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A GPS COVERAGE MODEL

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BIOGRAPHY

Dr. Trent A. Skidmore is on staff at the Ohio University Avionics Engineering Center where he is currently involved in the development of a Global Positioning System (GPS) coverage model. He also serves as principal investigator for the Visual EEG Tracking System (VETS) program and contributes to the improvement of the very-high-frequency omnirange (VOR) en route navigation system. He is a graduate of Ohio University (Ph.D., 1991) and Michigan Technological University (M.S., 1988 and B.S., 1986), all in electrical engineering. His research interests include digital signal processing, communication theory, and biomedical engineering.

ABSTRACT

This paper summarizes the results of several case studies using the Global Positioning System coverage model developed at Ohio University. Presented are results pertaining to outage area, outage dynamics, and availability. Input parameters to the model include the satellite orbit data, service area of interest, geometry requirements, and horizon and antenna mask angles. It is shown for precision-landing Category I requirements that the planned GPS 21 Primary Satellite Constellation produces significant outage area and unavailability. It is also shown that a decrease in the user equivalent range error dramatically decreases outage area and improves the service availability.

1. INTRODUCTION

An excellent summary documenting the impending need for a comprehensive Global Positioning System (GPS) satellite coverage model is given in [1]. To be complete, this summary is repeated here:

"The continuous movement of navigation satellites with respect to the surface of the earth results in continual changes of the system coverage. There may be times when the number of satellites in view of an aircraft near a particular airport would be less than that required for executing a precision approach. The periods of time when precision approach coverage will be inadequate at given airports must be known well in advance in order that operations may be restricted.

A satellite-based precision approach system requires a high level of availability within the service region to ensure operational suitability of the system. At the present time, a precise requirement for availability is not defined; however, preliminary studies indicate that system unavailability should be well below one minute per day. Critical sources of unavailability result from poor satellite geometry, planned satellite down time, known satellite failures, and planned ground equipment down time (e.g., a differential reference station). Thus the majority of the satellite system unavailability is predictable. The primary consequence of predictable unavailability is the need to schedule around the known outages. Since a single satellite covers a large geographical area, a satellite outage could potentially affect a large service area. This would result in major operation, capacity, and economic concerns. For instance, a one-hour outage in a metropolitan area would result in multiple simultaneous missed approaches and simultaneous replanning for many aircraft in the air.

Note that unpredictable outages are primarily a safety concern because of their significant effect on the guidance of aircraft during the approach and landing phase. The contribution of unpredictable outages to the overall system unavailability is anticipated to be small compared to the predictable outages, but this assumption must be verified.

A computer model would be used initially to characterize the coverage, and to analyze the size, duration, and dynamics of the outage areas under a wide variety of failure scenarios and for different system architectures. Input parameters to the model

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would include the service area of interest, satellite orbit data, geometry requirements, horizon and antenna mask angles, and satellite reliability data.

The descent of the aircraft while on an approach, along with the movement of navigation satellites, may also result in different optimal sets of satellites guidance at the initiation and at the conclusion of the approach. The impact of using a four or five channel receiver with potential satellite switching during the approach versus an all-in-view receiver must be addressed. The computer model can then be used as a tool to evaluate different system architectures.

...The criticality of this issue is judged to be HIGH, since coverage definition is necessary for the assurance of adequate system performance."

In order to address the GPS coverage issues, the Ohio University Avionics Engineering Center has been developing a comprehensive GPS coverage model. The different modules that comprise the model have been used in various applications as documented in reference [2]. This paper summarizes the most recent developments and highlights the model's unique features and capabilities. The results of several case studies are presented in order to gain an appreciation for the types of parametric studies the model will facilitate. The presentation concludes with a brief summary of additional work that is necessary in order to allow the GPS coverage model to be used as a complete system-analysis tool. It should be emphasized that the current model is capable of evaluating not only the present satellite architecture, but will eventually become a tool for designing and evaluating alternative satellite-based navigation architectures to meet precision-approach requirements.

2. CASE STUDIES

2.1 Introduction

This section details the results of several case studies involving the various modules which comprise the coverage model. For each case study presented, the test conditions are stated and results given. This is followed by a discussion and summary of the important conclusions.

The two case-study scenarios analyzed by the coverage model are summarized in Table 2.1. The parameters displayed in the table were chosen for validation purposes and to determine a near-global perspective on the system performance. Although these were chosen to be representative of the model's capabilities, additional work is still needed in order to develop minimum standards for time and space increments.

