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RECEIVER AUTONOMOUS INTEGRITY MONITORING USING A 24-SATELLITE GPS CONSTELLATION

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RECEIVER AUTONOMOUS INTEGRITY MONITORING USING A 24 - SATELLITE GPS CONSTELLATION

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BIOGRAPHY

Dr. Alison Brown has over seven years experience working with GPS. Presently she is the director of GPS operations at Applied Technology Associates, Inc., responsible for all GPS related systems engineering and analysis contracts. Previously she worked at Litton Aero Products where she was responsible for the design and development of their third generation GPS card set.

Dr. Brown holds a B.A. in engineering from Cambridge University, an M.S. in Aeronautics/Astronautics from MIT and a Ph.D. in mechanics and Aerospace from UCLA. She has three GPS related patents pending and has published numerous papers on GPS related topics. She has been an active member of RTCA SC-159 working on a Minimum Aviation Systems Performance Standard (MASPS) for GPS. She chaired the SC-159 Integrity Working Group and is presently secretary for the GPS Integrity Channel (GIC) working group. She is also the editor for the ION Satellite Division newsletter.

ABSTRACT

The Global Positioning System (GPS) will become operational in the 1990s and will provide global, continuous accurate navigational service for aircraft, ships, and land vehicles. Recent studies by the Transportation Systems Center (TSC) have shown that the proposed 18 satellite constellation, even with the three active spares, will not provide adequate reliability for aviation usage in the National Airspace System. For this and other reasons the Department of Defense (DoD) is considering increasing the number of satellites in the constellation to 24.

It is essential that the satellite signals be monitored to ensure that no malfunctions have occured. While the DoD Control Center takes care of most of the malfunctions, it is possible that subtle problems could occur before the Control Center had the satellite shut down or indicated poor health in the navigation data. This monitoring could be performed on the ground. However, receiver autonomous integrity monitoring (RAIM) is possible under certain conditions, allowing errors to be detected by the GPS receiver itself without expensive ground equipment.

With the 24 satellite constellation, there are always a minimum of 6 satellites in view anywhere. If satellites are tracked to near the horizon, then generally 7 or more satellites are in view. By using redundant information from five satellites with favorable geometry, it is possible to detect when a single satellite has failed (DETECTION), although it may not be possible to determine which one failed (ISOLATION). If six satellites are visible with good geometry then it is possible to both detect and isolate the errant satellite, and remove it from the constellation. Isolation of the failed satellite would allow an aircraft on a non-precision approach to continue to a landing. If the failure was detected but not isolated, then it would be necessary to conduct a missed approach.

In this paper, the 24 satellite constellation is studied to investigate the conditions under which both failure detection and isolation are possible using RAIM.

1.0 24 SATELLITE CONSTELLATION GEOMETRY

Two 24 satellite constellations were analyzed, a 3-plane and a 6-plane constellation. The relative phasing of the two 24 satellite GPS constellations are shown in Tables 1 and 2. To study the geometry of the 24 satellite constellation over the continental United States (CONUS), coverage must be investigated over 24 hours, 25 to 50 degrees north latitude, and 60 to 130 degrees west longitude. However, by taking advantage of the symmetries in the 24 satellite constellations, the size of the area to be simulated can be greatly reduced.

Table 1. 3-Plane Constellation Satellite Labels and Phases

Orbital Plane	0°	120°	240°
SV#/Phase	0/ 0°	1/ 15°	2/ 30°
	3/ 45°	4/ 60°	5/ 75°
	6/ 90°	7/105°	8/120°
	9/135°	10/150°	11/165°
	12/180°	13/195°	14/210°
	15/225°	16/230°	17/255°
	18/270°	19/295°	20/300°
	21/315°	22/330°	23/345°

Table 2. 6-Plane Constellation Satellite Labels and Phases

Orbital Plane	0°	60°	120°	180°	240°	300°
SV#/Phase	0 / 0°	1/ 15°	2/ 30°	3/ 45°	4/ 60°	5/ 75°
	6 / 90°	7/105°	8/120°	9/135°	10/150°	11/165°
	18/270°	19/295°	20/300°	21/315°	22/330°	23/345°

The constellation looks identical to a user if time and user coordinates are shifted or reflected in a particular way (Ref. 1). There are three fundamental symmetries for the 3-plane constellation and four for the 6-plane constellation. Other symmetries can be derived by applying these fundamental symmetries repeatedly. Tables 3 and 4 tabulate the transformations associated with these symmetries.

