Further Development of Galileo-GPS RAIM for Vertical Guidance

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BIOGRAPHY

Alex Ene is a Ph.D. candidate in Aeronautics and Astronautics working in the Global Positioning System (GPS) Laboratory at Stanford University. His research focus is software simulation in the area of combined GPS/Galileo signals, positioning error threat space and integrity. He holds a Bachelors in Astronomy and Astrophysics and a citation in German Language from Harvard University.

ABSTRACT

With the much anticipated deployment of Galileo, a new partner will rise on the sky of Global Navigation Satellite Systems (GNSS). Equally anticipated is the launch of the modernized block III GPS satellites, which will provide numerous enhancements to the existing system. It is expected that both Galileo and the modernized GPS will become fully operational within the next 10 years. As a consequence, efforts have been initiated at the global level in order to contrive ways in which to gain the full benefits of having two independent multifrequency systems available to the user.

One of the hard problems that stand-alone GPS has been trying to address over the years is that of measurement integrity. Providing guidance during the landing approach phase of aircraft flight is one of the most challenging applications for satellite-based navigation because both high accuracy and user safety are required during the procedure. By combining two frequencies, users will be able to remove the ionospheric delay, which is currently the largest error, and thus increase the positioning accuracy by more than 50%. This reduction in nominal error bounds together with the presence of a larger number of satellites is going to increase the robustness against satellite failures or hazardous pseudorange errors. Previous studies [Ene et al. 2006] suggest that, using Receiver Autonomous Integrity Monitoring (RAIM), it might be possible to provide a 35m Vertical Alert Limit (VAL) worldwide, with a bound on the maximum error and without the need for additional augmentation, even in the event of one satellite failure, one constellation failure or a multiple satellite failure.

The purpose of this work is to investigate which Vertical Protection Level (VPL) values could be achieved with RAIM under conservative failure assumptions. Both the RAIM algorithm and the corresponding threat model presented in the previous paper [Ene et al. 2006] have been revised. The previously defined threat model is refined to include measurement biases, and the study on degraded operation modes is also extended to include partial GPS and Galileo constellations and to appreciate the impact of critical satellites. It was found that an unaided dual Galileo-GPS constellation yielded VPL values under 20m for nominal operation conditions, and that moderate biases or degenerate constellations can increase the VPL up to around 35m. These protection levels will likely enable APV-II landings at all runway ends in the world without the need for a SBAS or GBAS.

INTRODUCTION

In anticipation of the future launches of dual-frequency GNSS satellites, such as Galileo and GPS III, a series of new developments has taken place in the field of RAIM. Of particular interest were the topics of multi-constellation RAIM and analyzing the impact of multiple simultaneous ranging failures. Over the past two decades, studies of RAIM techniques have known a considerable development, accompanying the steady improvements in service by the GPS system to civil users of satellite navigation. Pioneers of RAIM, such as R. Grover Brown [Brown & Hwang 1986], Young C. Lee [Lee 1986], Mark A. Sturza [Sturza 1988] and Bradford Parkinson [Parkinson & Axelrad 1988] have made significant contributions to these algorithms even before GPS became fully operational in January 1994. Later on, while the civil GPS signals still contained the Selective Availability (SA) degradation until year 2000, a significant group effort took place for defining RAIM standards that would be applicable to civil aviation [Lee et al. 1996]. At the turn of the millennium, with the announcement of the planned deployment of the European Galileo system, renewed efforts were made to reap the anticipated benefits of having two interoperable constellations available for navigation purposes. Given the expected increase in the number of ranging sources for the aviation user, a breakthrough is expected to be made in the use of satellite navigation for precision approaches and other critical operations. Recent developments have already been published in an effort to improve the original Least Squares (LS) and Solution Separation (SS) RAIM algorithms. Newer flavors of RAIM include *NIO*RAIM [Hwang & Brown 2005], the Optimally Weighted Average Solution (OWAS) algorithm [Lee et al. 2005], Multiple Hypothesis Solution Separation (MHSS) [Pervan & Pullen 1998] and snapshot and sequential algorithms based on the Generalized Likelihood Ratio (GLR) [Nikiforov & Roturier 2005]. A special mention needs to be given as well to Pieter B. Ober for the most comprehensive theoretical treatment of modern RAIM methods to date [Ober 2003], which, along with the previously referenced work, could constitute the basis for significant further development.

Vertical errors are critical during aviation precision approaches, and they are also generally greater than horizontal errors for satellite-based positioning, because of the inherent geometry between the receiver and the ranging sources. The purpose of this work is to evaluate the performance of an unaided dual-frequency Galileo-GPS constellation from a vertical integrity standpoint for aviation precision approach. Its intent is to build on a previous study [Ene et al. 2006] and enhance the existing threat model to bring its assumptions a step closer to reality and investigate what Vertical Protection Level (VPL) values could be achieved with RAIM under conservative failure assumptions. The focus of the current study will be on a single algorithm, as a tool for testing the integrity performance of the dual constellation within an extended threat model. Among the RAIM algorithms enumerated above, Multiple Hypothesis Solution Separation (MHSS) was chosen because of its better use of the measurement information and its intrinsic ease of covering a comprehensive error threat space.

A multitude of degraded operation modes were also investigated. A *degraded mode* is considered to be the circumstance when one space vehicle (SV), an entire constellation (GPS or Galileo) or part of a constellation needs to be excluded from the position computation based on unavailability or the presence of “do not use” integrity flags broadcast by a system external to the RAIM device. One particular case is the degraded mode in which a single satellite needs to be excluded. If the satellite has a significant role in providing a good geometry for the position measurement, it is called a *critical* satellite. In the worst-case scenario, the most critical SV in view can suffer an outage and become unusable. One way to measure the robustness of a navigation satellite system is to determine the magnitude of the impact of such an outage on the overall VPL. Another example of degraded mode operation is while the Galileo or modernized GPS constellations are still being populated with SVs and are not yet fully operational.

