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Analysis of Use of Receiver Autonomous Integrity Monitoring (RAIM) in a GPS Wide-Area Augmentation System (WAAS)

Dr. Young C. Lee
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MITRE Corporation, McLean, Virginia

ABSTRACT

Among different augmentation alternatives for Required Navigation Performance (RNP) use of GPS, a GPS Wide Area Augmentation System (WAAS) could provide precision approach capability over a wide geographic area with a single system. Currently, the FAA is sponsoring research to determine how to make the WAAS concept satisfy RNP requirements for precision approach. Integrity is especially important because it has a direct impact on safety over a wide area. In order to improve integrity beyond the level provided by the ground segment of the system and to guarantee required local accuracy, use of receiver autonomous integrity monitoring (RAIM) in conjunction with the WAAS system may be advantageous. Should RAIM be used, there are questions regarding its availability.

The paper analyzes availability of RAIM and availability of navigation when an alternative WAAS integrity concept called VMAX is used. The analyses show that while the availability of navigation with the VMAX concept is higher than the availability of RAIM, neither one meets stringent WAAS RNP availability requirements. These results point to the need to analyze alternative concepts.

INTRODUCTION

The Federal Aviation Administration (FAA) is in the process of developing and implementing a GPS Wide-Area Augmentation System (WAAS) that will improve the integrity, accuracy, and availability of GPS-based satellite navigation for all phases of flight down to Category I (CAT I) precision approaches. Of all the requirements of civil aviation, integrity is the most important and stringent because it has a direct impact on safety. Candidates for WAAS integrity monitoring include the following:

- Receiver Autonomous Integrity Monitoring (RAIM)
- WAAS signal-in-space monitoring via independ-ent ground stations
- Combinations of the above

RAIM conducts a consistency check among ranging signals from different satellites. For this reason, performance and availability of RAIM depend on the level of redundancy, that is, on the number of satellites in view of the user, which in turn, depends on the number of satellites in the constellation and elevation mask angle [1 - 3]. It has been found that with the currently planned GPS constellation and even with some simple form of augmentation such as barometric altimeter aiding, availability of RAIM is good enough only for supplemental use down to nonprecision approach phase of flight [4, 5]. In fact, GPS avionics using RAIM were approved for supplemental use in the National Airspace System

(NAS) in 1993.

A GPS WAAS has the potential of being able to provide navigation capability for all phases of flight down to and including CAT I precision approach. The WAAS, which is an enhancement of the GPS Integrity Channel (GIC) Concept first proposed by MITRE/CAASD [6], will consist of a network of ground stations (including reference stations, monitor stations, master control stations) and multiple geostationary satellites that will relay messages generated by the ground network. The relayed messages will include integrity data and wide-area differential GPS corrections. In addition, the geostationary satellites will provide additional pseudorange signals, thus improving availability of navigation and RAIM integrity functions. According to the current FAA plan, the WAAS will be implemented in two phases. In the first phase, the system would provide Required Navigation Performance (RNP) capability down to the nonprecision approach phase of flight by providing integrity data for GPS satellites and additional pseudorange signals for the geostationary satellites. In the second phase, wide-area differential corrections would enhance accuracy of the GPS position to such an extent that RNP precision approach capability can be provided. Implementation of the second phase would require a policy decision by the U.S. Departments of Defense (DOD) and Transportation (DOT).

Alternative integrity concepts for the WAAS are described in detail in [7]. In summary, the WAAS ground segment consists of two separate networks: one for generating corrections and the other for monitoring the correction and calculating residual errors after correction. Corrections will be generated and broadcast separately for clock and ephemeris data per satellite and for ionospheric delay per grid cell node. Residual errors after correction observed by the ground monitoring network will also be broadcast to user avionics. Even though the WAAS ground segment monitors errors, it would be advantageous if RAIM could be used to provide additional protection in case of spoofing, unannounced GPS satellite delta-V maneuvers, loss of coverage by WAAS as well as such local phenomena as tropospheric anomalies, ionospheric anomalies, and multipath. However, an important question is whether RAIM would be available a sufficient fraction of time to meet RNP availability requirements. For this reason, RTCA SC-159 Working Group 2 has asked MITRE/CAASD to assess its availability.