Table 3. 3-Plane Constellation Fundamental Symmetries

Symmetry Number	1	2	3
Time (t')	t	t-8.5hr	3.5hr-t
User Latitude (ϕ')	$-\phi$	ϕ	ϕ
SV# (n')	n+12	n-7	5-n

Table 4. 6-Plane Constellation Fundamental Symmetries

Symmetry Number	1	2	3	4
Time (t')	t	t + 2.5 hr	1.5 hr - t	-1.5 hr - t
Latitude (ϕ')	$-\phi$	ϕ	ϕ	ϕ
Longitude (λ')	$\lambda + 180^\circ$	$\lambda + 22.5^\circ$	$-22.5^\circ - \lambda$	$22.5^\circ - \lambda$
SV# (n')	n + 12	n - 5	9 - n	15 - n

The line-of-sight (LOS) vector of a satellite observed at time t and location (ϕ, λ) in latitude and longitude can be computed from the following equations. The satellite is located in orbital plane Ω with phase angle u.

$$N = -r \sin\phi \cos u \cos(\Omega - \lambda) + r \sin\phi \sin u \cos i \sin(\Omega - \lambda) + \qquad (1)$$

$$E = r \cos u \sin(\Omega - \lambda) - r \sin u \cos i \cos(\Omega - \lambda) \qquad (2)$$

$$D = -r \cos\phi \cos u \cos(\Omega - \lambda) + r \cos\phi \sin u \cos i \sin(\Omega - \lambda) + -r \sin\phi \sin u \sin i + R - e^2 R \sin^2\phi \qquad (3)$$

Table 5 summarizes the effect of the symmetry transformations shown in Tables 3 and 4 on the line-of-sight vector to the GPS satellites.

Table 5. Transformed Satellite Coordinates and Components of Line-of-Sight Vector

Symmetry Number	1	2	3, 4
$\Omega' - \lambda'$	$\Omega - \lambda - 180^\circ$	$\Omega - \lambda$	$180^\circ - \Omega - \lambda$
u'	$u + 180^\circ$	u	$180^\circ - u$
N'	-N	N	N
E'	E	E	-E
D'	D	D	D

1.1 IRREDUCIBLE DOMAN

By repeatably applying the symmetries shown in Tables 3 and 4, the area of irreducible doman can be generated for the 3-plane and 6-plane 24 satellite constellations. Conversely, global coverage can be simulated by mapping any location on the earth into the irreducible domain. Figures 1 and 2 show the mappings in time and longitude for the 3-plane and 6-plane constellations. These mappings repeatably use transformations 2, 3, and 4. Locations can be mapped in latitude from the northern to the southern hemisphere using Transformation 1. The irreducible domains for the 3-plane and 6-plane satellite constellations are given in Table 6.

