Analysis Performed in Support of the Ad-Hoc Working Group of RTCA SC-159 on RAIM/FDE Issues

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BIOGRAPHIES

Young C. Lee is a member of the Principal Staff at MITRE/CAASD. He has been working in the area of GPS integrity since 1986, in support of the Federal Aviation Administration (FAA). He has also been actively participating in RTCA SC-159, currently serving as the secretary of the committee and as the chairman of its Ad-hoc Working Group addressing RAIM/FDE issues. He received his B.S. from Seoul National University and his M.S. and Ph.D. from the University of Virginia, all in electrical engineering.

Karen Van Dyke is a member of the technical staff with the Center for Navigation at the U.S. Dept. of Transportation Volpe Center. Karen has conducted availability and integrity studies for aviation applications of GPS for all phases of flight, including precision approach in support of RTCA SC-159. Ms. Van Dyke also was involved in a recent study of GPS vulnerabilities and interference mitigation techniques for all modes of transportation for the Office of the Secretary of Transportation. Ms. Van Dyke served as the President of the Institute of Navigation from 2000-2001. She received her BS and MS degrees in Electrical Engineering from the University of Massachusetts at Lowell.

ABSTRACT

In 1999, the FAA requested that RTCA SC-159 address one of the recommendations from the study performed by the Johns Hopkins University (JHU) Applied Physics Lab (APL) on the use of GPS and augmented GPS for aviation applications. This recommendation was to investigate methods to improve Receiver Autonomous Integrity Monitoring (RAIM) and Fault Detection and Exclusion (FDE) algorithms. In response to the FAA request, an Ad-hoc Working Group was formed within SC-159. Although this paper mainly summarizes the analyses performed by the authors in support of the Ad-hoc Working Group, it also includes deliberations with other members of the Working Group.

This paper covers five areas. First, the paper analyzes the availability of the RAIM/FDE function based on the GPS Standard Positioning Service (SPS) Performance Standard recently updated by DoD to compare the results with those obtained by the JHU/APL study. Second, alternative autonomous integrity monitoring methods are evaluated and compared with the conventional snapshot-based RAIM. Third, an investigation is performed to determine if new RAIM and FDE availability criteria that are consistent with operational requirements would provide higher availability. Fourth, the paper revisits FDE availability requirements and discusses how the requirements could be made less difficult to meet. Finally, it describes the findings of the Ad-hoc Working Group based on the GPS SPS Performance Standard.

INTRODUCTION

For the last several years, the aviation community has invested a great deal of funding and effort to transition from the current ground-based navigation and landing system to satellite-based navigation using GPS and augmented GPS in the National Airspace System (NAS). However, concerns have been expressed regarding the robustness of the satellite-based navigation system. Of particular concern is that GPS and its augmentation (e.g., Wide Area Augmentation System (WAAS) and Local Area Augmentation System (LAAS)) signals are vulnerable to intentional and unintentional interference such that safety may be compromised. In response to such concerns, the FAA, the Air Transport Association (ATA), and the Aircraft Owners and Pilots Association (AOPA) cosponsored the Johns Hopkins University (JHU) Applied Physics Laboratory (APL) to perform a study to answer the question of whether GPS and augmented GPS could be the only navigation system installed in an aircraft and the only navigation service provided by the FAA. The JHU/APL completed their study and published a report in 1999 [1].

One of the assertions made in the JHU/APL report was that stand-alone GPS cannot meet the identified requirements for navigation (except for the oceanic en route phase of flight). The assertion was made assuming a certain constellation policy, assuming that the GPS constellation has 30 satellites and assuming that GPS provides civil access to two frequencies. Based on this observation, the JHU/APL report recommended investigation searching for a “better” Receiver Autonomous Integrity Monitoring (RAIM) algorithm. To address this JHU/APL recommendation, the FAA turned to RTCA SC-159 for assistance, which, in turn, formed an ad-hoc Working Group to address the issue. While the Ad-hoc Working Group was searching for a “better” RAIM method, the group learned that the revision of the GPS SPS Signal Specification, which was to be soon published, might include changes that might have a significant impact on RAIM/FDE performance and availability. For this reason, the Working Group decided to examine the changes in the revision of the Specification when it is published and closely evaluate their implications.

This paper mainly describes the analyses performed by the authors in support of the Ad-hoc Working Group, but it also includes their deliberations with other members of the Working Group to address relevant issues. Our paper consists of five areas. First, we analyze availability of the RAIM/Fault Detection and Exclusion (FDE) function. This is because the JHU/APL assertion regarding the unaugmented GPS with a 30-satellite constellation appears somewhat pessimistic compared with the availability analyses previously conducted by others, in [2] for example. However, rather than attempting to duplicate the JHU/APL analysis and make a direct comparison, we focused on gaining a different perspective on availability results, considering factors that were not considered in the JHU/APL study, such as use of barometric altimeter aiding, a lower mask angle, and a weighted position solution. The use of weighted solutions is particularly important because with discontinuation of Selective Availability (SA), the pseudorange accuracy depends significantly on the elevation angles of the satellites and thus varies among different satellites. Second, we examine alternative autonomous integrity monitoring methods to see if any other methods can be more effective than conventional RAIM, which is based on a consistency check among all subset solutions using only the current measurements (snapshot). Third, in an attempt to find a way to obtain higher availability, we investigate new RAIM and FDE availability criteria consistent with operational requirements. Fourth, we revisit the FDE availability requirement of 0.99999, which was assumed in the JHU/APL study, and discussed what could be done to make it less difficult to meet the FDE availability requirement. Finally, we discuss what the Ad-hoc Working Group discovered in the recently published GPS SPS Performance Standard [3], which had replaced the GPS SPS Signal Specification [4].

The next five sections address each of the above five areas. The last section summarizes the report.

ANALYSIS OF RAIM/FDE AVAILABILITY

The results of our RAIM/FDE availability analysis are contained in Appendix C. This section summarizes the results after examining assumptions that affect the results of the analysis.

Assumptions Affecting the Results of RAIM/FDE Analysis

Results of RAIM/FDE availability depend significantly on assumptions regarding the following factors:

- Satellite constellation (total number of satellites, orbital positions)
- Satellite failure and restoration statistics
- User-Equivalent-Range-Error (UERE) and RAIM/FDE for a weighted position solution
- Mask angle
- Barometric altimeter aiding

Each of these factors is discussed below.

Satellite Constellation (total number of satellites, orbital positions)

In our analysis, the following three satellite constellations have been considered:

- The Optimized 24 constellation, which is described in RTCA DO-229 (WAAS MOPS) and is the baseline for RTCA SC-159 availability analyses.
- The Optimized 24 constellation plus the two INMARSAT geostationary (GEO) satellites, which will be used for WAAS and have a GPS ranging signal (POR at 178^o E, and AOR West at 54^o W).
- A 30-satellite GPS constellation in six orbital planes proposed by Boeing [5].

Availability can change significantly, not only with the total number of satellites, but also with the satellite positions.

Satellite Failure and Restoration Statistics

There are two approaches with regard to an assumption on satellite availability in RAIM/FDE availability analysis. One approach is to assume certain satellite failure and restoration statistics. The JHU/APL analysis took this approach. The other approach is to assume that a fixed number of satellites are out of service and the rest of the satellites are operating at 100 percent. Our analysis adopted this second approach.

