Fault Detection and Elimination for Galileo-GPS Vertical Guidance

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BIOGRAPHY

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ABSTRACT

In anticipation of the future launches of dual-frequency GNSS satellites, such as Galileo and GPS block III, a series of new developments has taken place in the field of Receiver Autonomous Integrity Monitoring (RAIM). Of particular interest were the topics of multi-constellation RAIM and analyzing the impact of multiple simultaneous ranging failures. 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. The reduction in nominal error bounds by removal of the ionospheric delay term from the measurements, together with the presence of a larger number of satellites is going to increase the robustness against satellite failures and hazardous pseudorange errors.

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 an unaided combined Galileo-GPS constellation under conservative failure assumptions. The foundations that enable the methods developed in this paper have already been laid in previous work [2] by identifying a viable RAIM algorithm for monitoring dual-frequency ranging signals and conducting detailed parametric studies to identify what threat space needs to be covered with future RAIM algorithms. Given a better understanding of the threat model and the proposed multiple hypothesis algorithm, the final contribution to a new dual-constellation RAIM is made here as a detailed study of a Failure Detection and Elimination (FDE) method, with the purpose of improving the navigation Protection Level (PL) where possible. Virtual simulations of this new technique have been conducted and preliminary results indicate that VPLs in the vicinity of 10m under nominal conditions are achievable. These protection levels will likely enable LPV 200 landings at all runway ends in the world without the need for a Ground or Space-Based Augmentation System (GBAS or SBAS). Furthermore, since the PL is a direct function of the measurement residuals under this approach, a tool will be developed for predicting VPL values ahead of time, before a critical navigation operation is set to begin.

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 future capabilities and limitations of RAIM usage for aviation precision approaches with GNSS as the primary means for navigation will also be discussed in the context of current aviation navigation requirements for landing and take-off. Also, the need for ground aiding to the aviation user equipped with RAIM will be assessed.

INTRODUCTION

The intent of this paper is to complete a previous study [1, 2] 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. This algorithm is based on a multiple hypothesis approach to RAIM proposed by Pervan et al. [6], and further developed in Ene et al. [1]. Aside from the addition of tools for FDE and VPL prediction, this algorithm is identical to the one described in [2], while a new name was chosen to reflect the fact that the algorithm has evolved and is significantly different from the versions proposed in earlier papers. The Weighted

Integrity Risk Solution Separation (WIR-SS) algorithm was adapted to make a better use of the measurement information and its advantages also include an intrinsic ease of covering a comprehensive error threat space. The WIR-SS algorithm is different from other types of RAIM proposed in earlier literature, in that the actual measured range error residuals have a direct impact on the VPL, as they are used to compute both full and partial position solutions, i.e. based on a subset of the satellites in view. Also, a new way is used in here to define satellite failures, based on the "uncertainty in the state of nature" assumption as enunciated in section 7.2 of [5]. 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). No information on the actual error distribution during a failure event is available to the user or the navigation system. A fault can affect one space vehicle, an entire constellation (GPS or Galileo), or part of a constellation, and the fault can be unknown to the user or it can be already detected and 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. As part of the WIR-SS algorithm, a multitude of possible degraded operation modes are probabilistically taken into account. The fault scenarios will be reproduced by computing position solutions based only on a subset of the SVs in view, considered to be healthy, while the remaining failed satellites will be omitted. Each such failure mode 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 if unknown failures are actually present in the measurements. It is the duty of the RAIM algorithm to make sure this misleading information does not become hazardous with a greater than specified probability. An example of degraded mode operation are the incomplete Galileo or modernized GPS constellations 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 the satellite has a significant role in providing a good geometry for the position measurement, that is called here a critical satellite. In the worst-case scenario, 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.

The new dimensions added here to the WIR-SS 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 which 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) 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 the *dispatch VPL* availability forecast; all that is required is that the satellite configuration relative to the user is computed ahead of time for the planned operation.

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 an earlier papers [1, 2] to observe the influence of factors that are external to the integrity monitor, such as the mask angle, number of available SVs, the Galileo Signal-In-Space-Accuracy (SISA)/ GPS 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 GBAS or SBAS monitoring, and of the interoperability between Galileo and GPS.

WIR-SS ALGORITHM

The underlying principle behind this algorithm is that 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. 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. 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.

