Multiple Hypothesis RAIM with Real-Time FDE and Forecasted Availability for Combined Galileo-GPS Vertical Guidance

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BIOGRAPHY

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ABSTRACT

The number of ranging sources for the aviation user is expected to increase with the Galileo system becoming fully operational over the next decade, and the projected launch of a modernized GPS III constellation. The reduction in nominal error bounds by removal of the ionospheric delay term from the dual-frequency measurements, together with the presence of a larger number of satellites is going to increase the robustness against satellite failures and hazardous pseudorange errors. Consequently, a significant improvement in integrity will be available for the use of satellite navigation during precision aircraft approaches and other critical operations.

With a better understanding of the threat model and the multiple hypothesis RAIM algorithm previously reported [Ene, 2006], the final contributions to a new dual-constellation RAIM are made here. A method for Failure Detection and Elimination (FDE) is proposed, with the purpose of improving the navigation Protection Level (PL) where possible. Also, a new capability is added to the RAIM algorithm to provide a conservative forecast of PLs anywhere in the world without the need for real-time range measurements. Since the PL is a direct function of the measurement residuals under this approach, a tool will be developed for predicting PL values ahead of time, when a critical navigation operation is about to begin. Vertical errors are critical during aviation precision approaches, and they are also generally greater than horizontal errors for satellite-based positioning. The purpose of this work is to investigate what Vertical Protection Level (VPL) values could be achieved with RAIM under conservative failure assumptions. Once vertical guidance is accomplished, the same algorithm can be applied in two dimensions to provide a Horizontal Protection Level (HPL) as well.

Computer simulations of the new techniques for FDE and VPL prediction have been conducted and preliminary results indicate that VPLs in the 10-20m range are achievable. These protection levels would enable LPV200 landings (the equivalent of Cat I ILS) at all runway ends in the world without the need for a satellite-based or ground-based augmentation system (SBAS or GBAS). A conclusion will be presented on the capabilities of dual-constellation RAIM to assist an aviation user in meeting the integrity and continuity requirements for landing aircraft. The approaches to measurement integrity of both GPS and Galileo [Oehler, 2004] will be compared within the framework of the Weighted Integrity Risk Solution Separation (WIR-SS) algorithm, while possible improvements to the GNSS constellation will be discussed, that could increase the benefits to the RAIM user.

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 et al. 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, constitutes 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 complete a previous study [Ene 2006] investigating 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. A Multiple Hypothesis Solution Separation (MHSS) algorithm was chosen because of its better use of the measurement information and its intrinsic ease of covering a comprehensive error threat space. The new dimensions added here to this algorithm are FDE and predictive capabilities. These enhance the satellite navigation service at different points in time. FDE can be employed by the user for real-time vertical guidance in order to select the best position solution offered by the satellites that are in view at a given instance. On the other hand, the VPL prediction tool can be employed in advance of a critical navigation operation (e.g. an aviation approach) that is set to take place, in order to produce a conservative forecast of the navigation solution availability at the time and location where the critical operation will be performed. No actual range measurements are required for generating an availability forecast; all that is required is that the satellite configuration relative to the user is computed ahead of time for the planned operation. The WIR-SS algorithm introduced here departs from previously presented versions of MHSS algorithms [Pervan et al. 1998, Ene 2006], as it is better suited for computing a *dispatch VPL* in that each possible failure mode influences the VPL independently. Also, a slight issue arising from the question whether the *a priori* probability of the existence of a measurement failure is or not influenced by knowledge of the range measurement residuals is eliminated by the new approach in this algorithm. The new developments of the algorithm also make it more consistent with the existing literature on the joint use of GPS and Galileo for airplane navigation integrity [Lee et al. 2006], in that the VPL value can be independent from the real-time measurements. However, the algorithm continues to be a significant departure from the model of classical RAIM [Brown 1992], in the way in which it deals with multiple failures, considering each failure scenario separately.

As part of the WIR-SS algorithm, a multitude of possible degraded operation modes are probabilistically taken into account. A degraded or *failure mode* is considered to be the circumstance when the distribution of ranging errors along one or multiple lines of sight (LOS) cannot be overbounded by a Gaussian distribution (e.g. the presence of a constant bias of any magnitude). A failure can affect one space vehicle (SV), an entire constellation (GPS or Galileo) or part of a constellation, and it can 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. Within the WIR-SS algorithm this failure scenario will be reproduced by computing position solutions based only on a subset of the SVs in view, considered to be healthy, while the remaining faulty satellites will be omitted. Each such failure scenario will be assumed to occur with a pre-determined probability. In the absence of an alert or flag, the user will continue to assume nominal conditions and could receive misleading information from the navigation system. It is the duty of the RAIM algorithm to make sure this misleading information does not become hazardous with a greater than specified probability (i.e. 10^{-7} per approach). An example of degraded mode operation is when the incomplete Galileo or modernized GPS constellations are used while they are still being populated with satellites and are not yet fully operational. Another specific case is the degraded mode in which a single satellite needs to be excluded due to the occurrence of a failure. If a 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 for a single user, the most critical satellite in view can suffer an outage and become unusable, causing the worst possible deterioration on the SV geometry (i.e. in terms of the Vertical Dilution of Precision (VDOP)) and also causing an increase in the VPL with respect to the case when that satellite were available and healthy. One way to measure the robustness of a navigation satellite system is to determine the exact magnitude of the impact of such an outage on the overall VPL.

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 earlier papers [Ene et al. 2006, Ene 2006] to observe the influence of factors that are external to the integrity monitor, such as the mask angle, number of available SVs, variance of the Gaussian range measurement error - e.g. the User Range Accuracy (URA), nominal measurement biases, and the prior probabilities of failure. This paper includes a review of previous studies and offers a discussion on the limitations of the RAIM algorithm, the possible benefits of additional ground and/or space augmentation, and of the interoperability between Galileo and GPS.

