Incorporating GLONASS into Aviation RAIM Receivers

Todd Walter, Juan Blanch, Myung Jun Choi, Tyler Reid, and Per Enge
Stanford University

ABSTRACT

Recently the Russian government issued a mandate on the use of their GLObal NAvigation Satellite System (GLONASS) for Russian operated aircraft [1]. There is some concern and uncertainty both in exactly what is required to satisfy the mandate and how best to conform to it. GLONASS recently re-established full operating capability and has 24 operational satellites in orbit. The addition of a second full constellation is, potentially, very beneficial to satellite navigation of aircraft. However, the GLONASS satellites do not have the same performance characteristics as the Global Positioning System (GPS) satellites. Therefore it is essential to understand these differences in any algorithm that seeks to determine a safe position based on the combined performance of these two systems.

INTRODUCTION

The most prevalent use of GPS in aircraft today is through the use of Receiver Autonomous Integrity Monitoring (RAIM) [2]. RAIM makes several assumptions about the performances of the satellites that it uses. Key among these are: the likelihood of erroneous data and the complete absence of simultaneous faults across multiple satellites. A recent analysis of GLONASS performance indicated that faults may be much more likely to occur on GLONASS satellites and it identified events where multiple satellites had simultaneous large errors [3]. The RAIM algorithms currently in use would not be able to meet the required integrity levels if they treated GLONASS satellites exactly as they do GPS satellites.

The United States has made very specific performance commitments for GPS to provide assurance that the RAIM assumptions will be met. To date, no other constellation provider has provided similar assurances. GPS also has an extensive service history with hundreds of satellite-years of operation. Since being declared fully operational in 1995 there have not been simultaneous faults on multiple satellites.

This paper examines modifications to RAIM that allow different assumptions to be placed on GPS and GLONASS. The proposed changes allow the user to benefit from this second constellation while retaining the requisite level of integrity. We specifically address the possibility of multiple faults in the GLONASS constellation. This proposal includes parameters describing GLONASS reliability that may be updated at a later date as operational history and performance commitments allow better knowledge of expected future behavior. We show how RAIM performance is affected with the inclusion of GLONASS.

The targeted service of this paper is horizontal guidance, which is the service that RAIM provides today. We will analyze performance against a maximum error limit of 0.3 Nautical Miles (NM). That is, the airborne algorithm should be able to assure that the Horizontal Positioning Error (HPE) is below 0.3 NM to within the desired integrity level. This is a value that supports en route through terminal operations and is currently supported by RAIM.

GPS BASED RAIM

RAIM has been approved for aircraft operations for more than fifteen years [4]. It was originally developed when Selective Availability (SA) was present on the GPS satellites [5]. This deliberate dithering of the satellite clocks created a nominal error source that was significantly larger than all other nominal errors. The error bounding of SA was modeled as a 32 m one-sigma Gaussian term that dominated the other overbounding terms. The primary error source originally considered was a large (> 150 m) clock or ephemeris error on one of the satellites. All other error sources were considered too small compared to the effects of SA or too unlikely to occur. SA was discontinued in 2000 and later RAIM algorithms were developed that assumed that the satellite Signal-In-Space (SIS) error could be described as being below the previous 32 m one-sigma value.

In 2001, the Air Force published the first Global Positioning System Standard Positioning Service Performance Standard (GPS SPS PS) [6]. This document defined the expected reliability of the SIS. It provided assurances that there would not be more than three major service failures per year, where a major service failure is a SIS error greater than 30 m, when a satellite is set healthy and broadcasts a sufficiently low User Range Accuracy (URA) parameter. In 2008, the Air Force updated the GPS SPS PS [7] and redefined major service failure to be a SIS error greater than 4.42 times the broadcast URA. This provided an even tighter bound on the error as the URA is most often set to 2.4 m.

The airborne RAIM algorithm uses measurement redundancy to detect errors on the SIS. These airborne algorithms have been designed to evaluate individual satellite major service failures. The measurement data for each satellite is compared to combined information from the other satellites in turn. If it is found to be inconsistent, the algorithm will next try to isolate the error to a particular satellite and then remove that satellite from consideration. If it is unable to isolate the satellite, then an alert will be issued. The algorithm also evaluates the largest undetectable error that may be present and bounds that with a value called the Horizontal Protection Level (HPL). Better SIS accuracy and greater redundancy lead to smaller values of HPL. Specific operations have associated maximum tolerable errors called Horizontal Alert Limits (HALs). If the HPL is below the HAL the operation is declared available.

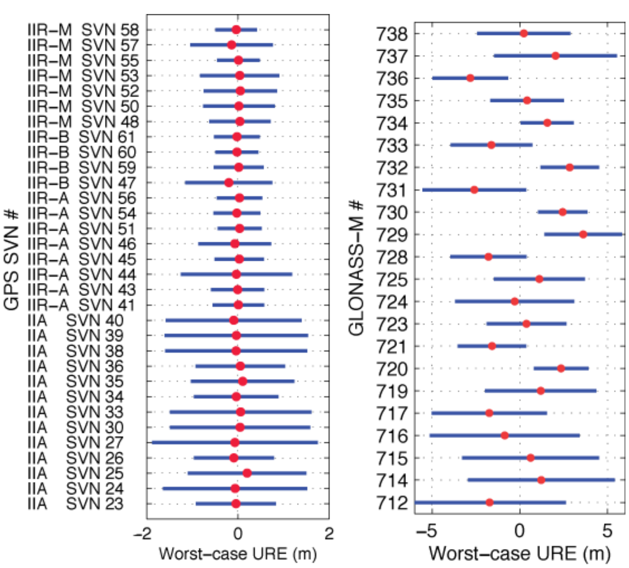

Figure 1. *A comparison of User Range Error (URE) between GPS (left) and GLONASS (right). Each line represents a satellite (most recently launched satellites at the top to oldest at the bottom). The blue lines indicate the 95% values and the red dots show the mean values.*

GLONASS PERFORMANCE

In order to incorporate GLONASS into airborne RAIM algorithms it is important to understand how GLONASS performs in comparison to GPS and to the assumptions of the algorithm. Two very important characteristics are the SIS accuracy and SIS reliability. Figure 1 shows a side-by-side comparison of recent SIS performance [3]. Each line represents a particular satellite, with oldest satellites at the bottom and the most recently launched at the top. Statistics for the worst-case User Range Error (URE) are shown for each satellite. The worst-case URE is calculated from the instantaneous satellite position and clock error. These errors are projected onto the lines-of-sight errors for users on the Earth and the largest value at any given time is recorded for each satellite. The red dot indicates the average of these values for the satellite and the blue bar indicates the approximate 95% containment.

