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GPS RISK ASSESSMENT STUDY

FINAL REPORT

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY
11100 Johns Hopkins Road, Laurel, Maryland 20723-6099
Operating Under Contract 98-JHU-01 With the Air Transport Association

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FINAL REPORT

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ABSTRACT

The Federal Aviation Administration (FAA) has initiated plans to transition from its present ground-based navigation and landing system to a satellite-based system using signals provided by the Department of Defense's Global Positioning System (GPS). However, GPS alone will not meet all aviation positioning requirements. To meet the National Airspace System (NAS) requirements, the FAA has proposed two augmentations to GPS: a Wide Area Augmentation System (WAAS) and a Local Area Augmentation System (LAAS). There have been expressions of concern regarding the robustness of this plan and whether the risks to dependence upon GPS have been adequately addressed. In response to this concern, the FAA, with co-sponsorship from the Air Transport Association (ATA) and the Aircraft Owners and Pilots Association (AOPA), issued a request for an impartial study. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) was selected to conduct that study, which is the subject of this report.

The report quantifies the ability of GPS, GPS/WAAS, and GPS/LAAS to satisfy Required Navigation Performance (RNP) as expressed by accuracy, integrity, continuity, and availability requirements. Additional navigation options that mitigate the identified risks were also evaluated. In particular, these options included potential improvements to the GPS Standard Positioning Service (SPS) and additional capabilities onboard the aircraft such as integration of additional sensors and application of GPS anti-jam technologies.

KEYWORDS: National Airspace System
Global Positioning System
Navigation

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EXECUTIVE SUMMARY

ES.1 PERFORMANCE

An independent risk assessment was conducted by the Johns Hopkins University Applied Physics Laboratory (JHU/APL) to determine if the Global Positioning System (GPS) and augmented GPS can satisfy the performance requirements to be the only navigation system installed in an aircraft and the only service provided by the Federal Aviation Administration (FAA) for operations anywhere in the National Airspace System (NAS). This report quantifies the ability of GPS, GPS with the Local Area Augmentation System (LAAS), and GPS with the Wide-Area Augmentation System (WAAS) to satisfy navigation performance requirements as expressed by accuracy, integrity, continuity, and availability requirements. Oceanic through Category III Precision Approach operations were evaluated with risks that present both normal and abnormal degrees of performance degradations. The primary conclusion is that GPS must be augmented to meet these requirements and that WAAS/LAAS can provide the required navigation performance. The study considered all known risks and its primary conclusion assumes the identified mitigation actions are instituted, and specific WAAS/LAAS configurations are implemented. The main conclusions of the study are as follows:

a. GPS with appropriate WAAS/LAAS configurations can satisfy the required navigation performance as the only navigation system installed in the aircraft and the only navigation service provided by the FAA.

b. Risks to GPS signal reception can be managed, but steps must be taken to minimize the effects of intentional interference.

c. A definitive national GPS plan and management commitment is needed to establish system improvements with civil aviation users and to provide greater informational access to the civil aviation community.

In particular, the final conclusion points to the need to develop a combined GPS and augmentations system design based on cost and performance trades among GPS system improvements, GPS operational policies, and WAAS/LAAS capabilities. Study findings with regard to the three system configurations considered are summarized in the following subsections.

ES.1.1 SATELLITE CONSTELLATIONS

Currently, 27 GPS satellites are operating. They provide the minimum basic configuration of 24 satellites (6 orbit planes of 4 satellites each) and 3 active on-orbit spares. The number of operating satellites could slip to 24 before additional replacements are added. In this study, the current constellation is assumed to be the nominal basic 24-satellite constellation (i.e., 6 by 4). The next logical extension of this geometry would be a 30-satellite constellation (i.e., 6 by 5), and that geometry was considered to represent an expanded GPS constellation that might practically be implemented.

The current GPS/WAAS test configuration is based on the current GPS constellation supported by two geostationary satellites (GEOS). Therefore, the base constellation for GPS/WAAS analysis was 24 GPS satellites and the current 2 GEOS. Improvements considered expansions up to five GEOS. GPS/LAAS analyses were based on the minimum acceptable GPS/WAAS configuration—a 24-satellite and a 30-satellite GPS constellation. Airport pseudolites (APLs) were also included to improve local geometry.