Figure 1. Mapping of Irreducible Domain For 3-Plane Constellation

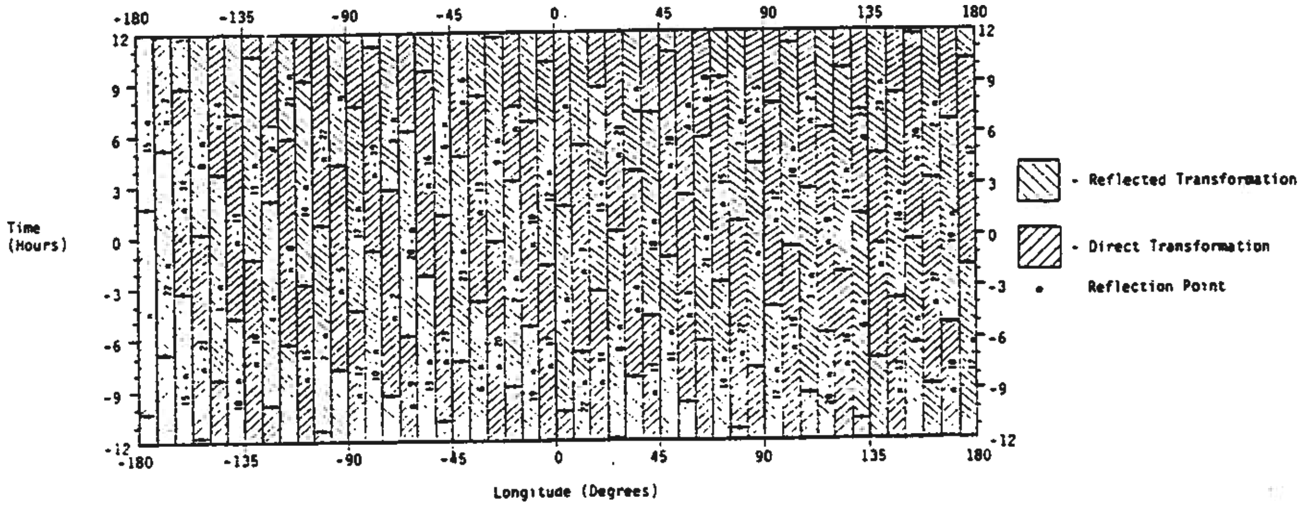


Figure 2. Mapping of Irreducible Domain For 6-Plane Constellation

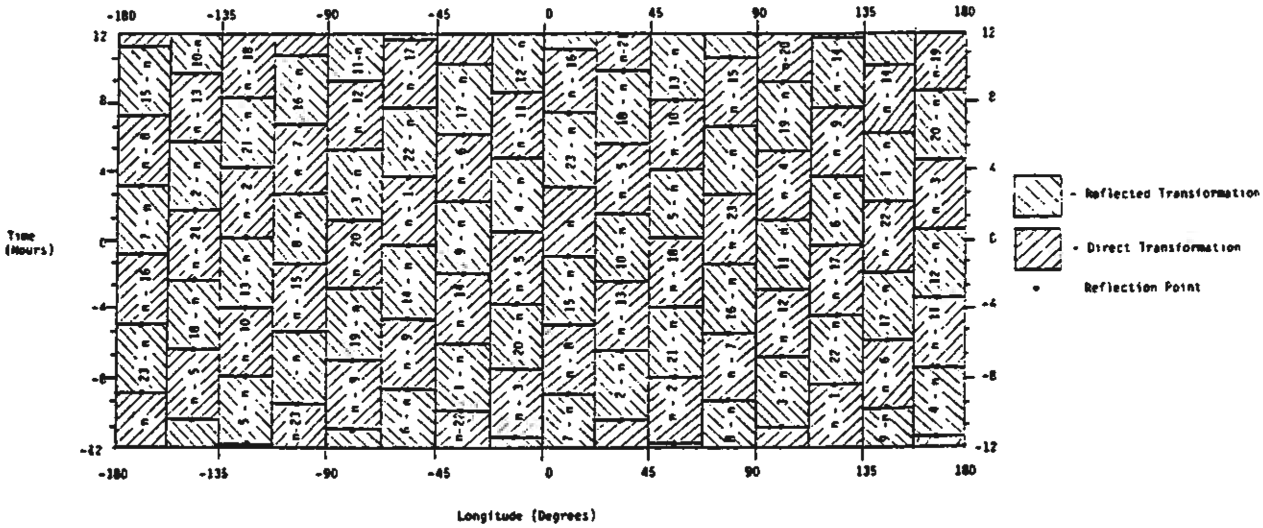


Table 6. 24 Satellite Constellation Irreducible Domain

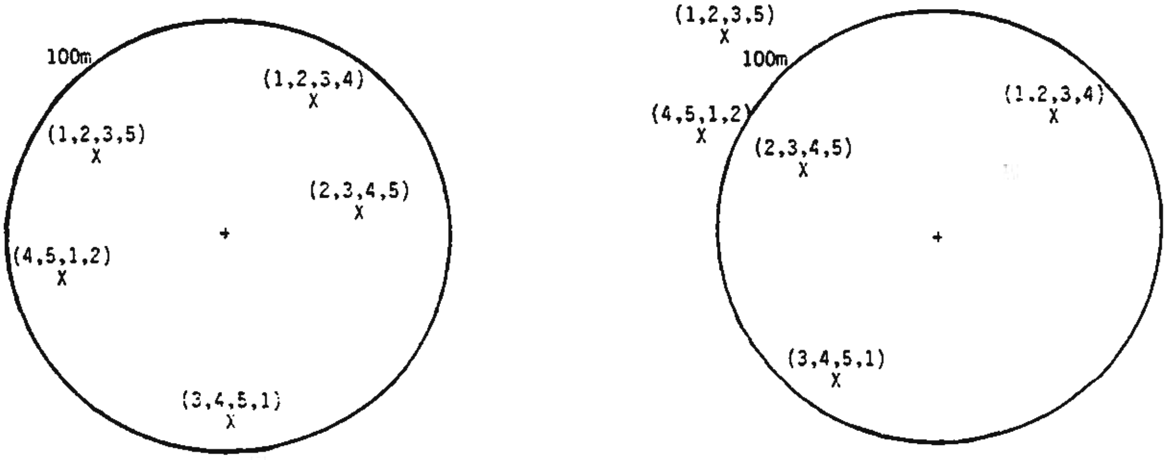
3-Plane Constellation	6-Plane Constellation
t = [1hr 45m, 13hr 45m) λ = [0, 7.5 degrees) φ =[0, 90 degrees)	t = [-45m, 3hr 15m) λ = [0, 22.5 degrees) φ = [0, 90 degrees)

