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RAIM Availability for Supplemental GPS Navigation

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ABSTRACT

This paper examines GPS receiver autonomous integrity monitoring (RAIM) availability for supplemental navigation based on the approximate radial-error protection (ARP) method. This method applies ceiling levels for the ARP figure of merit to screen out bad detection geometries under worst-case bias conditions. The ARP criterion value for each phase of flight is based on the integrity specifications stated in the RTCA Special Committee (SC)-159 supplemental Minimum Operational Performance Standards (MOPS) for GPS.

Applying the ARP criterion, extensive analysis was performed to determine the availability of RAIM over the conterminous United States, North Atlantic, Europe, Central East Pacific, and North Pacific during en route, terminal, and nonprecision approach phases of flight. The 21 primary, optimal 21, and optimized 21 + 3 GPS constellations were examined. The results demonstrate that RAIM is not available 100 percent of the time, even with 24 operational satellites. This is because there are times when only 4 satellites are visible, preventing RAIM detection altogether, and other times when the geometry of the visible satellites has an ARP that exceeds the ARP ceiling value.

INTRODUCTION

In addition to providing a navigation capability, a navigation system must have the ability to provide timely warnings to users when the system should not be used for navigation. This capability is known as the integrity of the system. During July 1991, RTCA Special Committee (SC)-159 completed the Minimum Operational Performance Standards (MOPS) for GPS as a supplemental navigation system. During the process of developing the MOPS, the committee focused heavily on determining GPS position integrity performance requirements for en route, terminal, and nonprecision approach navigation. For supplemental navigation, the system has only to detect that there is a soft satellite failure (not one that is catastrophic). A flag is then raised, and the pilot switches over to the primary on-board navigation system. Since the GPS Integrity Channel (GIC) has yet to be developed, integrity will be provided by algorithms within the receiver. This method is known as receiver autonomous integrity monitoring (RAIM).

The FAA is currently developing a Technical Standard Order (TSO) based on the MOPS and will then issue an Advisory Circular. The FAA plans to allow the use of GPS as a supplemental navigation system when DOD declares the system operational, expected to occur in late 1993 [1]. Recently, the FAA Satellite Operational Implementation Team (SOIT) has proposed to allow the supplemental use of GPS even before full operational capability as declared by DOD. RTCA SC-159 is currently in the process of developing MOPS for the use of GPS as a sole means navigation system, which involves not only detecting a satellite failure, but also isolating the satellite that caused it. It should be noted that since GPS will not have the availability to satisfy sole means requirements, RTCA SC-159 is examining the augmentation of GPS with GLONASS, geostationary ranging satellites, and other navigation systems, such as Loran and inertial. RAIM algorithms require that at least 5 satellites be visible to detect a soft satellite failure. Unfortunately, even with 24 operational satellites, there will be times when only 4 satellites are visible, preventing RAIM detection altogether, and other times when the geometry of the visible satellites prevents the detection of a soft failure. This paper examines the availability of GPS RAIM for supplemental navigation, based on the approximate radial-error protection (ARP) method.

APPROXIMATE RADIAL-ERROR PROTECTION (ARP) METHOD

As mentioned previously, there are two problems in detecting satellite failures using RAIM. The first is that there are occurrences when fewer than 5 satellites are visible to the user. The second involves cases in which the satellite geometry cannot provide failure detection within the required specifications established by RTCA SC-159 [2], which are listed in Table 1. Declaring these geometries inadmissible reduces GPS RAIM availability. The RAIM algorithm must incorporate an effective method for screening out the bad satellite geometries.

The ARP method, developed by R. Grover Brown of Iowa State University and described in this issue of *NAVIGATION* [3], is an effective method for screening out bad detection geometries under worst-case bias conditions. Small satellite pseudorange biases will result in relatively small position errors that need not be detected since they are contained within the allowable bound. Large bias errors result in large position errors; however, these errors are very easy to detect. The worst-case satellite bias errors are those which fall in between, moving the position error out beyond the alarm limit, yet not enough to allow easy detection.

The ARP method applies a unique detection threshold (in meters) for each number of visible satellites [3]. These values, shown in Table 2, were determined in order to meet the maximum allowable alarm rate of 0.002/h, as specified in the RTCA SC-159 Supplemental MOPS. The range residual param-

Table 1—GPS Position Integrity Requirements for Supplemental Navigation

Phase of Flight	Alarm Limit	Max. Allowable Alarm Rate	Time to Alarm	Min. Detection Probability
En Route	2.0 nmi	0.002/h	30 s	0.999
Terminal	1.0 nmi	0.002/h	10 s	0.999
Nonprecision Approach	0.3 nmi	0.002/h	10 s	0.999

Table 2—Detection Thresholds As a Function of the Number of Visible SVs Test Statistic = $\sqrt{[SSE/(n-4)]}$; Noise σ = 33 m

Number of Visible SVs	Chi-Squared Degrees of Freedom	Detection Threshold (m)
5	1	132
6	2	102
7	3	90
8	4	82
9 (or more)	5	77

eter was chosen as the decision test statistic, based on work performed by Parkinson and Axelrad [4].

The slope is defined as the rate of increase of the navigation horizontal radial error as a function of the test statistic. For each space/time point, if there are n satellites in view, there are n slopes. The larger the slope, the higher the probability of a missed detection. In the ARP method, the largest of the slopes, called the $\text{SLOPE}_{\text{max}}$, is used. Shown in Figure 1 is a plot of the navigation horizontal error vs. the test statistic for the deterministic (no-noise) model.