Table 2.1 Case-Study Initial Conditions

Test Conditions	Test 1 (World)	Test 2 (North America)
Max. N Lat.	90°	75°
Max. S Lat.	-90°	15°
Max W Long.	-180°	-170°
Max. E Long.	0°	-50°
Increment	5°	6°
Min. HDOP	-	2.3
Min. VDOP	-	9.2
Min. PDOP	6	-
Analysis Time	24 hours	24 hours
Time Increment	5 minutes	6 minutes
Constellation	Optimal 21	21 Primary

2.2 Case Study I: Counting Outages

As a first attempt at outage characterization, the duration and number of zero-failed satellite outages at each location in the search grid were determined. Figure 2.1 shows the Test-1 (World) outage contours. This result is essentially the same as that presented by Jorgensen [3]. Note that, in this case, even the complete constellation results in substantial outages. This is due to the fundamental limitations imposed by using the Optimal 21 Satellite Constellation. The inclusion of this result is not intended to be an analysis of the Optimal 21 Constellation, but is presented because of its importance to the validation of our model. The case studies shown throughout the remainder of the paper will be concerned exclusively with the GPS 21 Primary Satellite Constellation [4].

2.3 Case Study II: Outage Areas versus DOP

Shown in Table 2.2 are the Vertical Dilution of Precision (VDOP) requirements for the various categories of approach assuming a 6-foot user equivalent range error (95%) [5]. Table 2.3 expands upon this for the Category I landing by showing the required VDOP for different values of user equivalent range error (UERE). Throughout the paper, the required maximum allowable HDOP was chosen to be four times the specified VDOP.

The effect of varying DOP requirements (VDOP and/or HDOP) is of particular importance, especially when considering precision-approach issues. To determine the impact that the DOP requirement has on outage area, the model was used to characterize the outages based on the initial conditions set forth in Test 2 (North America). For this test, the GPS 21 Primary Constellation (as shown in Figure 2.2) was analyzed at three different DOP values for up to three failed

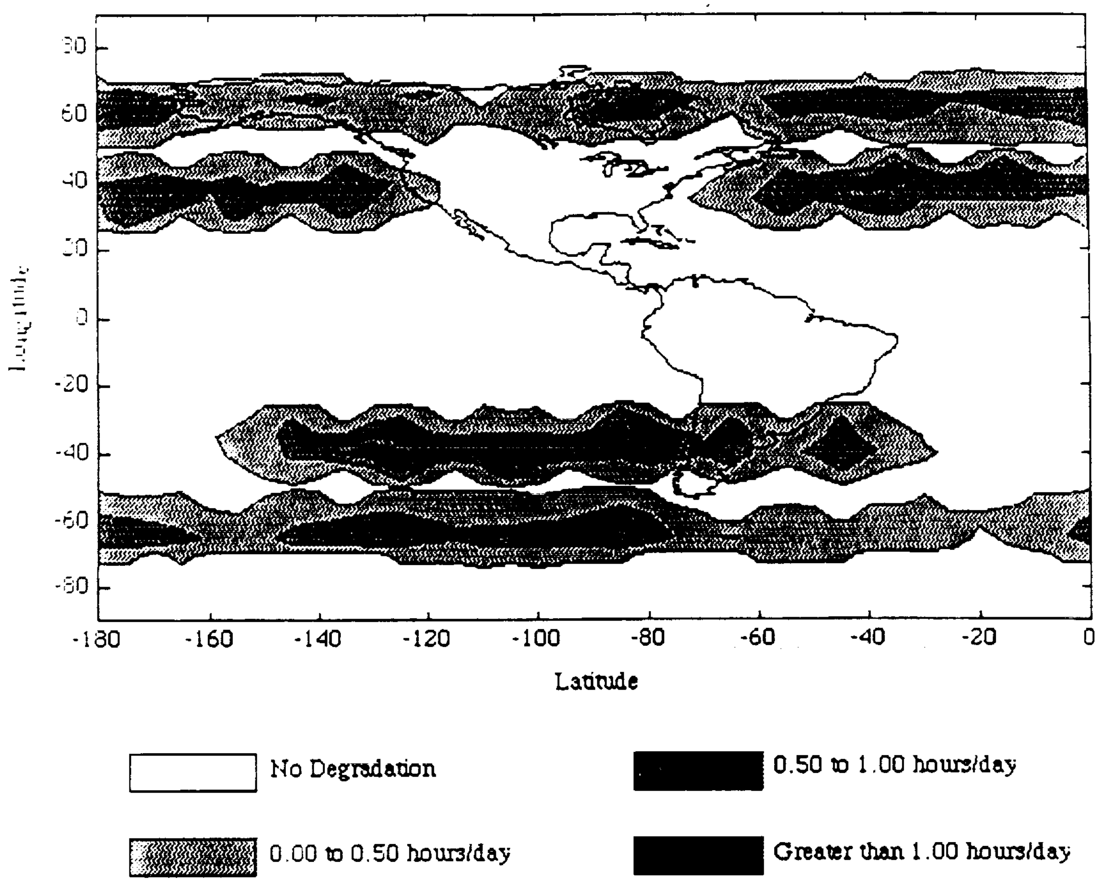

Figure 2.1 Accumulated Outages Per Day for Test 1. Contours show regions of degraded performance based on no failures in the Optimal 21 Satellite Constellation.