2.0 FAILURE DETECTION AND ISOLATION

To guarantee integrity, it must be possible to always detect when a satellite failure has occurred. To continue navigation with GPS after detecting a satellite failure, it must also be possible to isolate the failure to a particular satellite and discontinue use of that satellite for navigation. The failure isolation criterion is therefore more stringent than the failure detection criterion.

In Figure 3, two conditions are shown for navigation with 5 satellites in view (SV#s 1,2,3,4,5). In the first case, it is assumed that all satellites are operating correctly. Since only four satellites are required to form a unique navigation solution, there are 5 possible navigation solutions as shown in Figure 3. The solutions are formed respectively using satellites (1,2,3,4), (2,3,4,5), (3,4,5,1), (4,5,1,2) and (1,2,3,5). Given that any navigation solution with a PDOP < 6 has an accuracy of 100m 2dRMS, and assuming that all of the combinations of satellites give a PDOP < 6, then all five of the navigation solutions will be within 100m 2dRMS (~98%) of the true solution as shown in Figure 3.

Figure 3. Possible Navigation Solutions with 5 Satellites



Case 1: No satellite failures

Case 2: SV# 5 failed

The percentages of time for which these areas occur for the 3-plane and 6-plane constellations is summarized in Table 9.

Table 8. Time/Locations Where Failure Detection Geometry is Poor with the 3-Plane Constellation

Hr	Mn	Lat	Long	SV#	PDOP
5	50	50.0	0.0	18	12.2
			2.5	18	12.2
6	5	50.0	0.0	18	10.5
			2.5	18	10.6
			5.0	18	10.6
12	55	50.0	5.0	4	13.4

Figure 6. Locations Where Failure Detection Geometry is Poor with the 6-Plane Constellation

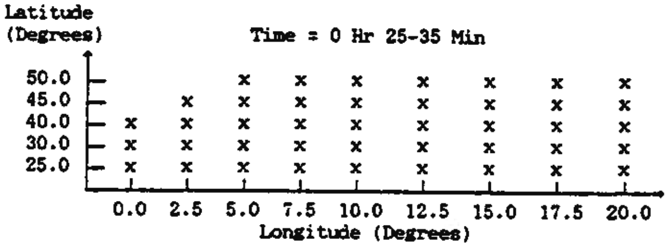


Table 9. Percentages of Time that RAIM Failure Detection Not Possible

3-Plane		6-Plane	
% Time	Max PDOP	% Time	Max PDOP
0.46%	13.4	6.56%	16.8

Although at first glance the results shown in Table 9. may seem to indicate that RAIM failure detection is not possible for some significant period, it is important to note the maximum level that the PDOP rose to during this period. Under normal conditions (PDOP < 6) the GPS navigation accuracy is 100m 2dRMS, so that a PDOP of 6 also allows an alarm limit of 200 meters to be set with low probability of false alarm. As discussed in section 2.0 and summarized in Table 7, an alarm limit of 200m and a navigation accuracy of 100m provides an integrity level of around 300m. If larger errors than 300m can be tolerated for integrity, then a PDOP of greater than 6 could be selected for the detection geometry criteria. A PDOP of 12, for example, would require an alarm limit of 400m to have a reasonably low probability of false alarm, a PDOP of 24 would require an alarm limit of 800m, etc. In Table 9, the maximum level that the PDOP reaches during the RAIM geometry deficiencies is shown to be only 17.

For the 3-plane constellation, an alarm limit of 446m could be set with a low probability of false alarm throughout the area of poor geometry. With the navigation accuracy provided by a PDOP of 13 (223m) the integrity level ensured would be 670m. As discussed in section 2.0 it is possible to guarantee higher levels of integrity with increased probability of false alarm by setting lower alarm limits. For the 6-plane constellation, following a similar argument, integrity could be ensured to 840m with low probability of false alarm and an alarm limit of 560m. This level of integrity is sufficient for all phases of flight except non-precision approach.