Since system noise and Selective Availability (SA) are neglected, the deterministic trajectory is a straight line with a certain slope. In considering the worst-case scenario, the bias is placed on the satellite that corresponds to the largest slope ($\text{SLOPE}_{\text{max}}$). The $\text{SLOPE}_{\text{max}}$ trajectory is the one that will pass closest to, or into, the missed detection sector. The ordinate point at which this

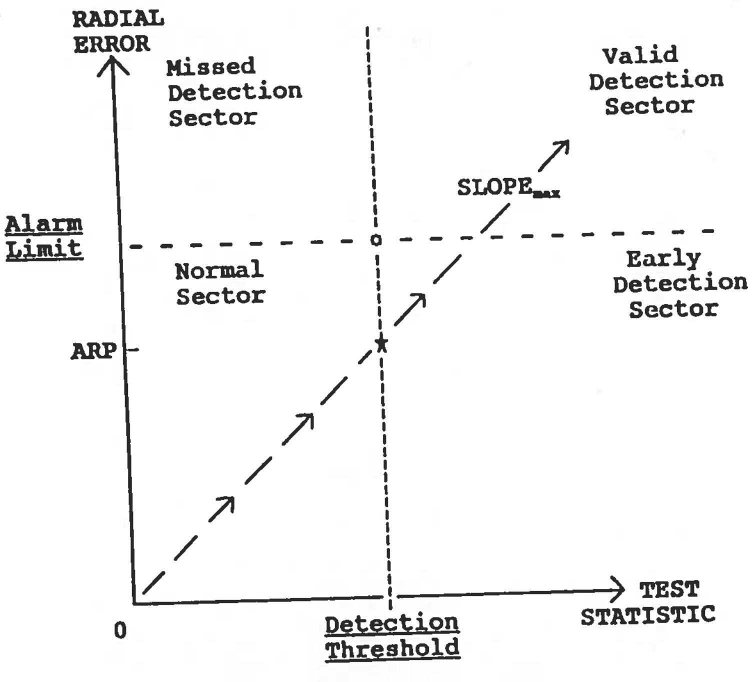

Fig. 1—Deterministic Error-Test Trajectory

trajectory intersects the detection threshold is by definition the ARP value. Both the ARP and the $\text{SLOPE}_{\text{max}}$ can be calculated in the GPS receiver.

The same trajectory is then considered with system noise and SA added (zero mean and $\sigma = 33$ m), where SA is considered to be the dominant effect. The trajectory now has an erratic trace to it, as shown in Figure 2. When the trajectory crosses the detection threshold, a flag is raised in the cockpit. A cluster of possible sample points is shown, surrounding a deterministic center point. Worst-case conditions, in terms of inducing missed detections, occur when the center point of the cluster is close to the alarm limit line. For the deterministic calculation, no-noise radial error is set equal to the alarm limit plus an added term. The added term is linearly related to the bias, which is added to the satellite pseudorange. The worst-case added term corresponds to the situation when the largest number of sample points passes into the missed detection sector.

Analysis has determined the worst-case added term for the nonprecision approach, terminal, and en route phases of flight [3]. This analysis has also established ceiling values for the ARP, shown in Table 3, which are applicable to the specifications in the RTCA MOPS for supplemental navigation.

ANALYSIS PARAMETERS

Satellite Constellations

Three GPS satellite constellations were considered in this analysis: the traditional 21 primary and optimal 21 constellations [5], and the more recent opti-

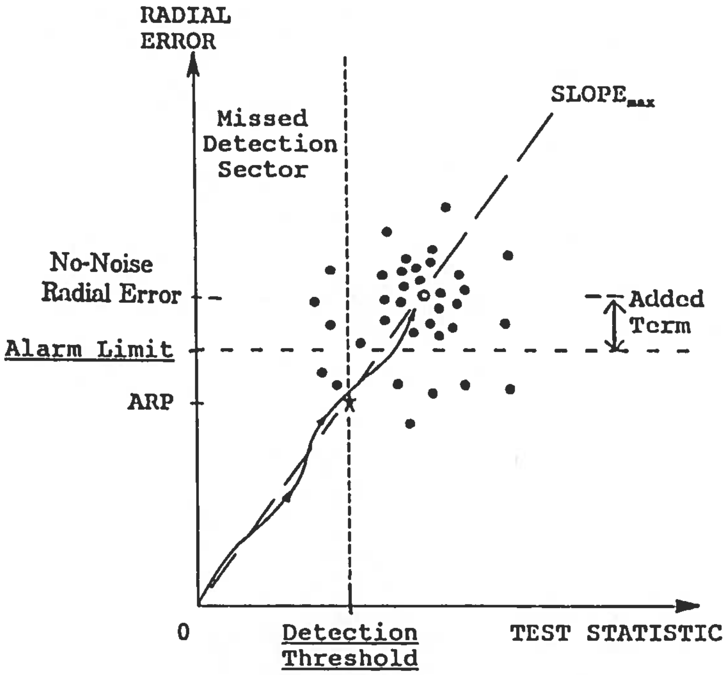

Fig. 2—Illustration of Term Added to the Alarm Limit, and Cluster of Sample Points Intruding into Missed Detection Sector

Table 3—ARP Ceiling Values (m)