WIR-SS FDE ALGORITHM

The WIR-SS algorithm used here adds FDE capabilities to the version described in detail in [Ene, 2006]. The underlying principle behind the algorithm is that the (prior) probability of occurrence of each failure mode is taken into account and a VPL is determined based on the Gaussian confidence bound that makes use of the entire integrity budget available. Multiple independent faults are considered in the combined constellation in order to cover all possible failure modes included in the threat space. Entire constellation failures are also considered for the case when common mode or correlated failures might occur. If the failure independence assumption were not sufficient, the current algorithm is easily adaptable to considering correlated failures as long as the prior probability for each separate failure mode can be provided. Such correlated simultaneous failures of two or more satellites in the same constellation were in fact already investigated and they are akin to a slight increase in the prior belief about the likelihood of such failure modes. The WIR-SS algorithm assumes the fault-free or *all-in*-view case (no known satellite failures) position solution as default and then it takes into account the possible presence of yet undetected failure modes. Each such potential failure mode has a prior probability of occurrence assigned to it and is allocated a fraction of the total integrity budget specified for the desired precision navigation operation. The total integrity budget needs to be divided between all the possible failure modes, and the resulting VPL will be very sensitive on the manner this budget is allocated. For the purposes of this investigation, integrity allocations for the different failure modes were made solely based on the a priori likelihood of each mode. More optimal ways to allocate the total integrity budget between failure modes are currently under investigation, such that the failure modes which pose a greater danger of a position error generating HMI to the airplane pilot will receive a greater share of the total integrity budget.

Normally, in applying any RAIM algorithm, multiple failures are neglected, for modes that are less likely than a certain threshold. The reason why certain improbable failure modes need to be excluded is that the entire satellite failure 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. Nonetheless, within the WIR-SS algorithm, instead of neglecting the possibility of an event generating Hazardous Misleading Information (HMI) to the user for the very improbable threats, it is conservatively assumed that the worst-case scenario (i.e. failure generating HMI) occurs. Thus, the failure priors for these threats are removed altogether from the total integrity budget as they have a small enough probabilistic impact on the total error or the resulting VPL. The overall integrity budget is taken here to be P(HMI) = 10^{-7}/approach in order to satisfy the FAA and ICAO requirements for civil aviation approaches up to CAT I landings. Additionally, a threshold of 10^{-8} has been chosen, below which probabilities of k simultaneous SV failures are directly subtracted from the total integrity budget instead of computing a position solution under each of the corresponding failure modes. Another way in which the WIR-SS FDE algorithm is different from other types of RAIM is that the actual measured range error residuals have a direct impact on the VPL, as they are used to compute each partial position solution (i.e. based on a subset of the SVs in view). The integrity risk is computed based on satellite geometry and the partial position solutions, but the prior probabilities of failure are fixed and impossible to be updated based on the actual range measurements. Consequently, the way integrity risk is allocated for each of the fault modes will not depend on the measured residuals. 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 probability distribution functions for all the modes, since the sum weights were actually dependent on the measurements in the original WIR-SS algorithm [Pervan et al. 1998, Ene et al. 2006].

The probabilities of satellite failure can be assumed to be lower if the user has the possibility to run a χ^2 check and independently 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 WIR-SS algorithm can also be applied after excluding such externally-detected faulty satellites. Additionally, an a priori probability of failure will be associated to each possible constellation failure for each approach. For single constellation RAIM, a constellation failure would mean a complete loss of availability, so the chance of it happening should be much smaller than the integrity threshold, otherwise RAIM algorithms would not be usable at all for single-constellation applications. On the other hand, for the dual constellation, this failure 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 the multiple constellation case, while the system should still able to provide the necessary integrity for precision approaches. The limiting value for the constellation failure rate of 10^{-7}/150s is considered here, which is borderline between allowing the use of single-constellation RAIM and requiring a second constellation to be in view at all times. This rate is much more conservative than the threat model currently used for GPS-only RAIM, and is equivalent to one failure every 47.5 years. At the moment, it is impossible to verify 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 a conservative constellation failure prior. Previous 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. In fact, any time when less than four satellites from the same constellation are in view, the dual constellation VPL value automatically becomes infinite. The reason is that at this point the user has to rely on at least one satellite from each constellation for a position fix. However, each of the two constellations 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.

The procedure through which one or more satellites can be purposefully eliminated before a position solution is computed, in order to achieve a better VPL and eliminate a potential SV failure is outlined below. Another reason why one would want to employ satellite elimination is improving the availability for the navigation solution. The name FDE was chosen for this procedure in order to comply with historical nomenclature in the field of RAIM; actually the question on whether a SV is failed or not is not as relevant as the question on whether eliminating one of the pseudoranges (and implicitly its associated measurement error) from the position measurement can provide a more accurate position with a smaller VPL confidence interval associated to it. The more measurements (satellites) are used by the algorithm, the better the geometry and the tighter the confidence bound that can be can set. Thus, VPLs based on a subset of the satellites in view will be most of the time larger than the all-in-view VPL. It is only important to exclude a SV from the measurement equations if a large ranging error corresponding to that satellite actually translates into a significant positioning error for the user. On the other hand, removing a healthy SV would have the opposite effect: it would increase the VPL, and detection would not happen since satellite elimination under nominal conditions normally degrades the geometry. Therefore, detection and elimination under this algorithm only occur when a SV causing a position error to the user can be removed from the position solution equation without actually increasing the overall integrity risk above the required 10^{-7} threshold.