Until now, RAIM algorithms have been considered mostly for the detection of horizontal errors with large protection limits associated with nonprecision approach, terminal, and en route phases of flight. However, RAIM calculations can also be performed on WAAS-corrected pseudoranges, providing both a horizontal and vertical integrity check. RAIM thresholds/parameters must be appropriately chosen, however, for precision approach horizontal and vertical protection limits, probabilities of undetected error, and alarm rates.

The paper first analyzes RAIM availability, which is compared with RNP availability requirements. Although RNP availability requirements have not been finalized, proposed availability requirement for precision approach navigation is 0.99999. After the RAIM availability analysis, the paper analyzes availability of navigation for an alternative WAAS integrity concept called VMAX, which can be used jointly with or in place of RAIM. In this alternative, the WAAS ground segment provides fault detection and residual errors for the individual satellites, while the user avionics ensures that the position estimation error at its location is within the protection limit required for the particular phase of flight.

It is noted that in using GPS for precision approach, accuracy and integrity requirements for vertical position are considerably more difficult to meet than those for horizontal position. For this reason, the current analysis is concerned only with the integrity of vertical position estimation.

AVAILABILITY OF RAIM

In the following analysis of RAIM availability, the criteria used and the rationale behind their selections are described along with the cases examined. This is followed by presentation and evaluation of results.

Criteria and Cases Used for RAIM Availability Analyses

Criteria for RAIM Availability

Availability is calculated strictly based on geometric outages. That is, for a selected constellation, non-zero probability of further satellite failures is neglected. For the geometric criteria, the FDI baseline algorithm of RTCA SC-159 [8] is used, except that a portion of the algorithm has been modified because our analysis is for vertical position estimation whereas the RTCA algorithm is designed for horizontal estimation. With this baseline FDI algorithm, the smallest protection limit that the algorithm can guarantee is computed. If this limit is smaller or equal to the protection limit required for the phase of flight (or decision height), then RAIM is available; if not, RAIM is not available. Obviously, the geometric criteria that determine availability of RAIM depend on such performance factors as allowable missed detection probability and allowable alarm rate as well as on other parameters such as satellite constellation and mask angle.

Standard Deviation of the Error in the Differentially Corrected Ranging Data

The effective one-sigma value of the WAAS-corrected pseudorange error (excluding the common bias) is estimated to be 1.3 m in [9]. In the current analysis, 1.3 m and 2 m are used, where the latter was chosen as a second, more conservative value to examine sensitivity of the results to the pseudorange error.

Correlation Time Constant

Although this parameter is not one of the parameters directly used to determine availability, it is used to convert an alarm rate and missed detection probability per approach to those per sample basis. On the basis on an observation that differential corrections would be broadcast at an average rate of once every few seconds, [10] assumes a correlation time constant of 6 sec. This value is used in the current analysis.

Allowable Alarm Rate

According to the SCAT-I MASPS [11], the allowable alarm rate for CAT I operations is 4.4 x 10^{-5} per approach. Assuming an approach lasts 2.5 min and a 6 sec correlation time for the range data, the allowable alarm rate of 4.4 x 10^{-5} per approach gives 1.8 x 10^(-6) per sample, which is used in the current analysis.

Missed Detection Probability (Pmd)

This is derived from the maximum allowable rate of undetected violations of the precision approach tunnel's outer containment surface. This maximum allowable rate was specified at 10^{-7} per approach for SCAT-I [11][1]. This requirement is the joint probability that a penetration of the precision approach tunnel's outer containment surface occurs and that it is undetected. Therefore, an undetected error rate that must be guaranteed by RAIM would depend on the occurrence rate of a penetration of the precision approach tunnel's outer containment surface[2]. This rate of penetration is difficult to estimate at this time because it depends on the whole WAAS design. However, it seems that a RAIM missed detection rate any higher than 10^{-3} to 10^{-2} per approach would not be very useful. On the other hand, use of a lower rate will reduce RAIM availability. For this reason, the two rates of 10^{-3} and 10^{-2} per approach have been selected for analysis. These rates per approach are equivalent to 4 x

10^{-5} and 4×10^{-4} per sample, respectively, assuming a precision approach duration of 2.5 min and a 6 sec correlation time constant for the differentially corrected range data. It is noted that the larger the RAIM missed detection rate, the higher the RAIM availability; however a larger missed detection rate can be used only if the WAAS ground segment can provide the correction signal with a higher level of integrity so that the overall integrity requirement may be met.