As can be seen, the GPS satellites have comparatively smaller errors. The GLONASS SIS errors have statistically larger means and variances. The GPS mean errors are typically a few centimeters or less, the GLONASS mean errors can be more than a meter. The GPS standard deviations are close to half a meter for the later satellites. The GLONASS standard deviations range from under one meter to nearly two. On average, the GLONASS errors are two to three times larger than the GPS errors. This is partially reflected in the broadcast URA values. The most common GPS URA is 2.4 m (the lowest possible value) while the most common GLONASS URA is 4 m. Both are conservative representations of nominal performance, but there is greater margin in the GPS values.

Figure 1 describes the nominal performance, in absence of major service failures. The airborne algorithm also needs to consider the faulted performance; the likelihood of larger errors not well described by the broadcast URA. This too has been studied previously [3]. Figure 2 shows the cumulative fault hours for both GPS and GLONASS over recent years. For GPS, the definition of a fault matches the major service failure definition. Prior to 2008 the definition from the 2001 GPS SPS PS is used and after 2008, the later version is applied.

GLONASS does not yet have a publicly available performance standard. Therefore the definition of a fault is open to interpretation. Further, the URA value is not stored in the standard files that record the broadcast information from the GLONASS satellites. Therefore, the GLONASS fault rates are more indicative than precise. We have followed the definition in [3] that a

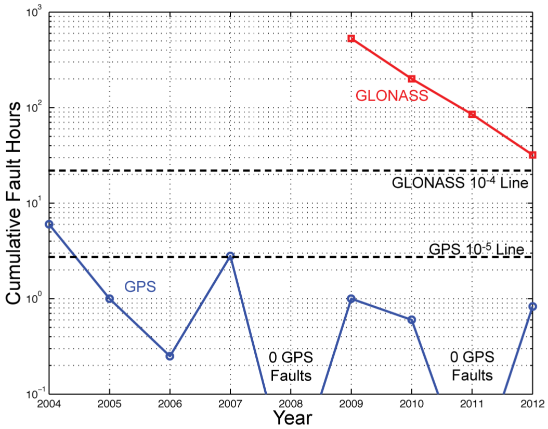

Figure 2. *Cumulative satellite fault hours by calendar year for GPS and GLONASS.*

fault occurs when the worst-case URE is greater than 50 m, the satellite is designated healthy in the broadcast ephemeris, and the time is within the specified fit interval. This definition may undercount faults as anything larger than 4.42 times the URA may be problematic. It may also over count faults as the error may have been flagged by increasing the URA. Regardless, we feel confident that this is a good indication of the relative levels of reliability.

Figure 2 shows that the fault rate for GLONASS is at least an order of magnitude larger than the fault rate for GPS. It is also obvious that GLONASS operation is improving and the overall fault rate is decreasing. It is possible that within a few years the two constellations will have comparable fault rates. However, at the current time, there is a substantial difference in the probability of a satellite being in a faulted state. Therefore, we feel it is essential to have the capability to model this parameter differently for the two constellations. We will tentatively assume the probability of GPS being in a faulted state to be 10^{-5} (the approximate value used by current RAIM algorithms) and use 10^{-4} for the corresponding probability for GLONASS.

Another important difference is the probability of simultaneous faults. The RAIM airborne algorithm only evaluates individual satellite fault cases and there are no known instances of simultaneous GPS faults. However the analysis of GLONASS performance has turned up several instances of concurrent faults on multiple GLONASS satellites [3]. Given that there have been four known examples in the last four years, we will initially approximate the probability of GLONASS being in a constellation-wide fault mode as 10^{-4}, although this number will require substantially more study and verification. As is the case for current RAIM algorithms, we will assume the probability of GPS having a constellation wide fault to be negligible.

MULTIPLE HYPOTHESIS SOLUTION SEPARATION (MHSS) ALGORITHM

In order to evaluate the performance of RAIM when combining signals from two different constellations, each with very different properties, we used an algorithm originally developed as part of a study for Advanced RAIM (ARAIM) [8]. ARAIM is being investigated to support vertical guidance. As such it has been developed with a much more detailed study of potential fault modes and their effects. Although originally developed for vertical guidance, the airborne ARAIM algorithms are equally suitable for horizontal guidance. Stanford has worked with many other collaborators to develop a Multiple Hypothesis Solution Separation (MHSS) airborne implementation that we will use throughout this paper [9]. The MHSS algorithm can account for different URA values, different probabilities of satellite faults, different probabilities of constellation fault, and different fault modes. As such it is a very flexible airborne RAIM algorithm and well suited to the study of the incorporation of GPS and GLONASS.