Previously, an official Department of Defense (DoD) position on satellite availability was that they would guarantee 21 satellites to be available with 98 percent probability [6]. The recently published GPS SPS Performance Standard states that 24 operational satellites must be available on orbit with 95 percent probability; however, an "operational satellite" is defined in that document as "a satellite that is capable of but is not necessarily transmitting a usable ranging signal." The document also states that "At least 21 satellites in the 24 nominal plane/slot positions must be set healthy and transmitting a navigation signal with 0.98 probability." For this reason, our analysis assumes up to 3 satellites out of service out of 24 in the constellation.

User-Equivalent-Range-Error (UERE) and RAIM/FDE for a Weighted Solution

When SA was the dominant error source, other error terms that heavily depend on the elevation angle were negligible. For this reason, the RAIM/FDE availability analysis for the case with SA typically assumed a fixed UERE value of 33.3 m for all satellites regardless of the elevation angles. Now that SA has been discontinued, errors that depend on the elevation angles make UERE values for each satellite significantly different. However, analyses conducted by others have used a fixed value even for the case without SA. Moreover, those analyses have developed different error budgets for the case without SA, resulting in a wide range of UERE values; for example, 12.5 m was used in the WAAS MOPS [7], while 7.5 m was used in the JHU/APL report [1]. A more accurate navigation solution requires proper weighting (or deweighting) of individual satellite range measurements, and weighting also should be used in the RAIM/FDE algorithms. The formulas used to calculate UERE are described in Appendix A. The formulas used to determine RAIM/FDE availability are described in Appendix B.

Mask Angle

With a lowered mask angle, more satellites are visible in general, and this, in turn, brings higher RAIM/FDE availability, as shown by the results of this paper. This is the reason that in the relatively benign environment of oceanic and remote operations, a mask angle of 2^o is recommended [8]. While a 5^o mask angle is typically assumed, a mask angle much lower than 5^o is likely to significantly increase susceptibility to multipath interference or errors caused by atmospheric effects that could cause a hazard in operations other than the oceanic en route phase. For this reason, mask angles of 5^o and 2^o have been considered in our analysis. One thing to note is that none of these formulas used to compute UERE has been validated for elevation angles below 5^o.

Barometric Altimeter Aiding

While barometric altimeter aiding was not assumed in the JHU/APL report, it can be implemented without significant cost or complexity and can bring significant improvement in availability for stand-alone GPS [9]. This is the reason that barometric altimeter aiding was initially required in Technical Standards Order (TSO)-129 for supplemental use of GPS [10]. In our analysis, the standard deviation of the barometric altimeter measurements (with GPS calibration when required) was assumed to be 50 m for nonprecision approach phase of flight and 300 m for all of the other phases of flight. These values are consistent with RTCA DO-229 (WAAS MOPS) Appendix G [7].

RAIM/FDE Availability Analysis

An analysis to examine the availability of RAIM and FDE with SA removed was conducted.

Parameters

The parameters used for the analysis are the following:

- Worldwide grid ranging from -90^o Nto 90^o N (latitude) and from 180^o W to -175^o W (longitude) sampled every 5^o in latitude and longitude
- Time interval: 5 minutes over a 24-hour period
- Mask angle: 5^o and 2^o
- Constellation:
  - **GPS:** The full 24 GPS satellite constellation, as well as with satellites removed from service. The satellites taken out of service were chosen to be *worst* satellites for RAIM availability with the Optimal 24 Constellation [11]. The *worst* one satellite was #15, the *worst* two satellites were #10 and #15 and the *worst* three satellites were #8, #10, and #15. As a point of comparison, "best" and "average" case failures also were examined.
  - **GEO:** The two satellites used for WAAS and visible over CONUS (AOR-W and POR) used as additional ranging sources.
- Phase of flight:
  - Nonprecision approach (NPA)
  - Terminal
  - Domestic en route
  - Oceanic en route
- With and without barometric altimeter aiding
- Output
  - Minimum availability: availability at the location experiencing the most RAIM outages

- – Average availability: availability determined by averaging the availability across all of the grid locations
- – Maximum outage duration

Summary of Results

While all the results are tabulated in Appendix C, they are briefly summarized below:

- The use of barometric altimeter aiding significantly increases RAIM availability and thus reduces the maximum RAIM outage duration almost by a factor of three (Table C-2 and Table C-4). Figure 1 graphically demonstrates the availability of RAIM for NPA with the 23-satellite constellation (SV #15 out of service). The maximum outage duration in minutes at each location is shown in the figure. The availability plot was generated by the RAIM Graphical Information System (RGIS) software tool that the Volpe Center developed for DFS Deutsche Flugsicherung in Germany. However, even with the use of barometric altimeter aiding, there can still be significant RAIM outages when multiple satellites are taken out of service (Table C-3).
- Reducing the mask angle increases the number of visible satellites, which in turn will increase availability as shown in Tables C-5 and C-6 for a mask angle of 2^{o}. However, satellites at low elevation angles are more susceptible to atmospheric effects and multipath and are deweighted accordingly as discussed in Appendix A. One thing to note is that the ionospheric and tropospheric models used to compute the UERE have not been validated for elevation angles below 5^{o}. For this reason, the results for a mask angle of 2^{o} should be interpreted with caution.
- Since FDE requires one additional measurement, the availability is significantly lower than for RAIM (Table C-7 and C-8). Even with all satellites operational, FDE outages can be greater than an hour and a half at a location.
- A 2^{o} mask angle substantially increases FDE availability, but still does not provide 100 percent FDE availability for any phase of flight (Table C-9). Although not shown in Appendix C, availability was also analyzed with a 30-satellite constellation and a 5^{o} mask angle. The analysis shows that a 30-satellite constellation with all 30 satellites operating (i.e., actively transmitting) with barometric altimeter aiding does provide 100 percent availability for all phases of flight, even under single frequency assumptions. However, the assumption that all 30 satellites are operating is much more optimistic compared with the 30-satellite constellation assumed in the JHU/APL report in which the availability of operating satellites is governed by some fixed satellite failure and restoration rates. It should be noted that in order to have 30 operating satellites on the average, significantly larger number of satellites must be maintained.
- Since TSO C145/146 receivers can use the WAAS GEO satellites for ranging, these satellites can be used as an additional ranging source to improve RAIM/FDE availability. In this case, the availability