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 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 that very improbable threats generate Hazardous Misleading Information (HMI) to the user, 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 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}/approach 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 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 then generate the overall VPL as the union of all partial confidence intervals. This is a key difference from the original Multiple Hypothesis Solution Separation (MHSS) algorithm [6, 1], in which the overall VPL was based on the weighted sum of the probability distribution functions for all the modes, and the sum weights were actually dependent on the measurements.

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 faulty satellites. Additionally, an a priori failure probability of 10^{-7}/approach will be associated to each possible constellation fault. 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 likelihood that the system needs to fall back into the mode in which it relies on only one constellation. For that reason, a greater 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 accepted in this case, and the system should still be able to provide the necessary integrity for precision approaches. The 10^{-7}/approach failure rate considered here is equivalent to an average of one failure every 47.5 years. Thus, 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 [2] 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 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 for positioning), so the integrity requirement cannot be satisfied.

SIMULATION RESULTS

Simulations were performed in order to test the WIR-SS RAIM algorithm against the comprehensive threat model described above. 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 default value for the 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 of the 99.5% VPLs 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.

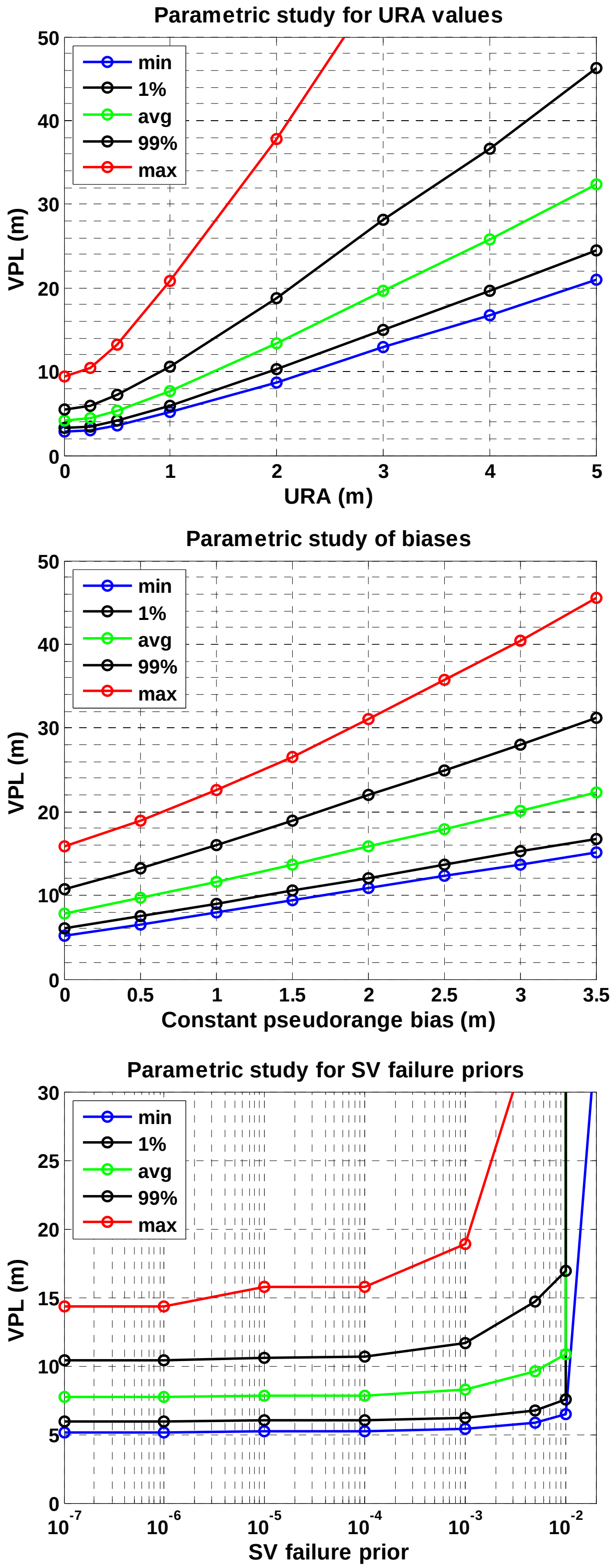

Figure 1. Graphic summary of parametric studies simulation results of the sigma URA error term (top), measurement bias (middle), and the satellite failure prior (bottom) influence on the VPL.

