The World After SA: Benefits to GPS Integrity

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Abstract

The Presidential Decision Directive (PDD) on the Global Positioning System (GPS) recommends that Selective Availability (SA) be removed by 2006. The question remains: if SA were to be turned off, how significant are the benefits to the GPS community? This paper examines the benefits of removing SA as it relates to airborne GPS integrity and demonstrates that there are substantial improvements in the availability of GPS integrity.

The study evaluates the current TSO C-129 Receiver Autonomous Integrity Monitoring (RAIM) algorithm, which provides fault detection for supplemental use of GPS. Fault detection and exclusion (FDE) functionality for primary means navigation will be contained in the Wide Area Augmentation System (WAAS) equipment (TSO C145/C146), but is designed to be used independent of WAAS. The availability of GPS integrity is examined globally and the results are compared to RAIM and FDE availability with SA on the system.

Other augmentations to improve availability, such as the use of geostationary satellites for ranging and additional GPS satellites in the constellation, also are considered, as well as variation of the mask angle. Speculations about improvements from a combined GPS/Galileo system also are provided.

The results of this analysis demonstrate a significant improvement in the availability of the fault detection and exclusion functions if SA is turned off and the other augmentations are incorporated. This capability may provide major benefits to countries who either do not plan to implement a WAAS-type system, or may not have one until well into the next century. Although these results hinge on the removal of SA, it is important nonetheless to quantify the magnitude of improvement in the availability of GPS integrity.

Introduction

Ever since DoD announced its policy of implementing SA on GPS, the civilian and military communities have been at odds over the need to keep SA on the system, especially during peacetime. The National Academy of Public Administration (NAPA) and the National Research Council (NRC) studies have recommended that the DoD turn off SA, while the RAND Corporation study concluded that it is not very detrimental to the civilian community to leave it on, due to the widespread implementation of differential GPS systems. The White House policy statement on GPS, known as the Presidential Decision Directive (PDD), was released March 29, 1996 and stated that it is the intention of DoD to turn off SA within a decade. The President of the United States will make an annual determination starting this year on the continued implementation of SA.

This paper examines the issue as it relates to airborne GPS integrity and demonstrates that there are substantial improvements in the availability of GPS integrity if SA were to be removed.

Background

The use of GPS for aviation is expanding rapidly worldwide. Within the United States, GPS has been approved as an IFR supplemental navigation system for domestic en route through nonprecision approach (NPA) phases of flight, and as a primary means system for oceanic navigation.

GPS differs from traditional land-based navigation systems because the satellites and areas of degraded signal coverage are in constant motion. If a satellite fails, or is taken out of service for maintenance, it is not known intuitively which areas, if any, may lose coverage. Also, GPS does not have a built-in real-time monitoring system which will satisfy aviation requirements. GPS receivers that are certified for aviation must have integrity, which means they can provide timely warnings to users when the GPS system is unreliable for navigation.

GPS integrity for supplemental navigation is provided by a method known as Receiver Autonomous Integrity Monitoring (RAIM). A certified GPS receiver has a RAIM algorithm which uses an overdetermined solution to perform a redundancy check of the measurements. The RAIM algorithm computes a horizontal protection level (HPL) that is based on the geometry of satellites at a given point in time. The HPL is the radius of a circle in the horizontal plane, centered at the true aircraft position, that is assured to contain the indicated horizontal position, with a given probability of missed detection and false alert.

Each phase of flight has a maximum horizontal alert limit (HAL) that it can support. For example, the horizontal alert limit for nonprecision approach is 0.3 nautical miles (555 meters). If the HPL exceeds this alert limit, RAIM is said to be unavailable for that phase of flight. Technical Standard Order (TSO) C-129, requires GPS receivers, certified for supplemental IFR navigation, to have RAIM [1].