Finally, a standardized threat model needs to be defined in order to facilitate the comparison between results obtained with the various methods and algorithms proposed to date for the purpose of autonomous integrity monitoring. In order to accommodate the different assumptions in the existing literature, parametric studies were conducted in the earlier paper [Ene et al. 2006] to observe the influence of factors that are external to the integrity monitor, such as the mask angle, User Range Accuracy (URA) and the prior probability of satellite failure. This paper offers an update of the previous studies and brings the addition of an investigation on the size of nominal measurement biases.

Based on the results of computer simulations using the MHSS algorithm, a conclusion will be drawn about the capabilities of the unaided combined constellation and direction for future work will be laid out. The current work evaluates what is the maximal threat space against which it is possible to offer protection, and does not involve Fault Detection (FD) techniques.

POSITION MEASUREMENT ERROR SOURCES

Previous literature seems to be much in agreement on a theoretical way to describe errors at the user. For that reason, a standardized error model (also used by [Lee et al 2005]), was considered appropriate. The nominal ranging error distribution consists of zero-mean noise, allowing a Gaussian overbound, and a small bias in each channel:

$$\nu_i = \varepsilon_i + b_i.$$

In this model, the nominal position error variance for satellite *i* is described by the equation:

$$\sigma_i^2 = \sigma_{URA}^2 + \sigma_{i,tropo}^2 + \sigma_{i,iono\text{-}free}^2 + \sigma_{L1L5}^2.$$

The different components of the error are normal distributions characterized by a zero mean and the above standard deviations. In the presence of correlated errors, the measurement noise Σ-matrix (see Appendix) would no longer be diagonal. Possible origins of error correlation between different SVs need to be examined in order to determine how significant the deviations from the independence assumption are. The different possible components of the error will be discussed below along with the amount of correlation they introduce in the measurements.

The clock and ephemeris errors are assumed to be independent identically distributed (iid) normal variables (σ_{URA}) under nominal, healthy satellite conditions. Infrequently, clock and ephemeris errors can also affect an entire constellation, but this possibility is already included in the model as constellation failures. Ionospheric delays are normally the major term contributing to the correlation between the pseudorange errors. However, the use of a dual-frequency receiver can eliminate these large correlated error terms based on the frequency dependence of ionospheric delays, as it was shown in [Klobuchar 1996]. Effectively, the use of dual frequency measurements replaces a dominant source of highly correlated ranging errors with practically independent error sources. In the same article, Klobuchar also discusses second order ionospheric effects and the phenomenon of ionospheric scintillation occurring at low latitudes. The higher order effects have a small enough magnitude, which does not mandate the introduction of an additional error source in the above variance equation. It has been determined that these higher order terms only affect the pseudoranges by 1-2 cm, which is insignificant in the context where the current MHSS algorithm computes the overall Vertical Protection Level (VPL) itself up to a centimeter level accuracy. An analytic model for simulating scintillation errors does not exist at present. This type of atmospheric events cause unpredictable errors and are able to cause GNSS receivers to lose lock on all satellites in a certain solid angle of the sky. A more detailed discussion accompanied by simulation of these ionospheric effects needs to be made, while its role in diluting continuity needs also be addressed by future work.

The tropospheric effects are another example of correlated errors; nevertheless, their impact is negligible given the much smaller relative magnitude of tropospheric errors compared to the other error terms. The troposphere model used here ($\sigma_{i,tropo}$) matches the one in the WAAS MOPS [RTCA DO 229D 2001] and is assumed to be bounded by the same confidence level. Receiver noise and multipath are bounded by the provided $\sigma_{i,iono\text{-}free}$ term. It should be noted that, like in Ground- and Space-Based Augmentation Systems (GBAS and SBAS), receiver failure and excessive multipath terms, which can bring along a significant degree of correlation, are not explicitly put into the threat space. Nevertheless, RAIM offers some protection against such fault modes right at the user location, where no ground augmentation can. Finally, a fixed value was assumed for the interfrequency bias term, $\sigma_{L1L5} = 0.2$m. In conclusion, a RAIM system is good for detecting and possibly correcting independent measurement errors specific to each user, but a monitoring/augmentation system can be useful for broadcasting corrections for correlated errors and fault modes common to multiple users.

The case when the corresponding range error for a given SV is no longer overbounded by a Gaussian curve is defined here to be a *satellite failure*. Current RAIM algorithms can be expanded to handle different probabilities of multiple failures, but an independent fault model was adopted in light of the discussion above. Additionally, separate constellation failure modes will be considered for the case where correlated faults exist across either the GPS or Galileo constellations but not both. (As a matter of fact, no RAIM algorithm will protect the user against situations when a majority or all the satellites in each constellation broadcast erroneous signals.) Although the customary method of setting a failure threshold for pseudorange errors is a good binary discriminator, it does not help identify systematic errors when they are just below the threshold. In reality, instead of a zero-mean error, the position solution will include a bias, which can be caused by factors such as signal deformation, clock drift or the receiver itself. Consequently, there is a need to include bias terms in the threat space and the error model. For snapshot measurement algorithms, such as the one proposed in the present study, these biases can be slow-varying or stationary as long as their magnitude does not become greater than a given amount. The current work will conservatively consider integrity under the maximum possible amount of bias. A parametric study will be carried in order to appreciate the impact of such biases on the overall VPL and also to determine what is the maximum level of bias that can be supported by a receiver in the presence of a full Galileo-GPS constellation, while still providing integrity with a VPL lower than 35m. When computing the VPL in the presence of biases, the conservative approach from an integrity standpoint is to add the worst possible bias to the position solution in either direction. Adding a constant bias to the normally distributed component of the position error effectively modifies the value of the error mean, while preserving the shape of its probability distribution function (pdf) otherwise. In order to simulate the possible effects of biases in a given range on the VPL, the extreme value of the bias in either direction needs to be considered, and its effects on both upper and lower limits of the VPL range. Effectively, two integrity ranges need to be computed, one with all vertical position biases having the maximum value in the negative (down) direction, and another one with biases taking the extreme positive value (in the up direction). Subsequently, the union of these ranges will be determined, on which the final VPL value will be based.

