On the Use of Multiconstellation-RAIM for Aircraft Approaches

P.B. Ober – *Integricom*
D. Harriman – *Lockheed Martin STASYS Ltd*

BIOGRAPHY

Pieter Bastiaan Ober obtained his PhD from the Technical University of Delft in 2003. His areas of experience include the influence of multipath on GPS positioning, carrier phase differential GPS, ambiguity resolution and in particular integrity monitoring. He has undertaken a variety of studies in the use of navigation systems for different modes of transport, has performed performance analysis studies and has designed and developed positioning and integrity monitoring algorithms.

David Harriman gained his MSc. from Cranfield University in 1993, and has since worked on civil and military aviation navigation initiatives. He has experience obtained through studies and flight trials, specialising in integrated navigation and integrity. He is a Fellow of the Royal Institute of Navigation (RIN), and serves on the RIN Council.

1. ABSTRACT

This paper deals with the question: “Under which conditions future RAIM-based GNSS (in particular using GPS and Galileo) could be used for applications beyond NPA?” It shows that some often-used reasoning about the performance of RAIM-FDE algorithms contains fundamental flaws, which may lead to overestimation of performance. Furthermore, concerns are raised about the general assumptions of single failures and normally distributed measurement errors when RAIM would be used for demanding applications such as Approach with Vertical Guidance (APV)-I or APV-II approaches.

2. INTRODUCTION

Current Receiver Autonomous Integrity Monitoring (RAIM) Failure Detection (FD) and RAIM Failure Detection and Exclusion (FDE) algorithms and specifications have been developed in the context of the SBAS MOPS [DO229] as a backup to WAAS/EGNOS, and are therefore designed in the context of using RAIM-based GNSS as a supplemental system. When these algorithms are to be used with post-Selective Availability (SA) GPS combined with signals from other constellations such as Galileo, they need to be adapted to reflect the new environment in which they operate. Furthermore, when moving towards more demanding applications such as APV-I or APV-II approaches, the use of RAIM-based GNSS will also require a more careful performance assessment than currently available for FDE. In Section 3, the paper provides a high-level description of RAIM algorithms and their operating environment. Section 4 then discusses the fundamental difference between predictive and monitoring RAIM algorithms, which is used to show in Section 5 how the performance of RAIM algorithms is often evaluated incorrectly.

The paper also discusses concerns with the modelling that is currently used to support performance assessment of RAIM in Section 6 before ending with some concluding remarks in Section 7.

3. RAIM ALGORITHMS

This section briefly discusses the main properties of the RAIM algorithms as they have been described in literature; RAIM is considered to incorporate both failure detection and failure exclusion algorithms. A list of definitions of RAIM-specific terms used here is provided in Annex A.

3.1 Traditional RAIM applications and algorithms

Most RAIM algorithms that are used operationally were developed in the second half of the 1980-s. At that time only GPS was considered, and the main application was the use of GPS as a supplementary navigation system for the en-route phase of flight. Some important characteristics of the initial operation environment for RAIM can be summarized as follows:

- only a single system, GPS, was involved and no system inter-operability issues arose;
- the accuracy of GPS was at least an order of magnitude better than was required for the envisioned application, despite the presence of Selective Availability (SA);

- under nominal conditions SA was the single one dominant error source, which allowed an easy and simple (same for all satellites) characterization of the ranging errors and their time-correlation properties;
- the ranging errors to different satellites could be considered to be essentially uncorrelated.

In continental airspace, GPS with RAIM is still almost exclusively used as a supplemental system. However, in certain areas and in oceanic airspace, GPS with RAIM can be used for en-route navigation and non-precision approaches. For more demanding applications, specific requirements and standards for RAIM-based GNSS do not exist yet. The following quote from [Brown96] therefore seems to be as valid today as when it was written in 1996: “The performance of RAIM for sole-means navigation has not been assessed as thoroughly as it has for supplemental navigation. There are two reasons for this. First, specific requirements for FDI have not been recommended by RTCA SC159 as yet. When those recommendations do arrive, it is likely that they will not be identical with those for supplemental navigation …(as) the whole RAIM specifications matter must be reconsidered for sole-means navigation”. Reconsideration is also required when RAIM is to be used for applications with high accuracy and integrity requirements, which introduces many complications that were of little relevance for the initial application of RAIM, as discussed further in Sections 5 and 6.

