Flight Trials of a Geostationary Satellite Based Augmentation System at High Latitudes and for Dual Satellite Coverage

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ABSTRACT

Several flight demonstrations have taken place over the past few years to show how the Wide-Area Augmentation System (WAAS), currently under development for the Federal Aviation Administration, will increase GPS accuracy, availability, and integrity for aviation. These demonstrations have been carried out with the support of the National Satellite Test Bed (NSTB). Using the real-time GPS data available from the NSTB, flight tests were carried out to further show the possibilities of such a system to aviation.

Some concern has been noted for users at high latitudes (> 55 degrees) as to whether they will be able to reap the full rewards of such a system. Special attention has been paid to ability to track geostationary signals reliably from high latitudes. By using the prototype wide area differential GPS flight software developed at Stanford University in coordination with the NSTB, flight trials have been conducted in Alaska using geostationary satellites as a data link. Results are presented showing flight performance at these high latitudes versus a carrier-phase smoothed local-area differential GPS truth system. Additionally, by post-processing the data, the effects of excluding some of the Alaskan NSTB reference stations on flight performance are shown.

As we approach operational WAAS, there is interest in understanding the best strategy for integration of corrections from the multiple geostationary satellite signals that will become available. Flight tests have been done utilizing two geostationary satellites for GPS corrections. Performance results of the geostationary handover will be presented. In addition, by splitting the NSTB into two groups of stations the results of interoperation of GPS augmentation systems were flight demonstrated.

INTRODUCTION

Previous flight test papers [1-6] have demonstrated both the development of the NSTB reference network infrastructure and the benefits of the anticipated WAAS capability. This paper will extend that work by displaying the results for flight tests using L1 Geostationary (GEO) signals (results from [1,2] are for an UHF data link and [3-6] are for off-L1). Accuracy and integrity were evaluated in the air as well as on the ground.

Alaskan Flight Trials

Alaska is an important demonstration because it poses several challenges for WAAS [7]. The ionosphere, which is generally the most troublesome error source, is typically more active at high latitudes. Alaska is located squarely in the auroral zone known to have steep ionospheric gradients (Figure 1). Ionospheric estimation difficulty is further compounded by the sparse Alaskan

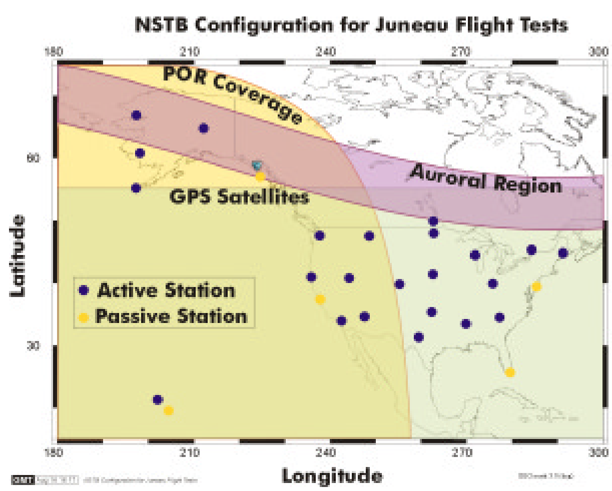

Figure 1. NSTB Reference Station Configuration and Inmarsat-III Pacific Ocean Region (POR) Footprint.

reference station network in comparison to the core network in the lower 48 states and Canada. Alaska is also a navigation challenge for WAAS because of the lack of visibility of the GEO satellites to maneuvering aircraft. The Inmarsat III Pacific Ocean Region (POR) satellite is at 178° West longitude. In southeastern Alaska this means a reasonably low 15° elevation.

One of the major goals in the Alaskan flight tests was to demonstrate WAAS performance despite the demanding environment. Tests were conducted flying into Sitka airport from Juneau to utilize the reference station data for a local area differential GPS codeset that will be described below. The local area results were used as a truth system to verify the wide area navigation solutions. These tests demonstrated acceptable performance despite operating in a region over 1000 km from the nearest active reference station (Fairbanks, Alaska).

Dual-GEO Flight Trials

Palo Alto, California is beneficially located within tracking range of two Inmarsat-III GEO satellites that are configured for broadcasting WAAS signals. Atlantic Ocean Region-West (AOR-W) is located at an elevation of 9.6° above the local horizon and Pacific Ocean Region (POR) is 18.4° in elevation in the Palo Alto area. This presented an opportunity to evaluate the utilization of two GEO signals in flight. Flight tests were carried out where both GEO satellites were sent corrections from the Stanford TMS and the user platform was configured for tracking the satellites simultaneously. The results of switching satellites versus the results from individual satellites are shown.