2.2 RAIM FAILURE ISOLATION SIMULATION RESULTS

To isolate a failure to a single satellite, it is necessary not only to detect that a failure has occurred, but also to show that a failure did not occur in the set of satellites with the failed satellite excluded. This requires that all sets of (N-2) satellites visible have good RAIM detection geometry. As with RAIM failure detection, as the PDOP increases for the (N-2) satellite subsets geometry, the integrity level that can be guaranteed decreases. Figures 7 and 8 show the percentage of times that isolation is not possible at the various PDOP levels.

Figure 7. Percentage of Times Failure Isolation Not Possible with the 3-Plane Constellation

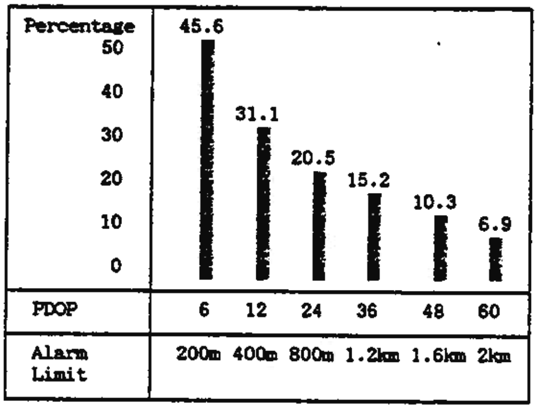
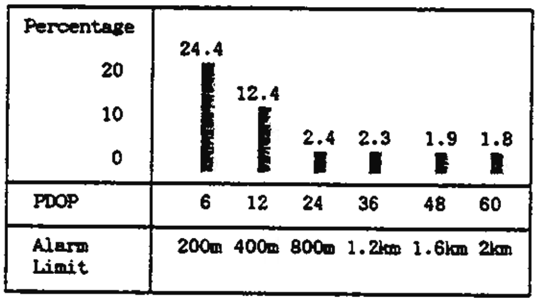


Figure 8. Percentage of Times Failure Isolation Not Possible with the 6-Plane Constellation



The numbers shown in Figures 7 and 8 are to a certain extent pessimistic. At one time, if any PDOP from a subset of (N-2) satellites exceeds the specified level, then a failure cannot be isolated to the two satellites excluded from that subset. However, failure isolation is possible for some of the visible satellites at that time/location. Figures 9 and 10 show the results of a weighted analysis, where the probability that failure isolation is not possible takes into account the probability that the particular satellite failed for which the isolation geometry is bad. As could be expected, the results are significantly improved. For the 3-plane constellation, the probability of a satellite failing in a location where it could not be isolated, assuming a PDOP $\geq$ 6, is 31.8%. For the 6-plane constellation the probability is only 14.3%. If higher PDOP levels are allowed, the failure isolation probability improves significantly. With a PDOP level of 24, which provides integrity to 1.2 km with an alarm limit of 800m, the probability of not isolating a failure decreases to 1.0% for the 6-plane constellation. This level of integrity is sufficient to meet existing en-route accuracy requirements.

In the second case shown in Figure 3, it is now assumed that SV# 5 has failed. It should be noted that the effect of this satellite failure on the navigation solution is dependent on the solution geometry, and so not every satellite failure will cause a navigation failure. In the case shown in Figure 3, only combinations (4,5,1,2) and (1,2,3,5) actually exceed the 100m (~98%) radius. However, we are guaranteed that at least one solution must be within 100m 2dRMS of the true position, since one navigation solution (1,2,3,4) does not use the failed satellite measurement. By comparing all five solutions (only one of which is now correct), we can detect that a satellite failure has occurred that has exceeded our navigation accuracy limits. The geometry condition for satellite detection therefore requires that every subset of (N-1) satellites out of the N satellites in view must have a PDOP < 6. This guarantees that out of the N possible navigation solutions with these (N-1) satellite subsets, there will always be at least one solution within 100m 2dRMS of the true position even when one satellite has failed.

The satellite failure alarm limit to be used with this technique, and the probability of false alarm are interrelated. From Figure 3, if all of the navigation solutions lie within the 100m (~98%) circle, then no two solutions can be more than 200m distant from each other. Therefore, if comparing position solutions results in a difference of greater than 200m, a satellite failure can be assumed to have occurred. This alarm level will guarantee integrity to around 300m, since the correct solution must be within 100m of the true position, and a 200m error is allowed before a failure is assumed to have occurred. If the alarm level is set at 100m between different position solutions, integrity will be provided to around 200m but the probability of false alarm will be increased as two solutions can exceed the alarm threshold but still be within 100m of the true position. The relationship between the alarm level set, the integrity provided and the false alarm rate is summarized in Table 7.