Mask Angle

A lower angle could be used for the en route, terminal, and nonprecision approach phases of flight. However, a 5 degree mask angle is selected, since it is the lowest angle usable for precision approach.

Protection Limit

Nominal HAT (Decision Height)	Total System Error (TSE)	FTE (2-sigma) [13, 14]	Protection limit
200 ft	110 ft	6.1 m	15.2 m
250 ft	123 ft	7.0 m	17.4 m
300 ft	135 ft	7.8 m	19.5 m
400 ft	165 ft	9.5 m	25.2 m

Table 1. Vertical Protection Limit as a Function of Decision Height

TSE = Half width of outer vertical tunnel corresponding to DH [15]
FTE values from both sources are essentially the same.
Protection limit = TSE - 20 ft (Half width of vertical aircraft dimension) - 4-sigma FTE

Vertical navigation sensor error protection limits for precision approach are shown in Table 1 as a function of decision height (DH). The derivation is based on the outer vertical tunnel half width corresponding to a DH, the vertical distance between the center of mass of a large aircraft and the bottom of the landing gear, and the 4-sigma value of vertical flight technical error for manual flight. DHs higher than 200 ft are considered since they are viable using WAAS if RNP requirements cannot be met for precision approach for a DH of 200 ft.

Satellite Constellations

As was stated, availability is calculated strictly on the basis of geometric outages, assuming zero probability of failure for the satellites. For this reason, the following two satellite constellations are used, which represent conservative and optimistic cases, respectively.

Conservative Case: A 21 GPS satellite constellation (its positions derived from the 24 Primary constellation with three satellites (SV 1, 10, & 11) failed giving typical coverage) is assumed. Since DOD guarantees only 21 operating satellites 98 percent of the time, the selected 21 satellite constellation is considered to give a reasonable lower bound of RAIM availability that can be expected under the published DOD policy. It is assumed that 2 geostationary satellites at 55 deg W and 179 deg W (Inmarsat III locations) augment the GPS constellation.

Optimistic Case: A 23 satellite constellation (its positions derived from the 24 Primary constellation with SV 10 failed giving typical coverage) is assumed. Because availability is calculated strictly based on geometric outages, this constellation is considered optimistic under the current DOD policy. It is assumed that 3 geostationary satellites at 15.5 deg W, 55 deg W, and 179 deg W (Inmarsat III locations) augment the GPS constellation.

User Locations: Five locations in CONUS: Chicago, Dallas/Fort Worth, Seattle, Los Angeles, and Boston.

Sampling Interval: 5 min

RAIM Availability Analysis Results

Pmd	sigma for residual range error	Location	DH = 200ft (PL = 15.2m)	DH = 250ft (PL = 17.4m)	DH = 300ft (PL = 19.5m)	DH = 400ft (PL = 25.2m)
4E-5	1.3 m	DFW	15.97	29.17	42.71	58.33
		Chicago	17.36	28.13	40.97	59.38
		Seattle	70.83	79.86	83.33	88.89
		LA	56.25	67.71	74.65	86.81
		Boston	23.61	39.93	48.96	62.50
	2.0 m	DFW	3.47	4.17	5.90	23.26
		Chicago	0.35	5.21	8.68	22.57
		Seattle	12.15	31.25	50.00	75.69
		LA	10.76	20.14	33.68	63.54
		Boston	1.74	4.51	10.07	30.90
4E-4	1.3 m	DFW	22.57	37.15	48.26	63.19
		Chicago	22.57	34.38	49.65	62.50
		Seattle	75.35	81.60	84.38	89.58
		LA	63.19	72.22	80.21	87.85
		Boston	29.51	46.18	54.86	64.24
	2.0 m	DFW	3.82	4.86	7.99	29.51
		Chicago	1.74	7.64	10.76	28.47
		Seattle	19.44	43.40	61.81	80.21
		LA	17.36	27.78	44.44	68.40
		Boston	3.13	7.99	13.19	40.97