Phase of Flight	Number of Visible Satellites 5	6	7 (or more)
En Route	2159	2262	2262*
Terminal	1077	1135	1135*
Nonprecision Approach	328	339	352

*The values for 7 or more visible satellites are conservative. Very few 7-in-view geometries have ARP values this large. These ceiling values could be stored in the GPS receiver, and then if the in-flight calculated ARP exceeded the ceiling value for the particular phase of flight, RAIM would be declared unavailable.

mized 21+3 constellation, which contains the actual target locations for the GPS satellites [6]. The 21 primary and optimized 21+3 constellations each contain 24 satellites, while the optimal 21 constellation contains 21. Failures of 1, 2, and 3 from the 21 primary constellation were considered since DOD has guaranteed that 24 satellites will be operational only 72 percent of the time, while 23 satellites will be available 89 percent of the time, 22 satellites 95 percent of the time, and 21 satellites 98 percent of the time [7]. Satellite failures were selected based on data obtained from the Aerospace Corporation for average 1, 2, and 3 failures from the 21 primary constellation. These selections are: 1 failure, involving SV #10; 2 failures, involving SVs #18 and #19; and 3 failures, involving SVs #18, #19, and #20.

Locations

Five coverage areas were examined in this analysis: CONUS, North Atlantic, Europe, Central East Pacific, and North Pacific. These regions, which are defined below in Table 4, were analyzed for the en route, terminal, and nonprecision approach phases of flight.

These regions were analyzed using a 5 deg latitude/longitude grid at 6 min time intervals over a 24 h period with a mask angle of 7.5 deg. RAIM availability over CONUS during nonprecision approach navigation was also examined using 5 and 2.5 deg mask angles.

Baro-Aiding

In drafting the TSO, the FAA has incorporated the requirement for ". . . automatic input of pressure altitude or barometric pressure-corrected data." Therefore, RAIM availability with GPS augmented by a barometric altimeter was also examined over the CONUS region. The barometric altimeter measurement is added to the set of satellite pseudorange measurements and

Table 4—Regions Used in RAIM Availability Analysis

Region	Latitude	Longitude
CONUS	65 °N–25 °N	125 °W–65 °W
North Atlantic	50 °N–35 °N	70 °W–0 °
Europe	70 °N–35 °N	10 °W–30 °E
Central East Pacific	40 °N–20 °N	175 °W–20 °W
North Pacific	60 °N–35 °N	140 °E–120 °W

is analogous to having an imaginary satellite directly overhead. The standard deviation of the barometric altimeter is assumed to be 200 m for en route navigation, 300 m for terminal navigation, and 50 m for nonprecision approach [8]. In the original analysis, 1200 m was applied for the terminal phase of flight; however, an error this large appears to be a very unlikely occurrence [9].

RAIM AVAILABILITY

In this analysis, RAIM failure detection was automatically determined to be unavailable if fewer than 5 satellites were visible to the user. If 5 or more satellites were visible, the ARP value was calculated. The ARP value for a given time-space point is the $\text{SLOPE}_{\max}$ multiplied by the detection threshold for the number of visible satellites (see Table 2). The ARP value was then compared with the ARP ceilings shown in Table 3. If the ARP value exceeded the ceiling for the particular phase of flight, RAIM was declared unavailable.

En Route Navigation

The percentage of RAIM detection availability for en route navigation over the five regions considered is shown in Table 5. For the 24-satellite constellations, RAIM is available for all the regions well over 99 percent of the time. Even with 1 failure from the 21 primary constellation, RAIM is available at least 99 percent of the time. However, when there are only 21 satellites, as in the cases of the 21 primary with 3 failures or the optimal 21, the availability drops to between 95 and 97 percent. It should be noted that the optimal 21 constellation will generally provide better coverage than the 21 primary with 3 failures since the optimal 21 is optimized for the best coverage worldwide with 21 satellites. A weighted average of RAIM availability is provided for the 21 primary constellation based on the probability of having that number of satellites operational.

In addition to determining the availability percentage, it is important to know the resultant outage duration. Figure 3 presents the duration of outages for the various satellite constellations and the number of occurrences of each outage over the CONUS region for en route navigation. These results are representative of the outage durations for the other regions, which are not presented here.

From the figure it can be seen that with 24 satellites, the outages are confined to between 6 and 12 min. It should be noted that a 6 min outage shown in the

Table 5—RAIM Detection Availability for En Route Navigation (percent)

Constellation	CONUS	North Atlantic	Europe	Central East Pacific	North Pacific
21 Primary—0 failures	99.69	99.83	99.74	99.71	99.64
21 Primary—1 failure	99.21	99.26	99.16	99.03	99.00
21 Primary—2 failures	98.21	96.62	97.95	98.33	97.55
21 Primary—3 failures	97.06	95.73	96.42	96.40	96.03
21 Primary—weighted avg. (0, 1, 2, & 3 failures)	98.25	97.50	98.00	98.06	97.72
Optimal 21—0 failures	97.59	97.23	97.59	97.53	97.28
Optimized 21 + 3—0 failures	99.83	99.85	99.78	99.87	99.83