ES.1.2 GPS WITHOUT AUGMENTATION

A 24-satellite GPS constellation without augmentation cannot meet oceanic, en route, terminal, and nonprecision approach service requirements of the NAS. The removal of selective availability and/or the addition of a second civil frequency did not alter this finding. The best performance was achieved with a 30-satellite constellation (with selective availability off and a second civil frequency available), and even that configuration met the required levels of service for only oceanic navigation.

ES.1.3 GPS/WAAS

A GPS/WAAS configuration with 24 GPS satellites and 4 GEOS can satisfy all NAS positioning requirements from oceanic through Category I approach. This result did not require any specific improvements to the GPS satellites. Performance is sensitive to the ionospheric correction methods and further analysis is recommended to better optimize the WAAS configuration (i.e., number of GEOS and number of ground stations). It must also be noted that the current GEOS establishment and replacement plan is not yet clearly identified; this plan must be defined to ensure the required capabilities are provided.

ES.1.4 GPS/LAAS

A GPS/LAAS configuration based on a 30-satellite GPS constellation or one with 24 GPS satellites and 4 GEOS can satisfy all precision approach requirements. Some airports will require ground transmitters that act like additional GPS satellites (APLs) and/or improved GPS antennas and extra receivers to achieve the highest availability levels (i.e., >0.99999). This level of performance will require no GPS satellite improvements.

ES.1.5 PENDING GPS SIGNAL IMPROVEMENTS

Because the current augmentation designs are responsive to the current GPS satellite signal conditions, the removal of selective availability and the addition of a second civil frequency did not have a major impact on the cases analyzed for this study. However, the pending GPS signal improvements are very important to system robustness and to eventual cost savings and/or performance improvements of the final system.

Removal of selective availability greatly reduces the information rate required for the corrections provided by WAAS and LAAS, which reduces the communications burden. More importantly, removal of selective availability could allow the system to maintain acceptable performance even with a brief interruption of communications. With GPS/LAAS, for example, the corrections provided at the start of an approach would be valid throughout the approach.

As announced by Vice President Al Gore in March 1998, the secondary military frequency (1227.6 MHz) would have an added signal modulation that could be used for civil applications. However, the second frequency referred to in this report is required to be in a portion of the spectrum that is internationally allocated for aeronautical radio-navigation services. A White House press release on 25 January 1999 announced that agreement has now been reached on the addition of a new GPS frequency (1176.45 MHz) that will provide the second frequency capability needed to serve the NAS requirements.

The impact of the second civil frequency will completely remove the requirement for ionospheric corrections for users equipped to take advantage of this feature, and it will improve the corrections provided by WAAS. If, at some future time, the full community were to shift to dual-frequency user equipment, the WAAS ground station requirements could be reduced significantly. The density of WAAS reference stations required for ionospheric correction is greater than that required for orbit determination or for integrity monitoring. Furthermore, the second civil frequency, and the proposed higher signal power, will mitigate interference concerns.

ES.2 RISKS

The only risks that proved significant are interference (unintentional and intentional) and ionospheric propagation effects (high sunspot cycle and scintillation); these risks are discussed in the following subsections.

ES.2.1 UNINTENTIONAL INTERFERENCE

Although there have been few reports of GPS receiver interference from the many Government and commercial transmitters currently operating in the NAS, a review of interference sources identified in RTCA DO-235 indicates that several have the potential for GPS signal disruption. Three potential interference sources were singled out for further analysis. The first and potentially most serious one is television broadcast. The current Federal Communications Commission (FCC) specifications allow out-of-band emissions of sufficiently high levels to interfere with GPS signal reception. A simulation effort, undertaken to evaluate television emissions, indicated that stations transmitting on channel 23 within line of sight of aircraft approach paths could readily deny GPS signal reception. However, this threat is easily managed by modifying television broadcast regulations to exclude unacceptable power levels in satellite radio-navigation bands, by testing for interference when FAA instrument approaches are first established, and by adding filtering to the television transmitter output that are found to interfere with GPS reception.

The second area of concern is commercial very high frequency (VHF) broadcast (e.g., taxi dispatch). The levels of power and typical antenna configurations restrict this threat to small regions near runways. VHF broadcast interference would also be managed by the same measures indicated for television broadcast.

The third possible threat is from over-the-horizon (OTH) military radar. OTH radar interference was not analyzed because insufficient information was available during this study. This threat is very restricted with regard to number and geography; therefore, it is not expected to be a significant risk. However, it is recommended that this emission source be further reviewed to ensure the risk is truly insignificant.

