,000 samples. Thus the sample period was taken at 2.55 years/16,000 = 8.062×10^8 seconds/16,000 = 50387 seconds/sample.

STANDALONE RESULTS

Based on the conditions of the previous section the standalone performance of EGNOS, MSAS and WAAS are presented in Figures 4, 5 and 6. Figure 4 shows the extensive EGNOS coverage with almost the entirety of the NPA region exceeding 4 corrected satellites 99.9% of the time. Similarly in Figure 6, the WAAS NPA region is nearly fully covered except for Northern Alaska.

SWITCHED RESULT

If a user was to operate between these SBASs then one strategy for integration would be to switch from the departure SBAS to the arrival SBAS en-route not sharing any information either explicitly in the user avionics or implicitly through ground infrastructure. This switching would occur at the location where the number of corrections for the arrival SBAS, on average, exceeds that of the departure SBAS. Based on the results from Figures 4-6 the boundaries described in Table 2 were used to generate the switched results in Figure 7.

As is clearly evident in Figure 7 there are severe coverage deficiencies at each of the SBAS boundaries. It will be shown in the next section that by combining information across SBASs the deterioration at the boundaries can be ameliorated.

Primary System	Longitude Range
WAAS	180° < Longitude ≤ 315°
EGNOS	-45° < Longitude ≤ 90°
MSAS	90° < Longitude ≤ 180°

Table 2. Switching Boundaries.

COMBINED RESULT

Combining data assumes that data has been exchanged at either at the master station level or integrated from multiple SBASs by the user. It is further supposed that all SBAS information is available to the user; either through multiple correction results or that the master station information has been fully integrated. Figure 8 shows the switched result (shaded region) from the last section on top of the combined result. The shaded region represents the area on the switched results where at least 4 corrected satellite signals were available to users 99.9% of the time. Without increasing the total number of stations between the three SBASs, it is clearly shown that the combined data increases the total coverage area worldwide. Specifically the Pacific and Indian Ocean regions have significantly improved coverage. Furthermore, by using a combination of the data for the three planned systems the entire Northern Hemisphere has 99.9% coverage of at least 4 satellites.

This improvement in performance is due to the strong geometrical leverage that adding wide geographical spacing of reference station brings. By combining data from multiple systems, the observability of satellites increases dramatically virtually eliminating the 'horizon' of the SBAS. Some complications are added by integrating the information at the user such as clock synchronization between SBASs, however, the information theoretic approach presented above suggests that little or no degradation in the final accuracy will be suffered in comparison to the fully integrated reference data case. Integrity is likely degraded with the linear assumption. Besides integrity there are other compelling reasons for integrating the reference data between the SBAS to improve the performance within the established service volume. Among these are that increased visibility of satellites will help dynamic orbit determination significantly [10] and similarly crossovers in ionospheric pierce points could help in determination of the delays due to the ionosphere.

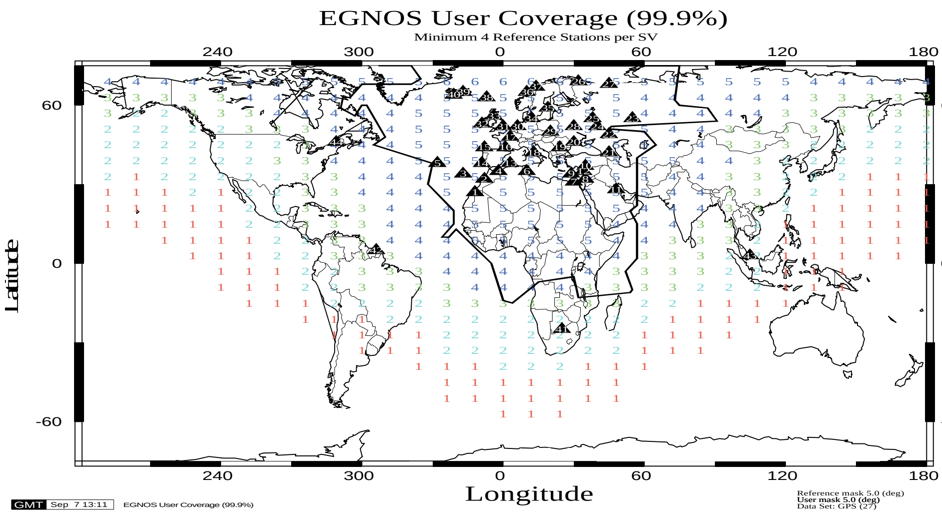

Figure 4.