Interoperability Flight Test

WAAS is one of at least three systems currently under development worldwide for the augmentation of navigation satellite systems for aviation [8,9,10]. Of significant concern are the methods and procedures that will be enacted to ensure that these systems provide near-seamless augmentation worldwide. This worldwide cooperation is generally referred to as interoperation. By utilizing the large geographical extent of the NSTB, it was possible to create two nearly independent SBAS configurations by breaking the NSTB stations into two groups. One set of stations were used by the first TMS process and sent to the first GEO satellite and the second group were used to form the corrections for the second GEO satellite producing independent streams of corrections. A flight test was executed to demonstrate the performance of a wide area user operating on the boundary of these two SBASs (selected as Palo Alto). Results are presented when considering each stream exclusively compared to when the messages are combined.

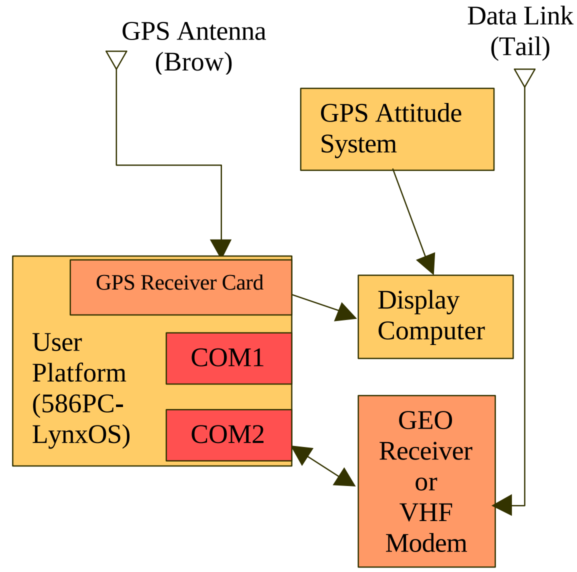

Figure 2. User Platform Setup During Flight Tests in Sitka, Alaska and Palo Alto, California

FLIGHT TEST SYSTEM

Figure 2 is a block diagram of the flight test system used both in Sitka and in Palo Alto. The GPS receiver card supplied the 10 Hz observables (pseudorange, carrier phase, time, etc.) to the wide area algorithm while the GEO receiver supplied the 250 bps WAAS messages (1 message per second). The computer was a Pentium-133 industrial rack-mounted system running the LynxOS real-time operating system. The output of the system was sent to a display computer that gave a real-time display of position and attitude to the pilot. While 10 Hz was not necessary for WAAS processing, the requirements of the display system demanded at least a 10 Hz update rate [7,13]. The results presented are subsampled to a 1 Hz output rate.

Figure 3 shows the cabin layout of the equipment with the WAAS rack towards the aft of the aircraft (foreground) and the attitude/display rack in the background. Additional equipment on the WAAS rack includes a video recorder for the camera mounted in the nose of the aircraft as well as a VHF radio modem used as a backup datalink.

Wide Area Software

The aircraft used for all flight tests was a Beechcraft Queenair specially modified for the multiple GPS experiments that commonly ran in parallel. As shown in Figure 4, the navigation GPS antenna is mounted on the brow of the plane (just above the pilots) and the GEO L1 receive antenna is mounted on the top of the tail.

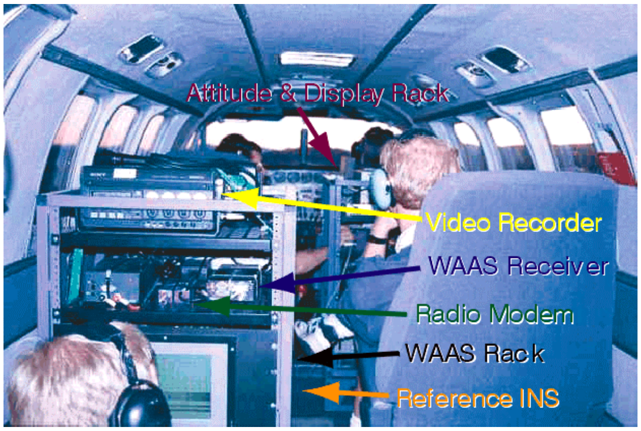

Figure 3. Equipment Setup Inside Cabin.

The antennas used for the attitude system were mounted just aft of the navigation antenna. Shown at the front of the aircraft is the nose-mounted camera used as a positioning reference (described below).

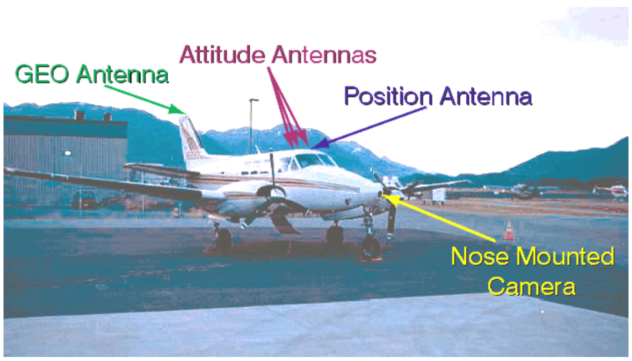

Figure 4. Aircraft Used in Flight Tests.