Table 2. Availability (Percent) of RAIM for 21 GPS and 2 Geostationary Satellites (Geos at 55 deg W and 179 deg W)

The results of RAIM availability analysis performed for the 21 GPS satellites and 2 geostationary satellites are shown in Table 2. It is observed that RAIM availability is low. Even for the most optimistic case (Pmd = 4×10^{-4}, residual error sigma = 1.3 m, and DH = 400 ft), RAIM availability ranges from 60 to 90 percent, while it becomes much smaller under other conditions. Table 3 shows the results for the 23 GPS satellites and 3 geostationary satellites. In this case, RAIM availability ranges from 77 to 98 percent for the optimistic case. This is still not high enough to make it possible to require RAIM to exist before a flight operation (precision approach) is conducted.

Pmd	sigma for residual range error	Location	DH = 200 ft (PL = 15.2m)	DH = 250 ft (PL = 17.4m)	DH = 300 ft (PL = 19.5m)	DH = 400 ft (PL = 25.2m)
4E-5	1.3 m	DFW	25.00	43.06	59.72	79.17
		Chicago	27.78	42.71	57.99	72.92
		Seattle	82.29	90.28	91.32	94.79
		LA	69.44	80.21	87.85	97.57
		Boston	51.04	67.71	74.65	87.50
	2.0 m	DFW	5.56	6.60	10.07	33.33
		Chicago	1.04	7.99	13.54	35.42
		Seattle	27.43	46.53	62.50	87.15
		LA	17.71	31.60	50.00	76.39
		Boston	7.29	17.36	30.21	60.76
4E-4	1.3 m	DFW	32.64	52.08	68.40	82.29
		Chicago	35.07	50.69	66.67	76.74
		Seattle	86.81	90.63	92.01	95.49
		LA	75.35	85.42	92.71	97.92
		Boston	59.72	71.88	78.13	89.93
	2.0 m	DFW	6.25	7.99	13.89	43.40
		Chicago	3.13	11.81	17.71	43.40
		Seattle	34.72	56.60	72.57	90.28
		LA	25.00	42.01	59.03	80.56
		Boston	12.15	24.65	38.89	68.75

Table 3. Availability (Percent) of RAIM for 23 GPS and 3 Geostationary Satellites (at 15.5 deg W, 55 deg W and 179 deg W)

From the results, one can observe the following:

- The value of sigma (the standard deviation of the range residual) has a dramatic impact on availability.
- Neither additional satellites nor a less stringent Pmd improves availability significantly.
- Availability varies widely depending on the user location. This is expected because the visibility of geostationary satellites varies significantly with the user location.
- Availability also varies widely depending on the DH.

As noted, RAIM availability is not high enough even with the 1-sigma residual error of 1.3 m. While RAIM availability would improve for a smaller residual error, it is doubtful that a value significantly smaller than 1.3 m could be used. For this reason, it is concluded that availability of RAIM would not be high enough to meet the RNP requirement even with more geostationary satellites if RAIM is required to exist before a precision approach is allowed to be conducted. This is true even with a reasonably high DH.

VMAX CONCEPT

In the WAAS, the ground segment monitors residual errors for individual satellites. On the other hand, the ultimate integrity goal for the user is assurance that its position error is within the protection limit required to assure safety in a given flight operation. In an alternative WAAS integrity concept proposed by MITRE [10], the WAAS ground segment and the user avionics cooperate to achieve this ultimate integrity goal. In this concept, the

WAAS ground segment calculates the value of the maximum range residual error, which it can guarantee with a high level of confidence for all users within the coverage area[3]. Using this maximum value, the user avionics calculates an upper bound on its position error. Only if this maximum position error does not exceed the maximum tolerable error associated with the current operation, can the flight operation be conducted. Otherwise, a flag is displayed or an alternate set of satellites is used.

The maximum satellite range error and the maximum position error are related via parameters similar to Dilution of Precision (DOP) (e.g., HDOP, VDOP). A parameter called HMAX developed in [12] was shown to relate a maximum horizontal position error to a maximum satellite range error. This was extended in [7, 10] for the vertical case and named VMAX.