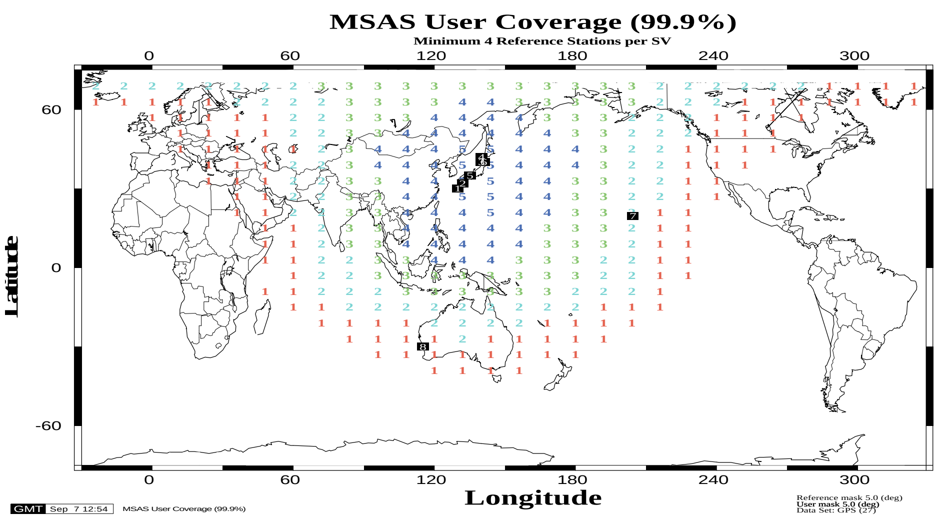

Figure 5

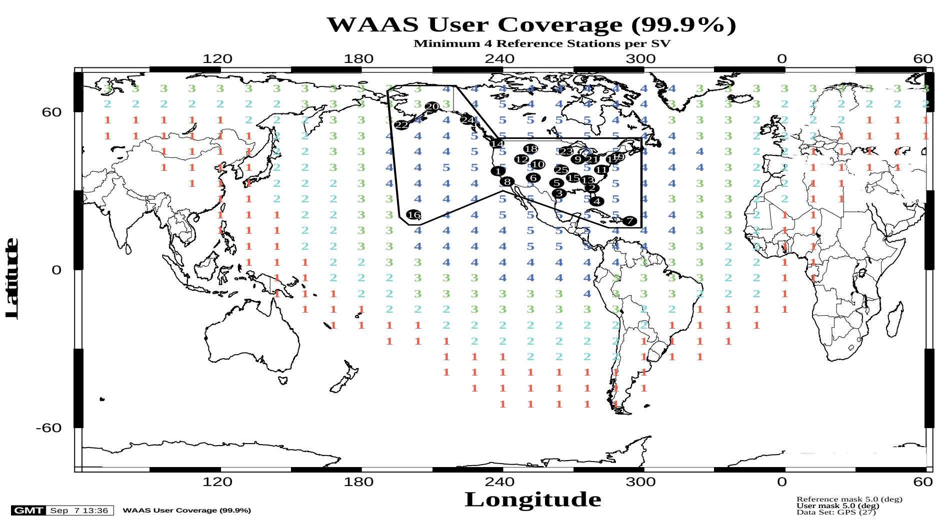

Figure 6

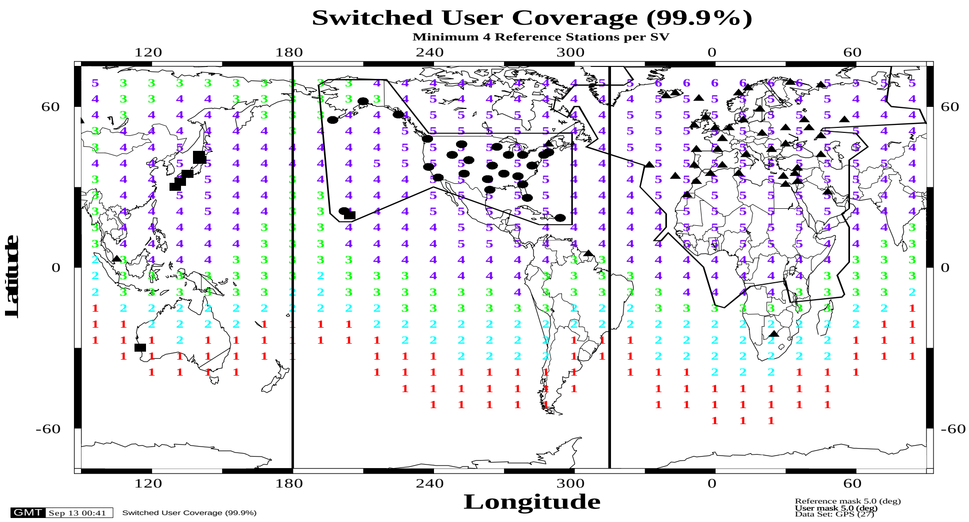

Figure 7

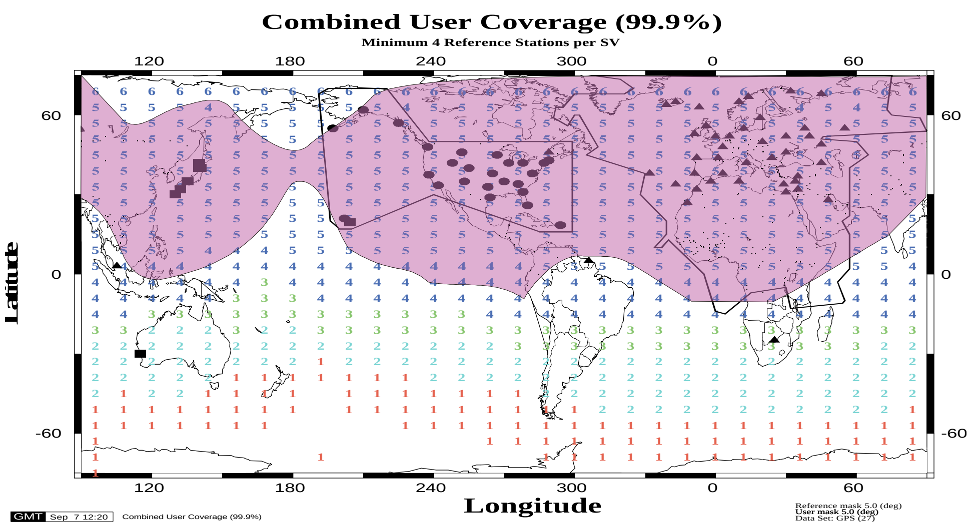

Figure 8

By using a combination of simulation and geometry, the proceeding sections have shown that integration of SBAS data across systems increases the number of corrections available to users operating in regions between SBASs. The next sections will extend these results to actual data collected through the NSTB. The NSTB is a prototype SBAS that has stations in the Coterminous United States (CONUS), Alaska, Hawaii, Canada as well as international sites. To study the effects of SBAS interoperability the CONUS and Canada stations were grouped as an independent SBAS and the Alaska/Hawaii stations were considered another. By studying the effects of these groupings on the resultant performance of users, we hope to extend our geometric simulations to real-world examples.

NSTB TESTS

Figure 9 shows the distribution of the NSTB stations across North America and Hawaii. To evaluate the interaction of distributed SBASs the NSTB stations were broken up into two grouping. The first group of stations was

Figure 9. NSTB Station Division.

in CONUS and Canada and the second group was comprised of Alaska and Hawaii.

UDRE