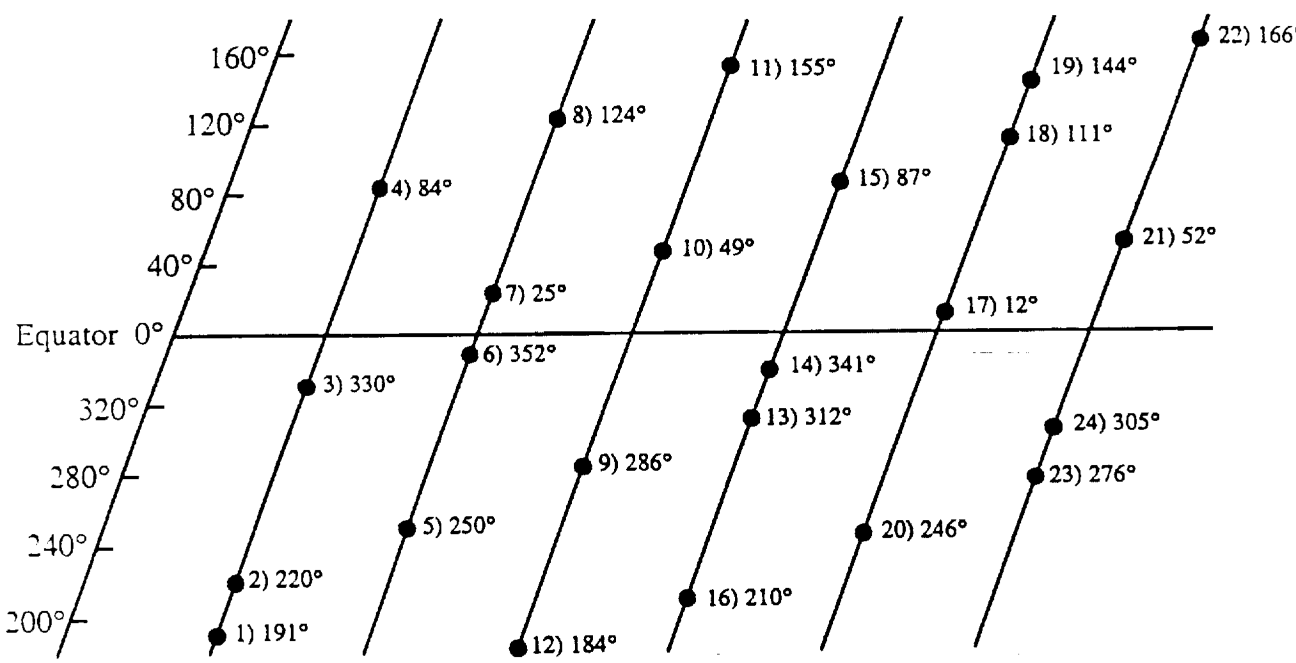

Figure 2.2 The GPS 21 Primary Satellite Constellation. The satellite numbering is based on the order in which the satellite ephemeris data is entered into the model.

satellites. Table 2.4 summarizes the worst and average satellite-failure combinations for each DOP condition.

Table 2.2 Vertical Accuracy as a Function of VDOP

Approach Category	Vertical Requirement (feet, 95%)	VDOP Requirement
I	13.5	2.3
II	5.6	0.9
III	2.0	0.3

Table 2.3 The Cat I Approach: VDOP and UERE

UERE (ft, 95%)	VDOP Requirement	Associated HDOP
6	2.3	9.2
3	4.6	18.4
1	13.8	55.2

Table 2.4 Worst and Average Satellite Failures

(HDOP, VDOP)	Worst Single Failure	Average Single Failure
(9.2, 2.3)	(22)	(11)
(18.4, 4.6)	(8)	(16)
(55.2, 13.8)	(22)	(20)
	Worst Double Failure	Average Double Failure
(9.2, 2.3)	(9, 22)	(5, 11)
(18.4, 4.6)	(6, 9)	(9, 20)
(55.2, 13.8)	(20, 22)	(5, 24)
	Worst Triple Failure	Average Triple Failure
(9.2, 2.3)	(10, 15, 22)	(1, 8, 23)
(18.4, 4.6)	(3, 6, 9)	(9, 10, 16)
(55.2, 13.8)	(1, 8, 22)	(8, 11, 19)

Note: Satellite numbering is based on Figure 2.2.