In the absence of SA, other satellite error characteristics need to be considered, and some of these are elevation dependent and thus different for each satellite. To cope with this effect a weighted-RAIM failure-detection algorithm has been proposed in (for example) [Walter95] and [VanGraas93]. This algorithm can be seen as a straightforward augmentation to the ‘standard’ RAIM algorithm: where the original algorithm was based on a least-squares positioning solution and failure detection based on the least-squares residuals, the new algorithm uses weighted least squares, which uses a different weighting factor for the different satellites in accordance with the varying standard deviations of signals at different elevations. However, it should be noted that further enhancements to the algorithms will be necessary to handle large constellations with different satellites (GPS, modernized GPS, Galileo), such as:

- different failure rates of different types of satellites in a mixed constellation;
- the occurrence of multiple simultaneous failures.

Furthermore, the ranging error models will have to be revised when RAIM is to be used for applications that require higher accuracies and protection levels, as will be further discussed in Section 6.

3.2 RAIM FDE algorithms

While the RTCA SC-159 decided not to propose a baseline FDE algorithm within the WAAS framework, a baseline algorithm has been developed in 1993 [Graas93][Graas96]. This algorithm attempts to find a set of redundant measurements that does not cause detection, and operates as depicted in Figure 1. Explicit identification and isolation of the malfunctioning satellite is not required. For example, when satellite 3 malfunctions and causes the FDE algorithm to correct an inconsistency, then a different set of redundant measurements must be selected such that the detection no longer occurs. Although unlikely, this new set could still include satellite 3. No action is necessary if satellite 3 was not used in the navigation solution, or if no detection occurred. While Van Graas’ algorithm was developed to use the best set of 6 satellites, its concept can easily be extended to larger subsets or an all-in-view operation. The latter all-in-view concept seems to have been adopted in many studies on the availability of RAIM for combined GPS and Galileo and by the RTCA, see for example [O’Keefe02], [WG62-07-05], [Ochieng01] and [VanDyke02]. It uses all satellites as long as there is no detected failure and falls back on the best subset without a detected failure when a failure is detected in the full set. Recent publications [VanDyke02], [Lee04b] suggest that the baseline algorithm described by Van Graas is still in use. This baseline also seems to form the basis of most of the previously performed studies into the use of RAIM for combined Galileo and GPS systems such as [Hewitson04] and [WG62-07-05] (and the studies therein described).

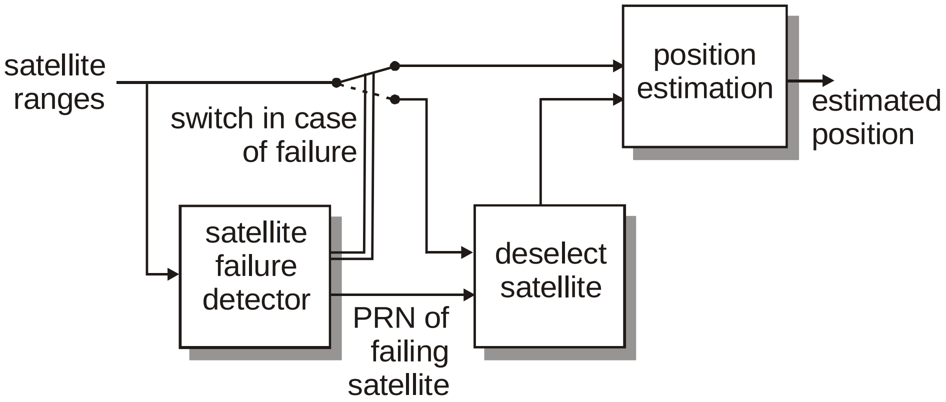

Figure 1. The operation of RAIM FDE. When a satellite is deselected after a failure is detected, the performance of the system will need to be evaluated conditionally on the fact that one of the measurements has been removed.

Two ‘different’ exclusion mechanisms exist; see for example [Lee96]:

- When there are *n* satellites in view, the first scheme searches for subsets of *n-1* satellites with no ‘detected-failure’ condition. In case of a single malfunctioning satellite, one of the subsets will not contain the failing satellite and therefore such a subset can be found with (generally) a high probability of success. It is possible that multiple subsets without a detected failure exist; in this case, one can best continue navigation using the one with the smallest test statistic, as this is the subset with the highest likelihood of excluding the malfunctioning satellite [Ober03]. In any case, the subset must offer sufficient integrity to enable further safe navigation. If required, this scheme is readily extended to exclude multiple satellites at once by also incorporating smaller subsets of n-2, n-3,…etc. satellites.