The bias number at the top of the VPL maps always shows the size of nominal biases considered and is not indicative of any specific failure that can be introduced separately in the measurements.

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 150s while running the simulations on a PC computer. 150 seconds is the specified duration in the integrity requirements for vertically guided airplane approaches, such as LPV and CAT I landings [3]. 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 other 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 and 2 summarize parametric studies, showing how the outcome of the WIR-SS algorithm simulation depends on the presence and size of nominal measurement biases (viz. the mean value of range measurement noise), the value of the URA (or the standard deviation of the Gaussian measurement noise in general), and the satellite and constellation prior probabilities of failure. The results of studies on the dependence of the VPL values on the measurement error under nominal conditions and the satellite failure priors are presented in Figure 1. The parameters on which the VPL results are very sensitive are the mean and variance of the nominal measurement error, instantiated here as the bias values and the satellite URA/SISA. A 1m change in the URA or the nominal bias can influence the average 99.5% VPL over the world by about 5-10m. In the absence of satellite clock and ephemeris errors, which are characterized by the SISA for Galileo and the URA for GPS, VPL values would be under 5m, due to the other terms in the error model (excluding biases). However, a 3m URA is sufficient to increase the 99.5% VPL values close to the assumed Vertical Alert Limit (VAL) at 35m.

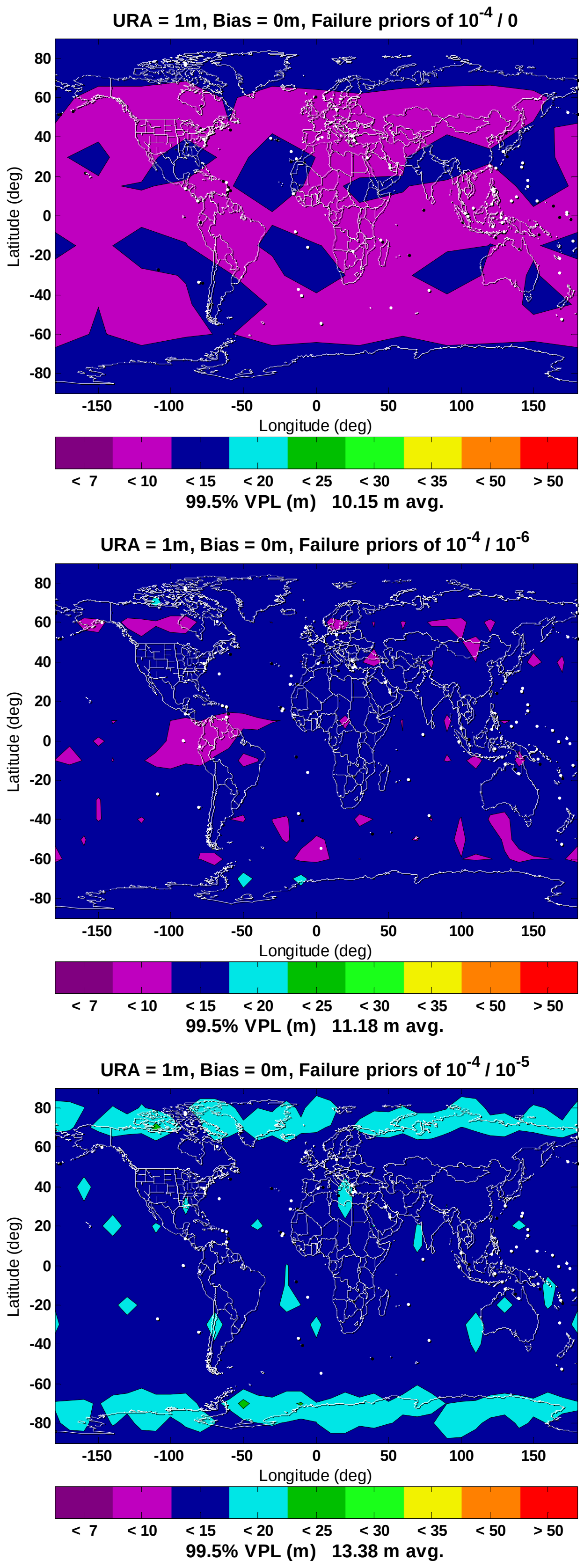

Figure 2. Parametric study for different values of the constellation a priori probability of failure: zero (top), 10^{-6} (middle), 10^{-5} (bottom).