Details of the MHSS algorithm can be found elsewhere [9]. What the algorithm does is evaluate the different fault modes given the specified probabilities of fault and determine the optimal probability of missed detection (P_{md}) for each mode (some modes might already be sufficiently improbable and not require any specific testing. For those that do require evaluation, the appropriate subset of satellites is selected and the resulting position solution is compared against the all-in-view. A subset is formed that excludes all satellites being evaluated for having a fault. This creates a subset that should be fault-free and when compared to the all-in-view solution, will reveal its corruption by the suspected fault(s). Assuming all comparisons pass, the HPL is then calculated along with the all-in-view position solution. If one of the evaluations should fail, then the algorithm needs to perform exclusion to remove the bad satellite(s) or else declare that a safe solution is unavailable. Although very important, the exclusion operation is beyond the scope of this paper. Because we assume different levels of reliability for GPS and GLONASS, we found that sometimes the addition of GLONASS satellites increased the HPL. We addressed this sub-optimal behavior by adjusting the fit as described in the appendix at the end of this paper.

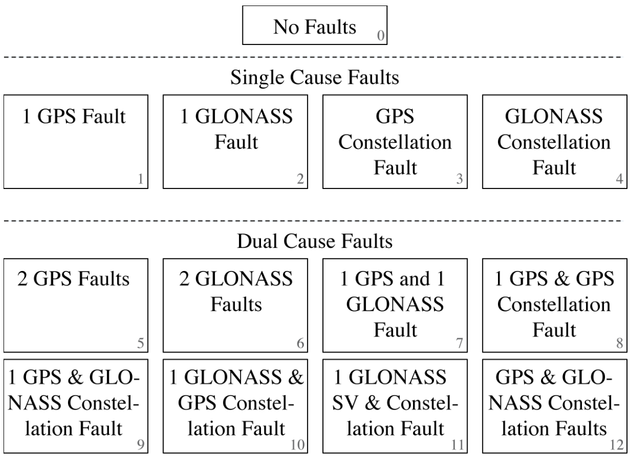

Figure 3. *The principle fault modes affecting the use of GPS and GLONASS.*

FAULT TREE AND FAULT MODES

The development of ARAIM has sought to carefully account for all sufficiently likely identified threats. We follow this approach and begin by identifying and then quantifying the likely threats. As previously mentioned, the current use of GPS-only RAIM considers only one sufficiently likely threat: a single satellite fault leading to a larger than expected ranging error. A single cause that leads to large ranging errors on more than one GPS satellite is considered sufficiently improbable. For GLONASS we will consider both the possibility of a fault affecting a single satellite and a fault affecting multiple satellites. As with traditional RAIM, we will not consider specific fault modes for ionospheric, tropospheric, or local multipath effects. All are considered to create horizontal positioning errors much smaller than the horizontal alert limit of 556 m.

Figure 3 lists the fault modes starting with the most likely mode of having no faults present in the system. The next group, Modes 1-4, list modes that arise when a single fault has occurred. Modes 1 and 2 correspond to a fault affecting an individual satellite and Modes 3 and 4 correspond to faults that can lead to errors on multiple satellites. Below these are the modes corresponding to two independent, but overlapping, faults. Modes 5-7 correspond to cases with overlapping individual Space Vehicle (SV) faults. Modes 8-11 correspond to cases with one SV fault and one fault that affects multiple satellites within the constellation. Mode 12 is the case where each constellation has a fault that affects multiple satellites within that constellation.

Table 1 describes these fault modes and also lists an upper bound on the prior probability of the fault being present at

Mode	Description	Prior Probability
0	Fault-free	~1
1	Single GPS SV fault	$N_{GPS} \times P_{sat,GPS}$
2	Single GLONASS SV fault	$N_{GLN} \times P_{sat,GLN}$
3	Fault affecting multiple GPS SVs	$P_{const,GPS}$
4	Fault affecting multiple GLONASS SVs	$P_{const,GLN}$
5	Two independent single GPS SV faults	$N_{GPS} \times (N_{GPS}-1) \times (P_{sat,GPS})^2/2$
6	Two independent single GLONASS SV faults	$N_{GLN} \times (N_{GLN}-1) \times (P_{sat,GLN})^2/2$
7	Single GPS SV fault and single GLONASS SV fault	$N_{GPS} \times N_{GLN} \times P_{sat,GPS} \times P_{sat,GLN}$
8	Single GPS SV fault and a fault affecting multiple GPS SVs	$N_{GPS} \times P_{sat,GPS} \times P_{const,GPS}$
9	Single GPS SV fault and a fault affecting multiple GLONASS SVs	$N_{GPS} \times P_{sat,GPS} \times P_{const,GLN}$
10	Single GLONASS SV fault and a fault affecting multiple GPS SVs	$N_{GLN} \times P_{sat,GLN} \times P_{const,GPS}$
11	Single GLONASS SV fault and a fault affecting multiple GLONASS SVs	$N_{GLN} \times P_{sat,GLN} \times P_{const,GLN}$
12	A fault affecting multiple GPS SVs and a fault affecting multiple GLONASS SVs	$P_{const,GPS} \times P_{const,GLN}$
13	Three or more overlapping independent faults	-

Table 1. *Fault mode descriptions and prior probabilities.*

any given time. N_{GPS} is the total number of GPS satellites in view of the user and being used to estimate the position. N_{GLN} is the corresponding number of GLONASS satellite being used. $P_{sat,GPS}$ is the probability that an individual GPS satellite is in the faulted state at any given instant in time. $P_{sat,GLN}$ is the corresponding probability for an individual GLONASS fault. $P_{const,GPS}$ is the probability that a single fault leads to large errors on more than one GPS satellite. $P_{sat,GPS}$ describes faults that may occur onboard one satellite that have no effect on the other satellites, while $P_{const,GPS}$ describes faults in the control segment that may be uploaded to more than one satellite or to design errors that lead to faults occurring at the same time. $P_{const,GLN}$ is the corresponding probability for the GLONASS constellation.