The first set of tests quantified the User Differential Range Error (UDRE) for test data collected over three days in June 1998. The UDRE is an estimate of the error bound for the combined pseudorange and clock error for a given satellite [11]. The UDRE values were mapped to the satellite position over the Earth at the time the data was collected. By accumulating the UDRE values over time a histogram can be developed to show the degradation of the accuracy of the satellite orbit and clock determination relative to the SBAS reference station locations. Again, the statistical bound of 99.9% was used. Before being plotted the UDRE values were quantized to the limits established in [7] to assure agreement with the values used to generate the contours with those values that can actually be transmitted to the user. The results for CONUS, AK/HI and Combined cases are shown in Figures 10, 11 and 12 respectively. These results are a strong function of the reference station geometry. Expanding the distribution of sites greatly enhances the size of the 99.9% UDRE envelope. Similar to the user coverage plots the UDRE degrades rapidly at the boundaries of the coverage area. The quantization helps keep the UDRE contour relatively flat except at the boundaries. Also of note is the fact that the integrated region of coverage in Figure 12 is larger than the union of the coverage areas in Figures 10 and 11. This again leads to the ability to conclude that the increased geometric leverage has added benefits beyond the obvious expansion of the coverage area. By increasing the path length of the tracking of a satellite, certain orbit determination schemes could be greatly enhanced [10].