The most important observation that can be made based on an analysis of the data contained in Table 2.4 is that the worst- and average-failure combinations change as a function of HDOP and VDOP. This is evidence to the fact that the coverage provided by the 21 Primary GPS Constellation is highly nonlinear and nonuniform. Figure 2.3 also illustrates this nonlinearity by graphically displaying the average and worst-case outage area as a function of DOP and the number of failed satellites. To further illustrate this nonlinearity, consider Tables 2.5 and 2.6. Shown here are the ratios of outage-area decrease as a function of VDOP (and HDOP) relaxation. For example, from the worst-case single failure of Table 2.5 it can be seen that relaxing the (HDOP, VDOP) requirement by a factor of six decreases the corresponding outage area by a factor of 210, with pronounced area reductions occurring in the other cases as well. It is also interesting that DOP relaxation has a greater effect on the average failure combination than on the worst-case failure combination. This may be due to the fact that the worst-case failure combinations are highly sensitive to DOP requirements.

Table 2.5 VDOP Relaxation and Outage Area (The Worst-Case Satellite Failure)

Number of failed SVs	Relax VDOP (2.3 : 4.6) (1 : 2)	Relax VDOP (2.3 : 13.8) (1 : 6)
0	30.64	752.05
1	15.08	210.10
2	5.93	25.94
3	3.37	7.91

Table 2.6 VDOP Relaxation and Outage Area (The Average Satellite Failure)

Number of failed SVs	Relax VDOP (2.3 : 4.6) (1 : 2)	Relax VDOP (2.3 : 13.8) (1 : 6)
0	30.64	752.05
1	20.25	356.22
2	12.66	109.91
3	8.50	44.34