This value of $P_{sat,GPS}$ can be determined by multiplying the probability of the satellite transitioning from nominal to faulted in any given period by the expected duration of the fault. The GPS SPS PS specifies that there will not be more than three major service failures in any given year. For a 31 satellite constellation there are 31 × 24 × 365 satellite hours in a year. Dividing into three faults yields a probability of fault onset of 1.1e-5/satellite/hour. The maximum fault duration is further specified as six hours. Thus, an upper bound on the probability of a satellite being in a faulted state is 6.6e-5/satellite. However, GPS has a historical record of removing faulted signals in less than 1 hour. As shown in Figure 2, the average cumulative fault hours per year is less than two. Thus, a value of 10^{-5}/satellite is a reasonable value for $P_{sat,GPS}$ and we will use it in our algorithms. This value also matches the approximate value used by current RAIM algorithms (they actually assume a total probability of 10^{-4} for all satellites in view). Figure 2 also shows that for a 24 satellite constellation GLONASS is approaching a value of 10^{-4}/satellite. We will assume that this trend continues and that 10^{-4} is a reasonable value for $P_{sat,GLN}$.

Current RAIM algorithms assume that $P_{const,GPS} = 0$. We will continue with that assumption as there is no evidence that such faults need to be taken into account. However, there is evidence of GLONASS constellation wide faults. One hour of such faults a year would lead to a value for $P_{const,GLN}$ of a little more than 10^{-4}. One hour every ten years would support a value close to 10^{-5}. Although multiple faults have not been observed for the last couple of years, we feel that 10^{-4} is a reasonable starting place for $P_{const,GLN}$.

Once we have the probabilities, all we need to know are the number of GPS and GLONASS satellites in the solution to be able to compute the prior probability of each mode occurring. The ARAIM algorithm will evaluate subsets corresponding to each mode. Each test will have an associated probability of missed detection. Safety is assured if the sum of the product of the missed detection and prior probabilities is below the requirement.

$$P_{MI} = \sum_{\text{modes}} \left(P_{prior,\text{mode}} \times P_{md,\text{mode}} \right) \le 10^{-7} \tag{1}$$

Thus any mode that has a prior probability greater than 10^{-7} must have a test that provides a sufficiently small probability of missed detection and modes that are below 10^{-7} may not need to be evaluated ($P_{md} = 1$) provided they are included in the sum. In examining the modes identified in Figure 3 and Table 1 we can determine which must have an associated test.

The probability that there is a fault on one specific GPS satellite and not on any of the other GPS satellites being used is given by

Mode	Description	Prior Probability
0	Fault-free	1
1	Single GPS SV fault	$N_{GPS} \times 10^{-5}$
2	Single GLONASS SV fault	$N_{GLN} \times 10^{-4}$
3	Fault affecting multiple GPS SVs	*0*
4	Fault affecting multiple GLONASS SVs	10^{-4}
5	Two independent single GPS SV faults	$N_{GPS} \times (N_{GPS}\text{-}1) \times 5{\times}10^{-11}$
6	Two independent single GLONASS SV faults	$N_{GLN} \times (N_{GLN}\text{-}1) \times 5 \times 10^{-9}$
7	Single GPS SV fault and single GLONASS SV fault	$N_{GPS} \times N_{GLN} \times 10^{-9}$
8	Single GPS SV fault and a fault affecting multiple GPS SVs	*0*
9	Single GPS SV fault and a fault affecting multiple GLONASS SVs	$N_{GPS} \times 10^{-9}$
10	Single GLONASS SV fault and a fault affecting multiple GPS SVs	*0*
11	Single GLONASS SV fault and a fault affecting multiple GLONASS SVs	$N_{GLN} \times 10^{-8}$
12	A fault affecting multiple GPS SVs and a fault affecting multiple GLONASS SVs	*0*
13	Three or more overlapping independent faults	-

Table 2. *Fault mode descriptions and prior probabilities as used by the proposed algorithm. The cells with the white background correspond to the nominal RAIM modes. The green shaded modes are all covered by evaluating a subset that tests all GLONASS satellites, and the red shaded cells are not directly evaluated but are subtracted from the integrity budget (1).*

$$P_{sat,GPS} \times \left(1 - P_{sat,GPS}\right)^{N_{GPS}-1} \tag{2}$$

However, since $P_{sat,GPS}$ is small, we can approximate this as $P_{sat,GPS}$. This approximation is used throughout Table 1. Table 2 reevaluates the prior probabilities using the specific probabilities described in this section. The first faulted Mode 1, must be evaluated as it is currently done in RAIM. Because GPS constellation wide threats are not considered, Modes 3, 8, 10, and 12 have zero prior probability of occurring and need not be further evaluated. The constellation wide GLONASS fault is evaluated by comparing the position solution with all satellites to the position solution with only GPS satellites.

Thus creating a subset that is not at all affected by any GLONASS fault mode. This test evaluates not only the constellation wide fault mode, but any fault mode that affects any number of GLONASS satellites. Thus, Modes 2, 4, 6, 11, and any associated higher order GLONASS-only fault modes are included in this evaluation. Therefore, the prior probability for this fault mode should be the sum of these modes. This sum can be conservatively estimated as

$$P_{prior,GLN} = N_{GLN} \times P_{sat,GLN} + P_{const,GLN} \tag{3}$$

The remaining Modes, 5, 7, and 9, can avoid needing evaluation provided there are not too many satellites. They are however included in the integrity calculation (1). This implies that

$$N_{GPS} \times P_{sat,GPS} \times \left(\begin{array}{l} \frac{N_{GPS}-1}{2} \times P_{sat,GPS} + \\ N_{GLN} \times P_{sat,GLN} + P_{const,GLN} \end{array} \right) \leq 10^{-7} \tag{4}$$

Given the probabilities assumed, this means that for 7 GPS satellites in view there can be no more than 12 GLONASS. If 10 GPS are in view then there can be no more than 8 GLONASS and if 12 GPS are in view, there can be no more than 6 GLONASS. Otherwise the neglected modes would take up more than the entire integrity budget. We recommend discarding the lowest elevation GLONASS satellites to ensure that there is some margin for the evaluated modes.