In summary, unintentional interference is not a major risk factor. Most interference difficulties reported by the aircraft community thus far have been the result of onboard interference, which is necessarily resolved during certification. While it is not possible to rule out future interference from offboard emitters, remedying such problems should not be difficult. The introduction of a second civil frequency will further reduce concerns about unintentional interference. Furthermore, the actions required to counter intentional interference will readily address this risk.

ES.2.2 INTENTIONAL INTERFERENCE

Intentional interference is by far the largest risk area; however, the planned avionics are designed to quickly recognize the onset of this threat. Assuming that sufficient resources are available to vector aircraft away from jammed regions, this threat will pose no safety risk. It can, however, create considerable disruption in traffic control and flight schedules. Methods to detect, locate, and prosecute those who intentionally jam GPS signals must be put in place to discourage such activities. Air traffic control procedures must also be established to manage affected aircraft. The study concludes that there is no credible spoofing threat and that, although real, jamming threats can be managed.

Further refinements of this analysis need to be based on specific threat definitions. The study was based on a threat the study team judged to be plausible with regard to economic and motivational characteristics. It is strongly recommended that the Department of Transportation (DOT), in cooperation with the intelligence community, establish specific threat definitions as a basis for further analysis.

Technologies are emerging that can greatly reduce vulnerability to GPS signal jamming. Techniques that can add 40 to 50 dB of additional rejection are possible; inclusion of such capabilities would virtually defeat the jamming threat considered in this study.

ES.2.3 LARGE IONOSPHERIC REFRACTION ERRORS

Considerable concern has been expressed about the impact of increased ionospheric refraction errors caused by spatial gradients during peaks of the sunspot cycle. A reasonable model of the ionosphere was created to evaluate this effect. It was found that errors produced did not significantly alter system performance for GPS only or LAAS, but did significantly degrade WAAS. It is important to note that the WAAS results regarding the larger ionospheric errors are sensitive to the ionospheric correction methodology. According to the definitions of the hazard risk index, its risk frequency is classified as “reasonably probable” and its consequence was considered “major” because of possible safety implications. With these classifications, the risk was determined to be “undesirable.” This risk can be mitigated by increasing the density of the wide-area reference sites (WRSs) and/or grid points, as well as improving the ionospheric correction algorithm. This area of WAAS ionospheric correction methodology should receive further analysis, but it is JHU/APL’s judgement that the WAAS configuration can be designed to meet the needed performance so that risk becomes “acceptable.” However, note that when the second civil frequency becomes available, the risk is eliminated.

ES.2.4 IONOSPHERIC SCINTILLATION

Ionospheric scintillation is most severe in equatorial regions and in the auroral region. The most likely means by which ionospheric scintillation affects GPS users in the Continental United States (CONUS) is in viewing GPS satellites through these regions. The auroral region covers the northern part of Canada between 65^o and 72^o N *geomagnetic* latitude, and the equatorial region covers zones at 15° ± 10° N and at 15° ± 10° S geomagnetic latitude. Only the northern equatorial zone is seen from the United States and only by two of the locations included in the study.

A conservative model was used to test the overall impact of including this effect in the normal system availability analysis. Its impact was to drop the availability below requirements at a few locations. Therefore, ionospheric scintillation must be considered as a risk factor. According to the definitions of the hazard risk index, its risk frequency is classified as “reasonably probable” and its effect was judged to be “minor.” With these classifications, the risk is determined to be “acceptable” with FAA approval.

ES.3 RECOMMENDATIONS

The following subsections offer recommendations in three areas: GPS, WAAS/LAAS, and risk mitigation.

ES.3.1 GPS

If civil aviation is to rely on GPS, greater access, cooperation, and agreement must exist on GPS operational control segment (OCS) procedures and future system performance. Specifically, the following must be addressed:

a. GPS operational procedures that support civil aviation policy need to be defined and implemented (e.g., signal monitoring, orbit management, and end-of-life operation and replacement strategies).

b. A means to convey full knowledge of failure rates and mechanisms that are essential to intelligent system design and operations must be established.

c. A process for Department of Defense (DOD) and DOT data collection and analysis must be established and sustained to characterize system performance and resolve incident reports (including international reports).

d. GPS specifications that reflect actual system performance and operational policies should be developed.

e. GPS coverage is currently limited by prediction of receiver autonomous integrity monitoring (RAIM) availability; current approaches are overly conservative by assuming all satellite failures are soft failures; and current algorithms are limited to “snapshot” position computations. These restrictions tend to increase reliance on the number of in-view satellites. Improvements to RAIM algorithms should be evaluated for possible cost reduction opportunities or performance improvements in the augmentation system structure.