RAIM algorithms require a minimum of five visible satellites in order to detect a failure. There are occurrences, however, when the geometry of the visible satellites prevents detection of a failure even with the Optimized 24 constellation of GPS satellites and with the current operational constellation of 28 satellites. Also, satellites occasionally are taken out of service for maintenance, thereby further reducing the availability of RAIM. TSO C-129 stipulates that barometric altimeter aiding must be employed an extra measurement to improve the availability of RAIM.

Figure 1 displays TSO C-129 RAIM coverage for nonprecision approach (NPA) over a twelve-hour period with the Optimized 24 GPS constellation [2], which is representative of the 24 GPS Block II satellites currently in orbit. The coverage is computed at five-minute time intervals for every five degrees of latitude and longitude, using a 7.5º mask angle as specified in the TSO and baro aiding. Since the GPS satellites are in approximately twelve-hour orbits, the coverage pattern will repeat itself in the opposite hemisphere during the next twelve hours.

Figure 1 demonstrates that even with 24 operational satellites, there are periods of up to 50 minutes in duration when GPS RAIM coverage is not available for a nonprecision approach at some locations. These outages will occur in the same location every day, although the time of day will shift by four minutes per day due to the sidereal orbit. The number of visible GPS satellites increases as latitudes approach the equator, which explains the higher availability in that region.

For GPS to be used as a primary means of navigation, the system must not only be able to detect the presence of an anomaly, but it also must be able to remove the faulty satellite from the solution. The integrity algorithm now requires six or more visible satellites. This technique is an extension of RAIM referred to as fault detection and exclusion (FDE). GPS alone will not be able to satisfy availability requirements for primary means navigation with FDE without additional satellites. The primary augmentation to GPS that the FAA is developing is the Wide Area Augmentation System (WAAS). Other possible augmentations include inertial navigation systems (INS), geostationary satellites for ranging, or satellites from another constellation such as Galileo or GLONASS.

RAIM/FDE Algorithm

As previously mentioned, RAIM (fault detection) requires a minimum of five visible satellites, while FDE requires a minimum of six visible satellites. The algorithm discussed in this paper is based on the parity space concept and uses the magnitude of the parity vector as the test statistic for detection of a satellite failure [3]. The inputs to the parity space algorithm are the standard deviation of the measurement noise, the measurement geometry, as well as the maximum allowable probabilities for a false alert and a missed detection.

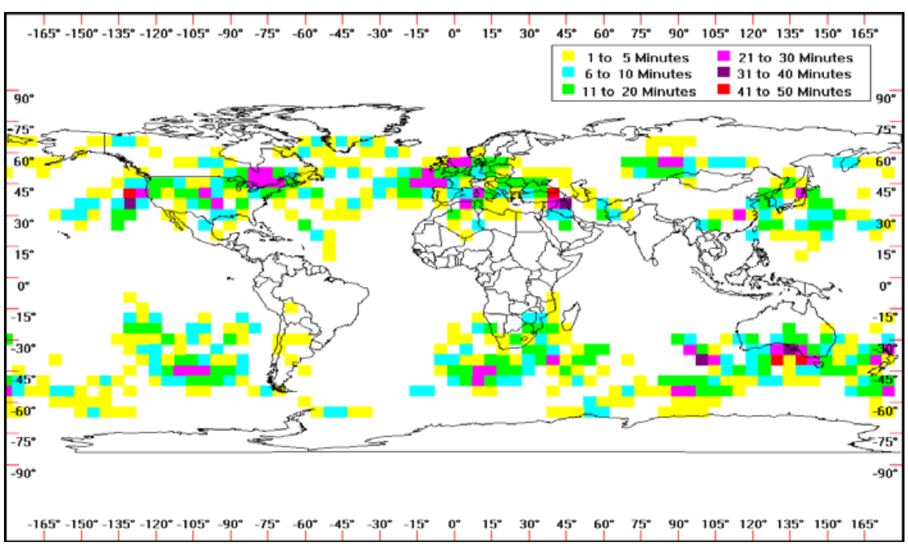

Figure 1 GPS RAIM Outages Over a 12 Hr. Period Based on TSO C-129 Criteria

Table 1 Integrity Performance Parameters for RAIM and FDE

Horizontal Alert Limit	Fault Detection Max. Allowable False Alert Rate	FDE Max. Allowable False Alert Rate	Missed Detection Probability
NPA 0.3 nmi Terminal 1.0 nmi En route 2.0 nmi Oceanic 4.0 nmi	0.002/hr (6.667×10^{-5}/sample)	10^{-5}/hr. (3.333×10^{-7}/sample)	0.001