The value for the *a priori* probability of satellite failure was examined in previous work [Ene et al. 2006] and it was found that it does not dramatically influence the VPL values as long as the relevant number of failures is considered. Therefore, a very conservative failure probability of 10^{-4} per satellite will be considered for the 150s duration of the civil aviation approach procedure, compared to the 10^{-4}/hour value that has been used by many other authors in previous RAIM studies. The total error budget for providing Hazardous Misleading Information (HMI) is strictly limited here for the case of precision approaches, such that the maximum allowable integrity risk is of 10^{-7}/approach. This is again a conservative assumption, as the current aviation navigation requirements allow for double that integrity risk; however, the choice was made to allow sufficient room for error when presenting the first results with the current algorithm. Ultimately, the integrity budget needs to be divided between all the possible failure modes, and the resulting VPL will be very sensitive on the allocation of this integrity budget. Normally, in applying any RAIM algorithm, multiple failures are neglected, for modes which are less likely than a certain threshold. The reason why certain improbable failure modes need to be excluded is that the entire threat space is extremely large and impractical to compute. Therefore, it is imperative to limit the computation of the position error only to the most dangerous events from an integrity point-of-view. At the same time, within the MHSS algorithm, one can afford to conservatively assume the worst case scenario (i.e. failure generating HMI), instead of neglecting the possibility of the existence of a HMI-generating event altogether for the remaining improbable threats, as they have a small enough probabilistic impact on the total error or the total integrity. In the current work, a threshold of 10^{-8} has been chosen, below which probabilities of k simultaneous failures are directly subtracted from the total integrity budget instead of computing a position solution for each of the corresponding failure modes. To exemplify this procedure, for a user with 18 SVs in view there will be a 99.82% chance of experiencing no measurement fault during a 150s approach interval, a $1.8 \cdot 10^{-3}$ chance of experiencing one failure, $1.53 \cdot 10^{-6}$ for two failures and $8.15 \cdot 10^{-10}$ for three simultaneous faults. Some authors would easily dismiss the possibility of multiple simultaneous failures by incorrectly assuming that a 10^{-4} failure prior per satellite implies that there is a 10^{-4} chance of getting a single failure, a 10^{-8} chance of getting two simultaneous failures, a 10^{-12} chance for three failures and so long, thus making higher-order failures extremely unlikely. Therefore it is important to mention here that the probability of occurrence for each failure mode needs to be carefully computed and the outcome of a possible failure needs to be always considered as it cannot be neglected for such life-critical applications as aerial navigation. The use of incomplete threat models, which disregard some higher order failures, thus slightly inflating the probability of the no-fault mode, is more likely to cause HMI to go undetected since it generally produces artificially lower VPL values.

MHSS ALGORITHM

The MHSS algorithm described here is a generalization of the algorithm proposed in [Pervan & Pullen 1998] for use in conjunction with LAAS. That algorithm was already tested against a CAT III VAL requirement of 5m and was demonstrated to achieve low VPLs. Furthermore, its assumptions are general enough such that it can be used for any RAIM-type of integrity computation. The (prior) probability of occurrence of each failure mode is taken into account and a search is performed for the VPL which most closely makes use of the entire integrity budget available. In the current study, multiple independent faults will be considered in the combined constellation, in order to cover all possible failure modes included in the threat space.

The MHSS algorithm is not used here for FD; it assumes the fault-free case (no known satellite failures) by default and considers all possible, yet undetected failure modes. The integrity risk is computed based on satellite geometry and the partial position solutions, but the prior probabilities of failure are fixed and cannot be updated based on the actual measurements. Consequently, equation (9) in [Pervan & Pullen 1998] had to be revised, such that the integrity allocations for each of the fault modes do not depend on the measurements either. One way to achieve that is to compute a partial VPL for each of the given individual failure modes, and not an overall VPL based on the weighted sum of the pdfs for all the modes, since the sum weights were actually dependent on the measurement in the original 1998 MHSS algorithm. These probabilities of failure can be assumed to be lower if the user has the possibility to run a χ^2 check and detect a satellite fault, or has access to external information such as integrity flags that may be broadcasted by the Galileo satellites or an external augmentation system (e.g. WAAS). The MHSS algorithm can also be applied after excluding such faulty satellites. Another reason why one would want to employ satellite elimination is improving the availability for the navigation solution.

In applying the MHSS algorithm, modes with more than a certain number of failures are not used for position calculations when that number of SV failures is less likely than 10% of the total probability budget, or 10^{-8}/approach for at most 24 satellites in view. As an example, for a 10^{-4} probability of failure it is necessary to consider up to two satellites out, while for any probability larger that $1.7 \cdot 10^{-4}$ three or more failures will be taken into account. The set of less likely modes will be considered as a separate unknown failure mode, and its corresponding integrity risk will be accounted for and diminish the total integrity allocation. Additionally, an *a priori* probability of failure of 10^{-7} per each approach will be associated to each possible constellation failure. As opposed to the failure prior for a single satellite, the constellation probability of failure was not present in previous literature on the topic of integrity. In fact, RAIM studies for a dual constellation started to be conducted only recently, for which such a failure probability actually makes sense. Therefore, this type of failure is a novel concept which needs to be carefully analyzed. For single constellation RAIM, a constellation failure means a complete loss of availability, so the chance of it happening should be much smaller than the integrity threshold, otherwise the RAIM algorithms will not be useful for precision approaches.

On the other hand, for the dual constellation, this probability represents the number of times the system needs to fall back into the mode in which it relies on only one constellation. For that reason, the probability that one constellation is "out" (i.e. using any pseudorange measurements from its satellites would cause HMI to be passed to the user) could be greater in this case, while the system should still able to provide the necessary integrity for precision approaches. The 10^{-7}/150 seconds failure rate considered here is equivalent to one failure every 47.5 years, so, at the moment, it is impossible to measure such system prior probabilities in practice. Nonetheless, with the exception of some loss in availability, it will be seen in this paper that VPL values under 15m can still be obtained even with the current conservative constellation failure prior. Current results expose problems only in the case of degraded operation modes with partly unavailable constellations, when there are less than 21 healthy SVs in each constellation. Any time when less than four satellites from the same constellation are in view, the VPL value automatically becomes infinite. The reason is that we have to rely on at least one satellite from the other constellation for a position fix. However, the second constellation is assumed to be 10^{-7} likely to fail entirely (thus leaving less than 4 total SVs available), so the integrity requirement cannot be satisfied.