The wide area software hosted on the PC in Figure 2 is a third generation code developed in June 1998 in an effort to bring as much code re-use to the user platform as possible from the TMS software. The advantage of using the TMS software as a starting point for the user platform code is that many of the routines necessary for data processing and navigation have been thoroughly tested and revised.

REFERENCE SYSTEMS

Visual

Common to each flight test is the use of a visual flight system [7,13]. As shown in Figure 2, the WAAS navigation solution is output to a visual display system that is available to the pilot in real time (Figure 5). This system is used as a check of the navigation accuracy. As the plane approaches the runway the pilot can observe the alignment of the display with the view from the cockpit. This gives both horizontal and vertical feedback for the qualitative accuracy of the system, to within a few meters.

For some of the flights the nose mounted camera was recording on a video deck that was time synchronized to another deck recording the output of the visual display system. Although the boresight of the visual display system was aligned to the view from the cockpit rather than from the nose, individual frames gave us very good information about our position accuracy. Both the cross-track accuracy versus the runway center-line as well as the along-track accuracy at the runway threshold were well observed to within one or two meters as indicated in Figure 5.

While this visual reference was invaluable during the initial system integration and test, it quickly became evident that a quantitative solution would be necessary to fully evaluate wide area performance.

Figure 5. Example of the Qualitative Visual Reference System.

Local-Area Differential GPS System

As a quantitative measure of navigation performance a new codeset was developed that uses a local area differential GPS solution. The WAAS navigation solution was compared against a double-differenced, carrier-smoothed code phase position solution (DDCSMC) based on the reference receiver located at Sitka for the Alaska flight tests and at Stanford University for the Palo Alto flight tests. A code-based method was chosen to eliminate the need for carrier-ambiguity resolution and it is also the basic algorithm selected for LAAS implementation. The accuracy is expected to be better than one meter. The smoothing filter used a weighting constant of 360, meaning that data from the last 359 epochs were used to smooth the current epoch's code phase data.

To determine the accuracy of the DDCSMC algorithm, data from the reference receiver was gathered for twelve hours on October 16, 1998. The DDCSMC solution was then calculated for each epoch and compared against the known, surveyed location of the antenna. Figure 6 presents the error in East, North, and Up over the test period.

The East and North errors were well within the expected one meter accuracy. The Up error was considerably noisier and exhibited two excursions to two meters of error. These excursions may be due to undetected and uncorrected cycle slips and investigations are continuing to determine the cause. For the WAAS performance solution, the horizontal "truth" produced by the DDCSMC is satisfactory for comparison purposes and the vertical solution is adequate in this role.

"Truth" Degradation with Distance from Reference Station

The DDCSMC solution is dependent on the distance to the reference receiver [14] and it has been suggested that the accuracy of the solution will degrade at a minimum rate of 3 mm per kilometer [15] and a maximum rate of 5 mm/km [16]. The most recent estimate [17] suggests that 5 mm/km may be used to estimate the degradation of accuracy due to ionospheric and tropospheric changes between the user and the reference station. Thus, for a flight test performed at 30 km from Stanford, the expected error in the DDCSMC solution would be 0.15 meters. A radius of 100 km was used as a limit for all flight tests to bound the atmospheric changes to within about 0.5 meters, which is roughly the error currently observed in the zero-baseline horizontal case. In the future when this zero-baseline error level is reduced, the bounding region may be reconsidered.

SYSTEM ISSUES

During the checkout and qualification of both the wide area and local area systems several issues became evident. While many of these issues were worked out during development, there are some unresolved problems we continue to study at this time.

Local Area DGPS System Errors - Static Verification (Zero-Baseline)

As illustrated in Figure 6, the local area system does have errors up to a meter in the horizontal and two meters in the vertical in comparison to a surveyed position. This uncertainty will distort the wide area results because the reported errors in the wide area system will be a combination of the actual error of the wide area system plus that of the local area system. Additionally, there is as of yet no cycle-slip patching for the carrier-smoothing algorithm. While in the air the motion of the aircraft will occasionally cause us to lose lock on low-elevation satellites. This will cause the local area measurements to revert to raw codephase accuracy until the carrier phase smoothing can reconverge. One problem encountered in post-processing was the fact that the local area system was not available continuously. Epochs of data were dropped primarily due to cycle-slips and therefore were unavailable for comparison. In the static reference data there are no issues with epoch loss. The results shown using this method will usually have a few more points than those utilizing the local area system. Checking the wide area system alone, it was found that the additional loss of availability due to the absent epochs in the truth system was marginal (< 0.6%). We are continuing work on these issues with the Local Area Augmentation System (LAAS) group at Stanford. In the meantime, some tolerance will have to be allowed for evaluating wide area performance in light of the local area DGPS uncertainties. Atmospheric effects, cycle slips and the zero-baseline errors up to two meters in the horizontal and up to four meters in the vertical will have to be taken into consideration when comparing the local area DGPS errors to the wide area error evaluation.