The output of the algorithm is the HPL, which defines the smallest horizontal radial position error that can be detected for the specified false alert and missed detection probabilities. The parity space method is based on chi-square statistics with n-4 degrees of freedom (DOF), where n is the number of visible satellites.

A characteristic slope line for each visible satellite is determined as a function of the horizontal position error vs. the test statistic. The satellite with the maximum slope will be the most difficult to detect. The horizontal protection level is determined by:

$$HPL = Slope_{max} \cdot pbias \quad (1)$$

where $$pbias = \sigma\sqrt{\lambda} \quad (2)$$

λ is the noncentrality parameter of the noncentral chi-square density function and σ is the standard deviation of the satellite pseudorange error.

The HPL is compared to the maximum horizontal alert limit for the phase of flight. If the HPL exceeds the HAL, then RAIM is unavailable. Subset solutions are then formed by removing one of the visible satellites at a time. The maximum of these subsets is the Horizontal Exclusion Level (HEL). The HEL is then compared to the HAL foe each phase of flight to determine FDE availability. The specifications for the maximum horizontal alert limit, as well as for the probability of false alert and missed detection probability are specified in Table 1 for each phase of flight.

Correlation Time without SA

A false alert occurs when no abnormal condition exists, but an alert is given to the pilot. Selective Availability is the most likely cause of false alerts and its effects are assumed to have a correlation time of two minutes. This corresponds a false alert rate of 6.667×10^{-5}/sample for supplemental navigation and 3.333×10^{-7}/sample for primary means navigation. Without SA, the ionosphere becomes the largest error source.

The correlation time is used only for false alerts. Within RTCA SC-159, there were two philosophies on what the correlation time is without SA. The first philosophy is that an ionospheric error large enough to cause an alert should be considered a true alert. Under this assumption, the correlation time is driven by the receiver noise. The smoothing time constant of the receiver noise is assumed to be on the order of two minutes.

The second philosophy is that the correlation time is approximately one hour, based on the average length of time satellites are visible to the user. The correlation time is kept the same as the above case on a per sample basis (6.667×10^{-5} or 3.333×10^{-7}), but the false alert rate is more stringent on a per hour basis [4]. In both cases the detection threshold remains the same as for the case when SA is on.

The WAAS Minimum Operational Performance Standards (MOPS) [2] has been modified so that the receivers take advantage of the improvement in FDE availability if SA is turned off. Keeping the detection threshold the same will minimize changes to the FDE algorithm to take advantage of the SA-off condition. The WAAS MOPS will allow the manufacturer to decide which false alert rate philosophy to follow.

Use of User Range Accuracy

The User Range Accuracy (URA) can be used to determine the status of SA. The URA for each satellite equals:

$$2^{(1+N/2)} \quad N \le 6$$
$$2^{(N-2)} \quad N > 6$$

where N ranges from 0 to 15. SA is assumed to be off if the URA is less than or equal to 16 meters ($N \le 6$).

The integrity solution may be weighted by each satellite's URA or the receiver may operate in a binary mode where SA is assumed to be either off, or on, all of the satellites.

GPS Error Budget

The accuracy with which a GPS receiver can determine position and velocity and synchronize to GPS time is dependent on a number of factors. GPS error sources are allocated into three categories: the space segment, control segment, and user segment. The error components which comprise these segments, as well as an estimate of the one-sigma value of each component is given in Table 2 [5].