DEGRADED OPERATION MODES FOR RAIM

In order to complete the study on how well RAIM algorithms can mitigate against the entire threat space, one has to examine degraded operation more in detail. Based on the discussion above, there is a lower limit on how many SVs a degraded mode can include, mainly due to the high constellation probability of failure that was considered. When the average number of SVs in view is less than 10, or if there are frequently less than 4 visible satellites from one of the constellations, overall availability starts to decrease rapidly, as in most cases a position solution cannot be determined with a confidence greater than $1\text{-}10^{-7}$.

The degraded modes simulate cases when one satellite or a larger part of a constellation are unavailable to the user, due to either the presence of integrity flags or to the fact that the respective constellation is still being populated with dual frequency satellites. In order to simulate launch schedules for the Galileo and modernized GPS satellites, it is possible to prepare almanac information files, which will contain only partial constellations. On the other hand, it is not necessary to limit the size of the constellations to 24 GPS satellites, or the nominal 27 for Galileo. An investigation will be made of the vertical performance in the presence of up to 30 active SVs for each of the constellations, in order to estimate the effect of active spares and other additional satellites on integrity. Since launching the total required number of satellites for a full constellation can require several years, this investigation could also be useful in determining how early the benefits of using Galileo-GPS RAIM will start being available to users. As part of the current work, various GPS and Galileo constellations were considered, with a total of 12, 16, 18, 20, 24, 27 and respectively 30 operational satellites in each. While Galileo SVs are spaced equally onto three different circular orbits, the GPS constellation is divided among 6 orbital planes, each with 4-6 SVs, including active spares. The celestial parameters of these orbits are publicly available for both GPS [Misra & Enge 2001] and Galileo [Zandbergen et al. 2005]. It should also be mentioned here that, in the case of the Galileo constellation, when the majority of the satellites in the same orbital plane are either not active or not healthy, degenerate SV geometries will occur and it will not be possible to determine a three-dimensional position based only on the remaining Galileo satellites in the other two orbital planes. Similarly, when orbital planes from the two constellations become aligned, a more minor dilution in the overall geometry will occur. These specific cases will require further study to evaluate their impact on the PL values.

Moreover, once both constellations are fully operational, there is a need for simulation of the scheduled or fortuitous satellite down times that could potentially eliminate critical satellites from a geometry point of view and significantly increase the VPL. A computer algorithm has been designed to determine which is the most critical satellite in the combined constellation and eliminate it; subsequently the corresponding worst-case VPL will be computed. One can employ the brute-force method by having the MHSS algorithm cycle through all subsets with one satellite out and compute the VPL for each of those. Alternately, one can compute the equivalent Vertical Dilution of Precision (VDOP), or more precisely σ_V [Walter and Enge 1995], as a satellite can be deemed critical for geometric considerations only, without taking into account the corresponding small Gaussian range errors. A case study was performed, comparing both of these methods and it was proven that there were only insignificant differences in the VPL values between the two approaches when the URA was taken to be 1m and in the absence of measurement biases. Multiple degraded modes were then simulated under these same conditions, in order to separate the influence of biases or large URA errors from that of degraded satellite geometry. Parametric studies on the influence of the URA on overall VPL were performed in [Ene et al. 2006], and the influence of biases was studied separately in this paper.

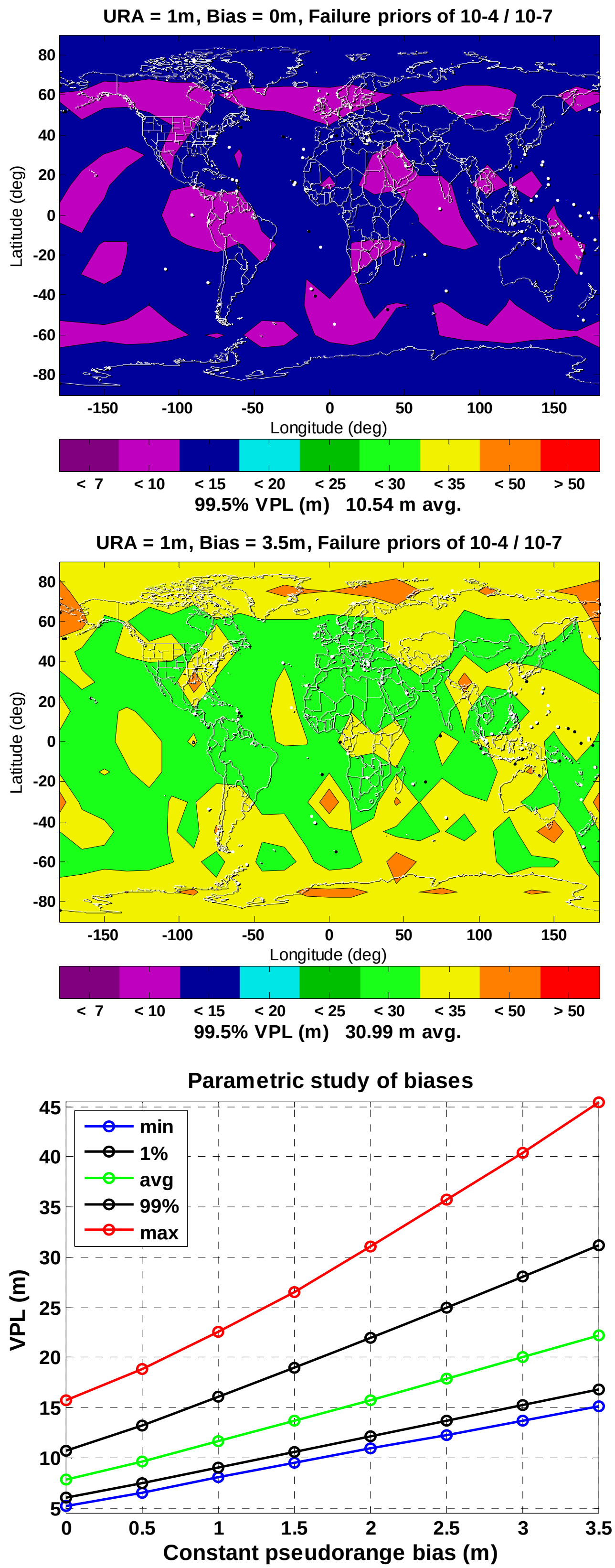

Figure 1. Bias parametric study. The VPL maps are reproduced for the no bias case (top), as well as for the maximum bias (middle). The bottom plot is a graphic summary of all the bias simulation results.