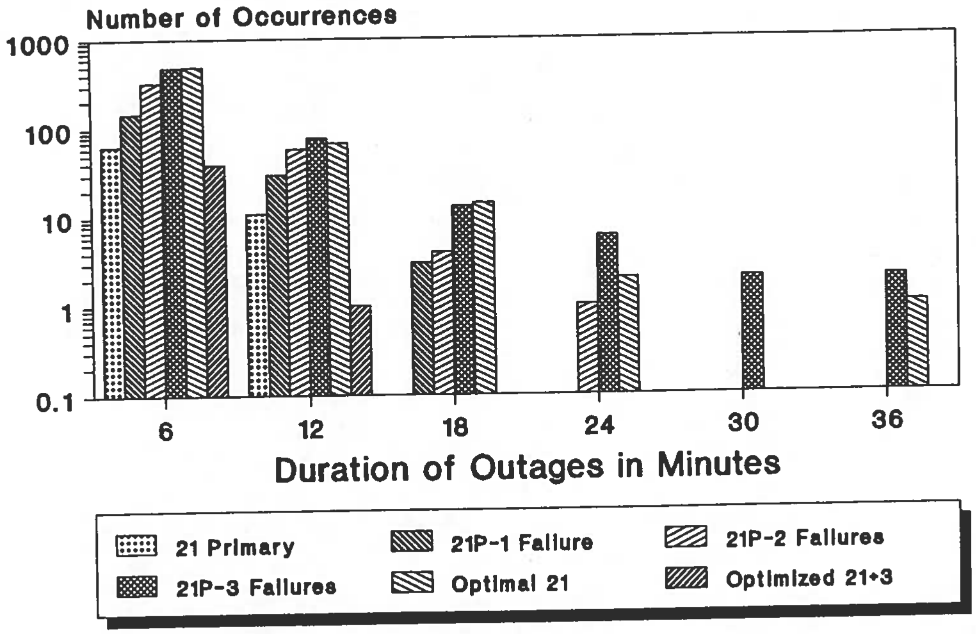

Fig. 3—Duration of Outages for En Route Navigation over CONUS

figure could actually last from 1 to 11 min since the data was sampled only every 6 min. The maximum outage duration is 36 min in the cases of the 21 primary constellation with 3 failures and the optimal 21 constellation.

Terminal Navigation

For terminal navigation, when there are no satellite failures, RAIM availability is again greater than 99 percent for the 21 primary and optimized 21 + 3 constellations. However, in the case of the 21 primary constellation with 3 failures, the availability decreases to approximately 93 percent. These results are presented in Table 6.

As shown in Figure 4, outages now last up to 18 min in the cases of the 21 primary and optimized 21 + 3 constellations. The results are worse for the 21 primary constellation, which has 13 occurrences of 18 min outages, as

Table 6—RAIM Detection Availability for Terminal Navigation (percent)

Constellation	CONUS	North Atlantic	Europe	Central East Pacific	North Pacific
21 Primary—0 failures	99.40	99.63	99.45	99.41	99.36
21 Primary—1 failure	93.38	98.40	98.28	97.78	97.99
21 Primary—2 failures	96.19	93.74	96.08	96.87	95.67
21 Primary—3 failures	93.91	91.97	93.64	93.69	92.98
21 Primary—weighted avg. (0, 1, 2, & 3 failures)	96.57	95.38	96.45	96.54	96.07
Optimal 21—0 failures	94.88	94.61	95.55	94.96	94.38
Optimized 21 + 3—0 failures	99.65	99.58	99.39	99.48	99.48

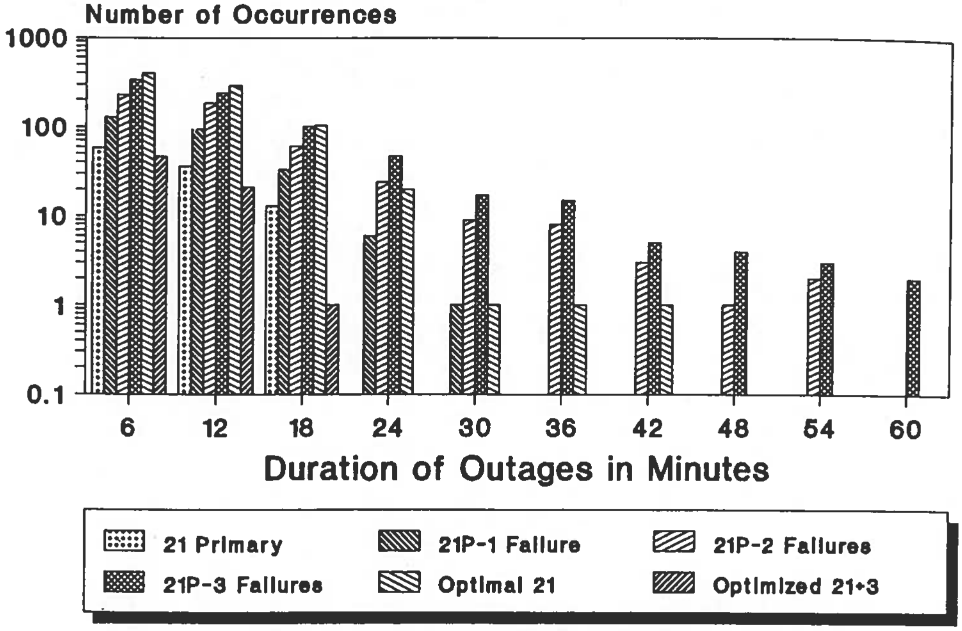

Fig. 4—Duration of Outages for Terminal Navigation over CONUS

opposed to the optimized 21 + 3, which has only 1. In the case of 3 failures from the 21 primary, outages last up to 1 h.