The most dominant error source by far is Selective Availability which produces a one-sigma error of 32.3 meters. These error sources are for the civilian coarse acquisition (C/A) code.

The effective accuracy of the pseudorange value is termed the user-equivalent range error (UERE). The system UERE is the root sum square (rss) of the individual error components. As shown in Table 2, the one-sigma UERE is reduced from 33.3 m with SA to only 8 m when SA is removed. Further reduction in the UERE can be obtained with the proposed 2nd and 3rd civilian frequencies to correct for ionospheric delay. A UERE of 6.6 m was examined to account for the ionospheric correction, as well as a UERE of 3.8 which includes additional benefits of GPS modernization [6].

A more conservative user error budget also was examined to account for larger receiver noise and ionospheric errors. The troposphere and multipath errors also were modified to agree with the supplemental GPS MOPS [7]. This error budget, shown in Table 3, results in a one-sigma pseudorange error of 12.5 m without SA. The root sum square (rss) of the receiver noise, multipath, and interchannel bias equals 5 meters which is consistent with the value in the current WAAS MOPS.

A one-sigma pseudorange error of 12.5 meters for GPS without SA was adopted by RTCA SC-159 Working Group 2 for inclusion in the WAAS MOPS. As shown in Equations (1) and (2), the magnitude of the horizontal protection level is directly related to the standard deviation of the pseudorange error. This reduction of HPL naturally will translate into a significant improvement in availability.

Table 2 Estimated GPS C/A-Code Pseudorange Error Budget

Segment Source	Error Source	GPS 1σ Error (m) With SA	GPS 1σ Error (m) Without SA
Space	Satellite Clock Stability	3.0	3.0
	Satellite Perturbations	1.0	1.0
	Selective Availability	32.3	-
	Other (thermal radiation, etc.)	0.5	0.5
Control	Ephemeris prediction error	4.2	4.2
	Other (thruster performance, etc.)	0.9	0.9
User	Ionospheric Delay	5.0	5.0
	Tropospheric Delay	1.5	1.5
	Receiver Noise and Resolution	1.5	1.5
	Multipath	2.5	2.5
	Other (interchannel bias, etc.)	0.5	0.5
System UERE	Total (rss)	33.3	8.0

Table 3 Conservative C/A-Code User Pseudorange Error Budget

Error Source	GPS 1σ Error (m) Without SA
Ionospheric Delay	10.0
Tropospheric Delay	2.0
Receiver Noise and Resolution	4.8
Multipath	1.2
Other (interchannel bias, etc.)	0.5
System UERE (rss)	12.5*

* Space and Control Segment errors remain the same (without SA)

Availability Analysis Parameters

Improvement in RAIM and FDE availability for oceanic through nonprecision approach phases of flight with SA removed were analyzed using the one-sigma values for the pseudorange error discussed in the previous section. This section summarizes the parameters used in the RAIM/FDE availability analysis.

Satellite Constellation

The availability analysis was performed with the GPS constellation consisting of 24 Block II satellites, known as the Optimized 24 constellation. This constellation is the RTCA SC-159 standard used for simulation purposes [2]. Up to three satellites were removed from the constellation to simulate satellite maintenance or failures. A 30 satellite constellation provided by Boeing Corp. also was analyzed, as well as the three Inmarsat geostationary satellites visible over the U.S. broadcasting a GPS ranging signal.

Analysis Grid

RAIM and FDE performance of GPS was evaluated over a worldwide grid of points. This grid consists of points evenly spaced every five degrees in latitude from 90ºN down to 90ºS and of longitude points around the globe, also spaced by five degrees. The grid was sampled every 5 min. in time over 24 hours. For evaluation of the geostationary satellite augmentation, coverage was evaluated only over the U.S.

Mask Angle

Although a 7.5 degree mask angle is specified in TSO C129, most receivers are now using a five degree mask angle and this is now the standard mask angle used for RTCA SC-159 analysis. A five degree mask angle was applied in this study.