SIMULATION RESULTS AND DISCUSSION

Simulations were performed in order to test the RAIM MHSS algorithm against the comprehensive threat model described above. According to system specifications, 30 Galileo satellites and 24 GPS SVs are assumed to be present in the nominal constellations. Likewise, different mask angles, of 5 deg for GPS and 10 deg for Galileo are used, as specified by the two system program offices. At each user location over the world, the 99.5th percentile VPL over the simulation period is mapped, to illustrate the high availability performance of RAIM. The maps are then colored by interpolation between grid points. It is important to emphasize the fact that current results reflect the performance on a nominal day under given assumptions, without any failures being intentionally introduced over the duration of the simulation.

Due to the expected 10-day Galileo constellation ground track repeatability, it will be very computationally demanding to run a simulation over the whole period of the Galileo constellation with frequent enough temporal sampling so as not to miss potentially short-lived critical geometry configurations. On the other hand, the orbital periods of each of the Galileo SVs will be approximately 14 hours, while GPS SVs complete a full orbit in about 12 hours. To ensure that a full orbit is observed for each of the satellites, the duration of the simulations will be set to 24 hours, making it possible to achieve sampling frequencies of every 150 sec while running the simulations on a PC computer. 150s is the specified duration for an airplane approach in the CAT I integrity requirements [ICAO 2005]. With regard to the celestial motions of the two constellations, it should be mentioned here that there will be a slow relative drift of the orbital planes over time. This means that any features or anomalies observed on the VPL maps will slowly move along geographic latitude lines, having the potential to

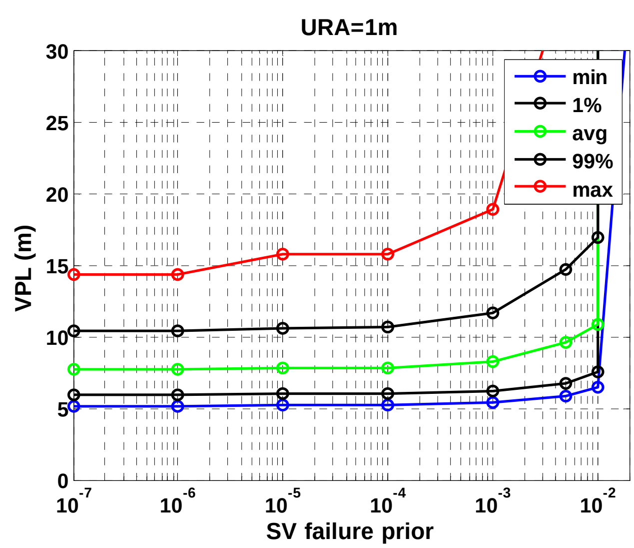

Figure 2. Failure prior parametric study.

affect any locations at the same latitude. For example, the presence of a weak geometry region, generating higher VPLs somewhere over the Pacific Ocean, will eventually affect continental areas as well, as the anomaly is revolving around the globe. In the future studies, longer simulation periods with less frequent time steps will also be attempted, such that these artificial features with no real geographical significance will average out along each latitude.

Figure 1 summarizes the outcome of the MHSS algorithm simulation in the presence of measurement biases. While in the absence of biases, VPL values are mostly around 10m over the entire globe, a 3.5m bias raises the protection level to the vicinity of 30m. Upon a visual estimation, the minimum VPL increases by 10m for each additional 3.5m of bias, while the maximum VPL value changes by 20m for each additional 2.5m of bias. What is the most relevant, however, is the evolution of the 99th percentile VPL, which seems to increase by 20m for an additional 3.5m of bias. Therefore, the presence of biases is an important limiting factor on the VPL values achievable with a Galileo-GPS constellation. Figure 2 is a revision of the study on the value of the failure prior presented in the previous paper. Besides a revision of the MHSS algorithm, the new results include more data points at higher failure probabilities. On the right hand side of the plot, it can be noticed how VPL values increase dramatically for failure probabilities of 10^{-2} or higher. It proves that above a certain probability enough satellites are likely to fail simultaneously, such that a position solution cannot be computed at all time steps and the 99.5% VPL becomes unavailable (viz. infinite in value). For a prior of 10^{-2}, the likelihood of six SV failures is higher than 10^{-8}/approach, but the number of probable simultaneous failures grows very rapidly as the satellite prior is increased beyond that value. For SV failure priors below 10^{-3}/approach, the average VPL is quite insensitive to the chosen failure priors. What changes significantly with the value of the prior, however, are the tails of the VPL distributions, making the worst case more extreme, as critical satellites for the geometry are more likely to fail. One parameter to which the VPL results are very sensitive is the URA value (Fig. 3), and implicitly the overall variance of the modeled nominal error. A reality check needs to be made for all values involved with this error model, since a 1m change in the URA in this case can influence the average 99.5% VPL over the world by about 8m. This indicates a stronger dependence of the results on the Gaussian error model than the influence of assumed failure priors or nominal biases.

A comprehensive set of simulations results covering the dual constellation degraded operation modes are summarized in Table 1. For each simulation, the number of GPS and Galileo satellites included in the combined constellation is given, as well as the overall 99.5th percentile VPL value for the entire world, and the percent of the points on the world map for which a 35m VAL is available at least 99.5% of the time. When a value is missing from the third column, it means that in over 0.5% of the cases a position solution could not be computed with a probability of HMI of less that 10^{-7}, due to an insufficient level of redundancy among the SVs in view. The presence of an infinite VPL value makes it also impossible to compute an average VPL for that case.