These recommendations will allow sensible cost and performance trades between possible GPS system improvements and the implementation and operation of the augmentations supporting civil aviation. In support of these augmentations and to benefit the full domain of civil applications, a need exists to clearly define a national GPS plan that includes the following:

a. Establish a firm agreement on the size and characteristics of the satellite constellation and signal structures that will be maintained for all navigation services.

b. Specify the timetable for planned improvements (e.g., removal of selective availability and providing the second civil frequency).

ES.3.2 WAAS/LAAS

The following GPS/WAAS actions should also be taken to support development of a national GPS plan:

a. Establish the size and characteristics of the GEOS constellation that will be maintained to support civil aviation requirements. The plan will allow for the WAAS configuration to sensibly evolve and adapt in response to the availability of GPS satellite improvements. This study concluded that four GEOS are required to augment the current GPS satellite capabilities.

b. Further analyze, design, and validate the ionospheric correction methodology to support sizing of the ground reference station requirements and mitigation of the ionospheric risks discussed previously. Analyze possible robust receiver designs for mitigation of scintillation effects. Validate both analyses using National Satellite Test Bed (NTSB) and Phase 1 WRS data.

ES.3.3 INTERFERENCE RISKS

The following recommendations are directed at system risks:

a. Develop regulations for all licensed transmitters that explicitly limit radio frequency (RF) emissions at satellite radio-navigation frequencies.

b. Require compliance monitoring of potential sources of satellite radio-navigation interference after maintenance or new construction.

c. Ensure that interference levels at satellite radio-navigation frequencies are measured during flight inspections at airports where GPS approaches are planned and where a potential unintentional interference threat exists.

d. Derive a DOT-authorized threat definition to support design of mitigation actions for intentional GPS signal interference.

e. Implement enforcement measures to discourage and remedy potential threats. Threat detection might be part of standard user aircraft reporting structure, but a separate airborne platform will be needed to locate the threat(s). This activity should naturally be coordinated with law enforcement agencies.

f. Develop traffic control procedures and provide training to overcome wide-area GPS signal outage caused by intentional interference.

g. Develop standards for onboard interference suppression system performance that address postulated threat(s), aircraft types, and postulated traffic control procedures.

h. Obtain measurements of underbody aircraft antenna gain and assess advantages of antenna locations to determine antenna pattern benefits.

i. Evaluate additional means for aircraft-based interference suppression. These might include antenna nulling and signal processing techniques and integration with inertial navigation instrumentation.

j. Review the risk of interference from military OTH radar.

ES.4 LIMITATIONS

The conclusions and recommendations offered here represent sound engineering judgements that are backed by considerable analysis. The timeframe for this study required that certain approximations be made in lieu of comprehensive simulations. The study results are believed to be conservative; margins were applied in those areas where the models and/or data sources were limited. The following limitations should be noted:

a. All performance analyses were based on snapshot measurement error statistics for an array of distributed geographic locations sampled every 5 min throughout one repeat cycle of the GPS constellation (i.e., one sidereal day). While this approach is believed adequate to estimate aggregate performance, verification of performance should be based on higher fidelity trajectory simulation.

b. Full aircraft trajectory simulations were restricted to evaluating interference effects using typical landing conditions with an antenna pattern derived from limited data sources. The television interference model was necessarily based on a very small data set.

c. No data were available to characterize high-definition television interference levels at the GPS frequencies.

d. Although the receiver model used to support this study is believed to be a good representation of typical receivers, the study did not explicitly account for actual receiver performance differences that may exist among users.

e. GPS/WAAS performance estimates were based on making adjustments to models derived from NSTB data. No detailed simulation was constructed for this analysis.

f. The ionospheric scintillation model used for this study was simplified, but the model used is believed to conservatively bound reality.

g. Time-to-alert analyses could not be explicitly included within the simulation structure used for these studies. The augmentation system’s ability to meet these requirements was based on evaluations of the system design constraints provided by current descriptions and specifications.