Baro Aiding

Improvement of availability by incorporation of a barometric altimeter also was included in this analysis for all phases of flight.

Availability Results

The results of this analysis demonstrate a significant improvement in availability and reduction of outage duration if SA were to be turned off. Availability increases most dramatically for NPA. Table 4 gives the availability for fault detection with the Optimized 24 SV constellation and a mask angle of 5º with baro aiding. For nonprecision approach, availability increases from 99.8% with SA to 99.997% if SA is removed with a UERE of 12.5m. Table 5 provides the maximum outage duration occurring at any location in the analysis grid. The maximum outage duration for nonprecision approach decreases from 45 min. to only 10 min. without SA (UERE=12.5m).

Table 4 Fault Detection Availability with a 24 SV Constellation

GPS 1σ Pseudorange Error	Horizontal Alert Limit			
	0.3nmi	1.0 nmi	2.0 nmi	4.0 nmi
33.3 m	99.798%	99.998%	100%	100%
12.5 m	99.997%	100%	100%	100%
8.0 m	100%	100%	100%	100%

Table 5 Max. Outage Duration for Fault Detection with a 24 SV Constellation

GPS 1σ Pseudorange Error	Horizontal Alert Limit			
	0.3nmi	1.0 nmi	2.0 nmi	4.0 nmi
33.3 m	45 min.	5 min.	0 min.	0 min.
12.5 m	10 min.	0 min.	0 min.	0 min.
8.0 m	0 min.	0 min.	0 min.	0 min.

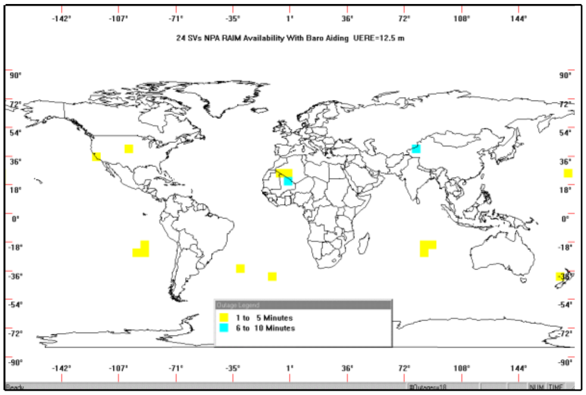

Figure 2 NPA Fault Detection Outages with a 5 Deg. Mask Angle and 1σ Pseudorange Error=12.5 m

Figure 2 displays the fault detection outages over the analysis grid for nonprecision approach if SA is removed with a UERE of 12.5 m. Note that there are very few outages and the maximum duration is 10 min.

Table 6 provides the availability results for fault detection and exclusion with the Optimized 24 SV constellation and baro aiding, while Table 7 gives the maximum outage duration. There is a substantial improvement in the availability of FDE for nonprecision approach, increasing from 89.5% with SA up to 99.9% if SA is removed with a reduction in the maximum outage duration from two hours to half an hour in the best case. However, these results suggest that additional augmentation still will be required to meet primary means requirements.

Table 6 FDE Availability with a 24 SV Constellation

GPS 1σ Pseudorange Error	Horizontal Alert Limit			
	0.3nmi	**1.0 nmi**	**2.0 nmi**	**4.0 nmi**
33.3m	89.468%	99.230%	99.806%	99.934%
12.5m	99.145%	99.880%	99.951%	99.978%
8.0m	99.654%	99.936%	99.971%	99.988%
6.6m	99.762%	99.948%	99.977%	99.990%
3.8m	99.908%	99.972%	99.988%	99.996%

Table 7 Max. Outage Duration for FDE with a 24 SV Constellation

GPS 1σ Pseudorange Error	Horizontal Alert Limit			
	0.3nmi	**1.0 nmi**	**2.0 nmi**	**4.0 nmi**
33.3m	120 min.	55 min.	30 min.	25 min.
12.5m	65 min.	30 min.	25 min.	15 min.
8.0m	35 min.	25 min.	20 min.	15 min.
6.6m	35 min.	25 min.	15 min.	15 min.
3.8m	30 min.	20 min.	15 min.	10 min.