Nonprecision Approach

As would be expected, RAIM availability coverage is the worst during nonprecision approach navigation. With no satellite failures, the 21 primary constellation, with an average of approximately 94 percent, provides slightly better availability than the optimized 21 + 3, which has an average availability of approximately 93 percent. As shown in Table 7, the most degradation in coverage occurs when there are fewer than 24 operational satellites. In the case of the 21 primary with 3 failures, RAIM is, on average, available less than 75 percent of the time. These results agree with previous work reported in [10], which examines RAIM detection availability for nonprecision approach

Table 7—RAIM Detection Availability for Nonprecision Approach Navigation (percent)

Constellation	CONUS	North Atlantic	Europe	Central East Pacific	North Pacific
21 Primary—0 failures	94.66	92.88	94.35	95.90	94.17
21 Primary—1 failure	89.28	85.53	88.06	87.35	87.39
21 Primary—2 failures	82.31	77.58	82.91	85.91	81.37
21 Primary—3 failures	73.40	69.52	76.04	77.37	73.12
21 Primary—weighted avg. (0, 1, 2, & 3 failures)	83.94	80.30	84.46	85.77	83.04
Optimal 21—0 failures	77.56	75.42	80.64	79.52	77.39
Optimized 21 + 3—0 failures	94.40	92.65	93.84	95.04	93.15

using a $\text{PDOP}_{\max}$ of 6 and a mask angle of 7.5 deg. In that study, RAIM is shown to have a mean availability of 95.59 percent with 24 satellites (21 primary constellation), 89.84 percent with 1 failure, 81.86 percent with 2 failures, 73.77 percent with 3 failures, and 81.49 percent for the optimal 21 constellation.

In terms of outage duration, there are instances with the 21 primary constellation of outages lasting up to 1 h; with 3 satellites removed from this configuration, outages can last over 3 h. These results are presented in Figure 5.

The effect of lowering the mask angle was examined as a method to improve RAIM detection availability and reduce outages during nonprecision approach. Mask angles of 5 and 2.5 deg were considered over CONUS for the nonprecision approach phase of flight. As shown in Table 8, the availability does substantially increase as the mask angle is reduced. Using a 5 deg mask angle, the availability ranges from approximately 85 percent during the case of 3 failures to greater than 98 percent when 24 satellites are operational. With a 2.5 deg mask angle, when there are no satellite failures, RAIM availability exceeds 99 percent for the 21 primary and optimized 21 + 3 constellations, and is greater than 92 percent for the others. However, the effects of multipath must be taken into consideration when the mask angle is lowered.

The duration of outages when applying a 5 deg mask angle is shown in Figure 6. The improvement of lowering the mask angle by 2.5 deg can readily be seen as the maximum outage duration has decreased from more than 3 h to approximately 1.5 h. The outages for the two 24-satellite constellations are confined to within 0.5 h. Figure 7 demonstrates the additional reduction in RAIM outages for nonprecision approach navigation if the mask angle can be reduced to 2.5 deg. Most of the outages last less than 1 h, with the exception of the 2 and 3 satellite failure cases, which can last up to 72 min. The number of occurrences of these outages has also been greatly reduced.

Barometric Altimeter

Next, RAIM availability is examined with the aid of a barometric altimeter. Only the CONUS region is considered during this portion of the analysis, but the results are expected to be indicative of the use of baro-aiding for the other regions. As shown in Table 9, there is a dramatic improvement in availability for all constellations considered. Close to 100 percent integrity coverage is achieved for the 21 primary and optimized 21 + 3 constellations during the en route phase of flight. In fact, all of the constellations have an availability greater than 99 percent for en route navigation. RAIM detection availability also increases for terminal navigation with the addition of baro-aiding, but the margin of improvement is not as large since the pressure altitude offset changes by approximately 300 m throughout the descent. However, RAIM availability is still greater than 99 percent for all constellations except for the 2 and 3 failure cases, and those have an availability greater than 97 percent. For the nonprecision approach phase of flight, there is a significant improvement, with an availability greater than 90 percent for all cases considered.

Figures 8, 9, and 10 demonstrate the significant decrease in outage duration for all three phases of flight when baro-aiding is applied. For en route navigation, there are only two 6 min outages for the 21 primary constellation and