The upper bound of the user vertical position error is obtained as follows:

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Upper bound of user vertical position error
                = VMAX * Maximum range residual error
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Just like DOP parameters, VMAX is determined solely by the user-to-satellite geometry, specifically by the direction cosine matrix. Therefore, the maximum vertical position error that the user derives on the basis of the above formula varies depending on the geometry. As was stated earlier, the user will be allowed to conduct the desired flight operation only when the position error upper bound does not exceed the maximum tolerable error associated with the current operation. Since this position error upper bound is proportional to the VMAX value, whether or not a desired flight operation may be conducted depends on the VMAX value. In other words, availability of the navigation service is determined by the distribution of VMAX values over time and place.

In the following, availability of navigation using the VMAX-based integrity monitoring function is analyzed. This is done by calculating VMAX at different locations and times and determining what percent of the time the VMAX is small enough to allow a desired flight operation. The criteria and conditions used in the availability analysis are described first. This description is followed by presentation and evaluation of results and discussion of further observations.

Criteria and Cases Used for VMAX Availability Analyses

Criteria for VMAX Availability

Availability is calculated strictly based on geometric outages just like the case for RAIM availability. That is, for a selected constellation, the non-zero probability of further satellite failures is neglected. For the geometric criteria, the VMAX formula derived in [10] is used. Navigation is considered available at a given DH if the VMAX multiplied by the maximum residual error is less than or equal to the protection limit for the DH; otherwise, navigation is not available. For the VMAX calculation, use of all satellites in view is assumed. In general, for any given set of satellites, use of a subset gives a larger VMAX value than the full set. Therefore, in case less than all-in-view satellites are used, navigation availability would be less than what the following results will show.

Maximum Residual Range Error

In the current analysis, 2.5 m and 6.5 m are used. 6.5 m corresponds to 5-sigma value for a one-sigma value of 1.3 m, which was used for RAIM availability analysis. 2.5 m was chosen somewhat arbitrarily but represents a rather optimistic assumption. It should be noted that maximum residual range error provided by the WAAS ground segment cannot be an absolute maximum but is associated with a small probability that the residual range error may actually exceed the maximum for some locations.

Missed Detection Probability (Pmd)

In the VMAX concept, a missed detection occurs when all of the following occur simultaneously:

- Actual residual range errors exceed the broadcast maximum
- Large residual range errors cause a position error exceeding the protection limit
- Calculation of the maximum position error based on VMAX gives a value less than the protection limit.

In order to reduce Pmd, it is necessary to estimate the maximum residual range error more conservatively. In case the maximum residual range error is a true maximum, Pmd would be zero. No attempt is made to characterize Pmd in the current analysis.

Alarm Rate

In the VMAX concept, a false alarm would occur when two following events occur simultaneously:

- Actual position error is within the protection limit
- Calculation of the maximum position error based on VMAX gives a value larger than the protection limit, resulting in denial of a desired flight operation.

Since VMAX is based on the worst-case scenario, a high alarm rate is expected. In fact, if the maximum residual range error is estimated conservatively, alarm rate would be close to 1 minus availability of navigation using VMAX. No attempt is made to characterize alarm rate in the current analysis.

Mask Angle

A mask angle of 7.5 deg, which is slightly higher than that used for RAIM availability analysis, is selected so that satellites at a low elevation angle with a large residual error may be avoided.

Other than the above, VMAX availability analysis employs an identical set of cases in satellite constellations, protection limits, user locations, and sampling interval as for the RAIM availability analysis.

VMAX Navigation Availability Analysis Results

Max residual Range error	Location	DH = 200 ft (PL = 15.2m)	DH = 250 ft (PL = 17.4m)	DH = 300 ft (PL = 19.5m)	DH = 400 ft (PL = 25.2m)
2.5 m	DFW	95.14	97.22	100.00	100.00
	Chicago	93.40	95.49	100.00	100.00
	Seattle	96.18	98.96	99.31	100.00
	LA	100.00	100.00	100.00	100.00
	Boston	88.89	94.10	96.88	97.92
6.5 m	DFW	0.00	0.00	1.39	38.89
	Chicago	0.00	0.00	1.04	48.96
	Seattle	0.00	0.00	6.25	61.46
	LA	0.00	0.00	2.08	64.58
	Boston	0.00	0.00	0.69	39.24