Our recommendation is that the MHSS algorithm evaluate the no fault mode (all satellites included in position estimate) with a conservatively assigned prior probability of one. It also evaluates each individual GPS satellite removed subset with a conservatively assigned prior probability of $P_{sat,GPS}$ (10^{-5}). And finally, it evaluates one subset in which all GLONASS satellites are removed from the estimate with a conservatively assigned prior probability given by (3). In all of the above evaluations the lowest elevation angle GLONASS satellites are discarded (if needed) to ensure that the evaluation in (4) is met. Further the left hand side of (4) is subtracted from the integrity budget of 10^{-7}. In our evaluations in the subsequent sections, we removed the lowest elevation angle GLONASS satellites until $N_{GLN} \leq 70/N_{GPS}$.

We are left with an algorithm that is very similar to the current RAIM algorithms except that it incorporates GLONASS and one additional subset is considered: the GPS-only case. If there are no GLONASS satellites in view, there is no need to evaluate this extra mode and the algorithm defaults back to one that matches the current algorithms. If there are not enough GPS satellites in view to form a position estimate ($N_{GPS} < 4$), the algorithm cannot proceed as the high likelihood of the constellation wide GLONASS fault requires mitigation by comparison of the GPS-only position solution to the all-in-view solution. The MHSS algorithm optimizes the P_{md} for the evaluated modes given the remaining integrity budget. Again details of this algorithm can be found at [9].

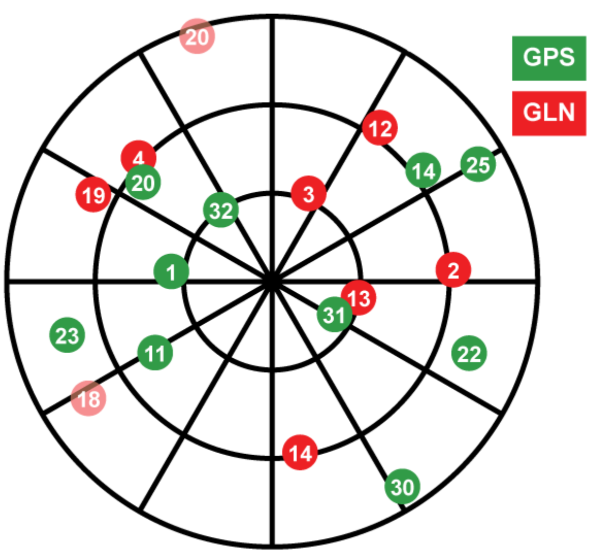

Figure 4. *Example skyplot of GPS and GLONASS satellite locations*

EVALUATION OF THE ALGORITHM

The algorithm described in the preceding section was evaluated using data collected by a multi-constellation capable receiver at Stanford University. This receiver collected multi-frequency data from all of the GNSS satellites in view. We used only the measurements from the GPS and GLONASS satellites. Figure 4 shows an example of satellite azimuths and elevations for one instant in time. As can be seen, the addition of GLONASS dramatically increases the number of measurements and improves their distribution in the sky. In this particular case, GLONASS satellites 18 and 20 are discarded to ensure that the conditions in (4) are met. However, we still have ten GPS and seven GLONASS satellites remaining with very good overall geometry and redundancy. There are likely better algorithms to determine which GLONASS satellites to discard (perhaps 19 would have been a better choice than 20), but the elevation based approach is simple and likely sufficient.

The measurements from our receiver were carrier smoothed to reduce the effects of multipath. Because our receiver is in a fixed location on the roof of our building, its multipath environment is significantly worse that that of an aircraft. Consequently, we chose to extend the smoothing time from the normal value of 100 seconds to two hours. We could do this because we have access to two frequencies and could use the L2 carrier measurements to conduct divergence-free smoothing [10]. This processing is different from the purely single frequency processing that would be conducted on an aircraft, however the net result is actually more similar to aircraft performance. We only used the L2 carrier to extend the smoothing time. We did not use the L2 code measurements to estimate and remove the ionosphere. Instead the divergence-free smoothing still contains the full L1 ionospheric delay value. The only significant difference is that we were then able to lower ground induced multipath effects down to aircraft multipath residual levels.

Because this is effectively a smoothed L1-only pseudorange, we still needed to remove an estimate of the L1 ionospheric delay. For this we used the single frequency ionosphere model broadcast from the GPS satellites (we used the same model on both GPS and GLONASS satellites). We also subtracted an estimate of the tropospheric delay based on the model specified in DO-229D [11].

For confidences we used the broadcast URA values. Unfortunately URA values are not contained in the RINEX navigation files for GLONASS, but fortunately we were able to obtain them directly from our receiver. The pseudorange integrity and accuracy covariances required by the MHSS algorithm are then given by

$$C_{\text{int}}(i,i) = C_{acc}(i,i) = \sigma^2_{URA,i} + \sigma^2_{UIRE,i} + \sigma^2_{trop,i} + \sigma^2_{air,i} \qquad (5)$$

where the ionospheric and airborne multipath overbounds, σ_{UIRE} and σ_{air}, are specified in Appendix J of DO-229D [11] and the tropospheric overbounding term, σ_{trop}, is specified in Appendix A of the same.

An extra clock state is added to the geometry matrix for the GLONASS satellites as specified in [9]. The all-in-view case, all single GPS SV out cases and the GPS-only case are then evaluated with the probabilities specified in the previous section. The position solution is then compared against the surveyed location of the antenna to obtain the Horizontal Positioning Error (HPE) and the MHSS algorithm provides the Horizontal Protection Level (HPL). The algorithm was run twice for each data set. Once with only GPS satellites to obtain the baseline performance of current RAIM algorithms, and again with both GPS and GLONASS satellites to evaluate the performance impact of including this second constellation.