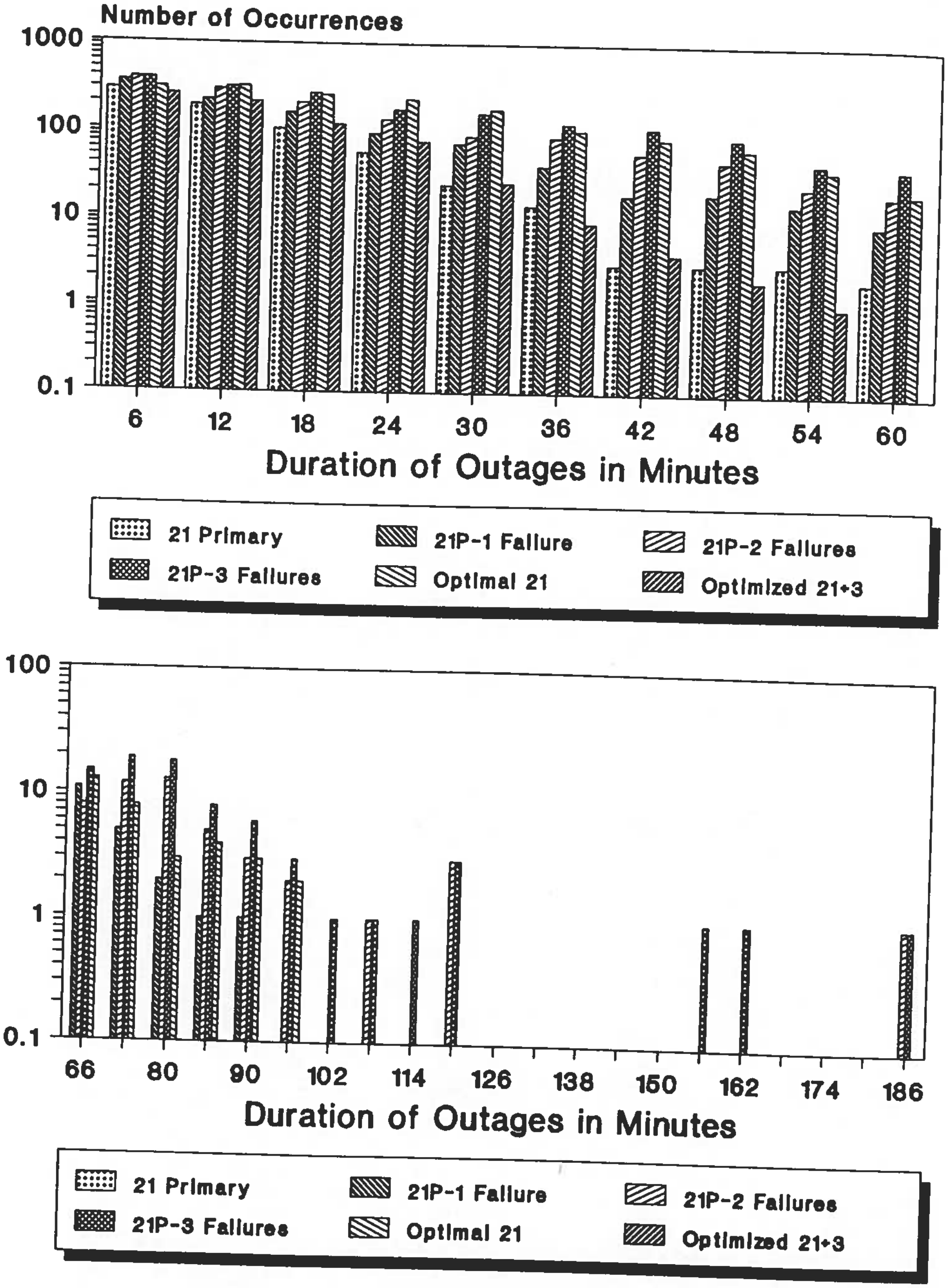

Fig. 5—Duration Outages for Nonprecision Approach Navigation over CONUS

four for the optimized 21 + 3 constellation. The maximum outage duration with 3 failures is shown to be 30 min. Outages still last up to 1 h for the terminal navigation case; however, the number of occurrences has decreased. In the case of nonprecision approach, outages are reduced to 36 min for the 21 primary constellation and 42 min for the optimized 21 + 3. In the case of 3 failures from

Table 8—RAIM Detection Availability over CONUS for Nonprecision Approach Navigation Using a Reduced Mask Angle (percent)

Constellation	5 deg Mask Angle	2.5 deg Mask Angle
21 Primary—0 failures	98.48	99.64
21 Primary—1 failure	95.54	98.32
21 Primary—2 failures	90.89	96.10
21 Primary—3 failures	84.72	92.59
21 Primary—weighted avg. (0, 1, 2, & 3 failures)	91.71	96.21
Optimal 21—0 failures	87.09	93.21
Optimized 21 + 3—0 failures	98.09	99.45

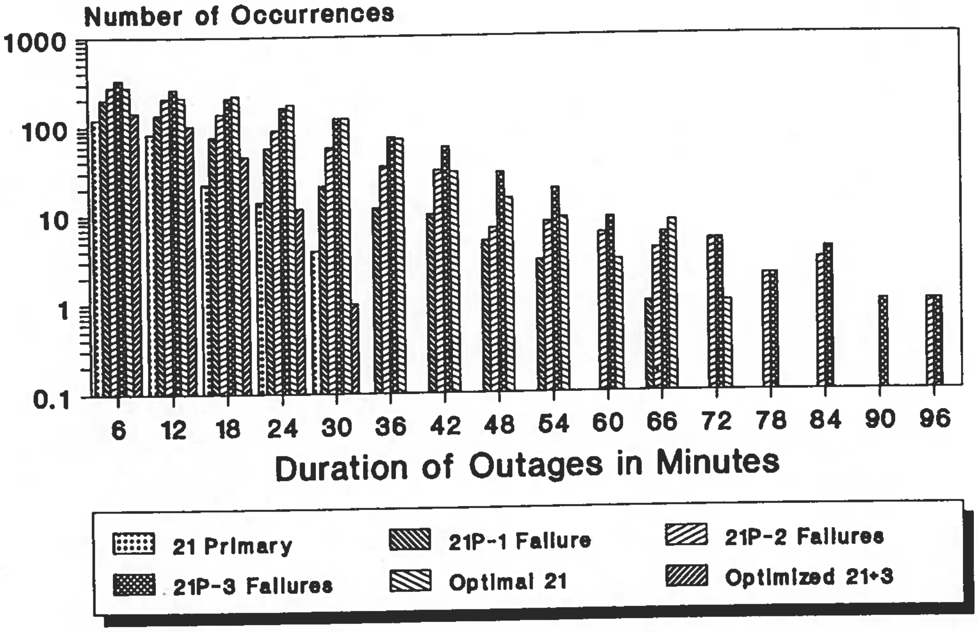

Fig. 6—Duration of Outages for Nonprecision Approach Navigation over CONUS Using 5 deg Mask Angle