- The second mechanism uses a set of *n* test statistics that are each tuned to detect a failure on one particular satellite. The largest of these test statistics therefore corresponds to the satellite that is most likely to malfunction.

While different in philosophy, it has been shown in [Ober03, Annex C] that these mechanisms are essentially equivalent. The main difference between the methods is that the second mechanism calls for an explicit ‘exclusion threshold’, while the threshold is more implicit (and adaptive) in the first method. Because of its easy of interpretation, the ‘subset’ based scheme will be used for reference in the remainder of this report – this is also the scheme that is used for most discussions on FDE within the RTCA SC159 framework, and that has been used in many RAIM FDE availability studies.

An alternative approach called Failure Detection and Isolation (FDI) is described in literature as well. The difference with FDE is that the isolation step in FDI only excludes a satellite when the probability of one particular satellite being in failure is sufficiently high [Lee96][Zink00]. As no further navigating is allowed when isolation is not possible, FDI will have a lower availability than FDE. For that reason, FDE seems to have been generally preferred. However, the rationale behind FDI of only excluding/isolating a satellite when the probability of removing the satellite that has indeed failed is important, and the loss of this notion in many FDE studies is dangerous as it might produce overly optimistic results, as will be further discussed in Section 5.

3.3 Step detectors

In the step detector, unreasonable pseudorange differences between consecutive measurements to the same satellite are detected. This serves to monitor large changes (steps) in pseudorange measurements in consecutive samples, which indicates that a failure has occurred. Should a large step be detected, then the malfunctioning satellite will be excluded from the positioning solution.

Step detectors offer another form of an integrity check, which complements the operation of the RAIM algorithm. They are required for primary use of RAIM FDE for oceanic operations [N8110.60] and for supplementary use as a backup for SBAS systems [DO229]. Step detection can be seen as a simple ‘sanity check’ on the received measurements. It is performed before the measurements are fed into the positioning and RAIM FDE algorithms

The step detector is generally designed to detect only relatively large jumps in order not to interfere with the RAIM FDE algorithms, and to ensure that the false detection rate remains sufficiently low not to degrade system continuity [Lee96]. In the current SBAS standard, the detector only removes satellites that cause steps of at least 700 meters. RAIM will thus remain responsible for smaller steps and ramp-like errors that build up slowly, such as satellite clocks that slowly drift off.

When a satellite is excluded by the step detector, the malfunctioning satellite has been positively identified and can safely be removed from the solution. The probability of removing the wrong satellite is then virtually zero. The remainder of this paper therefore exclusively deals with the case in which the RAIM-FDE algorithm is excluding the satellite.

4. INTEGRITY MONITORING AND PREDICTION

To ensure safe use of a navigation system, it is necessary to monitor its integrity to assess the quality of the estimated position in real time: RAIM is to be declared ‘available’ only when its performance meets the continuity and integrity requirements. Real-time performance monitoring is often complemented by performance prediction, which attempts to predict whether sufficient integrity will be present to support a certain operation. Monitoring and prediction are two fundamentally different tasks: for performance monitoring, one has access to the actual measurements and real-time measurement quality information, while prediction can necessarily only rely on models. When these models contain unspecified parameters such as the failure-induced biases, one needs to make extra assumptions. To stay on the safe side, these assumptions are to be conservative to avoid that the actual performance falls short of the predicted one.

A system that exploits RAIM will only be used for an operation as long as the monitored performance indicates that there is sufficient integrity: as soon as the monitor indicates a lack of integrity, the system becomes unusable and system continuity is affected, *regardless of the predicted integrity at that time*. One can thus conclude that in order to assess RAIM availability correctly, one should therefore predict the performance that will be reported by the on-board integrity-monitoring system.

Note that the distinction between predicted and monitored performance is not currently made in most discussions on system availability and RAIM, which might be due to the fact that it was irrelevant for traditional RAIM applications that were based on failure detection only: in these baseline FD algorithms, the monitored integrity did not use measurement information but was based on two predictable quantities: the geometry and the standard deviation of the range errors. This made the predictable and the monitored performance essentially the same. However, the use of real-time information in determining the operational performance has the advantage of being potentially far less conservative [Ober03][Ene06], but their performance is relatively hard to predict in advance.