The *nominal error distribution model* consists of zero-mean noise (allowing a Gaussian overbound) and biases in each channel: $\nu_i = \varepsilon_i + b_i$. In theory, a failure is defined based on whether the navigation error distribution can be overbounded by a Gaussian curve or not, but the only information which is available to a snapshot algorithm like the one employed in this work is the instantaneous value of the error and not its probabilistic distribution. In practice, navigation errors can affect the VPL and the measurement confidence level. Small errors might increase the integrity risk without causing the Probability of HMI (PHMI) to exceed the alert level; therefore, a FDE algorithm only needs to detect those errors that affect the VPL and PHMI. Many existing RAIM algorithms compare their test statistic to a threshold in order to make a "fault/no fault detected" decision. However, one of the caveats of this approach is that a constant failure bias can be just below the chosen threshold and thus go undetected for any length of time. Also, combined effects of errors along multiple LOS can push a particular test statistic over the threshold in the absence of a hazardous failure on any particular pseudorange measurement. Thus, the single failure assumption does not always hold to make exclusion possible. Lastly, in previous RAIM algorithms a separate analysis is also necessary to determine the probabilities of failed and false detection, and that of failed exclusion every time a detection threshold is employed. In the present algorithm, such additional analysis is not necessary, since it can be shown that one or more satellite exclusions do not affect the confidence level or the integrity that is already guaranteed for the position solution both before and after FDE. The WIR-SS algorithm only estimates the navigation errors for each partial position solution, but it does not define a threshold for failure, recognizing the probabilistic nature of position measurements. The proposed algorithm is already designed to be robust, in that it provides both availability and continuity in the presence of small amounts of random noise and moderate biases in the pseudorange measurement under nominal conditions. However, when the navigation error is large enough that the VPL would exceed the Vertical Alert Limit (VAL), a failure can be declared to reduce that PL. In simulation, large biases will be inserted on top of the noise in one or several pseudoranges to test the detection capabilities with the proposed method. The fact that WIR-SS is working with system-level failure probabilities (not based on the actual measurements) enables the algorithm to be able to generate a VPL interval not only for the full set of satellites in view, but also for any partial set of these SVs. Due to the assumed pseudorange measurement independence, all confidence bounds based on the full set or a subset are equally trustworthy in guaranteeing that at most 10^{-7} integrity risk lies in the tails of the probability distribution. As elimination is done after an exhaustive search, no information is discarded in the process and therefore the integrity risk or PHMI will not increase above the required limits upon satellite elimination.

For FDE with the WIR-SS algorithm, the VPL for the given all-in-view configuration is computed at first, as before. Additionally, partial VPLs are computed for subsets of all the SVs in view, for all possible such partial configurations after eliminating up to k measurements from the position solution equation. Here, k is the maximum number of satellites that will be attempted to be eliminated. It should be noted that the more partial VPLs are computed, the higher will be the computational complexity of the algorithm. At the same time, the more satellites are eliminated to form a partial position solution, the less likely it is that a lower VPL value will be obtained, since in the absence of large failure biases on most pseudoranges, satellite elimination only leads to a deterioration in geometry, and in turn to an increase in the VPL value. Therefore, a base case of one satellite elimination is exemplified in this paper. Once all VPLs based on subsets of the satellites in view are determined, the minimum of all those partial VPLs will be chosen. If this minimum partial VPL is smaller than the original all-in-view VPL, then a fault will be assumed on the k satellites eliminated from the corresponding subset (in here, the basic case k=1 is chosen).

VPL PREDICTION ALGORITHM

Under the WIR-SS algorithm, the real-time VPL depends on the range error residuals and is the union of all partial VPL intervals generated under the different failure assumptions included in the defined threat space. Thus, the overall VPL is practically determined by the largest such partial VPL interval, as long as one chooses the fault-free mode position solution as the position estimate and all other VPL intervals are centered around this position, called the all-in-view solution. If a forecast for the VPL value is needed before the actual range measurements were available, it is possible to conservatively predict this VPL value at a given point in the future based on the fact that the measurement errors are normally distributed around the true position, without actually measuring the specific value of these errors.

Given a continuity requirement for the navigation solution, an interval can be defined for the measurement errors around each partial solution, such that the continuity requirement is always satisfied. Proceeding in a similar manner as with the integrity risk budget, the total continuity failure budget is split between all possible failure modes into equal continuity allocations. Subsequently, the worst-case error residual that still satisfies the continuity requirement allocation is considered for each of the partial position solutions. That is done assuming again a distribution of the ranging errors that can be approximated by a Gaussian curve, and the error residual is then generated using a confidence bound approach similar to the way VPL is computed. The statistical worst-case navigation error is then considered in computing each partial VPL, before the union of all partial VPLs is taken in the same manner as in the case when real-time measurements are available. By this procedure, a conservative worst-case VPL is produced based only on the satellite geometry and the statistics of nominal errors. It is expected that this will be a conservative upper bound on the VPL that the user can determine in real time while performing the same precision navigation operation. If the largest error value which would still allow the required continuity level for the operation results in a VPL larger than the required VAL, then there is a chance that the approach will not be able to be performed safely and a warning is issued to the user. Likewise, other navigation requirements, such as position accuracy can also be integrated with the WIR-SS algorithm and results have been obtained showing the availability for navigation under a combination of different constraints imposed by user safety considerations.

Especially in aviation applications, it is important to be able to guarantee the user that the actual VPL will not exceed the required VAL, such that a precision operation will not even be attempted if there is a danger of HMI being passed to the user at any point during that operation. In particular, the predictive capability of the WIR-SS algorithm will be useful in reducing the number of missed approaches in cases where there is a danger that satellite navigation would not be able to guarantee the safety of the user throughout the planned operation. This capability allows civil aviation integrity to be enhanced to a superior level, where the navigation system does not limit itself simply to a 6 sec time-to-alert. On the contrary, this RAIM algorithm is also able to provide longer term forecasts such that when the satellite navigation system becomes unreliable a pilot does not need to seek a last-minute solution, but would be warned well ahead of time and would have time to seek an alternative means to land.