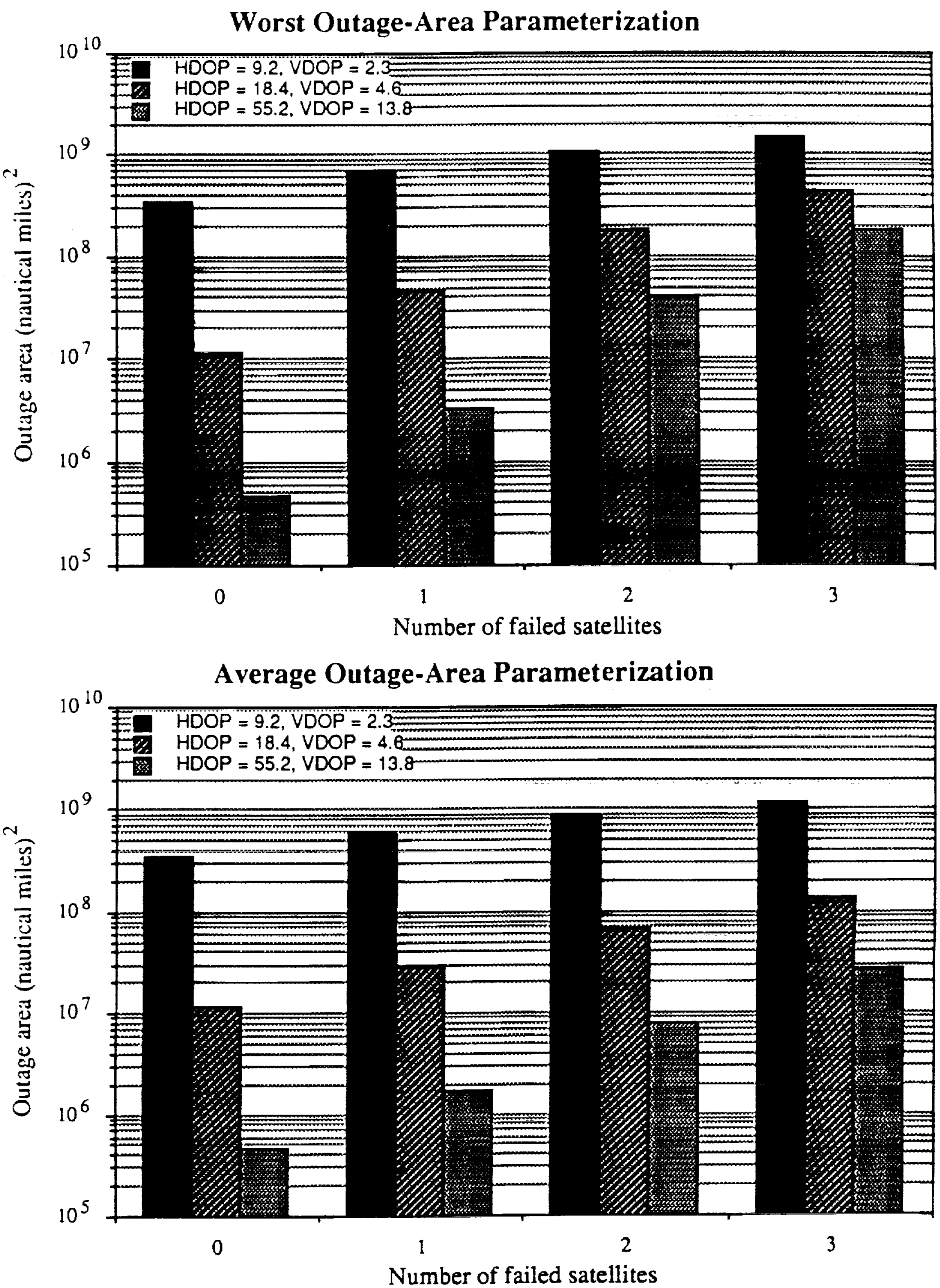

Figure 2.3 Worst-Case and Average Outage Area Parameterization. Shown is the zero-failure outage area along with the worst-case and average single-, double-, and triple-satellite failures as a function of DOP.

The histograms for the three-satellite failure case are shown in Figure 2.4. These demonstrate the distribution of failure combinations and the resulting outage areas. In each of the histograms it can be seen that the number of failure combinations close to the average is much greater than those close to the maximum. Thus, while averaging is not justified as a stand-alone means of system parametrization, it may be sufficient for a first-order approximation of system performance.

2.4 Case Study III: Outage Dynamics

A very important feature of the current model is the ability to generate movies, or slides, which give a time-dependent record of the outage areas. Figure 2.5 shows the outages generated during five consecutive five-minute intervals. The frames were generated using the Test-2 (North America) conditions. The outage contours are the result of failing satellites 1, 4, and 5 with a (HDOP, VDOP) requirement of (55.4, 13.8). The slides demonstrate that huge outages can appear and disappear very quickly. As one might expect, the outage contours generally exhibit an easterly movement. However, it also appears that the DOP requirements dictate outages more than the overall movement of the satellites. This is evidenced by the appearance and disappearance of the large outage areas.

The implication of these results is especially important when considering the outage-based alternate-airport issue. For an en route aircraft navigating in the middle of an outage area, the most probable course of action would be to maintain course and wait for the outage to dissipate. For an aircraft navigating in the terminal area, the issue of landing at an alternate airport is rather mute. Unless the primary airport is on the outside border of an outage, the probability of finding a suitable alternate airport is prohibitively low. Again, the most likely course of action would be to wait for the outage to dissipate. The situation is somewhat analogous to an aircraft entering a terminal with a single instrument landing system (ILS). If the ILS were to fail during an approach, a missed approach procedure would be taken, followed by further instructions from the ground station to the pilot. If an approach were being flown using GPS and an outage occurred, a monitoring station equipped with the GPS coverage model could quickly determine the nature and extent of the outage. Using a model capable of predicting the movement of the current outage, the pilot could be advised of the best course of action. While more work is undoubtedly needed in this area, the ability to track outages as a function of time should prove to be of great value in the evaluation of satellite-based navigation systems.

2.5 Case Study IV: Availability

To determine the availability (and subsequent unavailability) for each location in the North American search grid, the Markov state probabilities shown in Table 2.7 were used [5-8].

Table 2.7 Steady-State Markov Probabilities

Number of failed SVs	Markov Probabilities	Cumulative Probability
0	0.703	0.703
1	0.227	0.930
2	0.055	0.985
3	0.012	0.997
4	0.002	0.999
5	0.00042	0.99942
6	0.000071	0.999491

In order to create an outage record of workable size in the current computing environment, system availability was calculated by only considering up to three failed satellites. Thus, the maximum availability would necessarily be limited to 0.997, or an unavailability of 0.003 (1.000 - 0.997). This is equivalent to a minimum system unavailability of 4.32 minutes per day. While only allowing for three satellite failures seems somewhat prohibitive, it will be seen in the next section that the majority of unavailability is accounted for in just considering up to three satellite failures. Shown in Figure 2.6 are the unavailability contours for the North American continent. The plots dramatize the expected unavailability of the GPS 21 Primary Satellite Constellation as a function of location and dilution of precision. It is interesting to note the high degree of location dependency in each of the contours. From the contours it is evident that the stringent DOP requirement of (HDOP = 9.2, and VDOP = 2.3) results in substantial unavailability (2-7 hours) whereas the least stringent requirement (HDOP = 55.4, and VDOP = 13.8) results in significantly lower overall unavailability approaching the analysis-imposed 4.32 minutes-per-day limit.