Table 7. Integrity Levels Provided by Comparison of Position Solutions with 100m 2dRMS Accuracy

Alarm Limit	100m	150m	200m
Integrity Level	200m	250m	300m
False Alarm Rate	High	Medium	Low

When only five satellites are view, it is possible only to detect that a satellite failure has occurred using this 'snap-shot' approach. Unless a-priori information is taken into consideration (Ref. 2), there is no way to determine which of the five navigation solutions is the correct one, and hence determine which satellite failed.

To isolate the failure to a particular satellite, when N satellites are in view it is necessary to show that a failure did not occur in a subset of (N-1) satellites. This proves that the failure must have occurred in the satellite excluded from the (N-1) subset. Therefore, for failure isolation, there must be good satellite detection geometry for every subset of (N-1) satellites. This condition is met if PDOP < 6 for every subset of (N-2) satellites out of the N visible satellites. This requires at least 6 satellites to be visible. If only 6 satellites are in view, every combination of 4 satellites out of the six (there are 15 combinations) must have a PDOP < 6 for failure isolation to be possible.

Figures 4 and 5 show the percentages of time that N satellites are visible above a mask angle of 5 degrees for the duration of the simulation. Since there are always at least six satellites in view, there is always redundant information available for receiver autonomous failure detection and isolation.

Figure 4. Relative Number of Satellites in View Above 5° Mask Angle for the 3-Plane Constellation

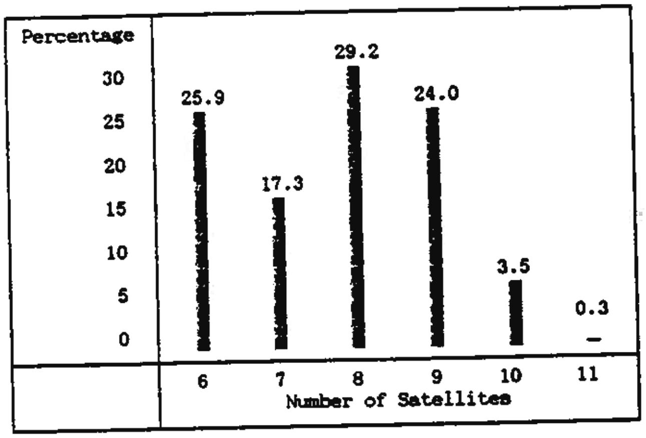
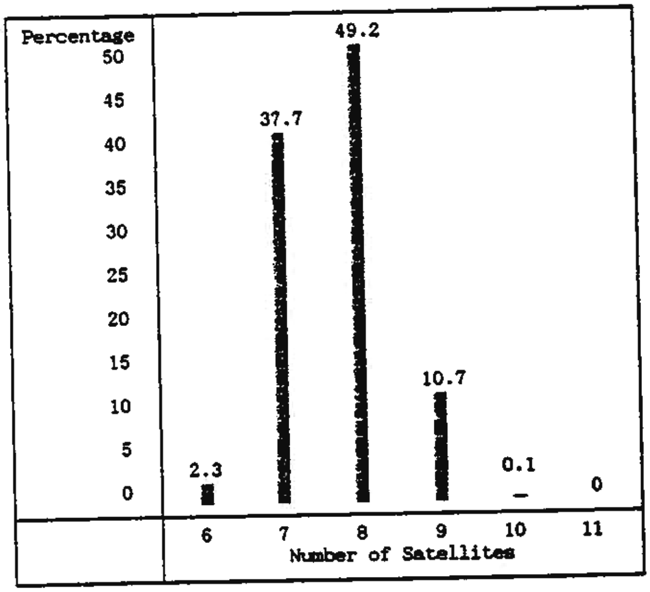


Figure 5 Relative Number of Satellites in View Above 5° Mask Angle for the 6-Plane Constellation



2.1 RAIM FAILURE DETECTION SIMULATION RESULTS

With the 3-plane constellation, there are only two areas where the geometry is deficient for RAIM. Both locations occur at 50 degrees latitude and last 10-20 minutes as shown in Table 8. Since the simulation only extended up to 50 degrees latitude, it is possible that this area of deficient geometry extends into higher latitudes.

The area of RAIM deficient geometry is more extensive for the 6-plane constellation. This area lasts for 10-20 minutes and extends over 25-50 degrees latitude as shown in Figure 6. This 'RAIM outage' occurs in a pattern similar to the navigation areas of degraded performance for the 18 satellite constellation.