SIMULATION RESULTS

Simulations were performed in order to test the WIR-SS RAIM algorithm against a comprehensive threat model including multiple simultaneous failures as well as constellation fault modes and an unknown clock bias between the two constellations. According to system specifications, 27 active 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, and a URA/SISA of 1m is assumed. At each user location over the world, the 99.5th percentile VPL over the simulation period is mapped in order to illustrate the high availability performance of RAIM. The maps are then colored by interpolation between grid points. A geographic average 99.5% VPL is also provided for each plot. 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, unless specified otherwise.

Due to the expected 10-day Galileo constellation ground track repeatability, it would 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. 150 seconds is the specified duration for an airplane approach in the CAT I integrity requirements [ICAO 2005]. Also, in order to take into account the worst possible alignment of the Galileo and GPS constellations, the three orbital planes of the Galileo constellation are aligned with three of the GPS orbital planes at the beginning of each simulation period. 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 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.

Figures 1-3 summarize parametric studies, showing how the outcome of the WIR-SS algorithm simulation depends on the presence of measurement biases, the value of the URA, and satellite and constellation prior probabilities of failure. Figure 1 summarizes the studies on the dependence of the VPL values on the satellite failure prior and the measurement bias under nominal conditions. On the left hand side plot, it can be noticed how VPL values increase dramatically for failure probabilities of 10^{-2} or higher. This proves that above a certain failure prior enough simultaneous satellite failures are likely to occur, such that a position solution cannot be computed at all time steps and the 99.5% VPL becomes unavailable, or infinite in 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. Similarly, in Figure 2 it can be seen how the VPL is also not very sensitive to the constellation failure prior, however this probability influences significantly the availability of the position solution for cases where a fewer number of active SVs is present in each constellation [Ene, 2006]. The parameters on which the VPL results are very sensitive are the nominal measurement error standard deviation (e.g. the satellites' URA/SISA) and bias values (Fig. 1, 3). A 1m change in the URA or the bias can influence the average 99.5% VPL over the world by about 5-7m. This indicates a stronger

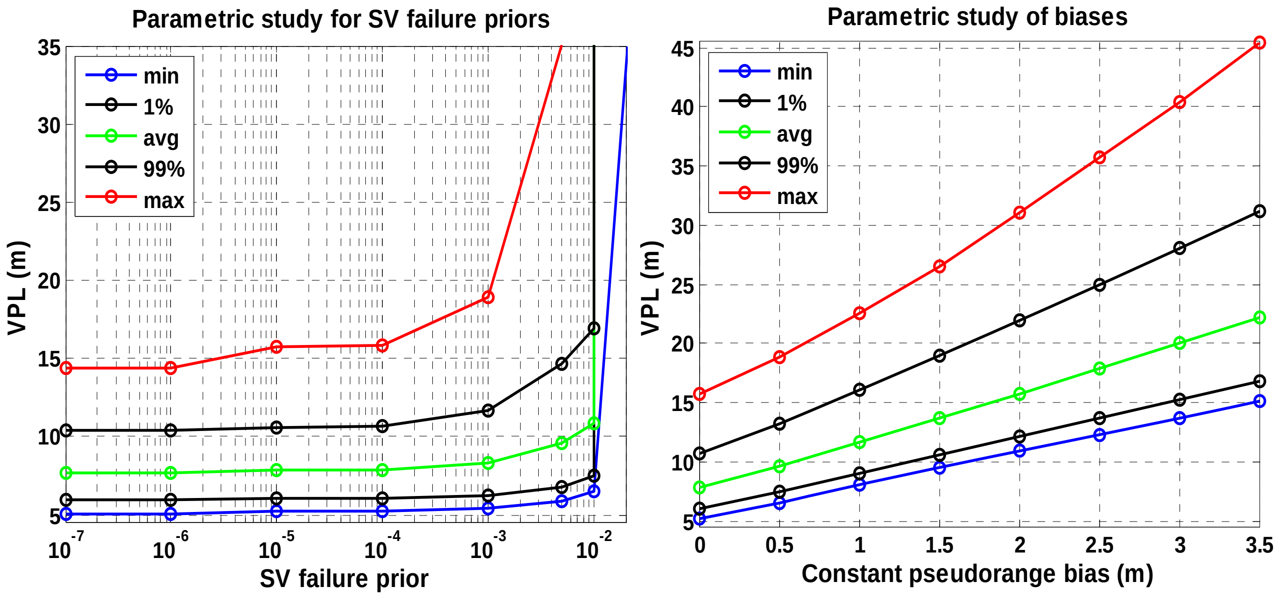

Figure 1. Parametric studies on the dependence of the VPL on satellite failure prior and on nominal biases.