Section 1

INTRODUCTION

The Federal Aviation Administration (FAA) has initiated plans to transition from its present ground-based navigation and landing system to a satellite-based system using signals generated by the Department of Defense's (DOD's) Global Positioning System (GPS). However, GPS will not meet all aviation positioning requirements. In particular, the requirement to be available virtually all of the time and to support precision landings will not be met with GPS alone. To meet the National Airspace System (NAS) requirements, the FAA has proposed two augmentations to GPS: a Wide Area Augmentation System (WAAS) and a Local Area Augmentation System (LAAS). GPS/WAAS is intended to support navigation for all phases of flight from oceanic through Category I precision approaches. GPS/LAAS is intended to support Category II and III precision approach requirements and to provide higher availability for Category I than the GPS/WAAS. However, concern has been expressed regarding the robustness of this plan and whether the risks to dependence on GPS have been adequately addressed. In response to this concern, the FAA, with co-sponsorship from the Air Transport Association (ATA) and the Aircraft Owners and Pilots Association (AOPA), issued a request for an impartial study. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) was selected to conduct this study, which is the subject of this report.

The study was completed in 6 months using skilled JHU/APL investigators teamed with some uniquely qualified individuals from Stanford University, supported by an experienced panel of reviewers from industry, academia, and Government. The independent risk assessment was conducted to specifically determine if GPS and augmented GPS could be relied on to meet all navigation requirements within the NAS. The evaluation relied heavily on simulation analyses to assess performance of GPS, GPS/WAAS, and GPS/LAAS against requirements, and, thus, development of mathematical models was a key element of the study. Generally, models were based on historical data in those cases in which the team judged the data to be the best source. In cases in which data were lacking, specification values were applied. The developed simulation tools were also used to assess how major system parameters [e.g., number of geostationary satellites (GEOS) and number of airport pseudolites (APLs)] could be varied to meet NAS performance requirements. Additional navigation options that mitigate the identified risks were also evaluated. In particular, these options included potential improvements to the GPS Standard Positioning Service (SPS) and additional capabilities onboard the aircraft, such as integration of additional sensors and application of GPS antijam technologies.

The following sections describe requirements, analysis methodology, performance analysis results, and the impacts of risks. More detailed discussion of simulation models is provided in the Appendixes C through K in a separate volume.

Section 2

NATIONAL AIRSPACE SYSTEM REQUIREMENTS

Performance requirements for each operation are shown in Table 2-1. The same requirements apply to all system and aircraft configurations. They represent service requirements and, as such, the study performance analyses assume all equipment onboard the aircraft is functioning properly. Values typically represent the most stressing requirements found in GPS/WAAS and GPS/LAAS documentation. The defining service requirement is availability. It is location dependent and varies by region. The table shows International Civil Aviation Organization (ICAO) threshold and objective requirements and the acceptable value for the Continental United States (CONUS) as set for this study (i.e., the *FAA* column). Exceptions are made for Alaska and GPS/WAAS Category I service where the availability requirement was set to 0.999.

Table 2-1 NAS Performance Requirements (as Modified from Original Statement of Work)

Operation	Accuracy (95%)	Integrity			Availability			Continuity (Loss of Nav.)
		Time-to-Alert	Alert Limit	Probability of MI	Thres.	Obj.	FAA^{++}	
Oceanic En route & Remote	12.4 nmi	2 min	12.4 nmi+	10^{-7}/hr	0.99	.99999	.999	1x10^{-5}/hr
Domestic En route	2.0 nmi	1 min	2.0 nmi+	10^{-7}/hr*	0.999	.99999	.99999	1x10^{-6}/hr
Terminal	0.4 nmi	30 sec	1.0 nmi+	10^{-7}/hr*	0.999	.99999	.99999	1x10^{-6}/hr
Non-precision	220 m	10 sec	0.3 nmi+	10^{-7}/hr*	0.99	.99999	.99999	1x10^{-5}/hr
Cat. I Precision	H – 16 m V – 7.7 m	6 sec	H-40 m** V-10-15 m++	2x10^{-7}/ approach*	0.99	.99999	.99999	5x10^{-5}/ approach
Cat. II Precision	H – 6.9 m V – 2.0 m	2 sec	H-17.3 m** V-5.3 m**	2×10^{-9}/ approach**	0.99	.99999	.99999	4x10^{-6}/ 15 sec
Cat. III Precision	H – 6.1 m V – 2.0 m	2 sec** 1 sec (goal)	H-15.5 m** V-5.3 m**	2×10^{-9}/ approach**	0.99	.99999	.99999	2x10^{-6}/last 15 sec 1x10^{-7}/last 15 sec (vertical)