The ratios of maximum and average unavailability as a function of DOP are summarized in Table 2.8. In comparing Table 2.8 with its counterparts for outage area (Tables 2.5 and 2.6), we see that relaxation of the DOP requirements has a similar nonlinear affect on unavailability. Also, it is again seen that the effect is greater on the average than at the extremes. In the

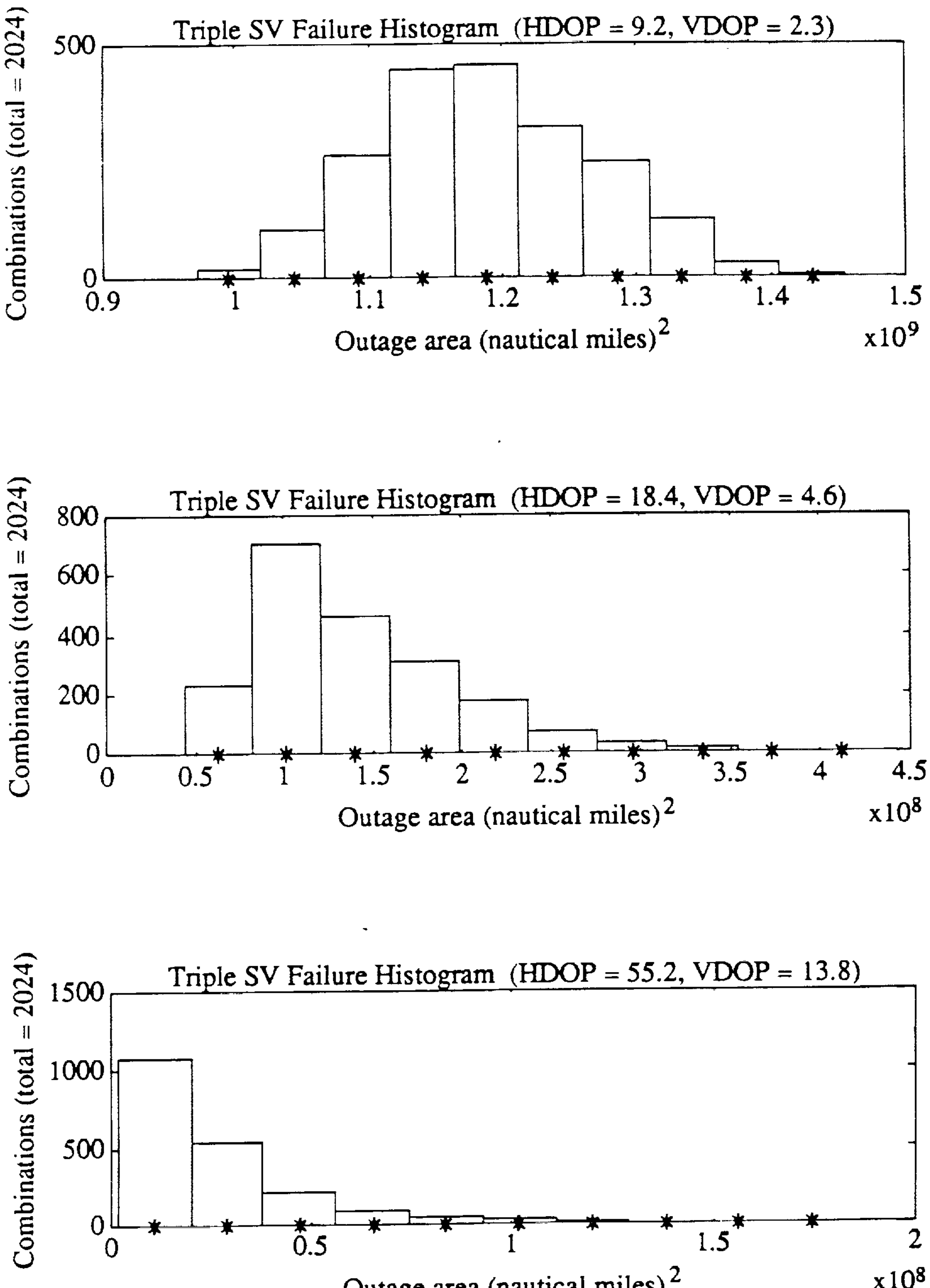

Figure 2.4 Triple Satellite Failure Histograms.
The number of triple satellite failures causing the specified outage area is given as a function of DOP.