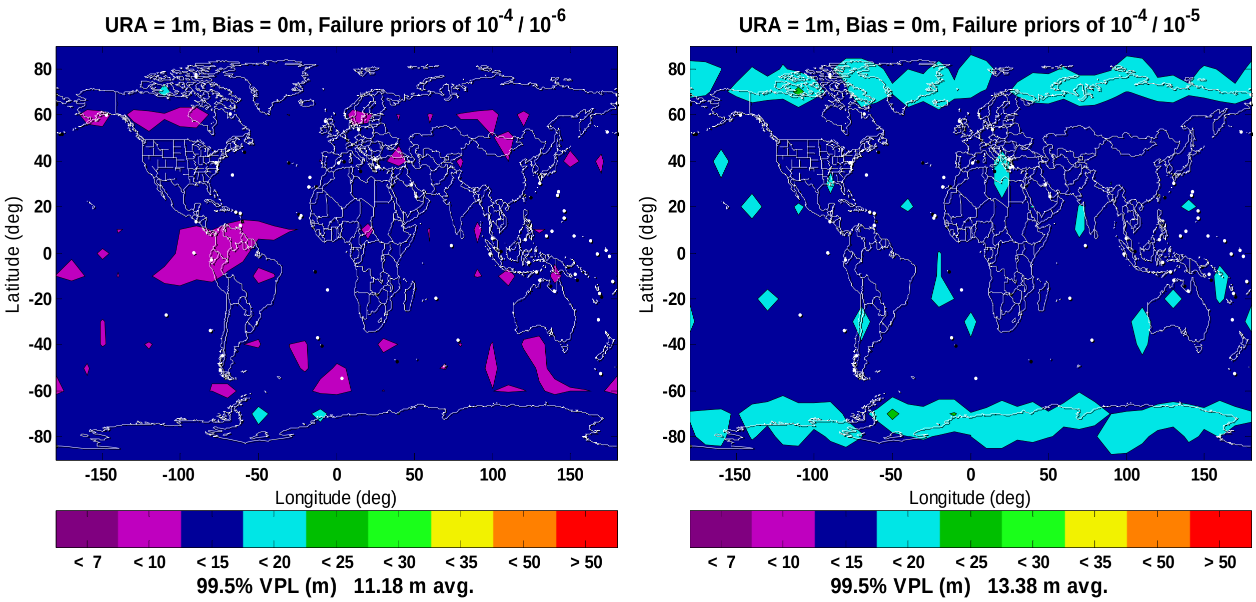

Figure 2. Parametric study on the influence of the assumed constellation failure prior on the VPL values. Failure priors are of 10^{-4} for individual satellites and 10^{-6}, respectively 10^{-5} for constellations per approach.

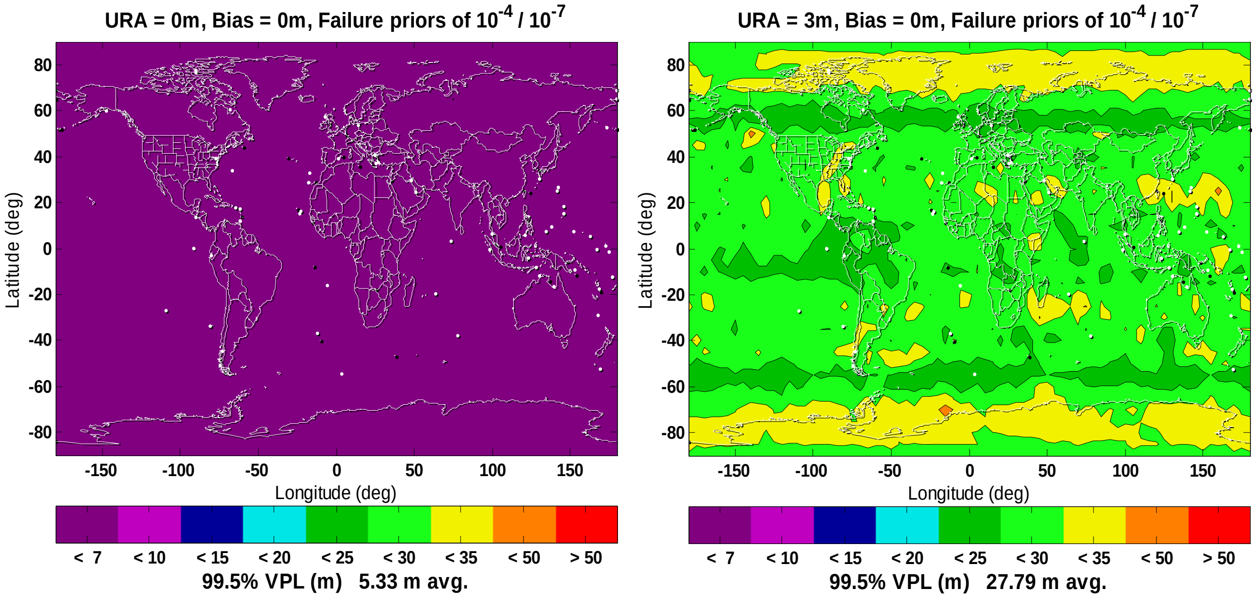

Figure 3. Parametric study on the influence of the URA value on the overall VPL.
Failure priors are of 10^{-4} for individual satellites and 10^{-7} for constellations per approach.

dependence of the results on the Gaussian error model than the influence of assumed failure priors. 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. The average VPL is not very sensitive to the chosen satellite and constellation failure priors, and it increases approximately linearly with the value of range errors and noise variance. In conclusion, the presence of biases and the system-specified variance for the clock and ephemeris errors are all-important limiting factors on the VPL values achievable with a Galileo-GPS constellation.

In figures 4 and 5, the effects of FDE can be observed when implemented in conjunction with the WIR-SS algorithm. First, FDE is run under nominal conditions, when only nominal noise and biases are simulated in the measurements (Fig. 4). It can be seen how a small improvement in the VPL of about 75cm is achieved due to increased confidence in the computed position solution and also due to the fact that a nominal ranging error that also causes a small position error can be discarded from the position solution equation to improve the agreement between position estimates using only the remaining SVs. Next, in Figure 5 it is shown how the VPL results change when a 10m bias is intentionally introduced on one of the range measurements to simulate a satellite failure. For every point on the worldwide latitude/longitude grid and at every time step, the most critical satellite from a geometry or VDOP point-of-view is identified and its ranging error is increased by 10m. This procedure ensures that the failure is implemented in the most