Message Loss

During the flight tests, unusually high rates of WAAS message loss as compared to expectation [18] led to a large number of correction message timeouts on certain satellites. These were predominately attributed to the dual GEO satellite tracking conditions. We are currently working with the receiver manufacturer to determine the cause of the message loss. It appears to be isolated to the receiver firmware. This message loss resulted in unusually large HPLs and VPLs when compared to our static reference stations.

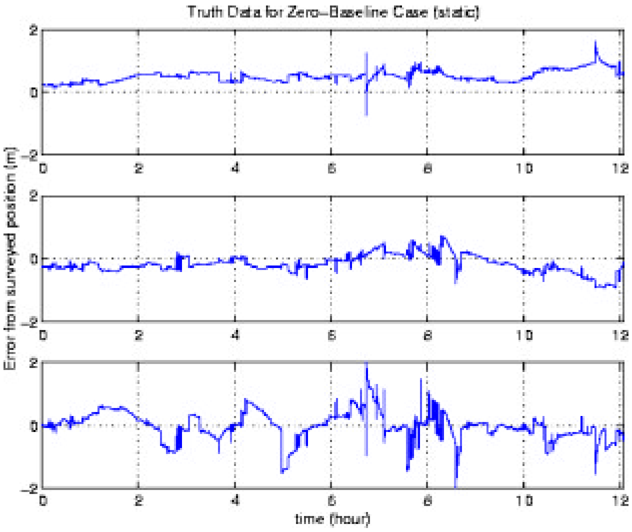

Figure 6. DDCSMC Minus Surveyed Position for Twelve Hours. Errors are in East, North and Up components.

Sensitivity to Receiver Noise Modeling

Appendix J of the MOPS [11] indicates a specified model of receiver noise for a receiver that meets given performance conditions. The manufacturer of our GPS receiver makes no claims to meet or exceed that specification. The elevation-based model from Appendix J is:

$$s\,(pseudorange) = 0.16 + 0.23e^{-elevation/19.6}$$

where the elevation is in degrees and the resultant one-sigma value is in meters. Figure 7 shows the flight test from October 23, 1998, in the horizontal using the MOPS Appendix J receiver noise model. While the number of alarm epochs in this analysis was zero, the number of epochs with misleading information (MI) were significant making up over 5% in more than 1 hour of flight time.

In contrast, Figure 8 shows the result for a receiver noise model that is based on SNR developed at Stanford for the reference stations in the NSTB. This model takes the following form:

$$s^{2}(pseudorange) = Ae^{-B*SNR}$$

The SNR is in C/No (Carrier-to-Noise Ratio, in dB-Hz) and the result is in meters-squared. The values of A and B used for Figure 8 are:

A = 2472.0
B = 0.2188

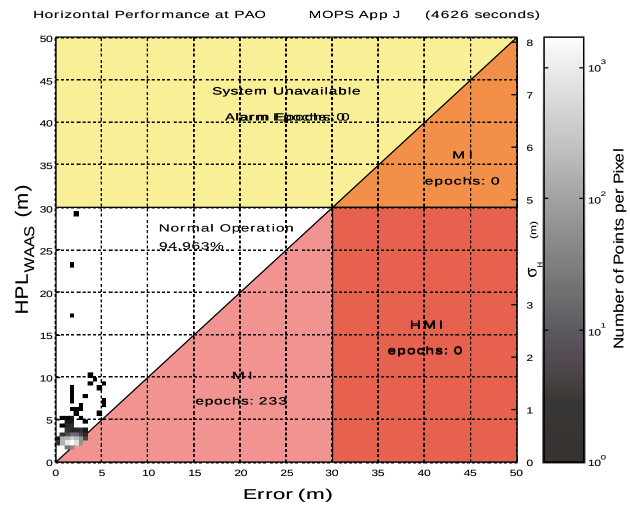

Figure 7. Flight Test Results Using the MOPS Appendix J Model for Receiver Noise.

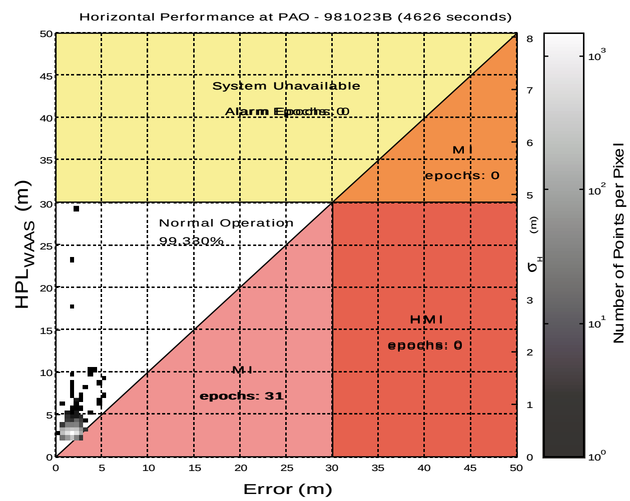

Figure 8. Flight Test Results Using the Stanford SNR-Based Receiver Noise Model.