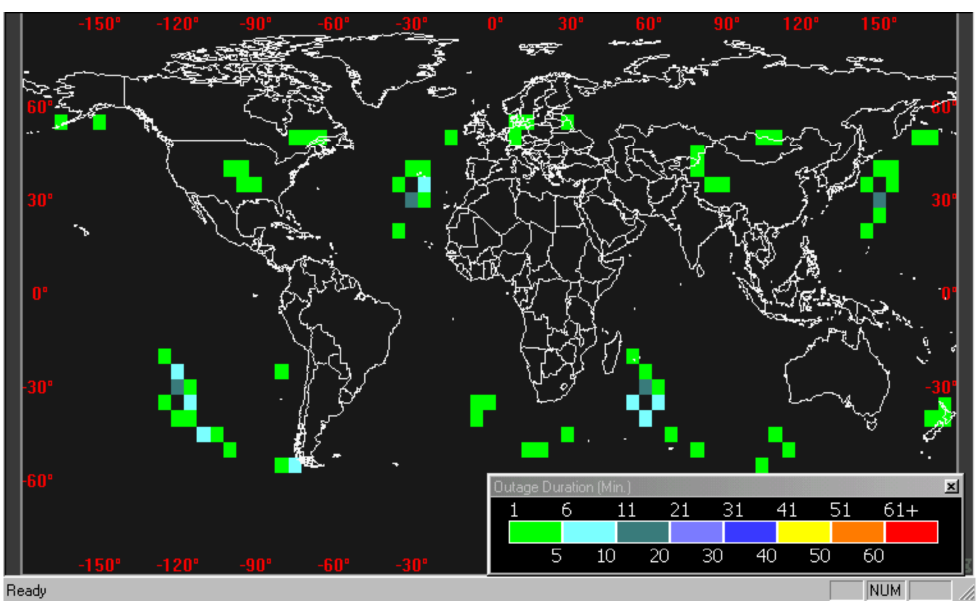

Figure 1—Maximum RAIM Outage Duration NPA RAIM with Barometric Altimeter Aiding (GPS Constellation with SV#15 Out of Service)

of RAIM even without the use of barometric altimeter aiding is fairly high (Tables C-12 and C-13). In fact, the use of the GEO satellites improved availability even more than incorporating barometric altimeter aiding. In the future, it is expected that there will be additional GEO satellites visible from CONUS to support WAAS, and ranging signals from other satellite-based augmentation systems such as EGNOS also can be used to further increase availability.

- Availability for FDE dramatically improves with the combined use of the GEO satellites with barometric altimeter aiding (Tables C-14). However, the maximum outage duration can still be long (Table C-15) and widely varies over location as shown in Figure 2 for NPA FDE outages over CONUS with all 24 GPS and the two GEO satellites operating and barometric altimeter aiding. An additional GEO satellite over CONUS would help reduce the outages that occur in the middle of the country.
- It should be noted that RAIM/FDE availability results presented in this paper are not as optimistic as those previously presented with SA turned off in [12] for example. There are two reasons for it. One is that our analysis is based on a weighted position solution. The other reason, which is probably a bigger factor, is that in our analysis, UERE values were derived from the new SPS Performance Standard, which guarantees URA (satellite clock and ephemeris accuracy) of 6 m. In contrast, previous analyses typically used a URA value of 3 m or less.
- In summary, with SA removed, 99.998 percent RAIM availability can be achieved for NPA and 100 percent availability for the other phases of flight with a 24-SV constellation and all satellites operating with use of barometric altimeter aiding and a 5^{o} mask angle. Also, this availability requirement can be met through the use of GEO satellite ranging with a 5^{o} mask angle and no barometric altimeter aiding if all GPS and GEO satellites are operating. This analysis also has demonstrated that high availability for FDE can be difficult to achieve, but 99.999 percent FDE availability can be achieved for stand-alone GPS for all phases of flight with a 30-satellite constellation with all 30 satellites operating and SA off, even without access to dual frequency. However, as noted above, significantly more than 30 satellites must be maintained in order to have 30 operating satellites on the average.

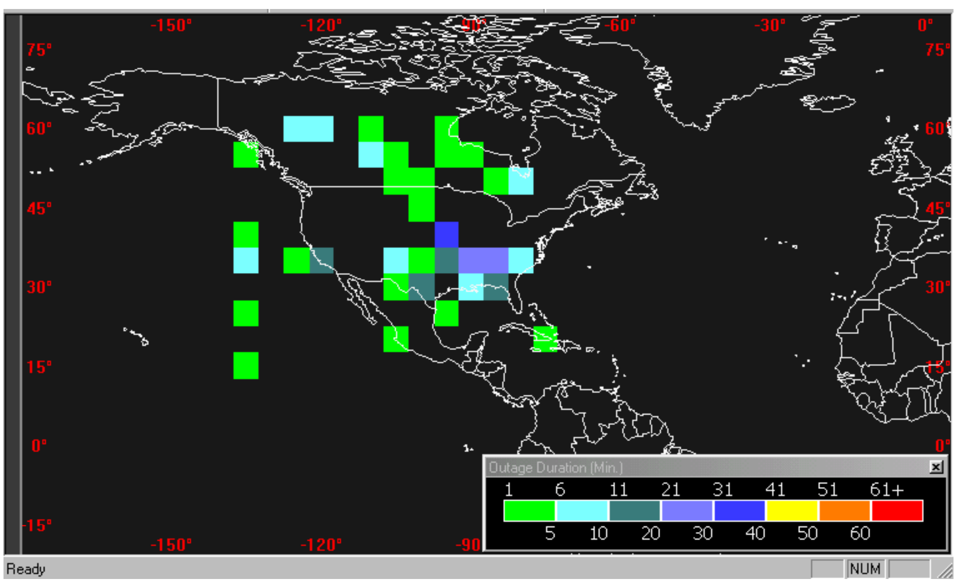

Figure 2—Maximum Outage Duration of NPA FDE with 24 GPS Satellites, Two GEO Satellites and Barometric Altimeter Aiding

ALTERNATIVES TO CONVENTIONAL RAIM

As stated earlier, the JHU/APL report recommended investigating ways to improve RAIM, implicitly suggesting a Kalman filter-based method. Such a method differs from conventional RAIM in that they use past measurements as well as current ones. Two such methods previously proposed have been considered: one is a multiple hypothesis tester using a bank of Kalman filters, and the other is a moving average filter RAIM. These will be discussed after a brief discussion of conventional RAIM.

Conventional RAIM

Conventional RAIM is based on a consistency check among current pseudorange measurements from different satellites. The thresholds are set such that a false detection will not occur more often than some specified rate. It is guaranteed that any position error exceeding some specified protection level will be detected with a 99.9 percent probability regardless of which satellite is faulty and what the fault signatures are like. With this 99.9 percent probability, along with the latent GPS satellite failure rate of 10^{-4}/hr, the integrity requirement of 10^{-7}/hr can be met.

In the implementation of conventional RAIM, a Kalman filter may or may not be used to process the satellite range measurements before they are used for RAIM/FDE decision and for position solution. Either way, RAIM/FDE availability basically remains the same.

Multiple Hypothesis Tester

This Kalman filter-based autonomous integrity monitoring method was proposed at the same time as a snapshot-based RAIM algorithm was first introduced [13, 14]. In this method, a bank of Kalman filters is used as a multiple hypothesis tester, where one hypothesis is assigned to each fault mode and another is assigned to a "no fault" condition. While the analysis in [14] limited the fault signature to a deterministic ramp with slope and a bias as its two variables, fault signatures of any other forms may also be considered.

The analysis in [14] showed that this multiple hypothesis tester is quite effective in both detecting and identifying the faulty satellite for those faults whose signatures are considered in the design of the bank of Kalman filters. However, for faults that are not considered in the design, the required level of integrity performance cannot be guaranteed. Because not every type of fault can be predicted and considered in the design, this method cannot meet the integrity requirement.

Moving Average Filter RAIM

Recently, a RAIM concept using a moving average filter has been published [15, 16]. This RAIM forms a test statistic by taking the moving average of the measurements including past measurements as well as the current ones. While the authors of these papers claim that fast fault detection is possible with the proposed method, the performance of this method depends on the fault signatures like the Multiple Hypothesis Tester.

Based on these observations, it is concluded that there is no autonomous integrity monitoring method better than conventional RAIM in order that the required integrity performance may be guaranteed regardless of the fault signatures.