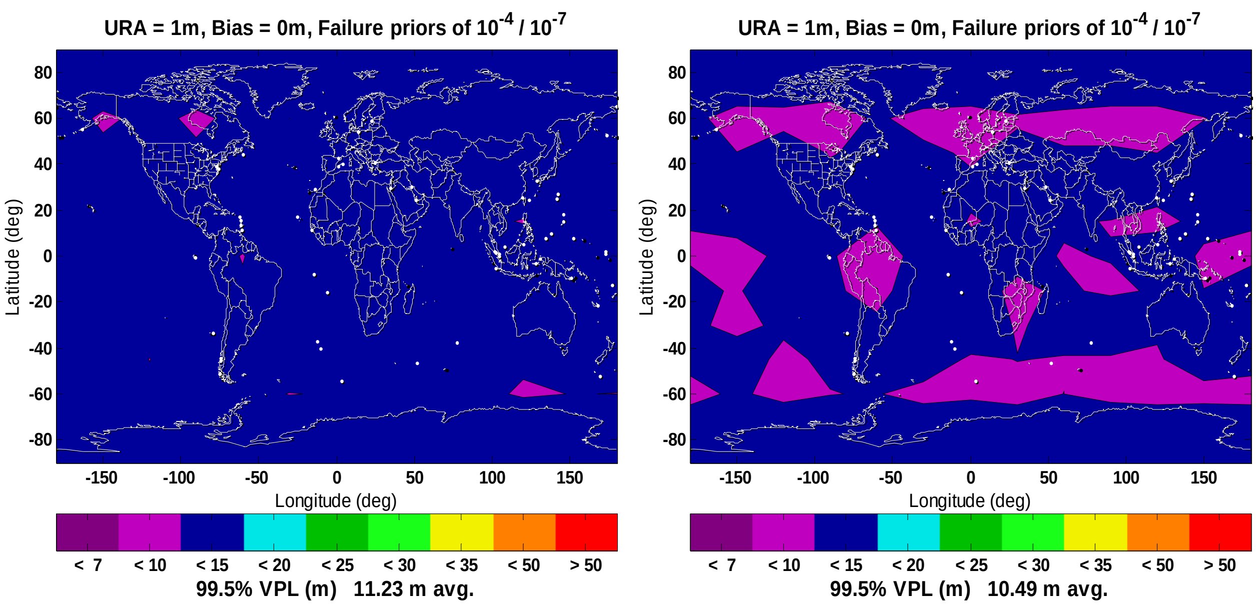

Figure 4. Applying the FDE algorithm leads to a slight improvement in the VPL under nominal conditions. Failure priors are of 10^{-4} for individual satellites and 10^{-7} for constellations per approach.

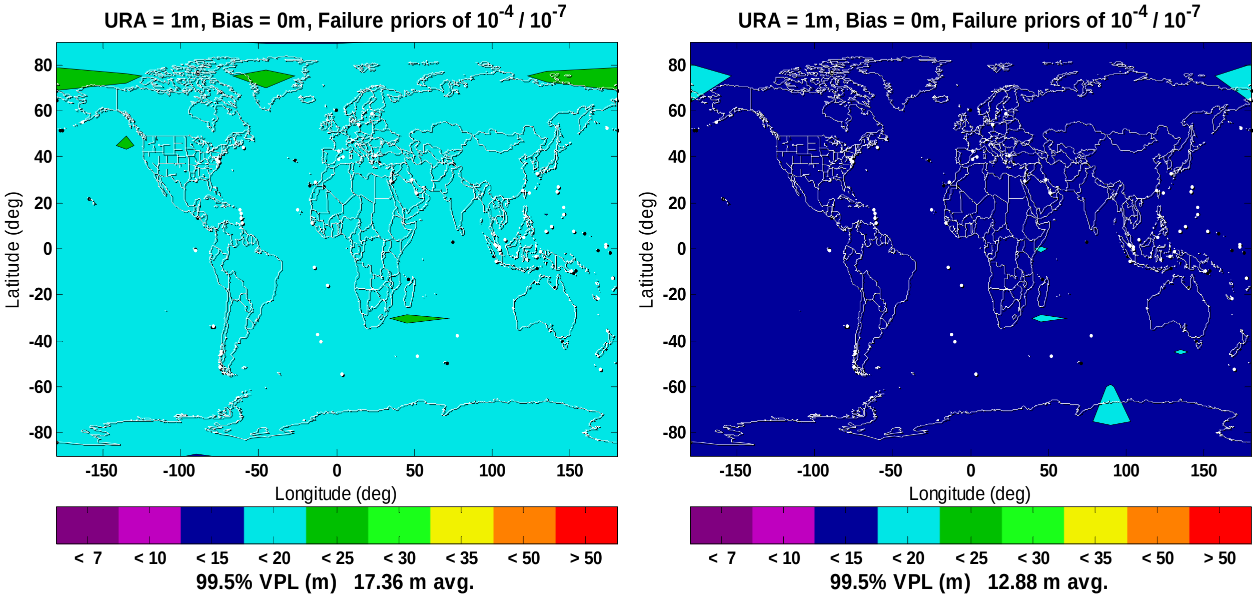

Figure 5. A 10m failure bias was introduced on the most critical satellite at every time step. On the left, the deterioration in the VPL values can be seen before and on the right after the FDE algorithm was applied to detect and remove the failure.