the 21 primary, outages last up to 96 min; however, this is a 50 percent reduction in outage duration over not using baro-aiding.

SUMMARY AND CONCLUSIONS

This analysis has demonstrated that GPS RAIM is not available 100 percent of the time for supplemental navigation, even when 24 satellites are operational. The availability degrades when fewer than 24 satellites are available. This is especially true for the nonprecision approach phase of flight, where outages in a region can last well over 2 h when only 21 satellites are operational. RAIM availability has been shown to improve significantly with the aid of a barometric altimeter, although the combination still does not provide 100 percent availability. The good news is that soft satellite failures are expected to

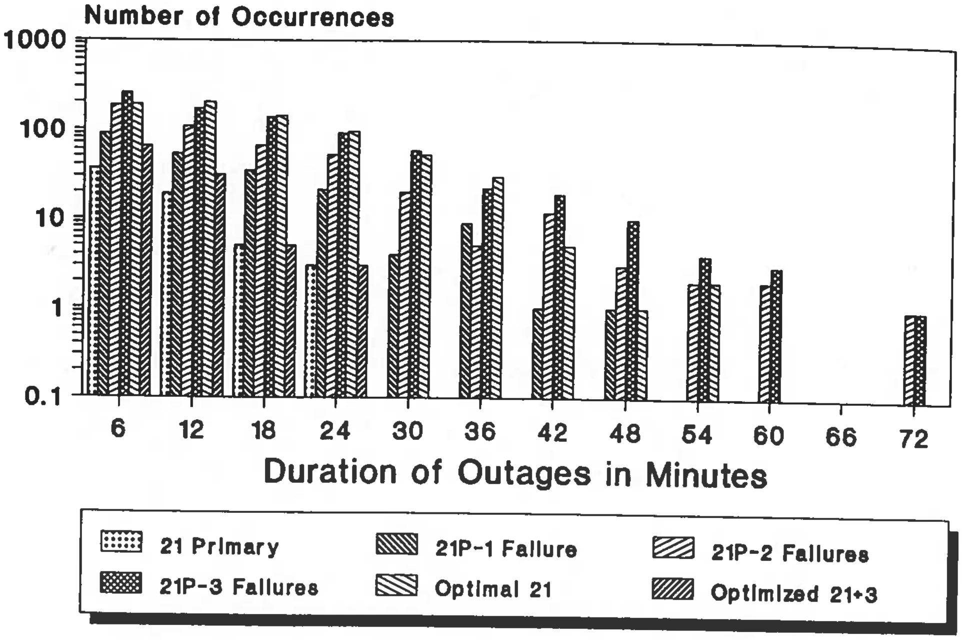

Fig. 7—Duration of Outages for Nonprecision Approach Navigation over CONUS Using 2.5 deg Mask Angle

Table 9—RAIM Detection Availability Over CONUS with Baro-Aiding (percent)

Constellation	En Route	Terminal	Nonprecision Approach
21 Primary—0 failures	99.99	99.84	99.02
21 Primary—1 failure	99.87	99.34	96.82
21 Primary—2 failures	99.79	98.46	93.90
21 Primary—3 failures	99.39	97.44	90.43
21 Primary—weighted avg. (0, 1, 2, & 3 failures)	99.54	98.48	94.53
Optimal 21—0 failures	99.96	99.16	96.13
Optimized 21 + 3—0 failures	99.99	99.90	99.20

be rare events for GPS. Based on the results of an IBM study, a conservative estimate is, on average, only 3.6 failures per year [11].

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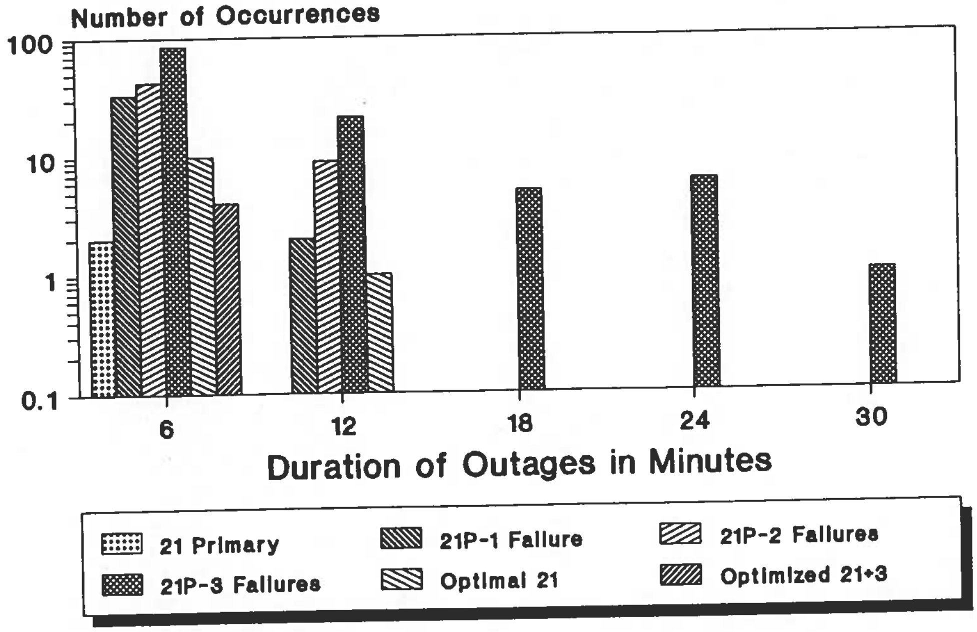