Table 8 FDE Availability for 24 SVs and 3 Geos

GPS 1σ Pseudorange Error	Horizontal Alert Limit			
	0.3nmi	**1.0 nmi**	**2.0 nmi**	**4.0 nmi**
33.3m	97.856%	99.846%	99.959%	99.989%
12.5m	99.905%	99.974%	99.996%	99.998%
8.0m	99.965%	99.989%	99.998%	100%
6.6m	99.976%	99.996%	99.998%	100%
3.8m	99.985%	99.998%	100%	100%

Next, availability was examined over the U.S. with use of the three Inmarsat geostationary satellites with a GPS ranging capability (AOR-E, AOR-W, and POR) and baro aiding. The results are provided in Tables 8 and 9. Note that there is a significant benefit in using the geostationary satellites for ranging even with SA still on the GPS satellites.

With SA turned off, an availability of three to four 9's can be achieved for NPA. Figure 3 displays the FDE coverage available with a UERE of 8.0m.

Table 9 Max. Outage Duration for FDE for 24 SVs and 3 Geos

GPS 1σ Pseudorange Error	Horizontal Alert Limit 0.3nmi	1.0 nmi	2.0 nmi	4.0 nmi
33.3m	75 min.	25 min.	15 min.	5 min.
12.5m	20 min.	15 min.	5 min.	5 min.
8.0m	20 min.	5 min.	5 min.	0 min.
6.6m	20 min.	5 min.	5 min.	0 min.
3.8m	15 min.	5 min.	0 min.	0 min.

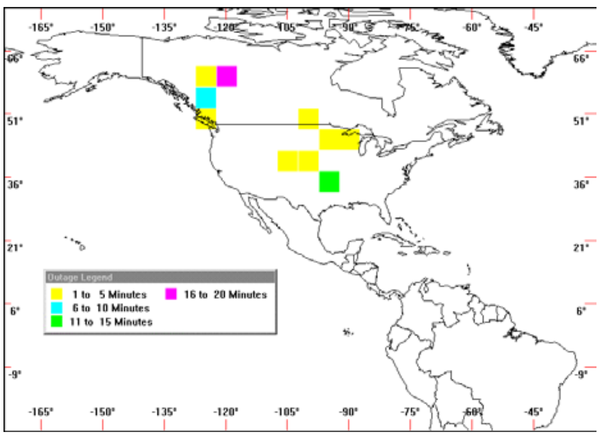

Figure 3 FDE Outages with 24 GPS SVs and 3 Geos Mask Angle=5 Deg. 1σ Pseudorange Error=8.0 m

Fault detection and FDE availability then were examined with an optimized 30 GPS satellite constellation. As demonstrated in Tables 10 and 11, availability approaches 100% for all phases of flight if SA is removed and baro aiding is incorporated. These tables also provide insight into the benefits of additional satellites, whether they are GPS or from another system such as Galileo or GLONASS.

However, one needs to account for the fact that satellites occasionally will be taken out of service for maintenance. FDE availability results for cases of one, two, and three satellites removed from the constellation were examined. The results for nonprecision approach are provided in Tables 12 and 13. The results demonstrate that with satellites out of service, availability drops below the 5 9's required by the FAA.

Table 10 FDE Availability for a 30 SV Constellation

GPS 1σ Pseudorange Error	Horizontal Alert Limit 0.3nmi	1.0 nmi	2.0 nmi	4.0 nmi
33.3m	99.439%	99.999%	100%	100%
12.5m	99.998%	100%	100%	100%
8.0m	100%	100%	100%	100%
6.6m	100%	100%	100%	100%
3.8m	100%	100%	100%	100%

Table 11 Max. Outage Duration for FDE for a 30 SV Constellation

GPS 1σ Pseudorange Error	Horizontal Alert Limit 0.3nmi	1.0 nmi	2.0 nmi	4.0 nmi
33.3m	45 min.	5 min.	0 min.	0 min.
12.5m	5 min.	0 min.	0 min.	0 min.
8.0m	0 min.	0 min.	0 min.	0 min.
6.6m	0 min.	0 min.	0 min.	0 min.
3.8m	0 min.	0 min.	0 min.	0 min.