Another set of simulations was performed in order to test the robustness of the combined Galileo-GPS constellation to critical satellite failures. An average increase in VPL of about 3-4m above the values for the full constellations

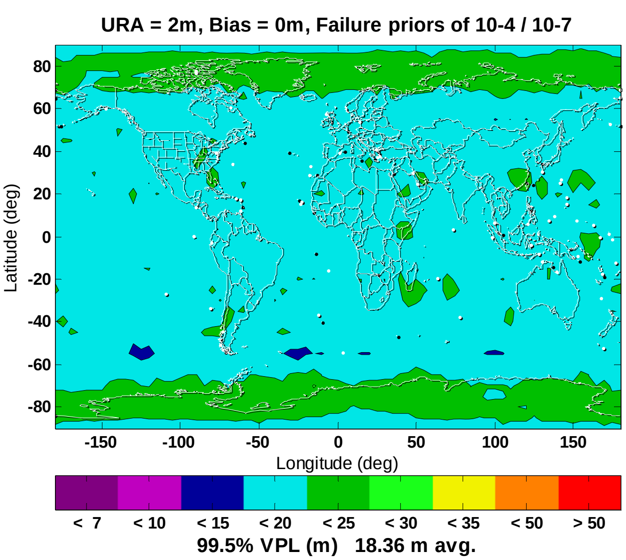

Figure 3. Dual constellation results when assuming a 2m value for the URA.

Number of satellites		99.5% VPL (m)	coverage with 99.5% availability
GPS	Galileo		
30	30	9.32	100%
27	30	9.73	100%
27	27	9.90	100%
27	24	10.53	95.69%
24	30	9.92	100%
24	27	10.08	100%
24	24	10.86	96%
24	18	-	18.15%
24	16	22.59	14.46%
20	20	13.95	78.76%
18	18	-	11.38%
16	24	33.09	1.84%
16	16	-	0.61%
12	12	-	0.00%

Table 1. Study of degraded operation modes.

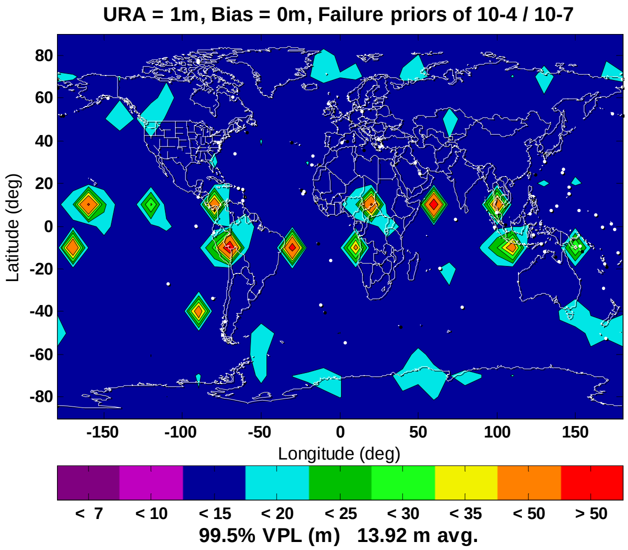

Figure 4. Dual constellation results after the elimination of the most critical satellite.

can be observed for the results presented in Figure 4. Since no previous study has been found, which determines how much the VPL deteriorates in the absence of the most critical satellite for stand-alone GPS and Galileo constellations, additional simulations have been performed also for the individual constellations. The VPL degradation upon losing the most critical satellite from a single constellation is much more significant, an average of 20m for Galileo and 30m for the unaided GPS. A more serious problem that affects single constellations upon the loss of the critical satellite is the diminishing in availability levels. The availability level is determined by comparing the VPL with the given VAL. In this paper, the performance of the Galileo-GPS constellation is demonstrated against a 35m VAL. By 99.5% availability, it is meant that the 99.5th percentile VPL needs to be at most equal to the VAL. While the dual constellation maintains its full level of coverage at 99.5% availability over the entire world in the case of a satellite loss, Galileo availability drops to an availability level as low as 80% after losing the critical satellite. Having the least number of average SVs in view for any user, only 8, as opposed to 10 for Galileo, the standalone GPS constellation only starts with a 95% availability even when operating in the nominal fault-free mode. This availability drops steeply to around 50% when the most critical SV is taken out. Also, the 99.5th percentile GPS-only VPL exceeds the 35m VAL for the entire surface of the Earth in all cases.

The trade-off between the assumed constellation failure prior and availability is illustrated in Figure 5. As mentioned above, the maximum possible value of 10^{-7} per approach for the failure probability was assumed in order to provide conservative results. However, simulations have been conducted for lower constellation failure priors as well as in the case of the degraded operation of GPS and Galileo. The results below reflect the performance with the two constellations depleted to 18 active SVs each. Lower constellation priors than 10^{-8} per approach prove to have an insignificant impact on the overall VPL, since the likelihood of a constellation failure becomes practically negligible. Also, for 24 or more active satellites in each constellation, 100% availability coverage is obtained for either assumption regarding the possibility of constellation failure. Nevertheless, if future Galileo and GPS constellations will not be guaranteed to have over 24 active SVs at any time, the question on how likely is a constellation failure becomes relevant. Whatever the required availability level between 90% and 99.9%, a lower constellation prior will improve the level of global coverage with that availability.