When failure detection and exclusion algorithms are considered, performance monitors will need to use real-time information, as the performance of the system will depend on the operational state of the system: it is known within the failure detection and exclusion logic whether satellites have been excluded or not from the position solution. As this is important information in assessing the actual performance of the system, it needs to be used accordingly, and using a predictive assessment of the performance may lead to wrong conclusions.

5. INTEGRITY IN FDE ALGORITHM TERMS

When using an FDE algorithm as described in Section 3, integrity is affected after a missed detection; in this case, a position failure remains completely unnoticed. Integrity is also compromised after a wrong exclusion (the detection of a failure followed by an exclusion), while a position failure remains present. To assess the integrity risk, the probability of wrong exclusion therefore needs to be considered as well as discussed further below. Finally, there also is a nonzero integrity risk in a nominally operating system, but this risk is not relevant to the discussion here and will not be further considered.

Assuming a detection is failure related, a wrong exclusion occurs whenever two conditions are simultaneously true:

- one of the subsets that still contain the malfunctioning satellite still has the smallest test statistic (A);
- the value of the test statistic in the wrongly selected subset is below the detection threshold of that subset (B).

Condition/event A has been considered in many of the early papers [Sturza90] [Kelly97] on failure isolation; the approximate probability of its occurrence is relatively simply established. Condition/event B corresponds to a missed detection in the selected subset. Its probability is readily established for a given size of the bias as well.

In terms of the above conditions, the probability of a wrong exclusion can be written as:

$$P_{WEX} = P(A \cap B)$$

Due to the fact that the events A and B are not independent, this probability is hard to evaluate. The exact influence of the exclusion part on the integrity performance is therefore difficult to assess. It is exactly this problem that Grover Brown seems to refer to when he stated in [Brown96] that “the state of the art relative to both FDI and FDE is still evolving, and it has not been decided at this time exactly what RAIM scheme will be recommended by the RTCA committee studying the matter” and “reason for lack of good performance data for FDI is that the methodology for solving the isolation half of the problem is still evolving”. It seems that not much has changed since this statement was made (1996); there still is a lack of guidance and a lack of understanding on the performance that can be obtained using RAIM FDI or FDE.

As a result, some simplifications are generally made. From basic probability theory it readily follows that:

$$P(A \cap B) \le P(A) \text{ (or } \le P(B))$$

In the earlier papers on failure isolation [Sturza90] [Kelly97], condition B is not considered and thus the following conservative bound is used:

$$P_{WEX} \le P(A)$$

The more recent failure-exclusion-based papers that are based on the baseline FDE algorithm of [Graas93] rather neglect condition A and use:

$$P_{WEX} \le P(B)$$

Note that all these quantities can be computed by prediction (based on models only) as well as being computed conditionally on the system information that is available at the time.

5.1 Integrity after an FDE exclusion has taken place

As long as no failure is detected and the full set of satellites is used in the position solution, the probability that misleading information is present is equal to the missed detection probability of the main failure detector. On the other hand, to be able to continue navigation after an exclusion has taken place, the subset that is selected should still provide sufficient integrity to the position solution. One can however not consider navigation on a subset a random event, as the performance monitor knows this is the case. *The integrity risk therefore needs to be computed conditional on the fact that a failure has been detected and a subset is selected for further navigation.*

In the case of a GNSS-only system, the integrity monitoring algorithms have no independent means to verify whether a detection is false or correct. As a result, as long as no further information is brought into the equation, they would need to assume that each satellite is equally likely to have failed. This makes the ‘a priori’ probability of seeing a failing satellite for the failure-detection algorithm in the subset equal to one for the whole constellation or approximately 1/N for each satellite, which is orders of magnitude higher than the a priori assumption for the full set (for GPS generally set to approximately 10^{-5} per hour per satellite or 10^{-4} per ‘constellation in view’, see also Section 6.2). The corresponding integrity trees are depicted in Figure 2, and illustrate this difference between the different operating statuses (‘using full set’ or ‘using subset after a detection’).

In practice, information on the probability of each satellite to have failed is present in the vector of the residuals of the position solution obtained with the full set of satellites, or equivalently in the values of the failure detection test statistics in the subsets. These residuals in fact represent the relative probabilities that a particular satellite has failed [Ober03]. In principle, this information can be used to obtain better ‘a priori’ probabilities of failure for each satellite in the subset that is used to continue navigation with. However, in the baseline FDE scheme such information is currently only implicitly exploited, while in many studies on FDE availability, its presence is completely neglected and the exclusion step of the FDE is treated in a predictive manner in which the event of selecting a subset is still considered to be random, as to be discussed next.