Figure 9. Probability that Failure Isolation Not Possible with the 3-Plane Constellation

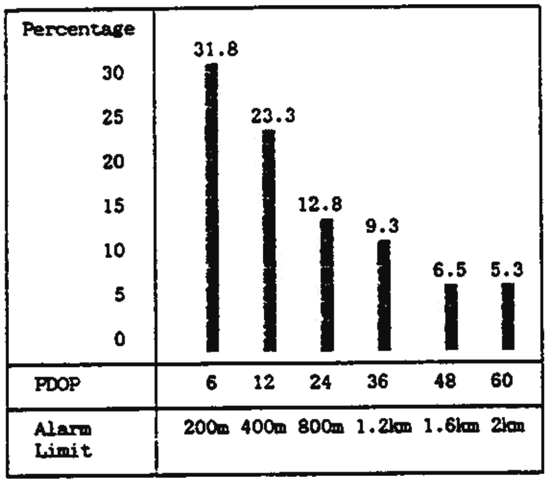
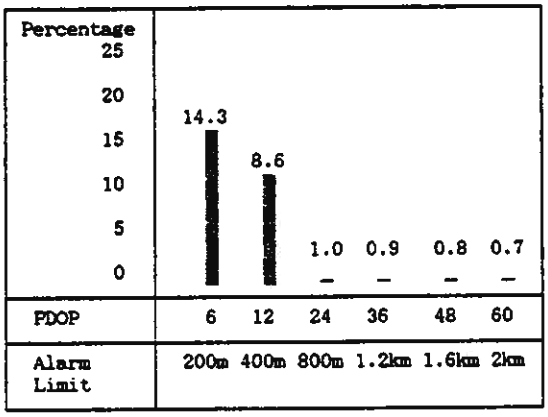


Figure 10. Probability that Failure Isolation Not Possible with the 6-Plane Constellation



2.3 POOR SATELLITE GEOMETRY CONDITIONS

To illustrate the geometry conditions under which RAIM failure detection and isolation are not possible, Figures 11 and 12 show the satellite positions at some of the time/locations where this occurs for the 3-plane and 6-plane constellations

In Figure 11 a poor failure isolation geometry is shown for the 3-plane constellation. In this case, no satellite failure can be isolated although the failure can be detected. This occurs since SV#s 8, 0 and 3 are near reflections in the E-W axis of SV#s 21, 5 and 2. Also, SV#s 2 and 3 are near reflections of SV#s 21 and 8 in the N-S axis.

In Figure 12 a poor RAIM failure isolation case is shown for the 6-plane satellite constellation. For this particular geometry, failures cannot be isolated to satellites 9 and 23 since the remaining satellites, (SV#s 0,1,3,4 and 5) only provide a PDOP of 8.

Figure 11. Failure Isolation Not Possible For SV#s 0, 2, 3, 5, 8, 21 (3-Plane Constellation).

Time = 1 hr 45 min Latitude = 40.0° Longitude = 2.5°

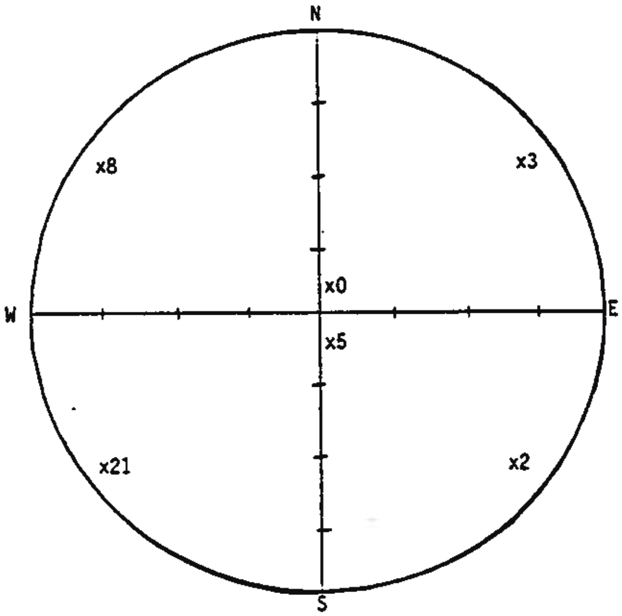
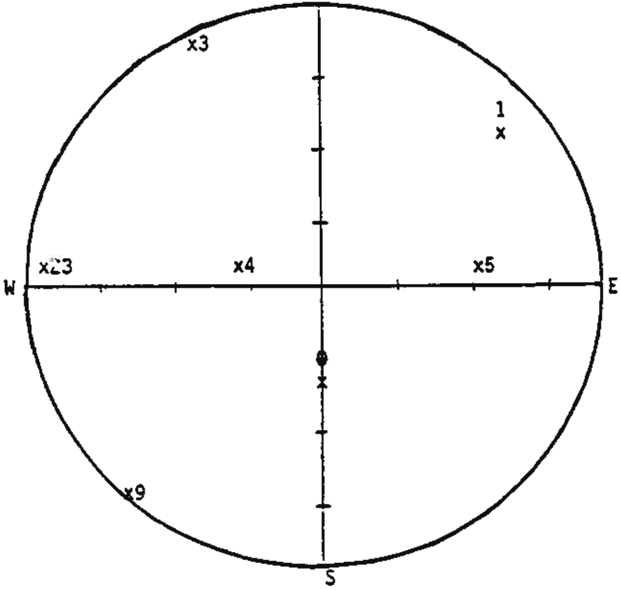