*FAA-E-2892C (draft)

+RTCA/DO-208

**RTCA/DO-245

++B. DeCleene

2.1 AVAILABILITY

The definition of availability used for this study was modified to recognize the unique nature of the operational procedures provided by GPS augmentations. In particular, all GPS-based operations include a predictive availability calculation before conducting the operation. For oceanic through Category I approach service, availability is defined as the probability that the predicted availability test is passed and that the actual accuracy and integrity requirements are met. Because continuity is not included within this definition, the requirement for acceptable service from oceanic through Category I approach is that both availability and continuity requirements are met. For Category II and III service, availability is defined as the probability that the predictive availability test is passed and that the actual accuracy, integrity, and continuity requirements are met. For these services, acceptable performance is assured when the availability requirement is met.

2.2 ACCURACY

Accuracy is the 95-percent radial horizontal navigation error and 95-percent vertical navigation error at the GPS antenna electrical center. The accuracy requirement must be met at all locations within the service volume at all times. Accuracy is only counted in cases where the system is predicted to be available before the start of an operation.

2.3 INTEGRITY

Integrity relates to the level of trust that can be placed in the information provided by the navigation system. As with accuracy, integrity is evaluated in cases where the system is predicted to be available before the start of an operation. Loss of integrity is defined as the occurrence of an unsafe condition without annunciation for a time longer than the time-to-alert limit. An unsafe condition is defined as the occurrence of misleading information, that is, when the true navigation error exceeds the alert limit specified for each phase of flight operation. Loss of integrity can happen in two ways. Either an onboard integrity alert algorithm does not detect the unsafe condition, or it is detected, but the annunciation takes longer than the time-to-alert limit. Integrity must be maintained throughout the operation.

Note that the integrity requirement is expressed in terms of three parameters shown Table 2-1. The integrity requirement includes a maximum time-to-alert requirement, a position error alert limit, and a probability of misleading information. The probability of misleading information is the probability that the navigation position error exceeds the position alert limit and this event is not detected.

2.4 CONTINUITY

The continuity requirement is expressed as a loss of continuity per unit of time. Given the system is predicted to be available before the start of an operation, a loss of continuity occurs when the onboard integrity alert algorithm raises an alarm that an unsafe condition exists. The probability that this event occurs at any time during the specified time interval during an operation must be less than the continuity requirement.

Section 3

ANALYSIS METHODOLOGY

3.1 GENERAL APPROACH

The general approach was to categorize the identified risk elements into those risks viewed as “normal” and those risks viewed as “abnormal.” Normal risks are factors that cause performance degradations consistent with design specifications for the GPS system and augmentations. For example, normal risks include scheduled and unscheduled satellite downings, ionospheric compensation errors, and unintentional interference caused by television broadcast. Abnormal risks include satellite “soft” failures that result in significantly misleading information, excessive ionospheric error attributable to the solar cycle or solar storms, and interference owing to malicious intent.

Study results are based on simulation analyses using the approach illustrated in Figure 3-1. Simulation models were developed using measured data wherever possible to accurately reflect the observed, rather than specification, performance of system elements. Models were largely based on published data.