Table 4. Availability (Percent) of Navigation Using VMAX for 21 GPS and 2

Geostationary Satellites (Geos at 55 deg W and 179 deg W)

Table 4 shows the results of navigation availability analysis performed with 21 GPS satellites and 2 geostationary satellites. With the maximum pseudorange error of 2.5 m, navigation availability is 100 percent for a DH of 400 ft at 4 out of 5 locations; for a DH of 200 ft, it reduces to between 89 and 100 percent, with an average of 95 percent. If a maximum pseudorange error value of 6.5 m is used, navigation availability is zero for all locations at DHs of 200 ft and 250 ft; it ranges from 39 to 65 percent even at a DH of 400 ft.

Max residual Range error	Location	DH = 200 ft (PL = 15.2m)	DH = 250 ft (PL = 17.4m)	DH = 300 ft (PL = 19.5m)	DH = 400 ft (PL = 25.2m)
2.5 m	DFW	100.00	100.00	100.00	100.00
	Chicago	98.96	99.31	100.00	100.00
	Seattle	96.18	98.96	99.31	100.00
	LA	100.00	100.00	100.00	100.00
	Boston	98.96	100.00	100.00	100.00
6.5 m	DFW	0.00	0.00	1.39	42.71
	Chicago	0.00	0.00	1.04	48.96
	Seattle	0.00	0.00	5.21	63.54
	LA	0.00	0.00	0.69	70.83
	Boston	0.00	0.00	0.00	52.78

Table 5.Availability (Percent) of Navigation Using VMAX for 23 GPS and 3 Geostationary Satellites (at 15.5 deg W, 55 deg W and 179 deg W)

Table 5 shows the results with the 23 GPS satellites and 3 geostationary satellites. With the maximum pseudorange error of 2.5 m, navigation availability is 100 percent at all 5 locations at a DH of 400 ft; however, it reduces to 96 to 100 percent at a DH of 200 ft. If a maximum pseudorange error value of 6.5 m is used, navigation availability becomes much more significantly reduced. In this case, navigation availability is zero for all locations at DHs of 200 ft and 250 ft, just like the case with the 21 GPS satellites and 2 geostationary satellites.

Residual Range Error	Pmd	Location	DH = 200 ft		DH = 250 ft	
			VMAX alone	VMAX or RAIM	VMAX alone	VMAX or RAIM
sigma = 1.3 m maximum error = 2.5m	4E-5	DFW	100.00	100.00	100.00	99.65
		Chicago	98.96	98.96	99.31	99.65
		Seattle	96.18	97.92	98.96	98.96
		LA	100.00	100.00	100.00	100.00
		Boston	98.96	98.96	100.00	100.00
	4E-4	DFW	100.00	100.00	100.00	100.00
		Chicago	98.96	98.96	99.31	99.65
		Seattle	96.18	97.92	98.96	98.96
		LA	100.00	100.00	100.00	100.00
		Boston	98.96	98.96	100.00	100.00
sigma = 2.0 m maximum error = 6.5m	4E-5	DFW	0.00	5.56	0.00	6.60
		Chicago	0.00	1.04	0.00	7.99
		Seattle	0.00	27.43	0.00	46.53
		LA	0.00	17.71	0.00	31.60
		Boston	0.00	7.29	0.00	17.36
	4E-4	DFW	0.00	6.25	0.00	7.99
		Chicago	0.00	3.13	0.00	11.81
		Seattle	0.00	34.72	0.00	56.60
		LA	0.00	25	0.00	42.01
		Boston	0.00	12.15	0.00	24.65

Table 6. Availability (Percent) of Navigation Using VMAX alone and with RAIM with 23 GPS and 3 Geostationary Satellites (at 15.5 deg W, 55 deg W and 179 deg W)

The VMAX navigation availability analysis is extended to determine how much navigation availability improves if RAIM and VMAX are used in combination, that is, if a flight operation is allowed to be conducted if either RAIM is available or VMAX declares that navigation is available. Table 6 shows availability of this combined use of RAIM and VMAX at DHs of 200 ft and 250 ft with the 23 GPS satellites and 3 geostationary satellites. It is shown that a joint use of RAIM and VMAX concept does not improve navigation availability significantly enough.