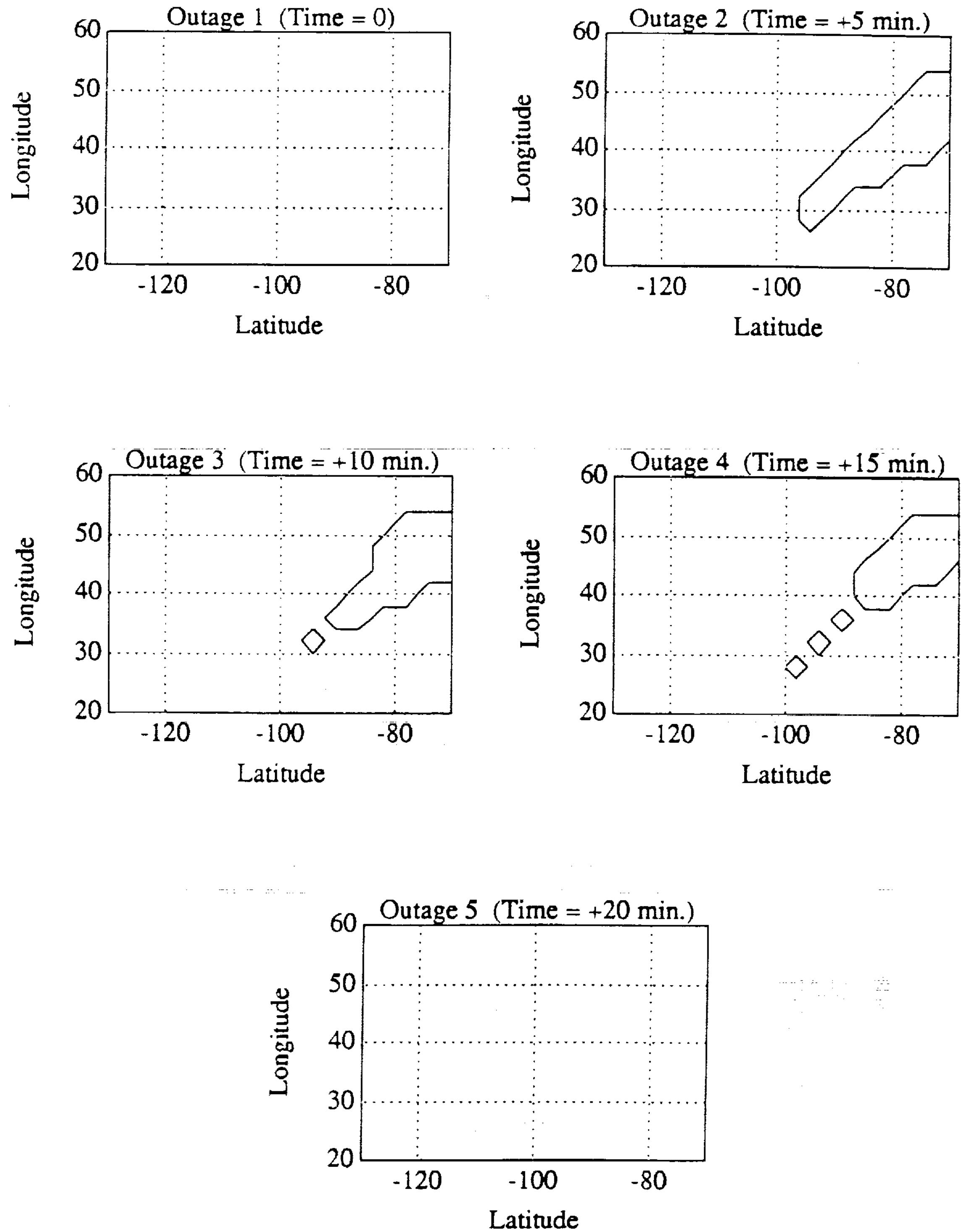

Figure 2.5 Outage dynamics as a function of time. Contours show outage regions as a result of failing satellites 1, 4, and 5 with a dilution of precision requirement of (VDOP = 13.8, HDOP = 55.2).