Figure 5 shows the results for 3 days of data collected February 27-29, 2012. As can be seen, the accuracy for either case is quite good (below 5 m at all times). The HPL is significantly reduced with the addition of the GLONASS constellation, despite the larger broadcast URA values and decreased confidence placed in its performance. While the GPS-only case often spikes above 100 m, the combined case always remains below 70 m. However, with 31 healthy satellites in the constellation, RAIM availability is almost always sufficient with the GPS constellation by itself.

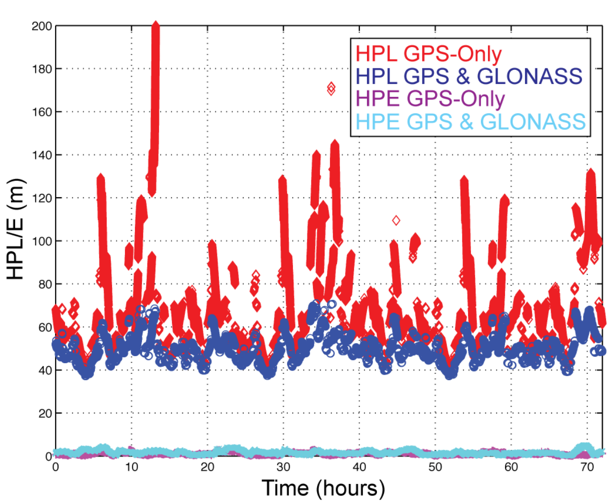

Figure 5. *Data from February 27-29, 2012 comparing the performance of GPS-only to GPS and GLONASS with both at full strength.*

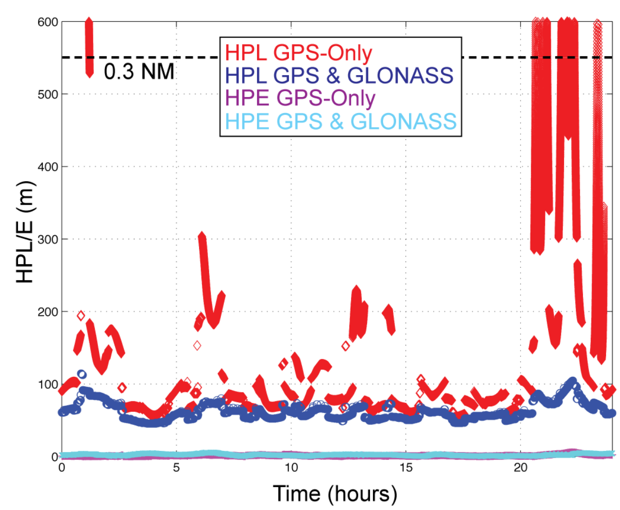

Figure 6. *Data from February 27, 2012 comparing the performance of GPS-only to GPS and GLONASS for depleted GPS constellation.*

The improvement offered by GLONASS is even more apparent when the GPS constellation is in a weakened state. Figure 6 compares performance on February 27, 2012 when several of the GPS satellites have been removed. We first removed the extra satellites that were not in any of the primary 24 slots (the removed satellites for this time period were PRNs 6, 10, 11, 26, 27, 30, and 32) to create the nominal 24 slot constellation. We then removed one of the primary slot satellites (PRN 20) to create a degraded 23 satellite constellation. It is important to remember that the GPS SPS PS assures only a 98% probability that 21 of the 24 slots will be filled and it makes no assurances for the extra slots. Thus, an even more degraded GPS constellation remains a possibility. In this scenario, the GPS-only HPL will sometimes go above the desired 0.3 NM HAL, and it even went above 100 NM. However, the combined solution always remained well below the 0.3 NM target.

AVAILABILITY SIMULATION

The previous section examined performance of the recommended combined GPS and GLONASS RAIM algorithm using data collected at one location. It serves as a proof of concept that GLONASS measurements and broadcast ephemeris information are nominally of sufficient quality to be combined in the proposed manner. We next evaluated the availability benefit for other locations. In this section we do not use receiver measurements, but instead evaluated performance using almanac based satellite locations and expected confidence values.

We modified our Matlab Algorithm Availability Simulation Toolset (MAAST) [12] software to model MHSS performance. MAAST was originally developed to evaluate Satellite Based Augmentation System (SBAS) performance, but it was straightforward to adapt MAAST to determine MHSS based RAIM performance. MAAST places a grid of simulated users (in this case a global five degree by five degree user grid). Almanacs for the two constellations are used to determine the locations of each satellite at each selected time (300 time steps were selected over a single sidereal day). For each user it is determined which satellites are in view and what their elevation and azimuth angles would be. The URA was set to a constant 2.4 m for GPS and 4 m for GLONASS. These are the most commonly broadcast values for each constellation. The values for σ_{UIRE}, σ_{trop}, and σ_{air}, were calculated according to DO-229D [11] given the satellite elevation and pierce point geomagnetic latitude. The geometry matrix was also determined using the satellite elevation and azimuth angles.

MAAST then evaluated the HPL using the same MHSS algorithm from the previous section. Figures 7 and 8 compare the GPS-only case (Figure 7) to the combined constellation case (Figure 8). For the period of interest, one of the GLONASS satellites (GC 743) was in maintenance mode and we decided to leave it out of the simulation as well. Thus, GPS was modeled as a 31 satellite constellation with all 24 primary slots filled and GLONASS as a 23 satellite constellation with one of its primary slots vacant. The figures demonstrate the clear benefit of adding GLONASS. Although the GPS performance is quite good, there are a couple of regions (Middle East and South Pacific) where it doesn't quite