Similarly, while in the absence of biases, VPL values are mostly around 10m over the entire globe, assuming a default URA of 1m, a 3.5m bias raises the protection level to the vicinity of 30m. Then, in the bottom plot, it can be noticed how VPL values also 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. Nevertheless, for SV failure priors below 10^{-3} (i.e. at most three failures are likely to occur with a probability greater than 10^{-8} per 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. Likewise, 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 [2]. The above studies indicate a stronger dependence of the results on the Gaussian error model than the influence of assumed failure priors. 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. 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.

FDE ALGORITHM FOR WIR-SS

The WIR-SS algorithm used here adds FDE capabilities to the version described in detail in [2]. The procedure outlined below shows how 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. Improving the availability for the navigation solution is another reason for employing satellite elimination. 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 here as is the question on whether eliminating one of the pseudoranges (and implicitly its associated measurement error) from the position equations, can provide a more accurate position with a smaller VPL confidence interval associated to it. The more measurements (viz. satellites) are used by the algorithm, the better will the geometry be and the tighter the confidence bound that can be can ultimately be 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. Removing a healthy satellite would have the effect of increasing the VPL, and hence detection would not happen since satellite elimination under nominal conditions normally degrades the geometry. Only if a large ranging error actually translates into a significant positioning error for the user, it is beneficial to exclude that satellite from the measurement equations. 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, adopted from Lee et al. [4], 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 VAL, a failure can be declared to reduce that PL. In simulation, large failure 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 in the partial solution space, the uncorrelated measurement information discarded in the process has no detrimental influence on the integrity risk or PHMI, which 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 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, by the argument above, 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 subsequent examples, the basic case k=1 is chosen.

To observe the effects of FDE when implemented in conjunction with the WIR-SS algorithm, a number of simulation results are presented in figures 3-6. First, FDE is run under nominal conditions, when only nominal noise and biases are simulated in the measurements (Fig. 3). It can be seen how a small improvement in the VPL of about 75cm is achieved due to the increased confidence in the computed position solution. Also, one nominal ranging error which also causes a small position error can be discarded from the position solution equation in order to improve the agreement between position estimates using only the remaining SVs. The next logical step is to show how the VPL results change when a failure bias is intentionally introduced on one of the range measurements to simulate a satellite failure (Fig. 4). 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 unfavorable way to the user, on the satellite that is the most needed for having good measurement geometry. Nominal zero-mean Gaussian noise (i.e. 0m nominal bias) continues to be simulated on the remaining satellite measurements. The regular WIR-SS algorithm results (Fig. 4 – top) show that the 10m bias on one satellite is still only as severe as assumed nominal biases of around 1m on all SVs in view (Fig. 1 - middle). Then, 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 faulty satellite will unequivocally cause the largest position errors when it is included in a measurement subset. If the failed satellite bias were 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 for 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 combined to produce 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