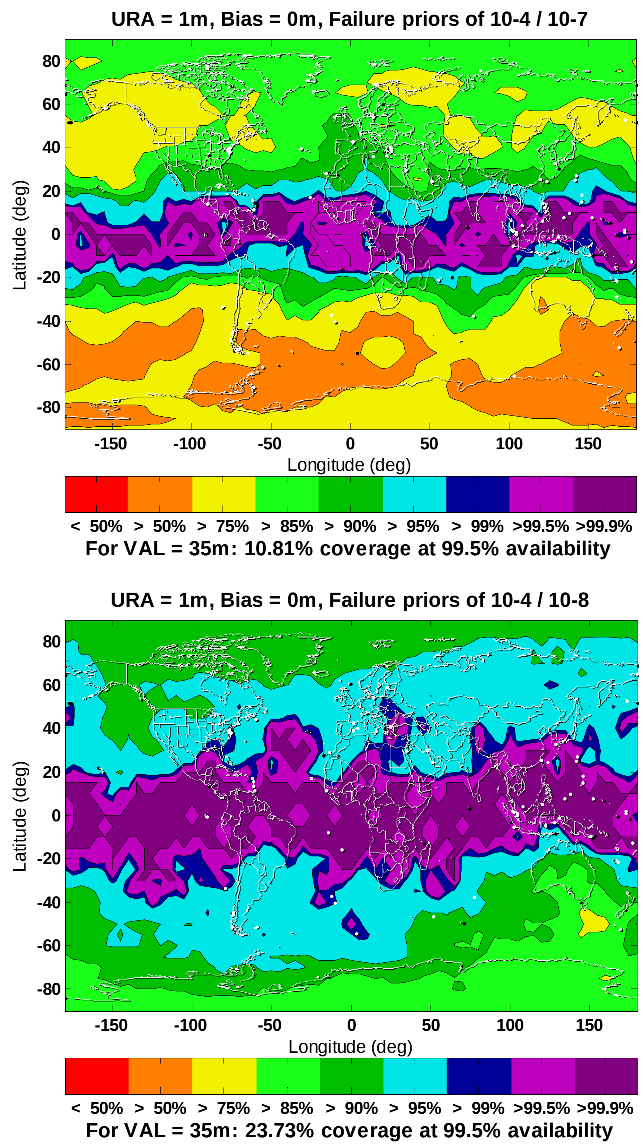

Figure 5. Illustration of the influence of the constellation failure prior on the availability for degraded constellations with only 18 active satellites each.

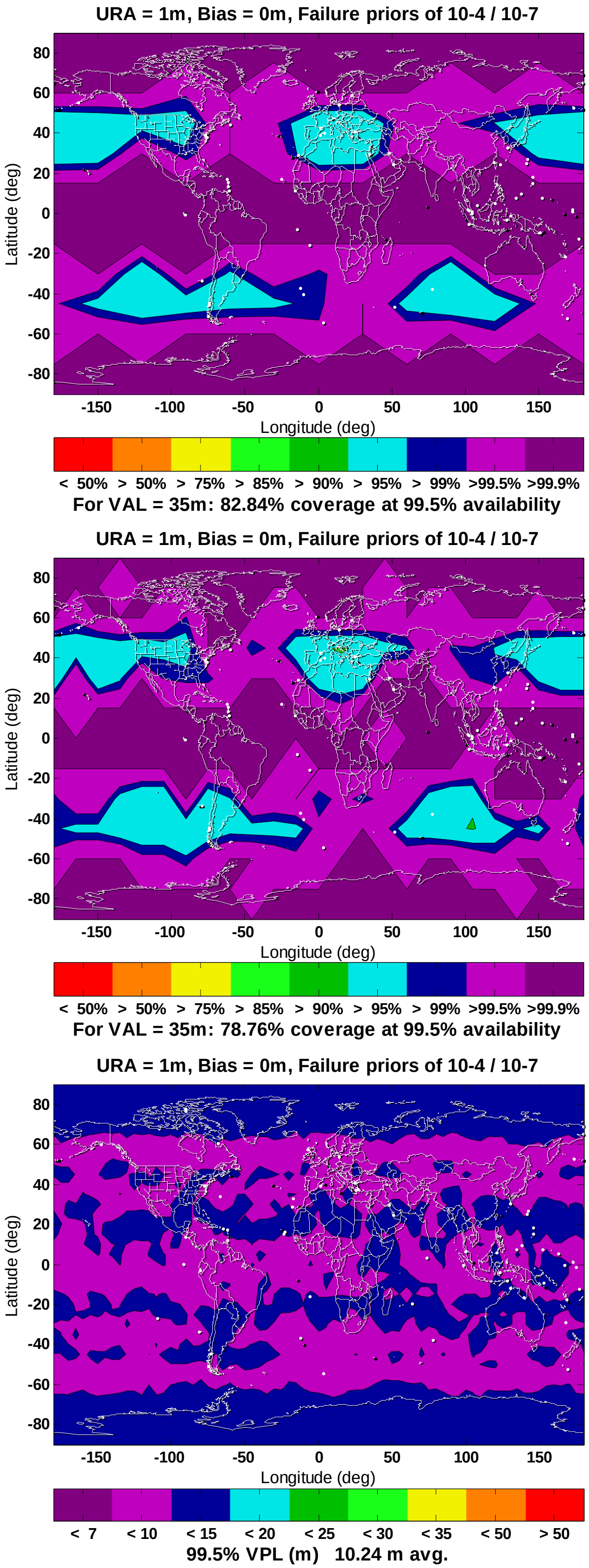

Figure 6. Galileo-GPS time difference: availability for degraded constellations with only 40 total active satellites (top) synchronized clocks, (middle) different times; (bottom) VPL map in the case of 54 total active satellites.

The last set of results (Fig. 6) illustrates the effect of clock synchronization (or lack thereof) between the Galileo and GPS satellites. Again, there are noticeable effects on the overall availability only in the case of depleted constellations, illustrated here for 20 GPS + 20 Galileo active SVs, and a slight difference in the average VPL for the full constellations. Having an additional time variable to determine leaves one less range measurement available for integrity monitoring. Effectively, this situation is very similar to the satellite elimination scenario above, except that the eliminated measurement is not the most geometrically critical one, so the deterioration of the VPL is less marked. In practice, when an arbitrary satellite is lost by the receiver during regular operation, it is not generally the most critical one. Therefore, the gain from synchronizing the two system times will be very similar to having an additional three SVs in orbit for the combined constellation (i.e. an additional satellite in view at any given time). All other results presented so far presume unsynchronized system times since no guarantees were offered so far by the Galileo and GPS program offices that a common clock will be adopted and implemented. It is however in the interest of all users of the dual system to have a single time unknown to determine from the measurements, thus allowing a slight benefit for both the integrity and availability of the position fix.

CONCLUSIONS

The method presented here is different from other RAIM algorithms, in that no threshold is set for the size of the range residuals in order to distinguish between failure and no failure cases. The MHSS algorithm makes a better use of the available information on the error residuals, allocating the integrity risk more efficiently between the different failure modes, based on their prior probability of occurrence. Therefore, no probability of false alert needs to be computed in conjunction with the current algorithm. The user will only be alerted if a VAL has been specified for the current operation and the computed VPL exceeds that value.