unfavorable way to each user, on the satellite that is the most needed for having a good measurement geometry. The regular WIR-SS algorithm results (Fig. 5 – left) show that this 10m bias on one satellite is still only as severe as assumed nominal biases of around 1m on all SVs in view (Fig. 1 - right). Nonetheless, once FDE is run on the measurement set containing the 10m failure, the algorithm consistently detects the satellite on which a large abnormal bias is applied and eliminates it from the measurements. In general, as long as the failure bias is consistently larger than the nominal measurement errors from the healthy SVs, the fault will unequivocally cause the largest position error when it is included in a measurement subset. If the failed satellite bias was comparable with the level of nominal noise on the remaining healthy satellites, then a different satellite might be excluded instead. However, that is not a cause of concern because the minimum possible VPL will be achieved nevertheless giving the most integrity to the user whether the removed satellite was faulty or some combination of SV geometry and signal propagation errors was the culprit for the largest positioning error seen by the user. In conclusion, the FDE algorithm brings an added layer of protection to the user against ranging errors that could translate into hazardous positioning errors, whether this happens under nominal or abnormal measurement conditions. From Figure 5 (right) it can be seen that even after the exclusion of the failed satellite the VPL still depreciates compared to its nominal values in Figure 4, because the removed SV was critical to the geometry. Inserting a fault on the most critical satellite for each user at every time step is certainly a very conservative way to determine what is the VPL in the worst-case scenario. In the future, a more realistic case may be considered, where at every time step a single SV is chosen, whose failure will have the worst possible overall effect on the integrity performance worldwide, though it might not represent the failure of the most critical satellite for each individual user. In real life, when a satellite fault occurs, it will not affect all the users in the world to the same extent. For some users that particular SV might not have been in view anyway, while for other users a signal from the same satellite is received, but the ranging errors might not have the most critical effect on the final position solution. In conclusion, it is expected that less conservative results will be obtained when the vertical integrity performance is measured against real data.

The simulation results for the VPL forecasting tool practically show an upper limit for the VPL in the presence of error residuals that are borderline to posing a continuity threat. Since no range measurements are used in producing the predicted VPL values, it must be conservatively assumed that threatening errors can exist along all ranging LOS and not only in a particular channel. The advantage of being able to provide a dispatch VPL to the user is the ability to guarantee integrity to a planned critical operation without the threat of continuity loss. Comparing the predicted VPL (Fig. 6 – right) with the case where a failure was simulated (Fig. 5 – left), it can be seen that the prediction tool ads a layer of robustness to the WIR-SS algorithm such that even 10m of failure bias on one of the range measurements would not threaten the required continuity for a critical operation to the aircraft user. In practice, the probability of a 10m erroneous bias in the GNSS measurements is much lower than 1. That explains why the real-time VPL, which is an expected value 99.5% VPL given the measurement residuals, is much lower than the dispatch VPL, which is an expected worst-case scenario VPL in the absence of any information on the pseudoranges. There is certainly a significant overall performance difference between the two types of VPLs and this can be seen by comparing figure 7 to figure 1 above. However, the VAL which needs to be satisfied for LPV200 civil aviation approaches is 35m (represented by the horizontal dashed line in Fig. 7). Thus the conservatism built into the prediction algorithm should not substantially reduce the ability to dispatch a flight. It can be seen that although the same quasi-linear relationship exists between the size of the VPL and the amount of URA and bias in the measurements, less pseudorange inaccuracies can be tolerated before the alert limit is exceeded in the case of predicted VPLs. Nevertheless, one can confidently assume that future modernized GNSS constellations will provide higher precision pseudorange measurements, thus lowering the nominal error term that is determined by both the URA and bias values. Even with today's GPS signals, the measurement errors are most of the time lower than the nominal errors in the conservative model used here, so it is expected that the current simulation results will prove to be conservative when the WIR-SS algorithm will be validated with real data.

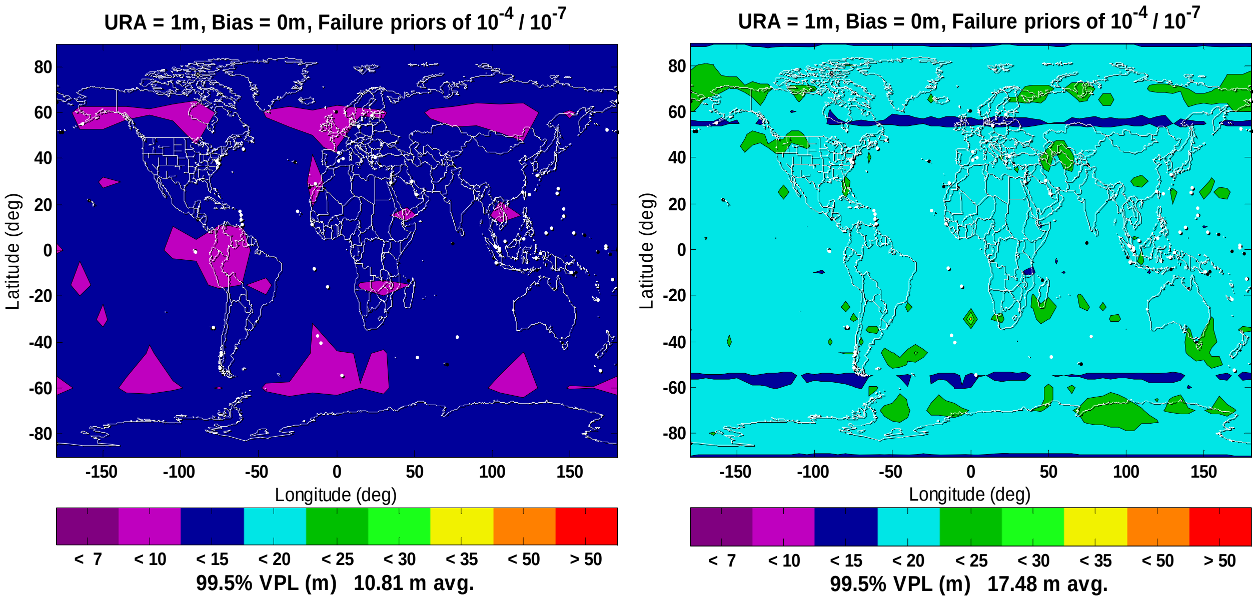

Figure 6. Comparison between the VPL values obtainable in real-time (left) and the conservative dispatch VPL values (right) resulted from applying the prediction algorithm without knowledge of the actual range measurements. Failure priors are of 10^{-4} for individual satellites and 10^{-7} for constellations