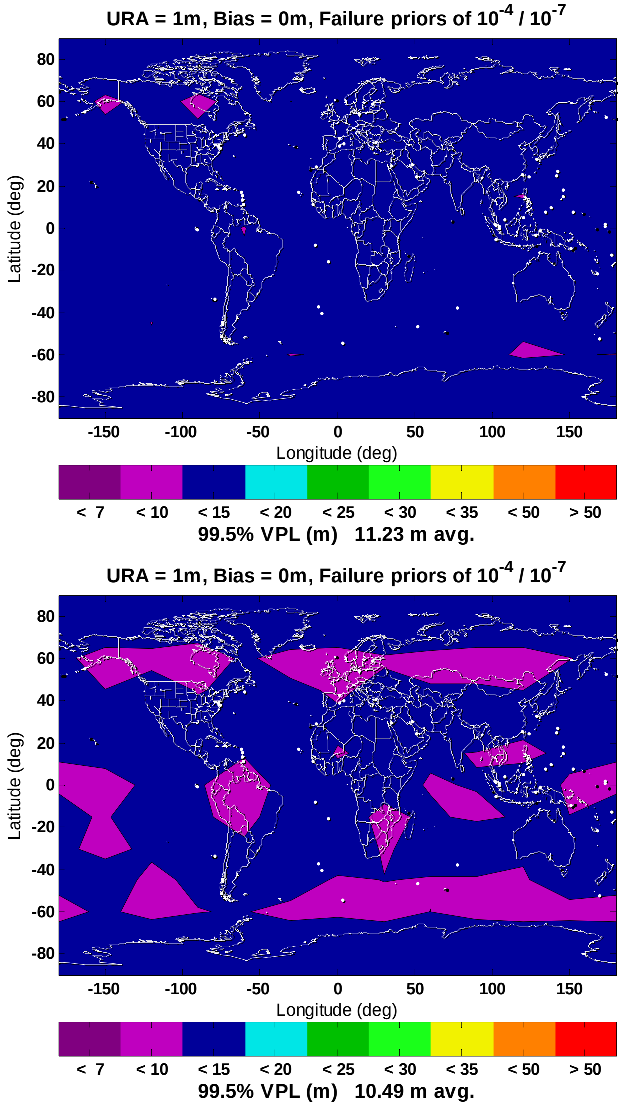

Figure 3. Dual constellation results before (top) and after (bottom) the use of the FDE algorithm under nominal conditions.

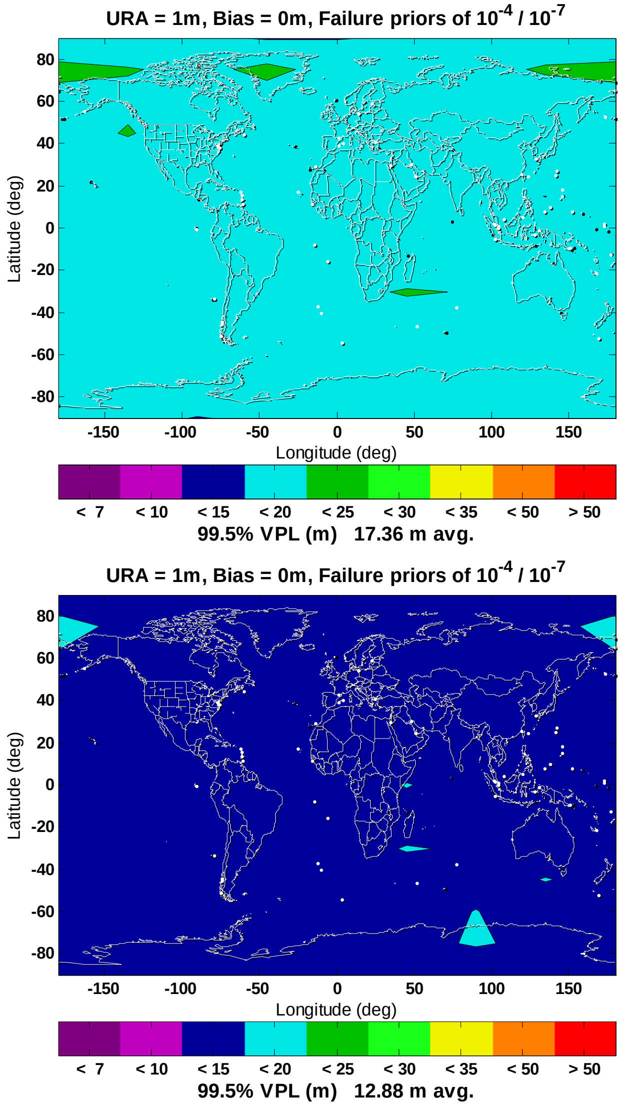

Figure 4. Dual constellation results before (top) and after (bottom) the use of the FDE algorithm, when a 10m error was intentionally introduced on the range measurement to the most critical satellite.

positioning errors, whether this happens under nominal or abnormal measurement conditions. From Figure 4 (bottom) it can be seen that even after the exclusion of the failed satellite the VPL still depreciates compared to its nominal values in Figure 3, because the removed SV was critical to the geometry.

Additional results show the benefits of FDE for the case of incomplete constellations, where less than the specified number of satellites are available to the user. This can be the scenario while SVs are taken down for maintenance and also when dual-frequency constellations are in the deployment phase and thus are not yet fully operational. It can be seen (Fig. 5) that even with only three of the Galileo satellites unavailable, there are user locations on the globe where the VPL will exceed the VAL and make vertically guided approaches unavailable. However, with the addition of FDE, not only are VPL values decreased overall, but availability is also restored to all users. Further depletion of the two constellations to 20 active SVs each shows a more critical picture in terms of coverage at 99.5% availability, even in the absence of intentionally introduced measurement failures (Fig. 6). Once again, when the FDE algorithm is employed, availability is restored to many of the users, such that geographic coverage is increased from under 60% to over 80% worldwide. In the light of these results, the usage of FDE to complement the basic WIR-SS algorithm is advised in all cases when real-time snapshot measurements of the ranging error residuals are available to the user.