The fact that the VPL was found to be quite insensitive to the chosen failure prior, and the conservative value used for this prior gives confidence that the current MHSS is a viable algorithm. The algorithm is tolerant to multiple simultaneous failures, and it makes it easy to account for a comprehensive threat space. On the other hand, partial constellations do not seem to satisfy the precision approach requirements for availability when less than 24 satellites are operational in each constellation. The prior probability of constellation failure plays a decisive role in determining the availability figure for the degraded operation modes. With the use of RAIM, an unaided Galileo-GPS constellation can provide nominal VPLs of under 20m, assuming a conservative threat space, and a URA of 1m. Even in the presence of biases of up to

3.5m, the unaided performance of RAIM was found to be appropriate in order to meet the 35m VAL requirement for aviation approaches, which is currently being considered for WAAS. As the magnitude of the measurement biases increases, the VPL values will degrade in a linear manner.

One important thing that was shown by the simulation results above is that the combined constellation is much more robust to satellite failures than any of the two individual constellations operating independently. The key factor is the increased number of average satellites in view, 18, which leaves enough room for the elimination of one or two faulty SVs without greatly endangering the integrity or availability performance for the user. Current work is in progress to implement Fault Detection and Elimination (FDE) capabilities for this algorithm. Furthermore, since the PL is a direct function of the measurement residuals under this approach, a tool is being developed for predicting VPL values ahead of time, before a critical navigation operation is set to begin.

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APPENDIX

The way in which one can compute the estimated navigation position error for SS-type algorithms will be described here in more detail. It is important that this procedure does not require actual pseudorange measurements (not available in simulation), as the RAIM algorithms provide a PL based only on the relative geometry between the user and the Galileo and GPS constellations.

As in the case of LS RAIM, one starts out with the linearized measurement equation for a number **n** of satellites in view:

$$\mathbf{y} = \mathbf{G} \cdot \mathbf{x} + \boldsymbol{\varepsilon} + \mathbf{b} \qquad (1)$$

The linearization took place around the estimate minus actual position *deviation vector* **x**, which is five-dimensional for the case of the dual constellation (North, East, Up and one time coordinate for GPS and Galileo each). A simplifying assumption could be made by considering a fixed, known Galileo-GPS clock bias, but the choice was made not to use that assumption here, in order to maintain generality. The other terms above are the **n** × 1 *measurement vector* **y** containing the differences between the expected ranging values and the raw pseudorange measurements to each of the **n** satellites, the **n** × 5 geometry or *observation matrix* **G**, the **n**-dimensional zero-mean Gaussian noise component of the *measurement error* **ε** and the *measurement bias* **b**. For the simulation purposes, the error along each satellite LOS was taken to be zero-mean Gaussian noise with the σ_i^2 variance defined earlier in this paper.

The weighted LS solution for **x** is given by:

$$\mathbf{x\_est} = (\mathbf{G}^T \cdot \mathbf{W} \cdot \mathbf{G})^{-1} \cdot \mathbf{G}^T \cdot \mathbf{W} \cdot \mathbf{y} \equiv \mathbf{K} \cdot \mathbf{y} \qquad (2)$$

where **K** is called the weighted pseudoinverse of **G** and the *weighting matrix* **W** is the inverse of the measurement noise covariance matrix **Σ**. For simplification, it was assumed that the error sources are uncorrelated between all the different SVs. Therefore, **Σ** is a diagonal **n** × **n** matrix:

$$\mathbf{\Sigma} = \sigma_i^2 \cdot \mathbf{I}_{n \times n} \qquad (3)$$

While the independence assumption may not be strictly true, it should be a reasonably good approximation. The equations subsequently derived do not depend on this assumption, which only makes them easier to implement in practice.

At this point, the Solution Separation RAIM algorithms employ the residuals from estimating the actual position error:

$$\boldsymbol{\delta}\mathbf{x} = \mathbf{x\_est} - \mathbf{x} = \mathbf{K} \cdot (\boldsymbol{\varepsilon} + \mathbf{b}) \qquad (4)$$

for the all-in-view solution. Assuming that the elements of the vector **b** can be either positive or negative, and that they are bounded in absolute value by an array **B** of maximum satellite biases, we can write the following inequality:

$$|\mathbf{K} \cdot \mathbf{b}| \leq \Sigma\, |\mathbf{K}_i| \cdot |\mathbf{b}_i| \leq \Sigma\, |\mathbf{K}_i| \cdot \mathbf{B}_i \qquad (5)$$

Thus, we can make a conservative replacement in equation (4), in order to account for the worst possible bias from an integrity standpoint – displacing each partial solution by its maximum vertical bias:

$$\boldsymbol{\delta}\mathbf{x} = \mathbf{x\_est} - \mathbf{x} = \mathbf{K} \cdot \boldsymbol{\varepsilon} + \Sigma\, |\mathbf{K}_i| \cdot \mathbf{B}_i \qquad (6)$$

For each position solution, including all satellites in view or just part of them, a (partial) VPL range will be computed. For the partial solutions, **x_est** and **x** will be replaced with the corresponding vectors based on a partial set of measurements. Of interest here is only the third element in **δx**, the vertical component of the navigation error. This element will be called $\mathbf{x}_v$, in agreement with the notation in [Pervan & Pullen 1998] used for describing the MHSS algorithm:

$$\mathrm{VPL} = \mathbf{x}_v \pm \mathbf{k}_v \cdot \boldsymbol{\sigma}_v \qquad (7)$$

where $\mathbf{k}_v$ is the number of standard deviations equivalent to the required integrity confidence interval ($\mathbf{k}_v$ = 5.33 for a 10^{-7} integrity risk) and $\boldsymbol{\sigma}_v$ is a measure of vertical accuracy derived from the covariance of the position estimate, equivalent with the VDOP in the non-weighted LS case:

$$\boldsymbol{\sigma}_v^2 = [(\mathbf{G}^T \cdot \mathbf{W} \cdot \mathbf{G})^{-1}]_{3,3} \qquad (8)$$

Then, the overall VPL for the SS algorithm will be chosen such that it defines an interval around the all-in-view estimated position including all the partial solution ranges.

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