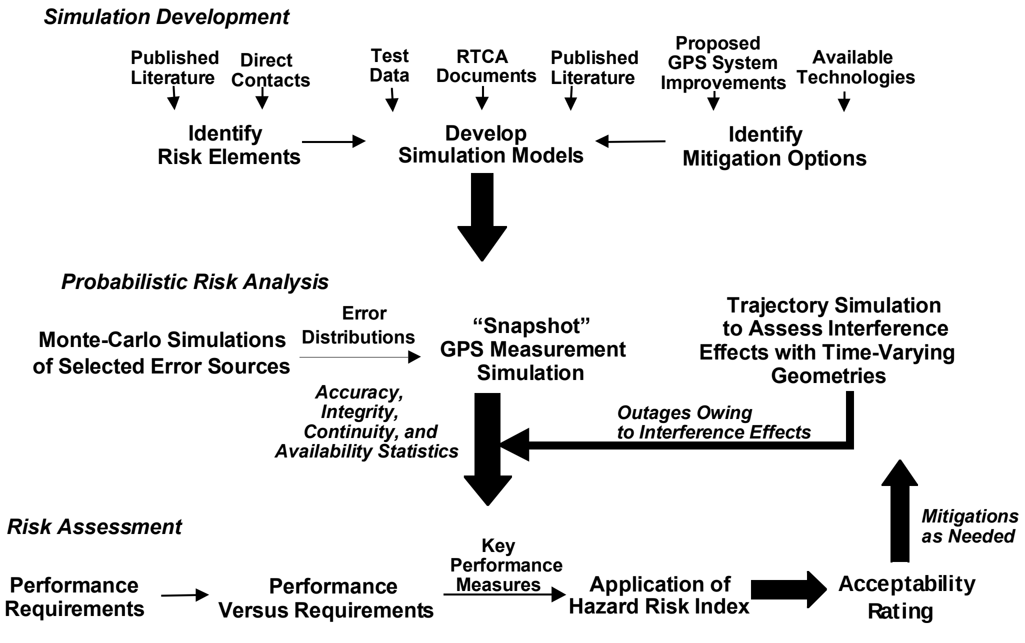
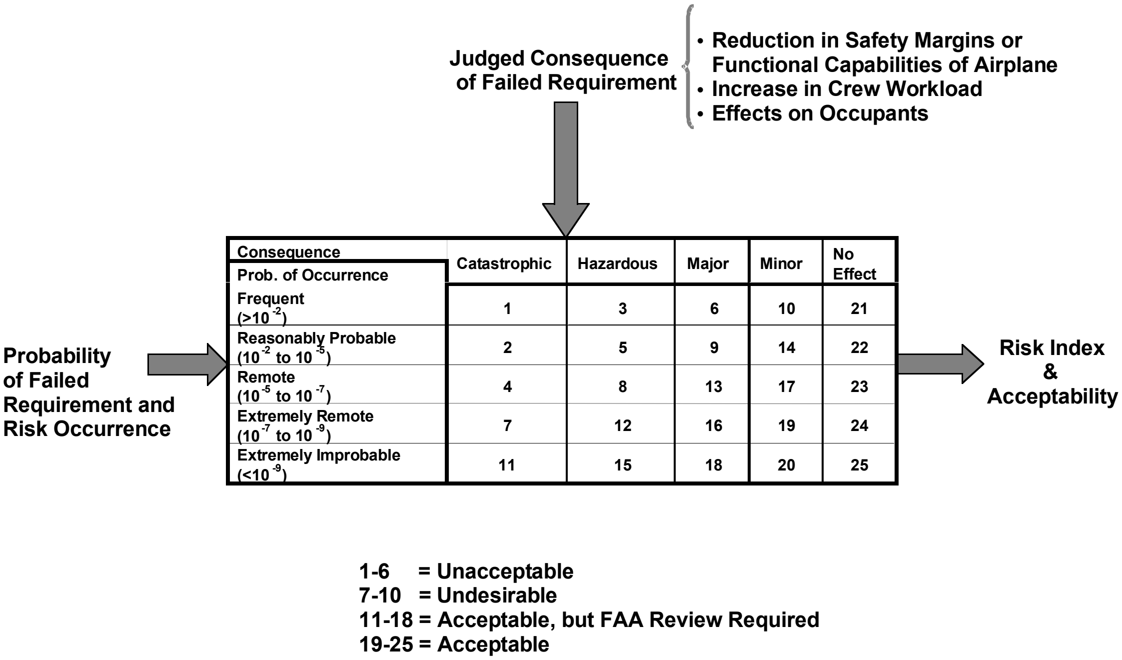


Figure 3-1 Risk Assessment Process

The probabilistic risk analyses were conducted in collaboration with Stanford University personnel. The principal tool to compute accuracy, integrity, continuity, and availability values was a GPS measurement “snapshot” simulation in which GPS performance is characterized in terms of the error statistics of single measurements taken at locations throughout the service volume and at times throughout the day. In addition, an aircraft trajectory simulation was used to assess GPS outage intervals owing to the time-varying interactions between aircraft motions, antenna pattern gain variation, and changing GPS satellite directions relative to the aircraft.

Availability was used as the key performance measure to evaluate the impact of each identified risk on system operation. A Hazard Risk Index was applied to rate the acceptability of each risk and determine the need for risk mitigation. The hazard risk characterization process is illustrated in Figure 3-2.