5.2 FDE availability

Within the more recent papers produced by (members of the) SC159 of the RTCA, as well as within many recent studies into the availability of RAIM such as [Lee99], [VanDyke01] and [WG62-07-05] and the referenced studies therein, RAIM failure detection and exclusion (FDE) is defined to be available whenever the detection function is still available after an exclusion has occurred in order to continue navigation. In terms of the discussion in the previous section, this means that RAIM is declared available whenever the protection level as computed for the subsets is smaller than the alert limit. The protection level that is largest among all subsets is sometimes referred to as the Exclusion Level (EL), which is therefore defined in a way similar to the protection level as the maximum position error that is not exceeded with some small probability while an FDE algorithm is in place [Lee96].

The papers mentioned above use the FDE algorithm as described in Section 3. In this approach, the probability of having a wrong exclusion is implicitly taken to equal the probability of missed detection in the subset that is used to continue operation with after a detected failure. While this is not explicitly stated anywhere, the protection level computations of the subsets (that is, the exclusion levels) seem to be based on the same value of the missed detection probability as for the full subset. However, due to the highly increased ‘a priori’ probability that a malfunctioning satellite is present as discussed in Section 5.1, the probability of missed detection allowed by the integrity monitor of the subset should be some orders of magnitude smaller than the probability of missed detection that was required for the full set of satellites. This implies that a really low failure-detection threshold

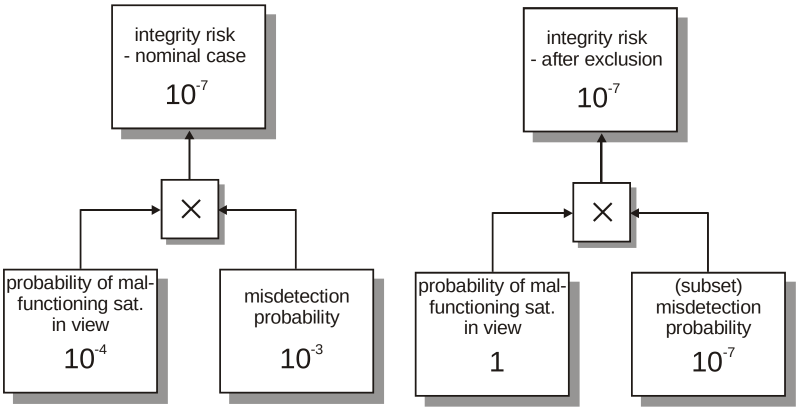

Figure 2. The integrity risk tree for RAIM when FDE is used. The two integrity risk trees correspond to the cases of nominal operation and the case in which a detection has been followed by an exclusion and the integrity of the operational subset is addressed.

is needed to maintain integrity, which would lead to a much higher false alert rate and a much lower availability of the overall system than is indicated in the previously mentioned RAIM availability studies.

One can conclude that the best-subset-selection method is unlikely to guarantee much gain over an FD-only framework as it is very hard for the system to maintain integrity once a failure has triggered a detection. To guarantee sufficient integrity without unnecessary loss of availability it will be required to use more information on the source of the failure as contained in the residuals of the position solution. When used effectively, this in fact implies that the gap between FDE and FDI will be bridged: when there are multiple subsets with a sufficiently high likelihood of being correct, this implies a large probability of picking the wrong set and integrity will only be maintained in case effectively only one of the subsets can be seen to be the failure-free one, as is exactly the philosophy behind the FDI algorithm.

6. MODELING CONCERNS

Although the baseline models as they have been discussed in this report have been used in many studies, they do have their limitations. Recently, concerns about these limitations have surfaced. The current status of these concerns is briefly discussed in this chapter.

6.1 Overbounding

In SBAS and GBAS systems, the protection level equations are related to the zero mean normal models of which the variances are provided to the user in real time. The integrity of these systems is only guaranteed when these real time models provide the user with conservative performance estimates. In technical terms, one expresses this by saying that the model distribution should over bound the actual error distributions.