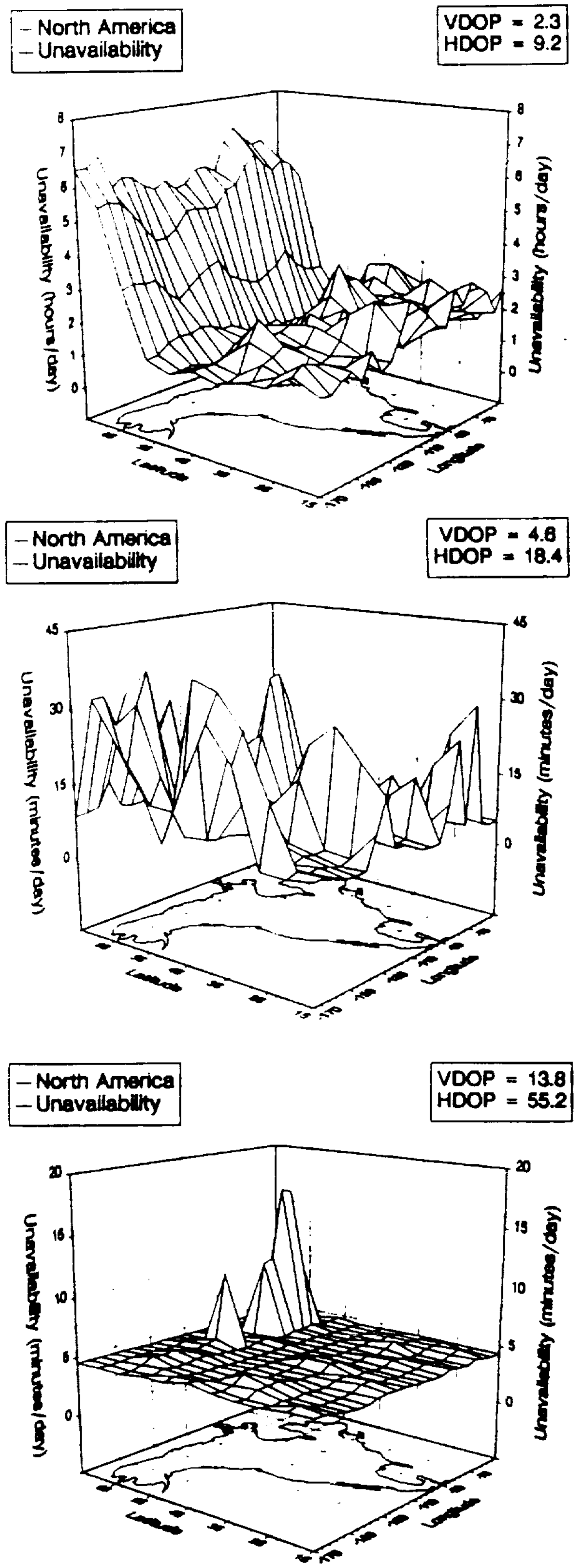

Figure 2.6 3-Dimensional Unavailability Contours. The three contour plots show unavailability as a function of location and dilution of precision (DOP).

next section, the model will be applied to a limited number of important locations in order to determine if they are representative of the entire North American search region.

Table 2.8 VDOP Relaxation: Worst and Avg. Unavail.

Number of failed SVs	Relax VDOP (2.3 : 4.6) (1 : 2)	Relax VDOP (2.3 : 13.8) (1 : 6)
Worst-Case Unavailability	10.92	24.92
Average Unavailability	14.65	33.11

2.6 Case Study V: Specific Airports

In an attempt to develop a benchmark for determining the number of satellite failures needed to best quantify the current system, the model was used to calculate the maximum and average unavailability experienced by the ten busiest airports in the United States (as reported by the Aircraft Owners and Pilots Association). Table 2.9 lists the name and location of these airports.

Table 2.9 The AOPA Ten Busiest U.S. Airports

Airport Name	Airport Location
1. Chicago O'Hare Int'l	41°58' N 87°54' W
2. Atlanta Int'l	33°38' N 84°35' W
3. Dallas/Ft. Worth Int'l	32°53' N 97°02' W
4. Los Angeles Int'l	33°56' N 118°24' W
5. Santa Ana	33°40' N 117°52' W
6. Van Nuys	34°12' N 118°29' W
7. Phoenix Sky Hrbr. Int'l	33°26' N 112°00' W
8. Long Beach	33°49' N 118°09' W
9. Denver Stapleton Int'l	39°46' N 104°52' W
10. Miami Int'l	25°47' N 80°17' W

Source: AOPA 1992 Fact Card (1990 Data), Aircraft Owners and Pilots Association, Frederick, Maryland.

For these locations, the model was run for up to and including six satellite failures. The maximum and average unavailabilities for failing 3, 4, 5, and 6 satellites for the ten busiest general aviation airports are shown in Table 2.10. These values are based on the Category I requirement of (HDOP = 9.2, VDOP = 2.3) assuming a UERE of 6 ft. (95%).

From Table 2.10 it can be seen that, on the average, the difference in the computed unavailability for running the model to three failures is only about two percent higher than running the model to its current limit of six failures. This appears to indicate that, in order to obtain a good approximation of system availability, the model need only consider up to three satellite failures. Naturally, as different constellations are evaluated, this assumption may no longer be valid and will require further investigation. It is worth noting that, while none of these airports represent the maximum unavailability discussed previously, they are representative of the average of the entire search grid to within 22%, or approximately 30 minutes of unavailability. While this seems to be a rough approximation, it may be justified in instances where a quick check is sufficient.

Table 2.10 Unavailability Calculations

Max. number of failed SVs	Maximum Unavailability (hours/day)	Average Unavailability (hours/day)
3	2.90	2.17
4	2.87	2.14
5	2.86	2.14
6	2.86	2.13

3. SUMMARY

The characterization of outages in the coverage provided by the Global Positioning System is of utmost importance when considering GPS as a sole means of navigation and as a navigation aid for flying a precision approach. The continued development of the Ohio University GPS coverage model will enable detailed parametric studies of various coverage issues. The application of the model was demonstrated through several representative case studies. These studies showed how various Dilution of Precision (DOP) requirements affect system performance.

Future work will include designing and running additional simulations to determine key system parameters. The model presented in this report will serve as a foundation for the development of a complete coverage model with the capacity of evaluating (and thus designing) a robust satellite-based navigation system.

ACKNOWLEDGEMENTS

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