EXAMINATION OF NEW CRITERIA FOR RAIM AND FDE FUNCTION AVAILABILITY

It has been observed that the current criteria for RAIM and FDE function availability might be more conservative than necessary to support operational requirements. This observation led to an investigation to see if high availability could be obtained by using new RAIM/FDE availability criteria that would still support the operational requirements. Although this investigation was previously published by one of the authors [17], it is summarized below because it is directly in line with our search for "better" RAIM methods. Our analysis will start by reviewing the current criterion for RAIM availability. Following this review is a description of the newly proposed criterion and the results for RAIM availability that could be obtained by implementing this new one over the current one. A similar analysis follows for the FDE criterion.

Current Versus New RAIM Availability Criterion

In order to understand why the current RAIM availability criterion was believed to be more conservative than necessary, we need to understand how RAIM works. This can be explained using Figure 3, which plots the position error against the test statistic. It shows typical variation of the pair of the position error and test statistic when each of the satellites fails with an increasing PR error magnitude. The pair follows more or less a straight line, slightly perturbed from it because of the presence of relatively small errors on the other healthy satellites. The slope depends on the user-to-satellite geometry and on which satellite has the dominant error (e.g., satellite j vs. satellite k in Figure 1). The objective of RAIM is to declare a fault detection, which occurs when the test statistic exceeds the detection threshold, before the position error exceeds the selected position error limit. Note that the fault of a satellite associated with a higher slope is more prone to a missed detection because it follows a path close to the missed detection region. Therefore, the probability of detection changes depending on which satellite is faulty.

RAIM defines horizontal protection level (HPL), which RAIM guarantees will not be exceeded by the position error caused by any satellite fault. If the position error exceeds HPL, it will be detected with a probability of at least 0.999. RAIM calculates HPL based on the maximum slope ($SLOPE_{MAX}$) assuming that a latent failure is always on the satellite whose failure is the most difficult to detect. On the other hand, for satisfactory navigation, the user position error shall not exceed the

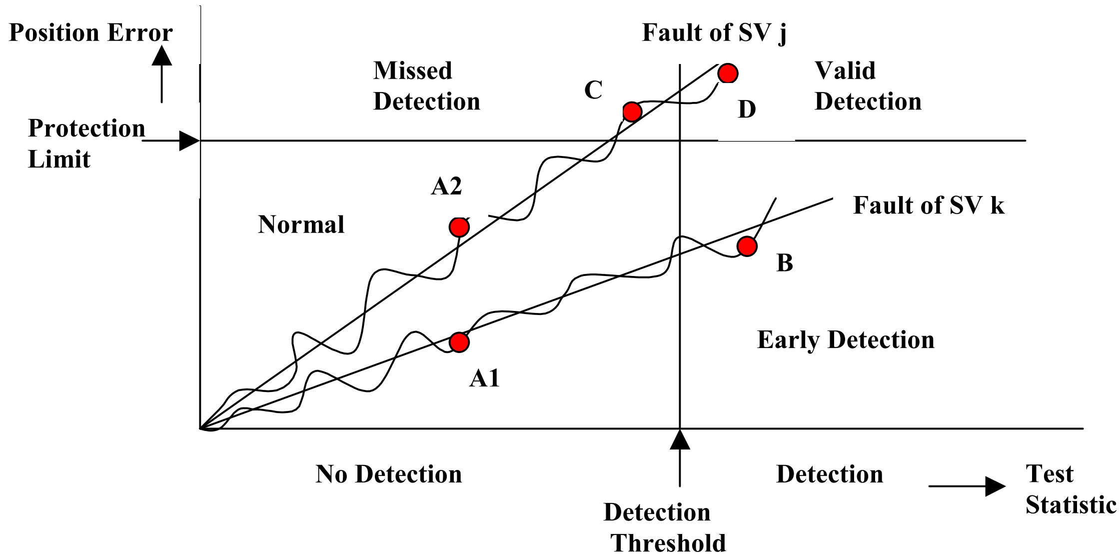

Figure 3—Illustration of Receiver Autonomous Integrity Monitoring (RAIM) Performance

horizontal alert limit (HAL) for a given mode of operation, which is 2 nmi, 1 nmi, and 0.3 nmi for en route, terminal, and NPA mode, respectively. If HPL for the user-to-satellite geometry is smaller than HAL for the given mode of operation, RAIM is available.

The assumption for RAIM that the latent failure would occur on the most-difficult-to-detect satellite ensures that a fault is detected at least with a 0.999 probability regardless of which satellite has failed. However, the assumption appeared unnecessarily conservative because when the user is navigating with a set of GPS satellites, it is not known which satellite could fail, if any one fails. It appears more reasonable to assume that failures are equally likely instead. Therefore, a new RAIM availability criterion can be set as follows: RAIM is available if the detection probability averaged over the satellites exceeds 0.999, and vice versa. Figure 4 shows an example case in which RAIM is not available according to the current criterion but is available according to the new criterion.

In order to see how much RAIM availability would improve, the new availability criterion has been analyzed and compared with the current criterion. The results are shown in Figure 5. The results are for RAIM availability averaged over eight representative locations in CONUS assuming SA is off. For the Optimized 24 constellation, availability is considered with the *worst* one satellite out of service (23 satellites are operating) and the *worst* three satellites out of service (21 satellites are operating).

Figure 5 shows that the availability improvement is not as significant as was expected. This was puzzling at first. However, with a little investigation, the reason was found from the following observation.

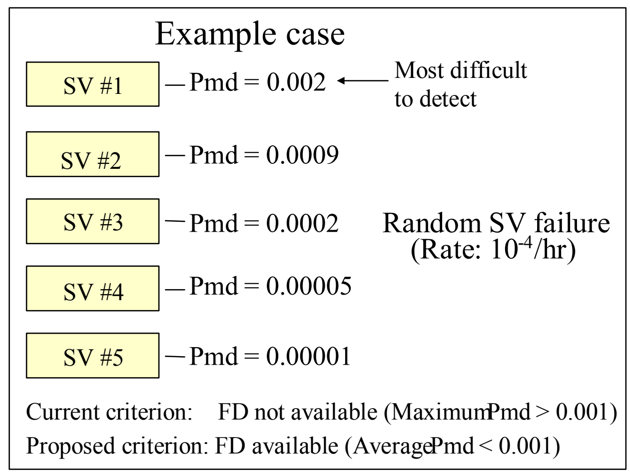

Figure 4—An Example Giving Different RAIM Availablity Decisions

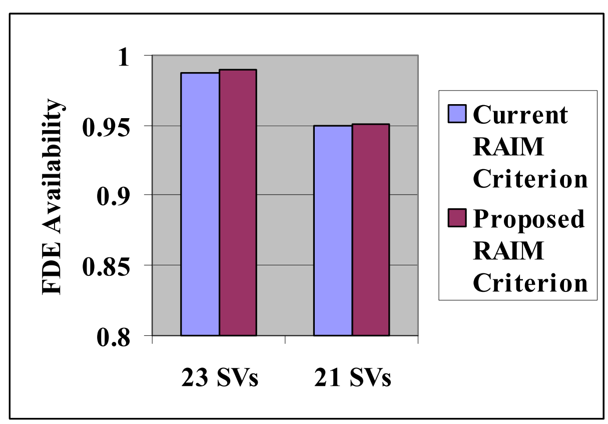

Figure 5—Availability of RAIM (FD) with the Current and New Criterion

The improvement in RAIM availability is obtained from those geometries for which $SLOPE_{MAX}$ is slightly larger than the threshold slope so that the probability of missed detection (P_{md}) for the hardest-to-detect satellite is larger than 0.001 but still small enough so that the P_{md} averaged with the other P_{md} values would remain less than 0.001. It is observed, however, that even if $SLOPE_{MAX}$ is larger than the threshold slope by 10 to 20 percent, the P_{md} for the detection of the hardest-to-detect satellite would quickly increase from 0.001 to, say, 0.01. This is because we are dealing with the tail end of a statistical distribution. Even if the P_{md} for the hardest-to-detect satellite is exactly 0.01, it is not possible to obtain an averaged P_{md} less than 0.001 when the number of satellites used for navigation is 10 or fewer.