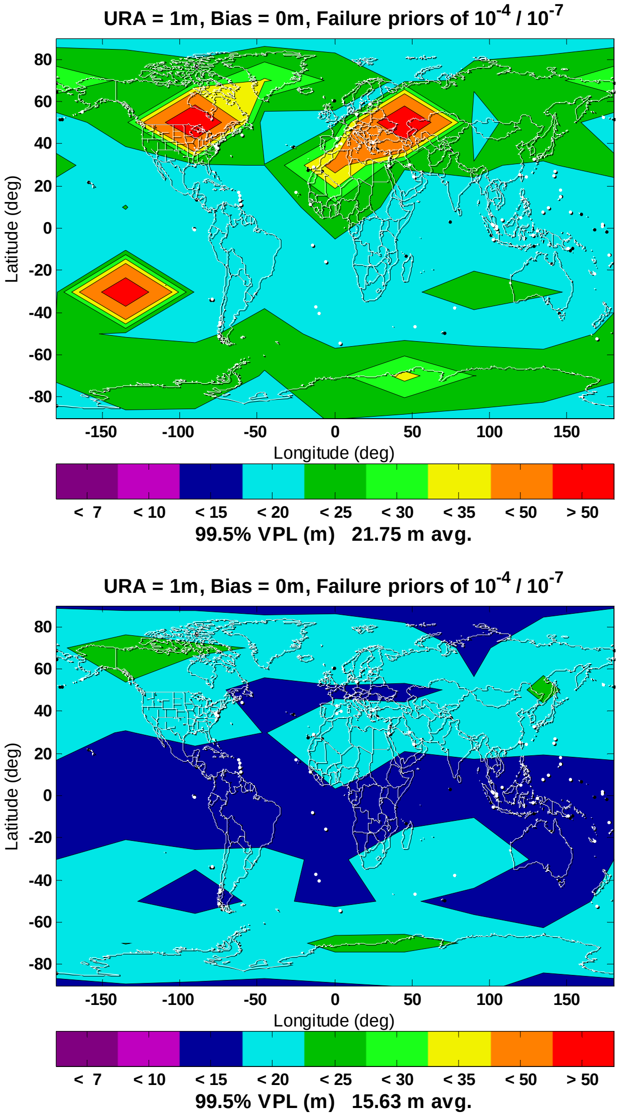

Figure 5. Partial constellation (24 GPS and 24 Galileo satellites) with a 10m error on the most critical satellite before and after the FDE algorithm was applied.