Although there is currently no ‘overbounding’ concept for unaugmented GNSS, the performance of RAIM should similarly be guaranteed to be never overestimated in order to rely on its use. Currently, RAIM is only used operationally with the use of GPS as a secondary system for the en-route phase of flight. The algorithms that compute the protection level ensured by RAIM estimate the RAIM performance on the basis of range errors that are dominated by Selective Availability (SA) [DO208]. These algorithms also assume that the errors in all ranges are statistically independent, which might not be fully accurate for all error sources but can indeed be assumed in the case of a dominating SA. Because in this post-SA era the real range errors are an order of magnitude smaller, it is safe to say that the current SA-based model is definitely very conservative.

When the usage of RAIM for more demanding phases of flight is to be considered, it will be required to take the utmost care in ensuring that the models that are used to assess its performance are fully validated and guaranteed to never provide optimistic outcomes. This means that:

- it might not be sufficient to use the UDRE values that represent the accuracy of the range errors at the 95% level only; it might be required to use more conservative values to ensure an accurate computation of the protection levels;
- it can probably no longer be assumed that the ranging errors of different satellites are statistically independent, both within a given constellation or between multiple constellations.

A RAIM availability assessment based on the single failure assumption published UDRE values and the assumption of independent range errors can be expected to generate optimistic results. However, it is difficult to quantify the degree of optimism; it would probably need an extensive validation campaign in order to ensure that integrity calculations can indeed be based on these models.

The same concern holds as with the other models like that of the UDRE, such as the model for Galileo and GPS time synchronisation error: validation is required to ensure that the use of this time-offset model does not lead to an optimistic view on the actual performance.

Note that in the Galileo SoL service, the UEREs that are broadcast are defined to overbound the errors in the sense mentioned – although it is to be confirmed that the open service provides access to the same UERE values as the ones that are used for the SoL. The corresponding UDRE-values that represent GPS ranging errors after SBAS corrections have been applied are also defined in the overbounding sense. When overbounding would indeed lead to a guaranteed conservative assessment of RAIM performance, this would be a strong incentive to always include SBAS before applying RAIM.

6.2 Failure models and failure rates

As pointed out in [Lee04], the GPS SPS specifies a major system failure as the situation in which the ranging error exceeds 30 meters or 4.42 times the User Range Accuracy as broadcast by the system, whichever is greater. Such failures are specified to occur at a rate of at most 10^{-5}/hour for each individual satellite. Range errors smaller than 30 meters might occur more frequently. In both [Lee04] and [WG62-04-10] it is mentioned that the likelihood of occurrence of smaller failures than 150 meters is unknown.

While not causing problems with the current en-route applications, ranging errors between 20 and 30 meters can easily cause misleading information when protection levels of around 20 meters have to be protected as in the case of APV-I in the vertical domain, especially when they can occur simultaneously on multiple satellites. Therefore, for new applications that demand a high level of accuracy, it is insufficient to define a failure as is currently done in the GPS SPS. This implies that:

- for high-accuracy applications such as APV-I, and CAT-I, the GPS SPS definition of a failure (range error exceeding 30 m) is not suitable;
- the failure rate of the GPS SPS specifications is therefore not applicable to these high-accuracy applications as dangerous range errors might occur much more frequently.

As a result, it is probably required to take the possibility of multiple satellite failures into account. In fact, this can be seen as an alternative or an extension to the use of conservative models for the UDRE: it might be an advantage in terms of availability to use less conservative models and accept a higher failure rate and the chance of multiple failures.

In the US, investigations have been carried out to gain a better insight in the actual performance of GPS and in the effects of improved future satellite design. This so-called GPS Integrity Failure Modes and Effects Analysis (IFMEA) project has been established to identify GPS integrity monitoring requirements, examine GPS failure data in order to identify integrity failure modes, examine the causes and effects of the failures, as well as their probability of occurrence, determine the impact of integrity anomalies on users, and recommend preventive actions [VanDyke04]. The IFMEA work might provide a technical basis for future updates to the GPS SPS Performance Standards and will help develop recommendations for improvements to future GPS satellites and the operational control segment. Onboard monitoring is a key factor in meeting the current failure rate of 10^{-5}/hour per satellite. Improved monitoring on future satellites is expected to be a powerful technique to meet a (potential) future failure rate of 10^{-8}/hour per satellite [VanDyke04].