Fig. 8—Duration of Outages for En Route Navigation over CONUS with Baro-Aiding

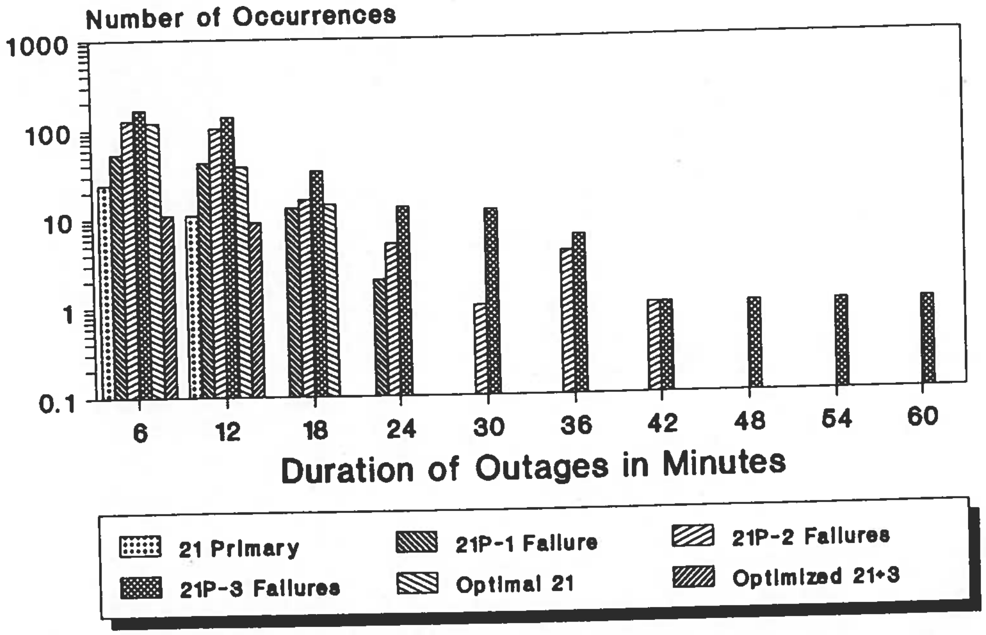

Fig. 9—Duration of Outages for Terminal Approach Navigation over CONUS with Baro-Aiding

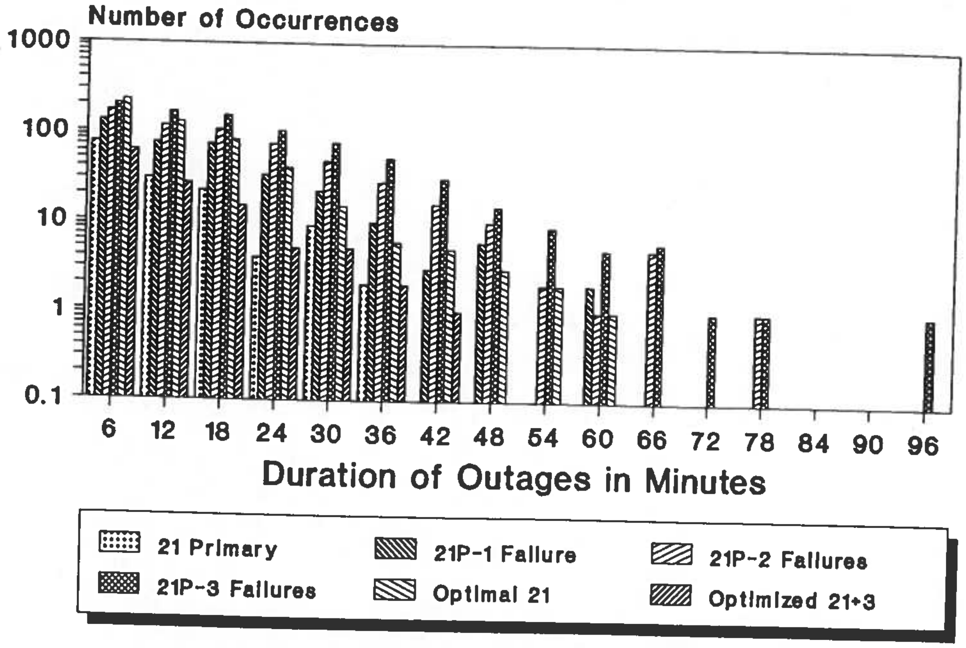

Fig. 10—Duration of Outages for Nonprecision Approach Navigation over CONUS with Baro-Aiding

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