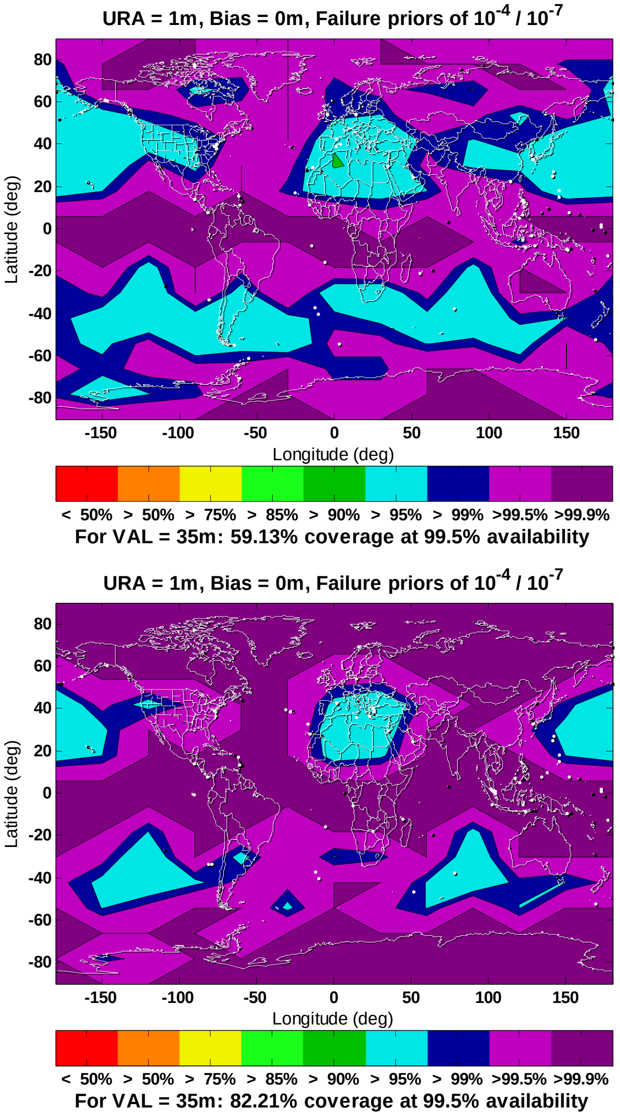

Figure 6. Availability figures for partial constellations (20 GPS + 20 Galileo SVs) with a 10m error on the most critical satellite, before and after applying FDE.

WIR-SS AND VPL PREDICTION

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 was needed before the actual range measurements were available, it is nonetheless possible to conservatively predict this VPL value at a given point in the future. That was achieved here without actually measuring the actual value of the error residuals, based on the fact that the measurement errors are normally distributed around the actual position according to a specified error model.

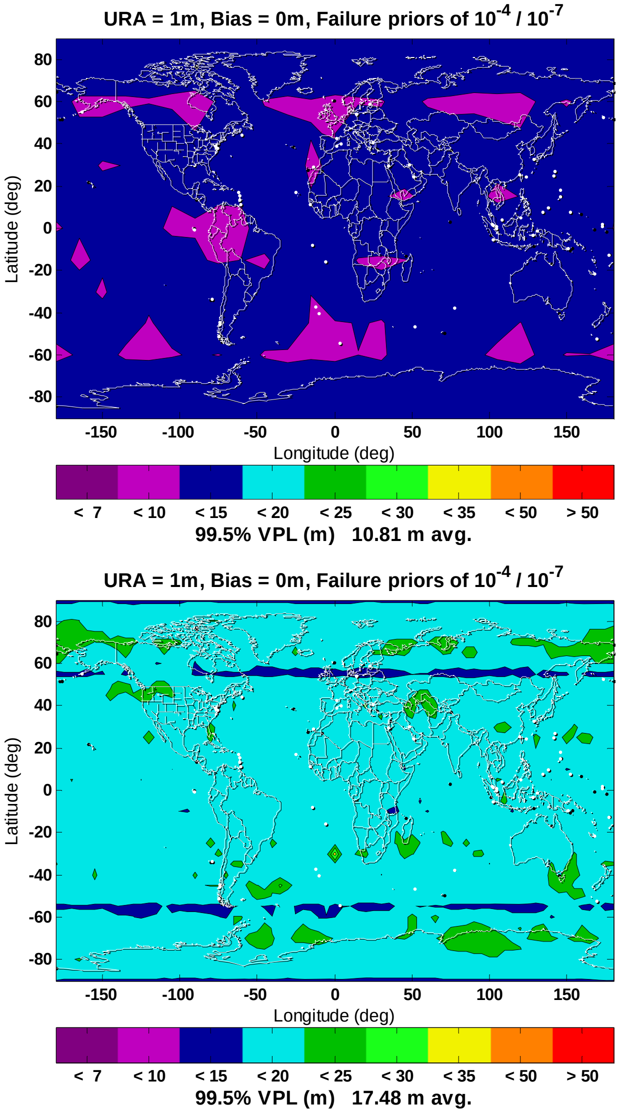

Figure 7. Dual constellation results before (top) and after (bottom) the use of the prediction algorithm.

Given a continuity requirement for the navigation solution (considered here to be 10^{-5}/approach), a corresponding uncertainty interval can be defined for the measurement errors around each partial solution, such that the continuity requirement is always satisfied. The total continuity failure budget is then split between all possible failure modes into continuity allocations, in a similar manner allocations are made for the integrity risk. Subsequently, the worst case error residual that still satisfies the continuity requirement allocation is considered for each of the partial position solutions. In other words, the statistical worst-case navigation error is considered in computing each partial VPL, before the union of all partial VPLs is taken by the same algorithm as in the case when real-time measurements were available. By this procedure, a conservative worst-case VPL is produced based only on the satellite geometry and the modeled statistics of nominal errors. It is expected that this will be an upper bound on the VPL that the user will determine in real time while performing a precision navigation operation.