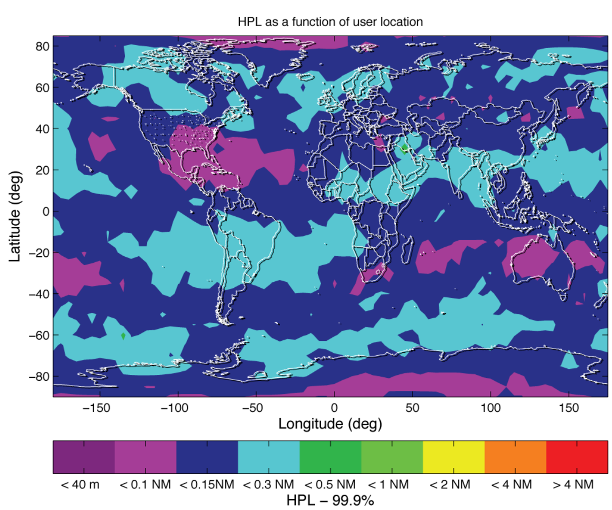

Figure 7. *Global availability analysis for a 31 satellite GPS constellation on January 13, 2013.*

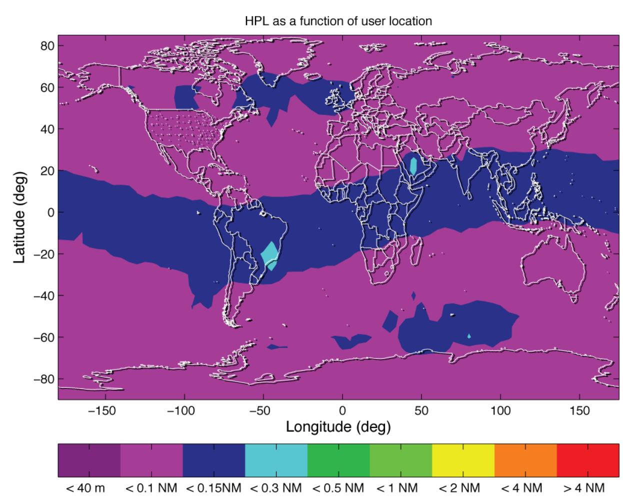

Figure 8. *Global availability analysis for a 30 satellite GPS constellation and 23 satellite GLONASS constellation of January 13, 2013.*

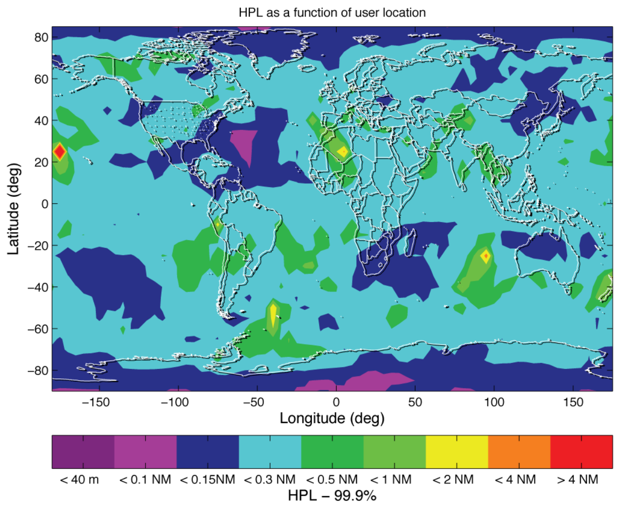

Figure 9. *Global availability analysis for a 30 satellite GPS constellation on January 13, 2013.*

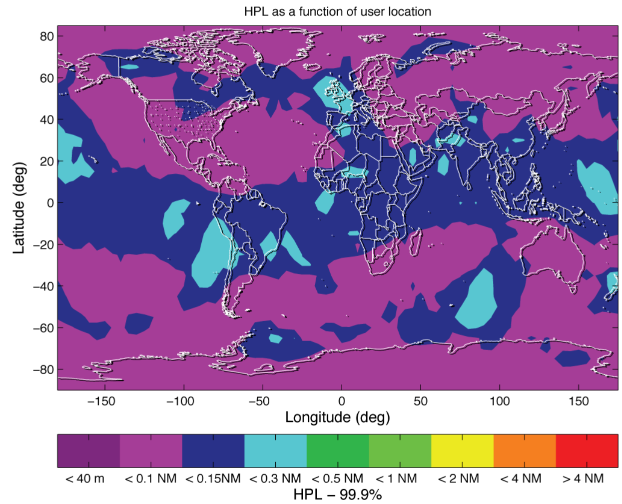

Figure 10. *Global availability analysis for a 30 satellite GPS constellation and 23 satellite GLONASS constellation on January 13, 2013.*

achieve the 0.3 NM target. When GLONASS is included, not only does every location meet the target, there is more than a factor of two margin in all but a few locations.

The band of worse performance near the equator is due to the fact that the σ_{UIRE} term is a function of geomagnetic latitude. For ionospheric pierce points within 20 degrees of the geomagnetic equator, the one-sigma vertical value is nine meters (this is then multiplied by the obliquity factor to obtain the full User Ionospheric Range Error (UIRE) term). This is the largest term in the pseudorange error covariance matrix and clearly affects availability in the near equatorial region.

Figures 9 and 10 compare performance when one of the GPS primary slots is unavailable. In this example, we removed PRN 21 from the GPS almanac. In Figure 9 the vast majority of users remain below the targeted value of 0.3 NM. Unfortunately some regions do go above and one region in the mid Pacific cannot even support an HAL of 4 NM. Figure 10 demonstrates that the addition of GLONASS brings every location back below 0.3 NM and again in most locations there is significant margin against the desired HAL.

FUTURE WORK

There is still much that needs to be done in the evaluation of the use of GLONASS. First and foremost, we must determine safe values for $P_{sat,GLN}$ and $P_{const,GLN}$. The corresponding values for GPS are well established and already in use by existing RAIM receivers. However, the values for GLONASS require significantly more study and international coordination. Ideally there should be a performance standard published by the operators of GLONASS to provide assurance for how they intend to operate the system in the future. This documented assurance of performance would serve as the basis for determining the appropriate degree of trust that should be placed in GLONASS.