The IFMEA work has already led to a more detailed characterization of the different GPS failure modes and the probability of their occurrence, see [DO229d, App. R]. This opens the potential to design RAIM algorithms that use this information in order to optimize their performance

6.2.1 Towards new algorithms

New RAIM algorithms are currently being developed to address some of the failure-modelling concerns mentioned, see for example [Lee04], [Ene06] and [Powe06]. They tend to deal in an optimized manner with specific failure (or threat) models that are hopefully more realistic than the ones previously being used. The close correspondence between optimal algorithms and the threat models that are being used shows that, unless a standardized threat environment is agreed upon, 'the' performance of RAIM is not well defined, as it used to be in the traditional, SA-dominated operating environment. In order to compare and select future algorithms, it therefore seems to be necessary to determine a standard representative operating environment first.

6.3 Dealing with correlated error sources

Current ways to compute RAIM performance assume that the ranging errors to different satellites are independent. This used to be (approximately) true in the times that SA was the dominant error source; however, it is certainly not true for propagation delays that affect multiple satellites at the same time.

In a multi-frequency environment, the troposphere will generally be the main error source. Mismodelling of the tropospheric delays will usually cause the delays on all satellite ranges to be over- or underestimated simultaneously. This will especially impact the vertical position error due to the fact that the satellite errors won't compensate each other (as in the case in the horizontal plane) as they all influence the vertical position in the same manner and therefore a large correlation between the zenith delay error and the height error exists: [Penna01] reports a correlation exceeding 0.95. In [Collins98] the following statements can be found on the vertical position bias due to an unmodelled tropospheric range delay (in both cases using the tropospheric model from [DO229]):

- the vertical position bias approximately equals the value of the maximum delay residual over all satellites in view; generally this is the satellite with the lowest elevation angle;
- the size of the maximum bias in the computed vertical position can have values of up to 4 meters for SBAS users; errors of 5 meters are predicted by extrapolating the results obtained from measurement campaigns.

RAIM algorithms can in principle deal with highly correlated errors provided that the correlation coefficients that describe the dependencies between the different satellites are known. In that case, RAIM can accommodate for these dependencies in the measurement covariance matrix. Neglecting the dependencies between measurements can lead to an overly optimistic assessment of the performance. Taking the correlations into account correctly will lead to more realistic RAIM availability figures that will be less optimistic than the figures presented in current studies such as the studies mentioned in [WG62-07-05]. This can be explained as follows: when the dependencies are unmodelled, the tropospheric errors will cause a substantial vertical position bias while the fact that they occur on all satellites simultaneously will prevent effective detection when such an error becomes excessive.

The estimates of [Collins98] show that residual tropospheric delays have the potential to cause a vertical position bias of several meters without the guarantee that this is reflected in the failure detector's test statistic. When this effect is not mitigated by improved delay estimation techniques, this will seriously impact the possibility of performing APV-II and CAT-I operations due to their high requirements on the vertical accuracy and vertical alert limit.

Due to the high correlations, the use of more satellites will only bring a limited improvement on the vertical position bias, if any. The conclusions of GPS-based studies are therefore expected to also be largely applicable to a combined Galileo/GPS environment.

7. CONCLUDING REMARKS

Current RAIM FD and RAIM Failure Detection and Exclusion (FDE) algorithm specifications have been developed in the context of the SBAS MOPS [DO229] as a backup to WAAS/EGNOS, and are therefore designed in the context of using RAIM-based GNSS as a supplemental system.

The FD and FDE algorithms need to be adapted to take the characteristics of the post-SA range errors and the presence of different types of satellites with different failure characteristics into account. The use of RAIM-based GNSS will also require a more careful performance assessment than currently available for FDE. Unless some reliable method to assess this performance becomes available, standards for acceptable implementations of RAIM should be developed to make its application in aviation feasible. A standardized threat model would greatly help in defining such an algorithm, as it is required to allow a good comparison of the performance of different algorithms.

A widely used availability criterion for RAIM-FDE states that availability requires that the probability of missed detection should be sufficiently small in both the full set of satellites as in all subsets of satellites. However, after a failure has been detected, the missed detection probability should be several orders of magnitude smaller than during nominal operation, due to the fact that the probability that a malfunctioning satellite is present has dramatically increased. Therefore, it can be concluded that this is not an acceptable criterion when assessing the availability of RAIM–FDE-based GNSS. At this moment in time, no suitable way is available to evaluate the availability of RAIM-FDE meaningfully; the current methods are likely to significantly overestimate RAIM performance and therefore RAIM-FDE availability. To guarantee sufficient integrity without unnecessary loss of availability it will be required to use more information on the source of the failure as contained in the residuals of the position solution. When used effectively, this in fact implies that the gap between FDE and FDI will be bridged: when there are multiple subsets with a sufficiently high likelihood of being correct, this implies a large probability of picking the wrong set and integrity will only be maintained in case effectively only one of the subsets can be seen to be the failure-free one, as is exactly the philosophy behind the FDI algorithm.