From the results, one can observe the following:

- The value of the maximum residual error has a dramatic impact on navigation availability when VMAX is used for integrity.
- Additional GPS and geostationary satellites do not significantly improve availability.
- Availability varies widely depending on the user location.

From the observation that navigation availability is so sensitive to maximum residual error and quickly reduces to zero for the maximum residual error of 6.5 m, it appears that the VMAX concept may not be suitable for the WAAS. In order to maintain a smaller value of maximum pseudorange error, more densely located ground stations and higher communication channel data rate are likely required. Even then, it may still be difficult to maintain a small upper bound residual error all the time in actual operations, even in the presence of a severe geomagnetic storm causing ionospheric disturbances, for example. Even if a relatively large residual error occurs only rarely, its impact on a significantly large area should be taken seriously.

From the above analysis of navigation availability using VMAX, further observations are made as follows:

- Availability of navigation addresses only the unavailability due to the user-to-satellite geometry. Evaluation of the overall navigation availability when integrity monitoring is based on VMAX should consider availability of the WAAS ground and space segments as well.
- Further availability analysis can be done as we learn more about what parameter values can be used, especially the maximum range residual error.
- It should be noted that the level of integrity for the VMAX-derived protection limit as derived by the avionics using VMAX is determined by the level of integrity of the broadcast data as determined by the WAAS ground segment. Therefore, it is important for the ground and space segments of WAAS to ensure with high confidence that the upper bound value of the residual errors broadcast to the user is indeed the maximum value that the range errors would not exceed (e.g., with an integrity level equal to or better than 10^(-7) per approach). This should be considered in the design of the ground and space segment of WAAS and in determining the upper bound values of the range error and the mask angles.

CONCLUSIONS

The RAIM availability analysis in the paper shows that with the currently planned GPS and geostationary satellite constellation (e.g., a maximum of 24 GPS and 5 or 6 geostationary satellites with potential failures), RAIM availability is definitely not high enough to meet the RNP requirements by itself. This does not mean, however, RAIM should not and cannot be used when it is available.

Noting that RAIM cannot take full responsibility, an alternative WAAS concept, which is based on a parameter called VMAX, was analyzed. In this concept, the user avionics calculate an upper bound on its position error on the basis of the maximum range residual error provided by the WAAS ground segment. Only if this maximum position error does not exceed the maximum tolerable error associated with the current operation, can the flight operation be conducted. Analysis of this alternative reveals that availability of navigation using this concept depends heavily on the maximum range residual error that can be guaranteed by the WAAS ground segment. Even with a rather optimistic assumptions on the satellite constellations and the maximum residual error, it is difficult to consistently achieve availability close to 0.99999, which is considered to be the availability requirement for RNP operation.

Availability of navigation with joint use of VMAX and RAIM was analyzed. Even in this case, availability is still not sufficiently close enough to 0.99999 even with the most optimistic assumptions. These results point to the need to analyze additional concepts, such as those in which a statistical rather than an absolute bound is transmitted in the WAAS message and/or computed by avionics.

The key parameters affecting availability, namely the standard deviation and the maximum of the residual error, depend on the integrity level that can be provided by the space and ground segments of the WAAS. Therefore, the analysis in this paper (or any extensions of it) can be used to determine the required level of integrity that must be provided by the space and ground segments to achieve a desired level of availability of an integrity monitoring function. This, in turn, determines the needed level of redundancy in the space and ground segments of the WAAS in terms of the number of geostationary satellites, the number of the ground monitors, and the integrity level within the individual reference and monitor stations.

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[1] While SOIT specification was 10^{-7} per approach for SCAT-I, something more stringent may be required for WAAS since many aircraft will be affected simultaneously. As will be seen, however, even with this less stringent requirement, availability of RAIM is not sufficiently high.

[2] The protection limits for integrity warning are derived on the basis of the half width of the outer vertical tunnel, as shown in Table 1. However, they may have to be somewhat smaller than the values assumed in this paper to give a pilot a chance to take a corrective action before penetrating the outer tunnel. This is currently under investigation at MITRE.

[3] Strictly speaking, WAAS guarantees only the signal-in-space pseudorange error. The maximum total pseudorange error is estimated by combining signal-in-space pseudorange error with avionics-induced error. See [10] for details.