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 when satellite navigation would not be able to guarantee the safety of the user throughout the planned operation. It must be mentioned that since the FDE algorithm seeks to eliminate those SVs for which the ranging errors also cause a position error to the user, it is not possible to use FDE in the absence of real-time measurements, for generating forecasted VPL values.

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 or large nominal biases 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. 7 – bottom) with the case where a failure was simulated (Fig. 4 – top), it can be seen that the prediction tool ads a layer of robustness to the WIR-SS algorithm such that even a 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.

To reveal the limitations of using WIR-SS for producing dispatch VPLs, a special case was considered where 30 active SVs are present in the modernized GPS constellation, but the Galileo constellation is not available at all (Fig. 8). It needs to be mentioned here that the current GPS constellation orbital parameters were used, which are not optimized for a 30-SV configuration, however it is not expected that optimized orbits will provide availability for a 35m VAL in the case of single-constellation RAIM. An optimized dual-frequency GPS constellation with 30 active SVs might provide the required operational availability in terms of expected value VPL given real-time measurements, but it will not be sufficient for meeting a required 35m VAL in terms of predicted performance for vertical guidance. If dispatch availability is required, then the presence of a fully operational dual constellation is much more critical than in the case when real-time measurements can be used for precise vertical guidance.

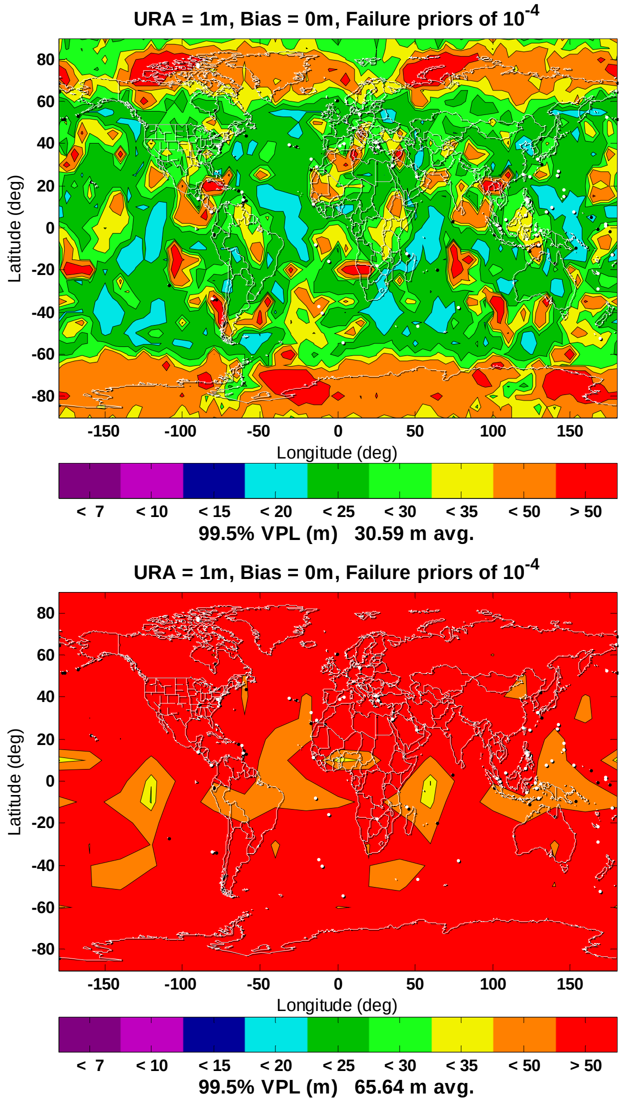

Figure 8. 30 SVs GPS constellation real-time and dispatch VPL results nominal conditions.

CONCLUSIONS ON THE USE OF RAIM FOR NAVIGATION OF CIVIL AIRCRAFT

When both the modernized GPS and Galileo constellations will be fully operational, it will be possible to implement in practice the RAIM algorithm presented in this study. Only GPS URA and Galileo SISA values are needed by the algorithm, along with a prior probability of failure for each satellite and for the constellations themselves. Any integrity flags broadcasted for either Galileo or GPS SVs will be entirely optional as long as the failure priors used are validated to be conservative, and it will be entirely at the latitude of the user whether to consider flagged satellites or not as part of their position solution aided by RAIM in real-time. 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. 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 active 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 on the average to the user.)

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.

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. 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 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.

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