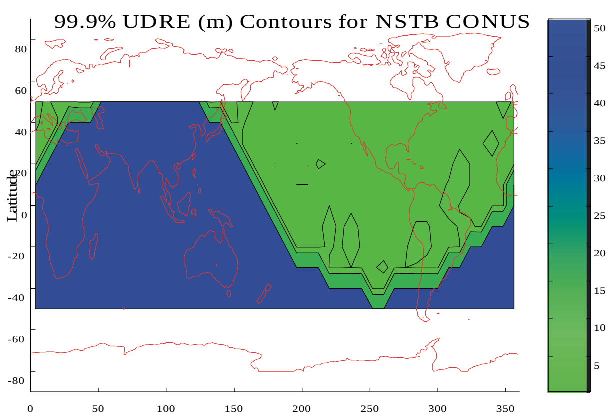

Figure 10

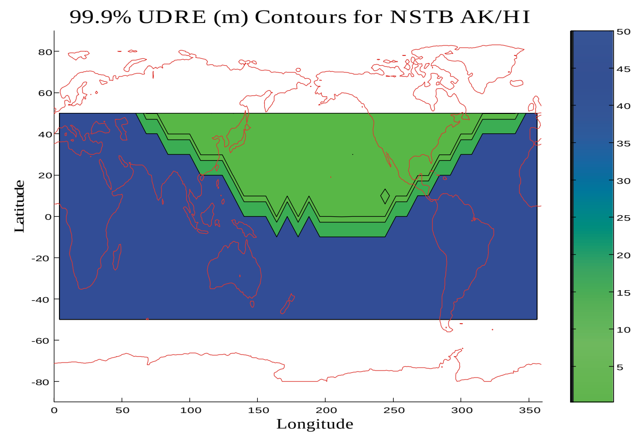

Figure 11

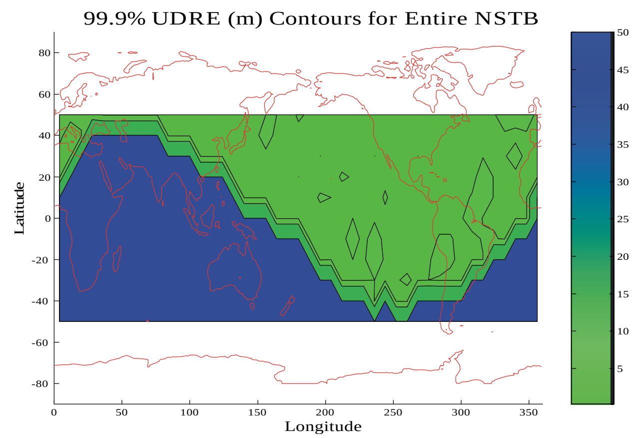

Figure 12

USER PERFORMANCE

For the cases of user coverage and UDRE contours, the boundaries of the SBAS regions with integrated result exceeded that of the sum of the individual regions. It is therefore reasonable to imagine that users on the periphery of SBAS service volumes could benefit from the addition reference data from outside the SBAS.

To investigate the user performance we utilized the master station and software developed at Stanford University for use with the NSTB. This software collects the data coming from the NSTB reference stations and formulates corrections. The first step of the process it to utilize the dual frequency data to make an estimate of the ionospheric delay as well as form the ionosphere-free carrier-smoothed codephase estimate. The codephase is further processed to compute the clock and ephemeris errors of each satellite. These estimates are formatted as in [7] and used to correct the measurements for those stations not utilized for creating the corrections.

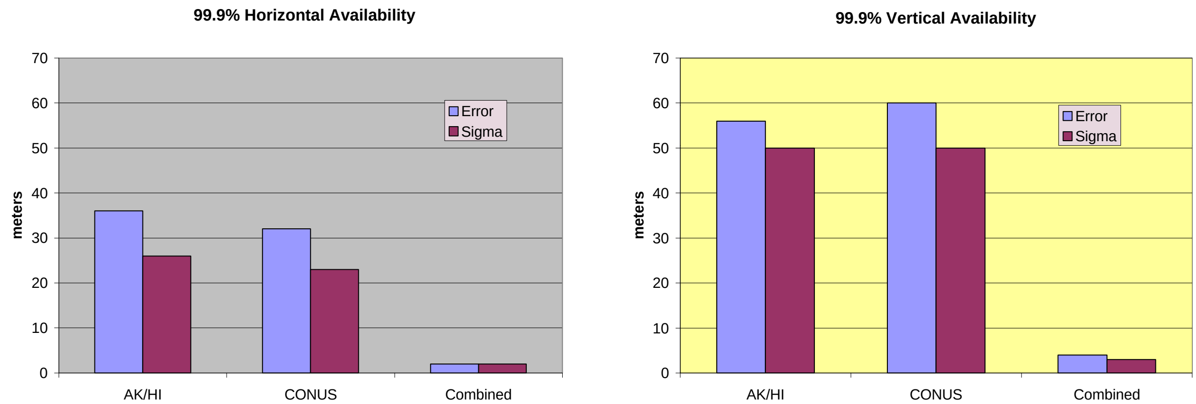

Figure 13. Sitka User Performance Data for Three Cases.