Figure 12. Failure Isolation Not Possible For SV#s 9 and 23 (6-Plane Constellation).

Time = 1 hr 35 min Latitude = 50.0° Longitude = 7.5°



3.0 CONCLUSIONS

It can be concluded from the simulation results presented in this paper that receiver autonomous integrity monitoring (RAIM) would prove effective were the GPS constellation to be increased to 24 satellites. The satellite coverage provided by both the 3-plane and 6-plane constellation is suitable to provide integrity for all phases of flight except for non-precision approach.

From the simulation results presented in Section 2.1, both the 3-plane and 6-plane satellite constellation continuously provide satellite failure detection geometries over CONUS with PDOP < 16. With the 24 satellite constellation, it is therefore possible to continuously detect when a satellite failure has occurred using RAIM. (However, the level of integrity that can be provided is dependent on the alarm limit selected with the associated probability of false alarm).

In Section 2.2, the simulation results for both failure detection and isolation using RAIM were presented for the 3-plane and 6-plane satellite constellations. The results were highly dependent on the level of integrity to be provided, i.e. the maximum allowable PDOP. If a PDOP $\leq$ 6 is required for integrity monitoring, then 32% of satellite failures cannot be isolated with the 3-plane satellite constellation and 14.3% cannot be isolated with the 6-plane constellation. If a lower level of integrity is sufficient (e.g. for en-route navigation), then higher values of PDOP can be tolerated and RAIM is significantly more effective. If a PDOP of 24 is considered to be sufficient for RAIM, then the probability that a satellite failure cannot be isolated drops to 12.8% for the 3-plane constellation and 1% for the 6-plane constellation.

From the simulation results it appears that the 6-plane constellation has marginally poorer geometry for satellite failure detection than the 3-plane constellation, but that the average satellite isolation geometry is significantly better. For this reason the 6-plane 24 satellite constellation would be preferable for receiver autonomous integrity monitoring.

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DESIGN OF DIFFERENTIAL GPS RECEIVERS FOR MARINE NAVIGATION

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Abstract

The Global Positioning System (GPS) is a satellite based navigation system, scheduled to become fully operational in 1989. Two classes of service will be available: the Precise Positioning Service (PPS) for military users, and the Standard Positioning Service (SPS) for commercial users. The PPS provides position to 16 m SEP, but in the interests of national security will be available only to a limited number of non-DOD users. The SPS is unrestricted but will only provide position to 100 m 2dRMS, which does not meet commercial maritime radio navigation or radio location accuracy requirements. However, by operating a GPS receiver in a 'differential' mode, substantially improved position accuracy is possible.

An RTCM special committee on differential GPS has recommended a suitable message format for broadcasting differential corrections. GPS navigation sets using these corrections can eliminate the GPS system errors from the navigation solution. The differential navigation accuracy is therefore primarily a function of the noise introduced by the receiver itself. The effect of the receiver noise on differential navigation accuracy has been studied for a variety of different receiver architectures under various dynamic environments. Considering cost/performance trade-offs, the optimum receiver architectures and potential navigation accuracies are discussed for differential GPS applications in marine navigation.

1.0 INTRODUCTION

The Federal Radionavigation Plan (FRP) requires 0.25 nm accuracy for oceanic and coastal marine navigation. This can be easily achieved using the Standard Positioning Service alone. Many other applications exist, however, where a more precise navigation reference is required. For Harbor Approach and in Harbor navigation, the FRP requires 8-10 m (2dRMS) navigation accuracy, and in some areas the International Association of Lighthouse authorities require 5 m navigation accuracy. Many other applications exist for a system that can provide 5 m positioning accuracy; for example, marine surveying, buoy positioning and civil oceanography.