Current Versus New FDE Availability Criterion

In order for GPS to be used as the only navigation system in an aircraft, mere detection of the presence of a fault is not sufficient. Upon detection of a fault, the satellite that is believed to be faulty should be excluded for continued navigation, which then relies on the remaining healthy satellites.

While there exist a few different variations, the FDE operation essentially works as follows for all. Upon detection of the presence of a fault, one satellite at a time is taken out, and the test statistic for each subset is tested against a detection threshold. Ideally, if one satellite is bad, all subsets except for the subset excluding the bad satellite will have test statistics large enough to cause an alarm condition. Therefore, the satellite that is missing in the subset with the smallest test statistic is identified as the satellite that is faulty.

The current FDE availability criterion is illustrated in Figure 6. According to the current criterion, FDE is available only if RAIM is available for every subset, where RAIM function availability is defined on the basis of the assumption that the satellite that fails is always the one that is the most difficult to detect as discussed earlier. As shown in Figure 6, we are actually making the *worst case* assumptions for two failures in a row. By requiring that every subset has to have RAIM available, we are assuming that the exclusion of a failed satellite would always result in a subset least likely to have RAIM (i.e., a subset with the largest $SLOPE_{MAX}$). Then, regardless of which satellite has been excluded, we again assume the latent failure of the hardest-to-detect satellite in that remaining subset in the availability decision. Because the outcome of which satellite would fail cannot be predicted and thus is randomly decided, this current criterion appears to be unnecessarily conservative. Based on this observation, a new FDE availability criterion is proposed as follows.

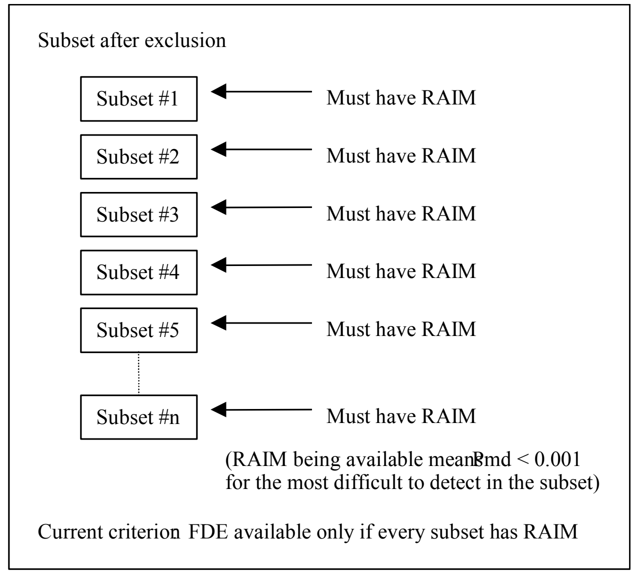

Figure 6—Current Fault Detection and Exclusion (FDE) Function Availability Criteria

As can be seen in Figure 6, each subset would have a set of (N-1) P_{md} values, each of which is associated with the latent failure of a satellite in that subset. Therefore, we deal with a total of N(N-1) P_{md} values. Two different approaches to a new criterion were considered. One is to assume that both the initial exclusion and the subsequent detection would all be randomly decided. In this case, an average P_{md} is obtained from all of the N(N-1) P_{md} values, and FDE is declared available if the overall average P_{md} is less than 0.001. The second approach is to assume that the exclusion of a failed satellite would result in a subset least likely to have RAIM, but the satellite that may subsequently fail would be randomly decided. When the average of all post exclusion P_{md} within this *worst case* subset is less than 0.001, the FDE function is declared available. Between these two alternative approaches, the second is chosen to assure continued navigation regardless of which satellite fails. In order to see how much FDE availability would improve with the new criterion, availability has been analyzed and shown in Figure 7. Again, the figure has been obtained for the same set of locations and same set of constellations as for Figure 5.

As was the case with the RAIM function, Figure 7 shows that with the new criterion, FDE availability improves but only slightly. The improvement, which is less than expected can be explained with similar reasoning as for the less than expected RAIM availability improvement.

FDE AVAILABILITY REQUIREMENT

The JHU/APL report asserts that stand-alone GPS cannot meet requirements for navigation (except for the oceanic en route phase of flight) if GPS is the only navigation service provided by FAA and is the only navigation

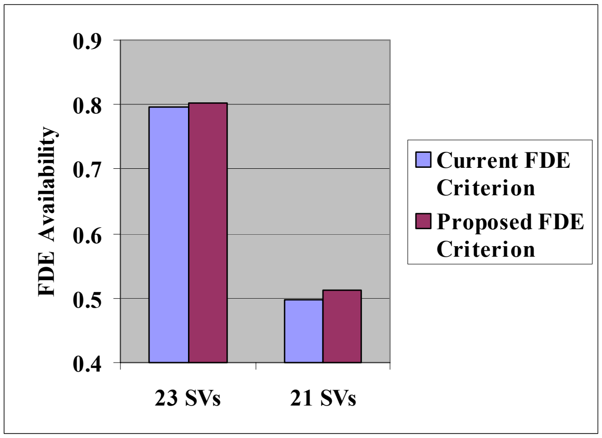

Figure 7—Availability of Fault Detection and Exclusion (FDE) with the Current and New Criteria

system installed in an aircraft. The assertion was made assuming a certain constellation policy, assuming that the GPS constellation has 30 satellites, and assuming that GPS provides civil access to two frequencies. That assertion is based on an assumption that both RAIM and FDE must have an availability of 0.99999. It is quite difficult to attain 0.99999 availability especially for FDE, with the satellite failure rates and the constellation size to which DoD has thus far committed.

If FDE is available, it allows continued navigation in the presence of a satellite failure (hard or soft). Therefore, the FDE availability requirement is closely coupled with the continuity requirement. However, the continuity requirements for stand-alone GPS and FDE availability requirement were never clearly established. In order to properly establish these requirements, it is necessary to know how wide the impact of a failure causing a loss of continuity could be and how much impact on traffic can be tolerated when GPS is used as the only navigation system required in the avionics and the only navigation service provided by the FAA. Because this kind of data is not available, a conservative value of 0.99999 has been used as the FDE availability requirement. The Ad-hoc Working Group discussed two ideas as a means to alleviate the problem.