For low-accuracy applications such as en-route navigation and non-precision approach NPA the distinction between 'normal ranging errors' and 'dangerous failure-induced errors' was readily made: ranging errors had to be at least an order of magnitude larger than the normally seen errors to have a significant impact on the position and bring it close to the Alert Limit (AL). This distinction is much harder to make when (much) higher accuracies are required; as a result, dangerously large errors might be much more frequent than has been assumed in many studies as they are much closer to the errors that are normally observed. At this moment in time, and especially for APV-I/II and CAT-I operations, there is insufficient clarity in the likelihood that multiple failures occur and in the exact impact of their occurrence. There is currently no validated manner of modeling the GPS and Galileo constellations, including representative threat models, to the required level of accuracy. As a result, no definite answer can yet be provided on the performance that can realistically be expected.

ACKNOWLEDGMENTS

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ANNEX A

The following list is based on [DO229] and [Lee96]. The definitions in both references are more or less the same, but vary in their level of detail and preciseness. The definitions presented here are concise versions of the definitions in these references, adapted to their application to RAIM. Definitions that are related to the vertical position error are equivalent to their horizontal counterparts and are not mentioned separately.

Horizontal Alert Limit (HAL)

HAL is the maximum horizontal position error allowable for a given navigation mode.

Horizontal Protection Level (HPL)

HPL is the horizontal position error that the FDE algorithm guarantees will not be exceeded for the fault detection function, in accordance with the missed alert and false alert requirements. It is a function only of the visible satellites, user geometry, and expected error characteristics.

Horizontal Exclusion Level (HEL)

HEL is the horizontal position error that the FDE algorithm guarantees will not be exceeded for the fault detection and exclusion function, in accordance with the missed alert and failed exclusion requirements. It is a function only of the visible satellites, user geometry, and expected error characteristics.

Positioning Failure

A positioning failure is defined to occur whenever the position solution error exceeds the applicable HPL (if the equipment is not aware of the navigation mode) or the HAL (if the equipment is aware of the navigation mode).

Alert

For the definitions of missed alert, false alert, and time-to-alert, an alert is defined to be an indication that is provided by the user equipment when the positioning performance achieved by the equipment does not meet the integrity requirements. This alert is one of the conditions that would cause a navigation alert.

False Detection

A false detection is defined as the detection (internal to the equipment) of a positioning failure when a positioning failure has not occurred.

False Alert

A false alert is defined as the indication of a positioning failure to the pilot or the FMS when a positioning failure has not occurred (a result of false detection). A false alert results in a navigation alert.

Missed Detection

A missed detection occurs when there is a positioning failure which is not detected by the FDE algorithm.

Time-To-Alert (TTA)

The time-to-alert is the maximum allowable elapsed time from the onset of a positioning failure until the equipment annunciates the alert.

Wrong Exclusion

A wrong exclusion is defined to occur when there is a positioning failure and a detection occurs, but the incorrect satellite is excluded and no subsequent detection takes place, resulting in a missed alert if the time-to-alert is exceeded. (Note: This is another term on which there has been a great deal of discussion within SC-159. Another possible definition considered was "identification of erroneous satellite upon detection of a fault"; that is, a condition in which the failed satellite remains in the solution after the exclusion operation regardless of its impact on position error.)

Incorrect Exclusion

An incorrect exclusion is defined to occur when the receiver performs a valid detection, but the failed satellite remains in the solution after the exclusion operation, regardless of its impact on the position error. An incorrect exclusion becomes a wrong exclusion only if a positioning failure results, as defined above.

Missed Alert

Positioning failures which are not annunciated (as an alert) within the time-to-alert are defined to be missed alerts.

Failed Exclusion

A failed exclusion is defined to occur when a true satellite failure is detected and the detection condition is not eliminated within the time-to-alert (from the onset of the positioning failure). A failed exclusion does not refer to exclusion of the incorrect satellite if the exclusion happens to eliminate the detection condition, thereby preventing an indication of loss of navigation.