We have performed some preliminary evaluation of error detection and exclusion with this algorithm, but there is still much work left to be done. We want to verify our implementation with many more cases of simulated faults to ensure that the algorithm is behaving as expected. Finally, we need to investigate the exclusion algorithm in more detail. Evaluating the GLONASS performance as whole rather than considering individual satellite faults simplifies the nominal running of the algorithm. However, when a fault is detected it might be advantageous to investigate individual GLONASS SV faults when performing exclusion, rather than discarding all GLONASS satellites whenever a fault on that constellation is observed. Once decided upon, the exclusion algorithm will also require extensive testing to ensure that it behaves as desired.

SUMMARY

This paper has proposed a simple method to incorporate GLONASS into an update to existing RAIM applications. The proposal requires only one additional mode be evaluated beyond what is already implemented by existing aviation RAIM algorithms. This additional mode tests the GLONASS satellite as a whole by comparing the combined GPS and GLONASS position against the GPS-only position. Although we have evaluated performance with an optimized multiple hypothesis solution separation algorithm, this approach could also be implemented in a traditional slope based algorithm.

An important point raised by this paper is that other constellations (including GLONASS) should not be assumed to have comparable in performance to GPS. GPS has, by far, the most extensive history of satellite operation. Newer constellations may have noticeably different levels of performance. Indeed, as we have shown, GLONASS performance does not quite reach the level of GPS performance. If this is not correctly taken into account, the user could be put at great risk by underestimating how likely certain fault modes are to occur or by failing to protect against observed fault modes altogether. The algorithm proposed here is able to account for these differences. As the actual performance level becomes better understood and accepted by the aviation community, the algorithm presented can be tuned to match the specified performance.

Despite the reduced performance levels assumed for GLONASS, including a constellation wide fault mode, the inclusion of GLONASS into the estimation results in a substantial improvement to performance. The combined constellation performance is able to deliver HPLs below 0.3 NM even for significantly degraded GPS constellations. This added robustness could be very useful in ensuring that horizontal guidance provided by satellite navigation achieves the desired level of performance even in the face of future uncertainty over constellation size.

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APPENDIX

There are some geometries such that the addition of a second constellation can degrade the Protection Level (PL). To mitigate this effect, it is sometimes desirable to center the all-in-view position away from the least squares position (which is designed to optimize accuracy not PL). An approach to minimize the PLs by adjusting the position is described in [13]. In this paper we used a simpler position adjustment that takes into account the specific situation.

We denote, s_{all}, the coefficients for the least squares position that includes GPS and GLONASS, and, s_{GPS}, the coefficients for the least squares position for GPS only. We look for coefficient of the form:

$$s = s_{all} + t\left(s_{GPS} - s_{all}\right) \tag{A.1}$$

The partial PL for fault i is (C is the covariance of the measurements and $s^{(i)}$ are the coefficients corresponding to subset i):

$$PL_i = K_{fa}\sqrt{\left(s - s^{(i)}\right)^T C\left(s - s^{(i)}\right)} + K_{md,i}\sigma_i \tag{A.2}$$

For the GLONASS out mode one can see that as we move towards the GPS only solution, the partial PL decreases. We have:

$$PL_i = K_{fa}\sqrt{\begin{array}{l} t^2\left(s_{GPS} - s_{all}\right)^T C\left(s_{GPS} - s_{all}\right) + \\ 2t\left(s_{GPS} - s_{all}\right)^T C\left(s_{all} - s^{(i)}\right) + \\ \left(s_{all} - s^{(i)}\right)^T C\left(s_{all} - s^{(i)}\right) \end{array}} + K_{md,i}\sigma_i \tag{A.3}$$

Let us suppose that for all modes except the GPS out mode, we have:

$$s^{(i)} \simeq s_{all} \tag{A.4}$$

We therefore have:

$$PL_i \simeq K_{fa}\sqrt{t^2\left(s_{GPS} - s_{all}\right)^T C\left(s_{GPS} - s_{all}\right)} + K_{md,i}\sigma_{all} \tag{A.5}$$

For the index corresponding to GLONASS out, we have:

$$PL_{GPS} = K_{fa}\sqrt{\begin{array}{l} t^2\left(s_{GPS} - s_{all}\right)^T C\left(s_{GPS} - s_{all}\right) + \\ 2t\left(s_{GPS} - s_{all}\right)^T C\left(s_{all} - s^{(i)}\right) + \\ \left(s_{all} - s^{(i)}\right)^T C\left(s_{all} - s^{(i)}\right) \end{array}} + K_{md,i}\sigma_i \tag{A.6}$$

$$\begin{array}{l} PL_{GPS} = \left(1-t\right)K_{fa}\sqrt{\left(s_{GPS} - s_{all}\right)^T C\left(s_{GPS} - s_{all}\right)} + \\ K_{md,GPS}\sigma_{GPS} \end{array} \tag{A.7}$$

To minimize the maximum of PL_{GPS} and PL_i, we find t such that:

$$PL_{GPS} = PL_i \tag{A.8}$$

We get:

$$\begin{array}{rl} t = & \dfrac{1}{2} + \dfrac{K_{md,GPS}\sigma_{GPS} - K_{md,i}\sigma_{all}}{2K_{fa}\sqrt{\left(s_{GPS} - s_{all}\right)^T C\left(s_{GPS} - s_{all}\right)}} \\ \simeq & \dfrac{1}{2} + \dfrac{K_{md,GPS}\sigma_{GPS}}{2K_{fa}\sqrt{\left(s_{GPS} - s_{all}\right)^T C\left(s_{GPS} - s_{all}\right)}} \end{array} \tag{A.9}$$

For K_{fa} and K_{GPS} we used:

$$\begin{array}{l} K_{fa} = Q^{-1}\left(P_{fa}\right) \\ K_{md,GPS} = Q^{-1}\left(\dfrac{PHMI}{P_{const}}\right) \end{array} \tag{A.10}$$