One was a scheme proposed by Bruce DeCleene of the FAA Aircraft Certification Service. In this scheme, FDE may not be required to be available for NPA under two conditions: (1) RAIM is available for the approach, and (2) FDE is available for terminal area navigation [18]. Upon detection of a fault during approach, the aircraft executes a missed approach, continues flight in terminal airspace and, depending on the duration of the FDE outage, the aircraft can proceed to the destination airfield when FDE is available for NPA or can fly to an alternate airport that either is unaffected by the GPS fault or has a non-GPS navaid. Because sufficiently high FDE availability is most difficult for NPA, such a scheme would enhance the possibility for stand-alone GPS to meet the identified requirements. However, the concept proposed here is still preliminary and requires further investigation with regard to its operational implications.

The other idea is based on an observation that it could be made less difficult to meet the FDE availability requirement if the satellite failure rate can be reduced. If detection of a satellite failure occurs (whether hard, soft, or false) and FDE is not available, either the isolation of the bad satellite is not possible or the integrity monitoring function (i.e., RAIM) is not available with the remaining satellites. Both of these events lead to loss of continuity where navigation cannot be continued with the integrity monitoring function. It is noted that in order for loss of continuity to occur, two events must occur at the same time: 1) a satellite failure detection and 2) FDE function being unavailable. The false detection rate is usually negligible compared with true failure rates. Therefore, if the satellite failure rate (combination of both the latent and hard failure rates) can be significantly reduced, the FDE availability requirement can be reduced correspondingly to meet the same level of continuity. For example, if the satellite failure rate can be reduced to a level equal to the allowable average probability of loss of continuity, then the continuity requirement can be met without requiring the FDE function altogether. However, as discussed earlier, the continuity requirement itself has not been well established for the identified operational use of stand-alone GPS. For this reason, this idea also needs further investigation particularly because the DoD is not yet ready to commit to a reduced satellite failure rate, as will be discussed in the next section.

It should be noted that with a reduced latent satellite failure rate, it also becomes easier to meet the FDE availability requirement because higher FDE availability can be attained. This can be explained as follows. The probability of missed detection (P_{md}) requirement of 0.001 was derived by dividing the Hazardously Misleading Information (HMI) probability requirement of 10^{-7}/hr (integrity requirement) by latent GPS satellite failure rate of 10^{-4}/hr. The latent failure rate was established on the basis of the GPS major satellite service failure rate specified in the GPS SPS Signal Specification [4]. (The same frequency of GPS integrity anomalies is specified in the GPS SPS Performance Standard [3], which replaces the Signal Specification.) It is stated in [4] that there can be up to three major service failures per year over the constellation, where a failure is qualified as latent, i.e., causing a PR error larger than 150 m (this value has been revised to 30 m in the recently published GPS SPS Performance Standard [3]) that goes unannounced per constellation per year on average. This corresponds to a failure rate on the order of about 10^{-4}/hr, assuming that the number of satellites in view of a user is typically 8. If the rate is reduced by a factor of 10, for example, the P_{md}

requirement of 0.01 would be sufficient to meet the same level of integrity requirement, namely 10^{-7}/hr. With the reduced P_{md} requirement, RAIM is more likely to be available for a given geometry, and higher RAIM availability can be attained, in general. Because FDE is defined to be available when RAIM is available for every subset of satellites and RAIM is more likely to be available for each subset, FDE is more likely to be available with the reduced P_{md} requirement.

REVIEW OF GPS SPS PERFORMANCE STANDARD

After SA was turned off in May 2000, a joint DoD/DOT Working Group was formed to revise the GPS SPS Signal Specification [4]. At the beginning, the DoD/DOT Working Group discussed the possibility of making changes for significant reduction of the latent failure rate, increased satellite availability, and the like. Because such changes could have a significant impact on RAIM/FDE performance and availability requirements, the Ad-hoc Working Group decided to postpone the finalization of its report until the updated SPS Signal Specification was published. However, DoD decided not to change the maximum latent failure rate they would guarantee. Apparently, their decision was based on the following:

- First, they redefined a major service failure from a latent failure causing a pseudorange error exceeding 150 m to a latent failure causing a pseudorange error exceeding 30 m. While this may have been readily possible with the discontinuation of SA, it might be more difficult to protect against smaller error threshold.
- Second, while the satellites have been much more reliable than expected, there is no contractual requirement for Block IIR and IIF satellites that guarantees a satellite failure rate below some specified level.

Besides the satellite failure rate, the Ad-hoc Working Group carefully reviewed the GPS SPS Performance Standard finally published in October 2001 [3] to determine if there were any changes that could impact RAIM/FDE performance and availability, such as increased satellite availability numbers. The Working Group identified some issues on some of the changes they made, as described below:

- The document states, "A HMI event occurs when the Signal In Space (SIS) User Range Error (URE) is greater than 30 meters (which was 150 m in [4]) while the satellite is set healthy but the User Range Accuracy (URA) multiplied out to 4.42 standard deviations is less than 30 meters." It is not clear, however, what happens if 4.42 times URA exceeds 30 m. The Performance Standard seems to imply that if 4.42 times URA exceeds 30 m, the satellite should not be used. However, there currently exists no requirement for GPS receivers to do that. For this reason, such an event might have serious integrity and safety implications for civil users.
- The document states, "In support of the service availability standard, 24 operational satellites must be available on orbit with 0.95 probability (averaged over a day)."

  In an appendix, an "operational satellite" is defined as a satellite that is capable of but is not necessarily transmitting a usable ranging signal. This means that an "operational satellite" may or may not be "operating" and providing SPS signals. The statement is confusing because it does not state how long a satellite needs to be in a non-transmitting (non-operating) state before it is no longer considered to be an operational satellite. It is also not clear whether the statement that refers to the 24 operational satellites means 24 satellites in the nominal plane/slot positions or it refers to the total number of satellites in the constellation including those that are not in the nominal plane/slot positions.
- It is also stated, "At least 21 satellites in the 24 nominal plane/slot positions must be set healthy and transmitting a navigation signal with 0.98 probability." This is similar to the previous DoD position published in [6] that they would provide at least 21 satellites in the 24-satellite constellation with 98 percent probability except that the revision states that it will maintain 21 or more satellites in the nominal slots.

As a result of these concerns, RTCA sent a letter to DoD asking for clarification on these issues in January 2002.

SUMMARY AND CONCLUSIONS

This paper documents an analysis performed to support the Ad-hoc Working Group of RTCA SC-159, whose objective was to address the recommendation in the Johns Hopkins University (JHU)/Applied Physics Lab (APL) study calling for an investigation to search for a more effective RAIM algorithm. The five areas of investigation reported in this paper along with a conclusion for each are summarized below.

- Availability of Receiver Autonomous Integrity Monitoring (RAIM)/Fault Detection and Exclusion (FDE) function has been analyzed. At first, the assertion in the JHU/APL study appeared somewhat pessimistic by claiming that—even with a 30-satellite constellation, SA off, and access to dual frequency—stand-alone GPS cannot provide the capability required as the only navigation system installed in an aircraft and the only navigation service provided by the FAA for any phases of flight other than the oceanic phase. However, a 99.999 percent availability requirement is very difficult to achieve for FDE and, although our analysis does not duplicate the JHU/APL analysis, it does appear that the results without the use of barometric altimeter aiding are similar to what they obtained. Our analysis focused on the impact of taking the *worst* satellites out of service plus considered factors that were not considered in the JHU/APL study such as use of barometric altimeter aiding, a lower mask angle, and a weighted solution. The use of weighted solutions is particularly important because with discontinuation of Selective Availability (SA), the pseudorange accuracy depends significantly on the elevation angles of the satellites and thus varies among different satellites. The analysis revealed that availability and the maximum outage duration of RAIM/FDE can be significantly worse than average depending on the chosen constellation and the location. It also shows that while barometric altimeter aiding significantly improves availability, a lowered mask angle does not improve availability as much for RAIM/FDE with a weighted solution since pseudorange measurements for low elevation satellites are deweighted with degradation of accuracy because of atmospheric and multipath effects.