The value for B is used for all NSTB reference stations and the value of A used is the median value of A for all of the reference stations. These values are based on long-term observations of the measurements at each receiver location fit to the functional form shown above. As is evident, the HPL values remain largely unchanged. However, the MI numbers have dramatically decreased from 233 to 31 and the availability has increased to over 99% indicating that this is a much better fit to the true error. It is clear that the effects of unmodeled or mismodeled receiver noise have a dramatic impact on the integrity and availability of WAAS. The remaining MIs are due to the fact that the new model still does not bound all of the user error. In addition, the local area system uncertainty is likely contributing to some of these MIs. Further work will investigate finding a proper noise model to fully bound the user errors. We believe that continued work on the cycle-slip patching for both the local and wide area systems will improve the receiver carrier-smoothed pseudorange estimates to the point where they are compliant with Appendix J of the MOPS.

FLIGHT TEST RESULTS

High Latitude, Single GEO Satellite, Sitka Alaska

During the period of August 1-12, 1998, flight tests and demonstrations were conducted in the southeastern part of Alaska [7]. These tests were primarily centered in the Juneau area, roughly 160 km away from the nearest reference station in Sitka Alaska (Figure 1). The Stanford University Testbed Master Station (TMS) was used to generate wide area corrections and send these messages in the WAAS-MOPS format [11] through the Inmarsat-III POR GEO satellite via the Testbed Uplink Station (TUS) [12]. As indicated in Figure 1, the Sitka reference station was set to passive (i.e. not used to generate wide area corrections) for all of the flights in Alaska. The flight locations in Alaska were at high latitude, where the ionosphere is generally more active, placing elevated stress on the wide area system.

On August 11, a flight from Juneau to Sitka allowed for a local area DGPS system to be employed as a verification of wide area accuracy independent of the visual reference system. Since the local area DGPS system will have degraded performance proportional to the distance from the reference station (as discussed previously), a radius of 100 km was used as the maximum extent that the reference system would be employed. The Sitka reference station data was not used by the Stanford TMS to formulate the corrections sent across the POR satellite. The Stanford TMS has the capability to generate navigation solutions at each of the reference stations.

Visibility of the GEO satellite proved to be a non-issue. During straight and level flight as well as banked traffic pattern turns, the GEO signal was rarely lost. To test the GEO reception in extreme conditions, a series of wing-overs were flown. During these maneuvers, correction messages from the GEO experienced short outages and WAAS position was sustained through roll angles of up to 45°.

Figures 9 and 10 show the comparison of the flight test data near Sitka to the solution produced by the TMS for the static reference station at Sitka at the concurrent times. Note a slight discrepancy in the number of epochs between the two, which is due to the times when the local area system did not produce a solution. The flight data at Sitka shows an operational value exceeding 99.8% in the horizontal, which is extremely encouraging considering the high latitude and that the GEO satellite was not used for ranging. That additional ranging source would significantly enhance the availability [19]. The user error mismodeling created misleading information (MI). When this is discounted the overall availability goes to 1-(2/4179)>99.95%. The vertical operational performance exceeds 98.5% where the effect of user error mismodeling is still evident. These MIs are not evident in any of the nominal output of the NSTB reference stations. Work will continue to eliminate these sources of MI in the wide and local area user codes as MIs are intolerable in an operational system.

Dual GEO Satellites, Palo Alto, California

Palo Alto, California is fortunate to be located within tracking range of two Inmarsat-III GEO satellites that are