Table 12 FDE Availability for NPA with a 30 SV Constellation with Up to 3 SVs OTS

GPS 1σ Pseudorange Error	UERE 12.5 m	8.0 m	6.6 m	3.8 m
30 SVs (0 SVs OTS)	99.998%	99.999%	99.999%	100%
29 SVs (1 SV OTS)	99.897%	99.962%	99.977%	99.999%
28 SVs (2 SVs OTS)	99.835%	99.958%	99.976%	99.999%
27 SVs (3 SVs OTS)	99.538%	99.850%	99.891%	99.990%

Table 13 Max. Outage Duration for FDE for NPA with a 30 SV Constellation with Up to 3 SVs OTS

GPS 1σ Pseudorange Error	UERE 12.5 m	8.0 m	6.6 m	3.8 m
30 SVs (0 SVs OTS)	5 min.	5 min.	5 min.	0 min.
29 SVs (1 SV OTS)	10 min.	15 min.	15 min.	5 min.
28 SVs (2 SVs OTS)	35 min.	15 min.	15 min.	5 min.
27 SVs (3 SVs OTS)	80 min.	50 min.	50 min.	20 min.

In order to meet the 5 9's availability requirement, there are a couple of options to improve availability. One is to use the geostationary satellites for ranging similar to what was previously analyzed with the 24 SV constellation. The other option is a proposal by the FAA to only require fault detection for nonprecision approach if FDE is available for terminal area navigation. The rationale behind this approach is that FDE is a conditional probability and the likelihood that an anomaly will occur on an approach when FDE is not available is quite small. Therefore, as long as the receiver can detect the anomaly and revert to terminal airspace, safety is maintained and availability for NPA is improved greatly.

Conclusions

This paper demonstrates that there are substantial improvements in the availability of GPS integrity, both for supplemental and primary means navigation if SA is turned off. Fault detection availability approaches 100% with a 24 satellite constellation and use of baro aiding. There is a significant improvement in the availability of FDE as well. Although the availability is not high enough to satisfy primary means requirements, it is important to quantify the magnitude of this improvement when SA is turned off. With a 30 SV constellation and use of baro aiding, FDE availability approaches 100% for all phases of flight. Similar results could be expected from augmentation by geostationary SVs or Galileo.

The WAAS MOPS has been modified so that receiver equipment is designed to take advantage of the increased availability if SA is turned off.

References

[1] Technical Standard Order (TSO) C-129, Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS), FAA Aircraft Certification Service,Washington, D. C., December 10, 1992.

[2] Minimum Operational Performance Standard for Global Positioning System / Wide Area Augmentation System Airborne Equipment, RTCA/DO-229, RTCA Inc., Washington D.C., January 16, 1996.

[3] Brown, R. G., *GPS RAIM: Calculation of Thresholds and Protection Radius Using Chi-Square Methods - A Geometric Approach*, RTCA 491-94/ SC159-584, Dec. 1994.

[4] Kovach, K., Maquet, H., Davis, D., *PPS RAIM Algorithms and Their Performance*, NAVIGATION, Fall 1995 Vol. 42 No. 3.

[5] Kaplan, Elliott D. et al, Understanding GPS Principles and Applications, Artech House, 1996.

[6] Kovach, K., *New User Equivalent Range Error (UERE) Budget for the Modernized Navstar Global Positioning System (GPS)*, Proceedings of the ION NTM January 2000.

[7] Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System, RTCA/DO-208, RTCA Inc., Washington D.C., July 1991.