- The analysis also has revealed the following:
  - With SA removed, 99.998 percent RAIM availability can be achieved for NPA and 100 percent availability for the other phases of flight with a 24-SV constellation and all satellites operating with use of barometric altimeter aiding and a 5^{o} mask angle. Even higher availability can be achieved with a 2^{o} mask angle. It should be noted, however, that the ionospheric and tropospheric models used to compute the UERE have not been validated for elevation angles below 5^{o}.
  - RAIM availability requirement of 99.999 percent can also be achieved through the use of GEO satellite ranging with a 5^{o} mask angle and no barometric altimeter aiding in case all GPS and both GEO satellites are operating.
  - This analysis also has demonstrated that high availability for FDE can be difficult to achieve. FDE availability of 99.999 percent can be achieved for stand-alone GPS for all phases of flight with a 30-satellite constellation and SA off, even without access to dual frequency if it is assumed that all 30 satellites are operating. It should be noted, however, significantly larger than 30 satellites must be maintained in order to have 30 operating satellites on the average.
  - 99.9 percent FDE availability for NPA and 99.997 percent or higher can be achieved through the use of GEO satellite ranging as well with a 5^{o} mask angle, use of barometric altimeter aiding, and 24 GPS satellites, if all of the GPS and GEO satellites are actively transmitting ranging signals. Since WAAS receivers (TSO C145/146) are designed to employ GEO satellite ranging, this high availability could be achieved operationally.
- Alternative autonomous integrity methods have been examined to see if any of the methods may be more effective than conventional RAIM, which is based on a consistency check. It has been concluded that no other autonomous integrity methods can consistently provide integrity monitoring to a required performance level irrespective of the fault signatures.
- In an attempt to find a way to obtain higher availability, new RAIM and FDE availability criteria that still can satisfy operational requirements have been investigated. However, the investigation revealed that the new criteria do not bring any significant improvement in availability.
- The JHU/APL assertion that stand-alone GPS cannot meet requirements for navigation (except for the oceanic en route phase of flight), if GPS is the only navigation system installed in an aircraft and the only navigation service provided by the FAA, is based on the assumption that 0.99999 FDE availability is required for such a system. This led the Ad-hoc Working Group to discuss two possibilities that could make it less difficult to meet the FDE availability requirement. However, it was determined that both of the ideas, although not without merit, require further investigation.
- Described were a few critical issues identified by the Ad-hoc Working Group in the recently published GPS SPS Performance Standard. Since these issues affect RAIM/FDE performance and availability, the Working Group had RTCA send a letter to DoD asking for clarification.

APPENDIX A: UERE CALCULATIONS

$$\sigma_i^2 = \sigma_{i.\,URA}^2 + \sigma_{uire}^2 + \sigma_{i,\,tropo}^2 + \sigma_{i,\,mp}^2 + \sigma_{i,\,tcvr}^2$$

Case 1: SA off, access to a single frequency

$\sigma_{i.\ URA}$ **(Clock and ephemeris error)** = 6 m (GPS Performance Standard)

IONOSPHERIC DELAY ESTIMATION ERROR

$$\sigma_{uire} = F_{pp}\,\sigma_{uive}$$

$$\text{where } F_{pp} = \left[1 - \left(\frac{R_e \cos E}{R_e + h_I}\right)^2\right]^{-\frac{1}{2}}$$

Re = 6,378.14 (km)

h_I = 350 (km)

$\sigma_{uive} = \tau_{vert}$ = 9 m 4.5 m for 0 deg ≤ $|\phi_m|$ ≤ 20 deg
4.5 m for 20 deg < $|\phi_m|$ ≤ 55 deg
6 m for $|\phi_m|$ > 55 deg

TROPOSPHERIC MODEL

$$\sigma_{i,tropo}^2 = \left(\sigma_{TVE} \cdot m(E_i)\right)^2$$

where

σ_{TVE} = 0.12 m

$$m(E_i) = \frac{1.001}{\sqrt{0.002001 + \sin^2(E_i)}}$$

MULTIPATH AND RECEIVER NOISE (DO-229c, APPENDIX J)

$\sigma_{mp} = 0.13 + 0.53e^{-\theta/10}$ (m) where θ is elevation angle (degree)

σ_{rcvr} = 0.1 (m)

APPENDIX B: HORIZONTAL PROTECTION LEVEL (HPL) FORMULA FOR WEIGHTED SOLUTION RAIM

Formulas for non-weighted solution RAIM can be found in [19]. The only difference between the weighted solution RAIM and the non-weighted solution RAIM is the formula for the maximum horizontal slope, which is shown below.

The threshold and pbias values are the same as in [19]. This is because the maximum false alarm rate is set at $0.333*10^{-6}$/sample, which is consistent with the WAAS MOPS specification [7] for SA off. The false alarm rate per hour depends on the correlation time constant for the measurement. If the correlation time constant is 2 min, as was the case with SA on, the false alarm rate would be 10^{-6}/hr; if the correlation time constant is 20 min, the false alarm rate would be 10^{-6}/hr. For derivation of these thresholds, see [19].

Hslope = $\sqrt{K_{1i}^2 + K_{2i}^2} \; * \sigma_i \,/\, \sqrt{1 - P_{ii}}$

where $K = (G^TWG)^{-1}G^TW$,
$P = GK = G(G^TWG)^{-1}G^TW$

G is the connection matrix and W^{-1} =

$$\begin{bmatrix} \sigma_1^2 & 0 & .. & 0 \\ 0 & \sigma_2^2 & .. & 0 \\ .. & .. & .. & .. \\ 0 & 0 & .. & \sigma_n^2 \end{bmatrix}$$

HPL = max{Hslope} * (normalized pbias)

APPENDIX C: AVAILABILITY AND MAXIMUM OUTAGE DURATION OF RAIM AND FDE

The results of the RAIM/FDE availability analysis presented are obtained for the following conditions:

- SA off, access to a single frequency
- Worldwide Availability (–90° to 90° N latitude and 180° W to –175° W longitude), every 5° in latitude and longitude sampled every five minutes in time over a 24-hour period
- Mask angle: 5° and 2°
- Constellation
  - Optimized 24-satellite GPS constellation
    The worst 23 satellite constellation
    (SV #15 removed)
    The worst 22 satellite constellation
    (SV #10, and #15 removed)
    The worst 21 satellite constellation
    (SV #8, #10, and #15 removed)
  - GEO: The two satellites used for WAAS and visible over the CONUS (AOR-W and POR) used as additional ranging sources
- Nonprecision approach (NPA), terminal, en route, and oceanic phases of flight
- With and without barometric altimeter aiding
- Output
  - Minimum availability: availability at the location experiencing the most RAIM outages
  - Average availability: availability determined by averaging the availability across all of the grid locations
  - Maximum outage duration

Table C-1. RAIM Availability Without Barometric Altimeter Aiding (5° Mask Angle)

Constellation	NPA		Terminal		En Route		Oceanic	
	Avg. %	Min. %	Avg. %	Min. %	Avg. %	Min. %	Avg. %	Min. %
24 SVs	99.903	97.917	99.990	99.306	99.998	99.653	99.998	99.653
23 SVs	99.294	95.833	99.867	98.611	99.940	99.306	99.975	99.306
22 SVs	97.152	90.625	99.215	97.222	99.539	97.917	99.760	97.917
21 SVs	95.851	88.194	98.856	96.181	99.360	97.569	99.640	97.569

Table C-2. Maximum RAIM Outage Duration Without Barometric Altimeter Aiding (5° Mask Angle)

Constellation	NPA	Terminal	En Route	Oceanic
24 SVs	30 min.	10 min.	5 min.	5 min.
23 SVs	60 min.	20 min.	10min.	10 min.
22 SVs	135 min.	40 min.	30 min.	30 min.
21 SVs	170 min.	55 min.	35 min.	35 min.