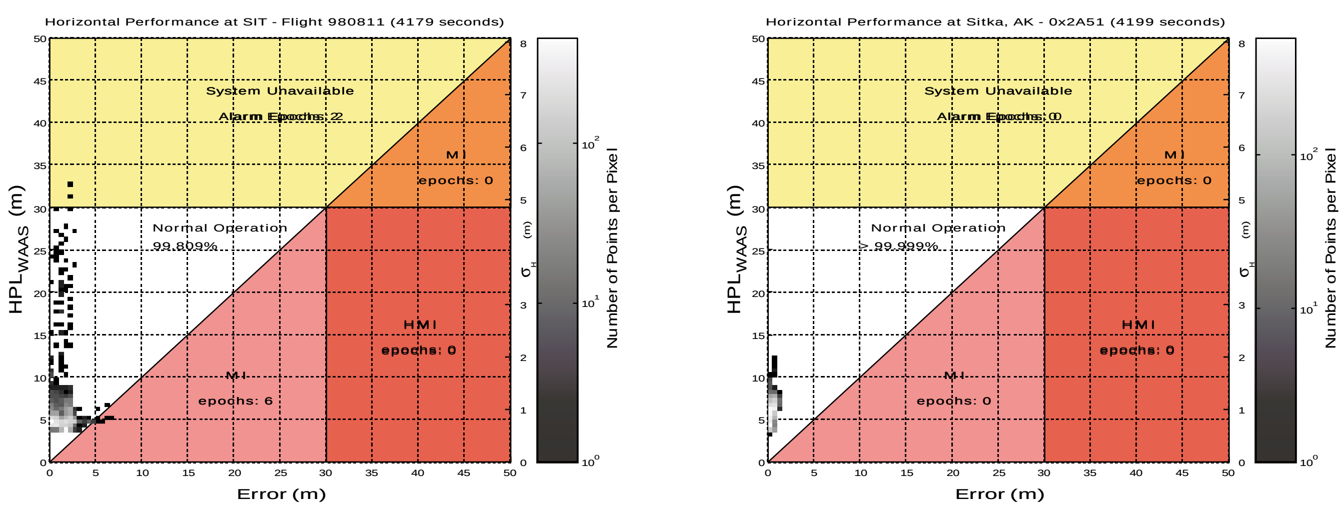

Figure 9. Comparison of Flight (Left) and Static (Right) Horizontal Results at Sitka. Note the effect in flight of message loss on the HPL and the modeling errors in horizontal error.

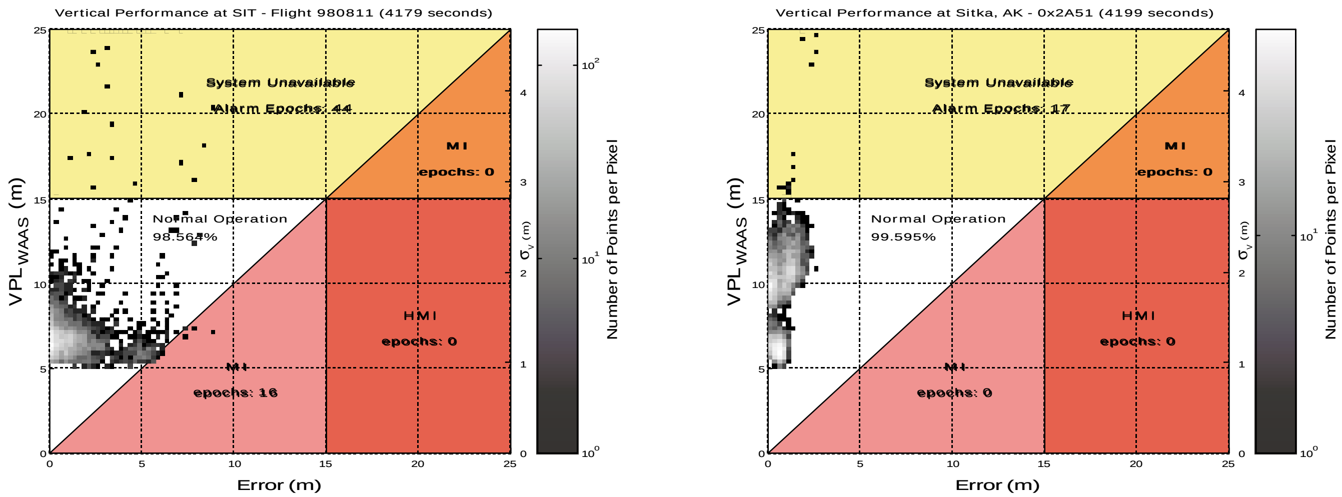

Figure 10. Comparison of Flight (Left) and Static (Right) Vertical Results at Sitka. Note the effect in flight of message loss on the HPL and the modeling errors in horizontal error

capable of broadcasting WAAS signals. This excellent location brought about an opportunity to test the advantage of utilizing two GEO satellites simultaneously to receive WAAS message corrections by the user platform (Figure 2). The wide area code used in the Alaska flight trials was modified to handle up to four simultaneous GEO satellites and allow for arbitrary switching among them. Each GEO message stream is kept independent of the others thus allowing for WAAS MOPS [11] compliant precision approach (PA) operation. For non-precision approach, terminal and en-route modes, the MOPS allows for combining corrections across GEO satellites as will be discussed in the next section. Static lab tests were conducted with dual GEO satellites on October 16, 1998 to verify the operation of the software. The first flight test with a dual GEO was performed on October 23, 1998.

The Stanford TMS was used to generate two message streams with substantially the same content. A simple algorithm was incorporated into the user platform software to instantaneously switch between the satellites when one signal level dropped below another. The flight tests were carried out on October 23rd and 30th 1998, originating at the Palo Alto Airport (PAO) in California.

Figure 11 shows the horizontal results for several approaches into NASA-Ames/Moffet Field in nearby Mountain View, California. On the left is the result when only PRN 122 (AOR-W) was used and on the right, PRN 134 (POR). In both cases, the availability exceeded 98%, again without using the GEO ranging signal on either satellite. When the highest power satellite is used in Figure 12, the availability increases to over 99% but is not as good as the PRN 122 results alone. The results indicate that while switching based on power provides acceptable performance it is not the optimal method. A method that employs the correction with the lowest HPL or VPL would produce more optimum results at the expense of further computations in the avionics.