This process can both be run real-time and in post-processed mode. Post-processing allows for multiple hypotheses to be formulated and tested. In this case we wanted to investigate the effect of differing sets of reference stations on a SBAS border-case user.

To understand the performance of a border user the Sitka Alaska reference station was chosen to be passive (not used for correction generation) for all tests. Three successive tests were run. First, the CONUS-only (plus Canada) stations were utilized to provide corrections to Sitka. Next, the Alaska (minus Sitka) and Hawaii stations were combined to provide the corrections. Finally, all stations were combined to provide corrections to passive Sitka. The results are summarized in Figure 13 for both horizontal and vertical 95% availability. As is evident in the plots the border case is dramatically improved by inclusion of data from the neighboring SBAS. Neither SBAS could independently provide availability of corrections to Sitka while together the coverage was nominal.

RESULTS AND CONCLUSIONS

Based on both the user coverage simulations as well as the UDRE contours from the NSTB it is clear that data sharing enhances seamless worldwide navigation.

Information theory suggests that cooperative data from interoperating SBASs can be combined at different levels with equivalent results however qualitatively there seems to be an advantage to combine data at the reference data level.

Based on the integration of planned systems significant user coverage might be possible to the entire Northern Hemisphere. By incorporating data from multiple SBASs the coverage area exceeds the union of the independent SBASs.

This work also showed that users on the borders of SBAS operations could be significantly impacted by the inclusion of additional reference station data utilized from an external SBAS.

FUTURE WORK

This work has suggested that there are compelling reasons for integrating the reference data between the SBAS to improve the performance within the established service volume. Among these are that increased visibility of satellites will help dynamic orbit determination significantly [10] and similarly crossovers in ionospheric pierce points could help in determination of the delays due to the ionosphere.

The UDRE is combined with the User Ionospheric Vertical Error (UIVE), geometry (satellite elevation and azimuth), plus an elevation dependent error due to SNR, multipath, and the Troposphere to give the Combined Differential Range Error (CDRE). The CDRE is the total estimate of the error on a given range measurement. Future work should characterize this parameter for interoperational SBASs.

ACKNOWLEDGEMENTS

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REFERENCES

[1] "EGNOS Status Report", Presentation to the Interoperability Working Group 3, Ottawa, July 1998.

[2] "GNSS Test System", Electronic Navigation Research Institute, Ministry of Transport, Japan, 1998.

[3] Enge, P., "Wide Area Augmentation of the Global Positioning System.", Proceedings of the IEEE, 84(8):1063-1088, August 1996.

[4] "Test Bed Reference Station To Test Bed Master Station Interface Control Document"; Version 3.1, August 1997, Federal Aviation Administration William J Hughes Technical Center.

[5] Dai, D. *et al.* "Interoperation of Distributed SBASs: Theory, Experience from NSTB and Future Perspective", Proceedings of ION GPS 98, Institute of Navigation, 1998.

[6] Bevington, P.R., Robinson, D.K., 1992, *Data Reduction and Error Analysis for the Physical Sciences*, Second Edition, McGraw-Hill.

[7] RTCA/DO-229 Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment, Proposed Final Draft, March 1998.

[8] Wessel, P., and Smith, W.H.F, "New Version of the Generic Mapping Tools Released", EOS Trans. Amer. Geophys. U., vol. 76, pp 329, 1995.

[9] Leon-Garcia, A., *Probability and Random Processes for Electrical Engineers*, 2nd Edition, Addison Wesley.

[10] Pogorelc, *et. al*., "Test Results of GPS and Geostationary Satellite Orbit Determination", ION National Tech. Meeting, Jan 97.

[11] Comp, C., *et. al*., "Improving WAAS Integrity and Availability: UDRE and GIVE Time Updates", Proceedings of ION GPS 97, Institute of Navigation, 1997.

[12] Fernow, J.P. *et. al*., "Interoperability Between SBASs", ION Annual Meeting, June 1997.