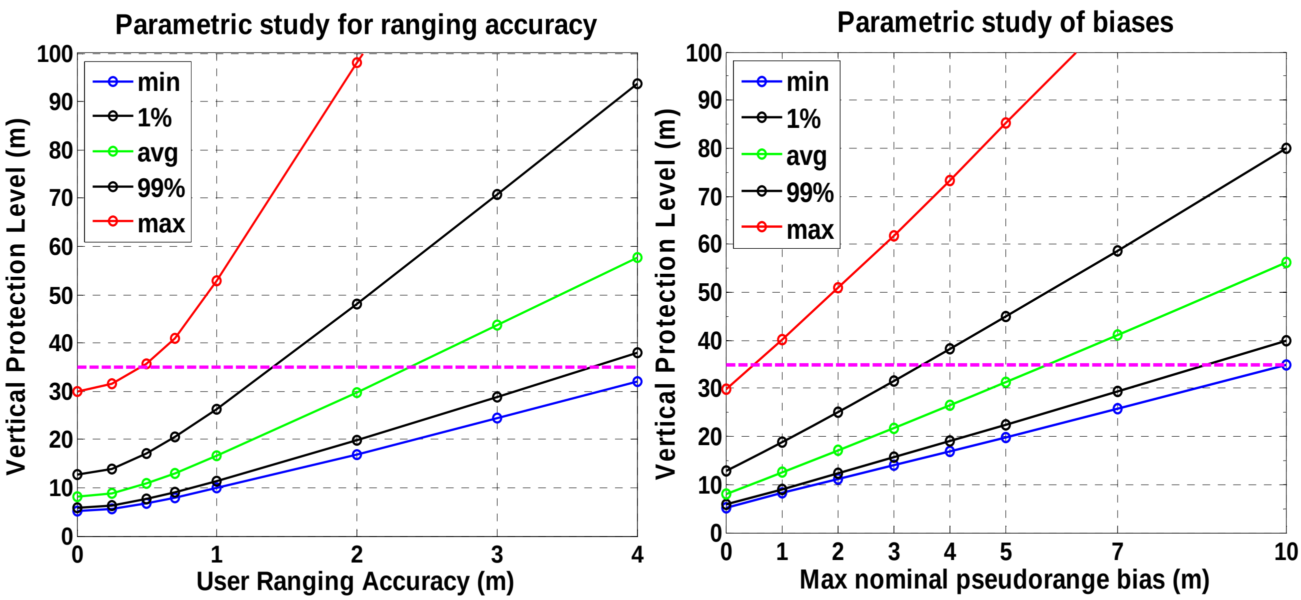

Figure 7. Parametric studies on the dependence of the "dispatch VPL" on satellite URA/SISA and on nominal biases.

CONCLUSIONS ON THE USE OF RAIM FOR NAVIGATION OF CIVIL AIRCRAFT

When both the modernized GPS and Galileo constellations are fully operational, it will be possible to implement in practice the RAIM algorithm presented in this study. Only GPS User Range Accuracy (URA) and Galileo Signal-In-Space-Accuracy (SISA) values are needed by the algorithm, along with a prior probability of failure for each satellite and for the constellations themselves. The value of SISMA calculated by the Galileo Sensor Stations (GSS) and broadcast by Galileo SVs is not necessary in order to calculate the integrity for the user. Any integrity flags broadcast for either Galileo or GPS SVs will be entirely optional as long as the failure priors used under RAIM are correct or conservative, and it will be entirely at the latitude of the users whether to consider flagged satellites or not as part of their position solution. Simulation results anticipate the possibility of using GNSS signals as the primary means for navigation in civil aviation. The RAIM algorithm is good for detecting and possibly correcting independent measurement errors specific to each user, but a monitoring and augmentation system can be used to broadcast corrections for correlated errors and common fault modes. However, one feature of the dual Galileo-GPS constellation that would significantly improve RAIM performance would be the interoperability in terms of system clock synchronization. In the present work it was assumed that there are two separate system time unknowns, one for each constellation, such that a minimum of five satellites from the combined constellation is needed in order to solve for the 3D position and two separate time variables. The additional satellite would thus not be available for performing RAIM redundancy checks and the integrity performance of the double constellation thus becomes equivalent to that of a combined constellation with three less SVs in orbit but a system time synchronized across all active satellites (due to orbital geometry, a third of the total number of active SVs is visible to the average user.) On the other hand, once the system times are synchronized, a new common mode failure possibility is generated, which does not allow the two constellations to be treated as independent any longer. One of the beauties of the use of two independent systems is that there is no common fault mode.

The method presented here is an advanced algorithm with some different philosophical assumptions from other RAIM algorithms, e.g. in that no threshold is set for the size of the range residuals in order to distinguish between failure and no failure cases. The WIR-SS 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. Furthermore, since the PL is a direct function of the measurement residuals under this approach, a tool was developed for predicting VPL values ahead of time, before a critical navigation operation is set to begin. Preliminary simulation results for the predictive algorithm are expected to improve as the method is currently in the process of being validated with real dual-frequency data.

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 WIR-SS is a viable algorithm. The algorithm is tolerant to multiple simultaneous failures, and it makes it easy to account for a comprehensive threat space. 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 LPV200 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. A separate study of single-constellation RAIM is being currently carried out in order to determine the minimum required capabilities of the SVs within that constellation, such that LPV200 guidance can be achieved even when a second constellation is not available.

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