The observed MIs in flight were due to the user receiver error model under-bounding the true errors. Additionally, inaccuracy in the local area reference system also contribute to the true errors in these charts, but the effect is not taken into account when calculating HPL or VPL. We will work to better model the noise and multipath in the user receiver and to improve our local area reference system. The prototype WAAS system did not suffer these problems at nearby static receivers with known antenna positions and known error models. Only sites with imprecise survey locations or poorly characterized noise models exhibit MI (misleading information).

Interoperability, Palo Alto California

The result of the previous section was with two message streams of substantially the same content. When operating with two SBASs, the message streams will be different, due to the different algorithms used in the individual master stations and due to the different reference stations used to formulate the corrections.

By utilizing the large geographic area of the NSTB, we were able to split the reference stations to create two message streams with significantly different visibility to the GPS satellite constellation. Figure 13 shows how the stations were distributed. Stations to the left were used to drive POR and stations to the right were used to drive AOR-W. The stations indicated in the middle were common to both groups to ensure ionospheric corrections were available to the user. In both correction streams the Stanford reference station was passive (i.e. not used to generate corrections).

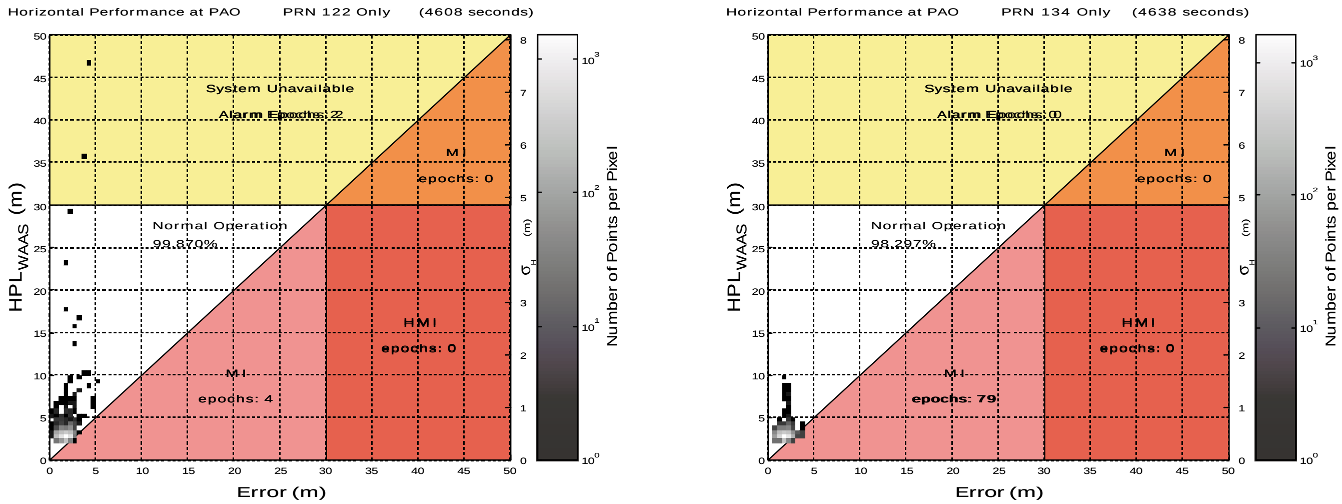

Figure 11. Individual GEO Satellite Horizontal Results, Palo Alto, California, October 23, 1998.

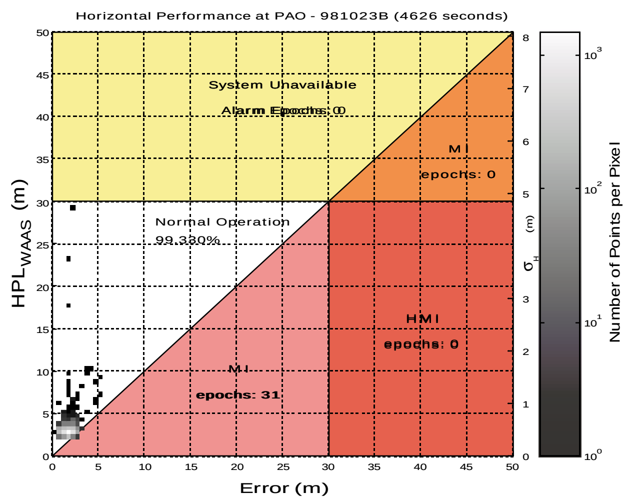

Figure 12. Horizontal Results when GEO Satellite with Highest Power (SNR) Selected as Primary Signal.

The common stations were necessary, as the user code did not support a mode at the time where ionospheric corrections were not necessary. By including the common stations, at least a few ionospheric grid points on either side of the flight area would be active.

There were only two significant changes to the user code beyond that used for the dual GEO satellite tests. First, the UDRE (User Differential Range Error) and UIRE (User Ionospheric Range Error) values were calculated for both correction streams (when switching, only one or the other is used) and these values were used to evaluate which GEO satellite correction would produce the smaller range variance. Second, the difference in system time between the two SBAS streams had to be taken into account. This was accomplished by taking the mean of the difference of the clock corrections for each satellite:

$$\Delta W = \frac{1}{N}\sum_{i=1}^{N}\left(B_i^{POR} - B_i^{AOR-W}\right)$$

where N is the number of GPS satellites that are corrected by both of the message streams and B is the total clock correction combining both fast and slow corrections. The result was used to adjust the pseudoranges for the secondary GEO satellite.