Table C-3. RAIM Availability With Barometric Altimeter Aiding (5° Mask Angle)

Constellation	NPA		Terminal		En Route		Oceanic	
	Avg. %	Min. %	Avg. %	Min. %	Avg. %	Min. %	Avg. %	Min. %
24 SVs	99.998	99.653	100	100	100	100	100	100
23 SVs	99.928	98.611	99.970	99.306	99.993	99.653	99.998	99.653
22 SVs	99.463	96.528	99.745	97.917	99.887	97.917	99.961	97.917
21 SVs	99.198	95.486	99.587	97.917	99.839	97.917	99.953	97.917

Table C-4. Maximum RAIM Outage Duration With Barometric Altimeter Aiding (5° Mask Angle)

Constellation	NPA	Terminal	En Route	Oceanic
24 SVs	5 min.	0 min.	0 min.	0 min.
23 SVs	20 min.	10 min.	5 min.	5 min.
22 SVs	50 min.	30 min.	30 min.	30 min.
21 SVs	65 min.	30 min.	30 min.	30 min.

Table C-5. RAIM Availability Without Barometric Altimeter Aiding (2° Mask Angle)

Constellation	NPA	Terminal	En Route	Oceanic
	Avg. %	Avg. %	Avg. %	Avg. %
24 SVs	99.988	100	100	100
23 SVs	99.862	99.985	99.995	99.999
22 SVs	99.002	99.816	99.905	99.978
21 SVs	98.473	99.710	99.870	99.961

Table C-6. RAIM Availability With Barometric Altimeter Aiding (2° Mask Angle)

Constellation	NPA	Terminal	En Route	Oceanic
	Avg. %	Avg. %	Avg. %	Avg. %
24 SVs	100	100	100	100
23 SVs	99.997	99.999	100	100
22 SVs	99.814	99.957	99.979	99.999
21 SVs	99.797	99.919	99.970	99.998

Table C-7. RAIM Availability with GEO Satellites Over CONUS Without Barometric Altimeter Aiding (5° Mask Angle)

Constellation	NPA		Terminal		En Route		Oceanic	
	Avg. %	Min. %	Avg. %	Min. %	Avg. %	Min. %	Avg. %	Min. %
24 SVs	100	100	100	100	100	100	100	100
23 SVs	99.948	98.611	99.998	99.653	100	100	100	100
22 SVs	99.853	97.917	99.988	99.306	99.995	99.653	100	100
21 SVs	99.815	97.917	99.975	99.306	99.988	99.653	100	100

Table C-8. Maximum RAIM Outage Duration with GEO Satellites Without Barometric Altimeter Aiding (5° Mask Angle)

Constellation	NPA	Terminal	En Route	Oceanic
24 SVs	0 min.	0 min.	0 min.	0 min.
23 SVs	20 min.	5 min.	0 min.	0 min.
22 SVs	30 min.	10 min.	5 min.	0 min.
21 SVs	30 min.	10 min.	5 min.	0 min.

Table C-9. FDE Availability With Barometric Altimeter Aiding (5° Mask Angle)

Constellation	NPA		Terminal		En Route		Oceanic	
	Avg. %	Min. %	Avg. %	Min. %	Avg. %	Min. %	Avg. %	Min. %
24 SVs	99.100	93.056	99.643	97.569	99.923	99.306	99.970	99.653
23 SVs	96.273	86.806	98.091	95.833	99.199	98.611	99.571	99.306
22 SVs	90.989	82.639	94.246	92.403	96.655	94.792	97.661	96.875
21 SVs	86.854	74.653	91.397	89.972	94.923	91.264	96.356	95.833

Table C-10. Maximum FDE Outage Duration With Barometric Altimeter Aiding (5° Mask Angle)

Constellation	NPA	Terminal	En Route	Oceanic
24 SVs	100 min.	35 min.	10 min.	5 min.
23 SVs	190 min.	60 min.	20 min.	10 min.
22 SVs	250 min.	95 min.	55 min.	25 min.
21 SVs	365 min.	130 min.	75 min.	45 min.

Table C-11. FDE Availability With Barometric Altimeter Aiding (2° Mask Angle)

Constellation	NPA	Terminal	En Route	Oceanic
	Avg. %	Avg. %	Avg. %	Avg. %
24 SVs	99.854	99.904	99.981	99.998
23 SVs	98.798	99.507	99.856	99.959
22 SVs	95.793	97.734	98.944	99.361
21 SVs	93.302	95.250	98.243	98.875

Table C-12. FDE Availability With 5° Mask Angle and "Average Case" Satellites

Constellation	NPA	Terminal	En Route	Oceanic
	Avg. %	Avg. %	Avg. %	Avg. %
23 SVs	96.328	99.520	99.887	99.957
22 SVs	92.150	95.137	97.358	98.227
21 SVs	90.224	93.350	95.250	96.779

Table C-13. FDE Availability With 5° Mask Angle and "Best Case" Satellites

Constellation	NPA	Terminal	En Route	Oceanic
	Avg. %	Avg. %	Avg. %	Avg. %
23 SVs	97.502	99.715	99.925	99.970
22 SVs	94.007	95.950	97.729	98.463
21 SVs	91.579	94.043	96.507	97.567

Table C-14. FDE Availability with GEO Satellites and Barometric Altimeter Aiding (5° Mask Angle)

Constellation	NPA		Terminal		En Route		Oceanic	
	Avg. %	Min. %	Avg. %	Min. %	Avg. %	Min. %	Avg. %	Min. %
24 SVs	99.893	97.569	99.997	99.653	100	100	100	100
23 SVs	99.648	96.875	99.992	99.653	99.997	99.653	100	100
22 SVs	98.404	92.361	99.925	98.611	99.975	99.306	99.998	99.653
21 SVs	97.631	91.667	99.881	98.264	99.973	99.306	99.997	99.653

Table C-15. Maximum FDE Outage Duration With GEO Satellites and Barometric Altimeter Aiding (5° Mask Angle)

Constellation	NPA	Terminal	En Route	Oceanic
24 SVs	35 min.	5 min.	0 min.	0 min.
23 SVs	45 min.	5 min.	5 min.	0 min.
22 SVs	110 min.	20 min.	10 min.	5 min.
21 SVs	120 min.	25 min.	10 min.	5 min.

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