A single flight test was carried out near the Palo Alto airport on December 13, 1998. The horizontal results of the interoperability test are shown in Figure 14. The increase in both observed errors and user uncertainty are evident with the combined solution producing a significantly improved distribution in HPL. The error distribution was largely unaffected because the errors are primarily due to the uncertainty in user pseudorange measurements that have no influence on the HPL/VPL distributions. With this relatively small number of data points it is hard to establish a quantitative value for the improvement in availability. However, the substantially consolidated distribution of HPL values qualitatively suggest a realizable improvement in availability.

Figure 13. Diagram of Stations Used for Interoperability Flight. Stations to the left were used to drive POR and stations to the right were used to drive AOR-W. The stations indicated in the middle were common to both to ensure ionospheric corrections (Stanford passive).

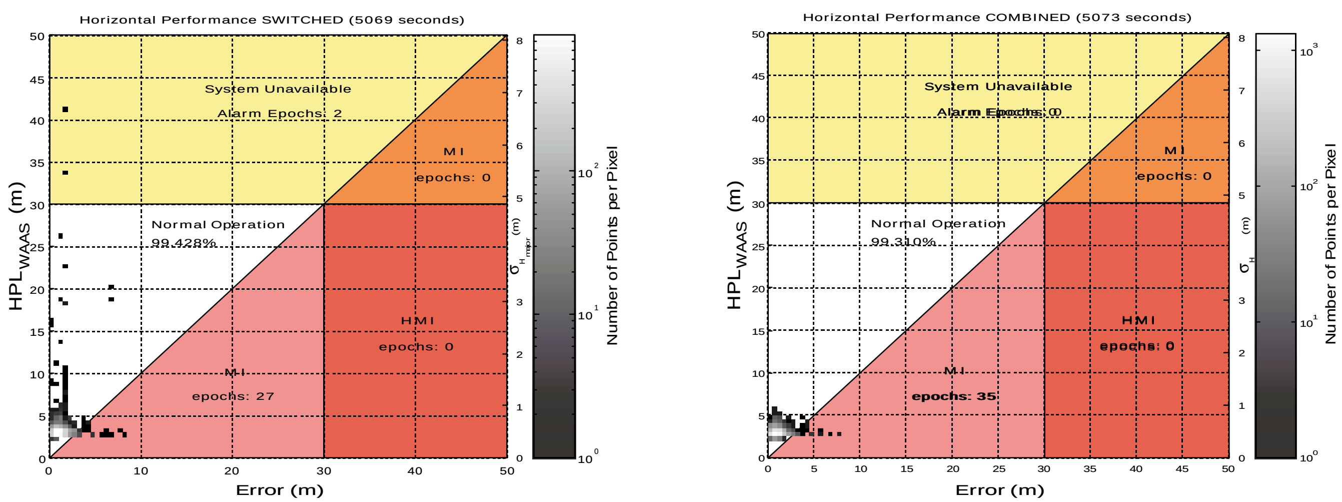

Figure 14. Comparison of the Horizontal Results when Switching Between GEO Satellites and Combining GEO Messages for individual GPS SVs.

CONCLUSIONS

The flight tests in Alaska this past summer demonstrated availabilities exceeding 98% with no Hazardously Misleading Information (HMI). This performance was achieved with known limitations in the reference truth system and without using the GEO as a ranging source. These tests demonstrated acceptable performance despite operating the aircraft over 1000 km from the nearest active reference station (Fairbanks, Alaska).

Test flights in the Palo Alto area demonstrated the advantages of dual GEO satellite operation. The availability exceeded 98% for all cases without using the GEO ranging signal on either satellite. When the highest power satellite is used, the availability increases to over 99%. The results indicate that while switching based on power provides acceptable performance it is not the optimal method. A method that employs the correction with the lowest combined HPL and VPL would produce more optimum results at the expense of further computations in the avionics.

A recent flight test exhibited the performance of a projected user on the boundary of two SBASs. Results were presented when considering each stream exclusively compared to when the messages are combined. Results showed the performance enhancement of a combined user solution made possible by interoperation of two different message streams. With the relatively small number of data points available from the flight test it was hard to establish a quantitative value for the improvement in availability. However, the reduction in the scatter of the HPL values qualitatively suggests that an improvement in availability can be achieved with little or no impact on integrity.

Epochs with misleading information (MI) were observed in multiple flight data sets. These were caused by an uncorrect model of the user pseudorange noise of the user platform receiver combined with uncertainty in the reference local area differential GPS. All MI points are intolerable in an operational system and we will continue to eliminate the sources of these errors in the user platform code as well as the reference system.

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