Consequence Prob. of Occurrence	Catastrophic	Hazardous	Major	Minor	No Effect
Frequent $(>10^{-2})$	1	3	6	10	21
Reasonably Probable $(10^{-2}$ to $10^{-5})$	2	5	9	14	22
Remote $(10^{-5}$ to $10^{-7})$	4	8	13	17	23
Extremely Remote $(10^{-7}$ to $10^{-9})$	7	12	16	19	24
Extremely Improbable $(<10^{-9})$	11	15	18	20	25

1-6 = Unacceptable
7-10 = Undesirable
11-18 = Acceptable, but FAA Review Required
19-25 = Acceptable

Figure 3-2 Hazard Risk Index

Definitions to judge operational consequences (AC 25.1309-1A) are as follows:

a. <u>Minor</u> – Failure condition that would not significantly reduce airplane safety and which involve crew actions that are well within their capabilities

b. <u>Major</u> – Significant failure condition that would

   (1) Reduce safety margins or functional capabilities of an airplane

   (2) Increase crew workload or conditions impairing crew efficiency

   (3) Produce some discomfort to occupants

c. Severe Major (Hazardous-ATA SOW, JAA) – Failure condition resulting in more severe consequences than major, such as

   (1) Larger reduction in safety margins or functional airplane capabilities

   (2) Higher workload or physical distress such that the crew could not be relied on to perform its tasks accurately or completely

   (3) Adverse effects on occupants

d. Catastrophic – Failure conditions that would prevent continued safe flight and landing

Performance analysis was conducted by comparing computed performance with requirements at 5-minute sampling intervals throughout one sidereal day (the repeat cycle for GPS constellation geometry) and at geographically distributed locations. The sample locations used in the study are shown in Figure 3-3. The locations were chosen to uniformly sample the service volume with emphasis on the most heavily used routes. Note that Guam, North Pacific route, and Reykjavik locations were not included in GPS/WAAS analyses, except for oceanic requirements, because they are outside the WAAS service volume. Reykjavik, North Pacific route, and Bermuda were not used in GPS/LAAS analysis because they are not airports in the NAS.

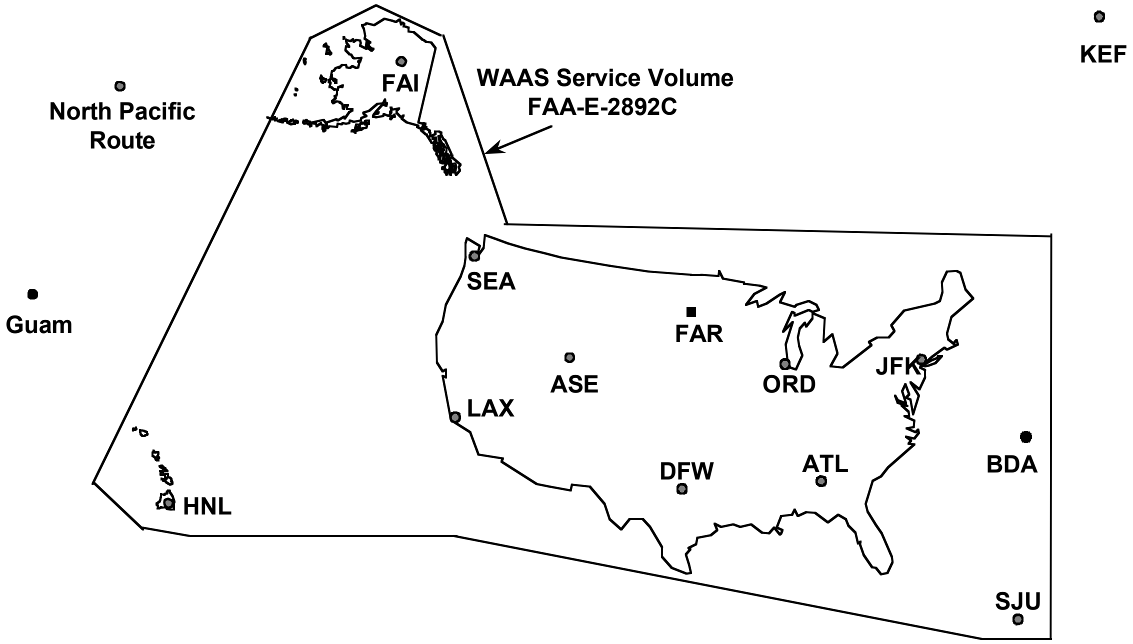


Figure 3-3 Locations Used for System Performance Analysis

3.2 KEY ASSUMPTIONS

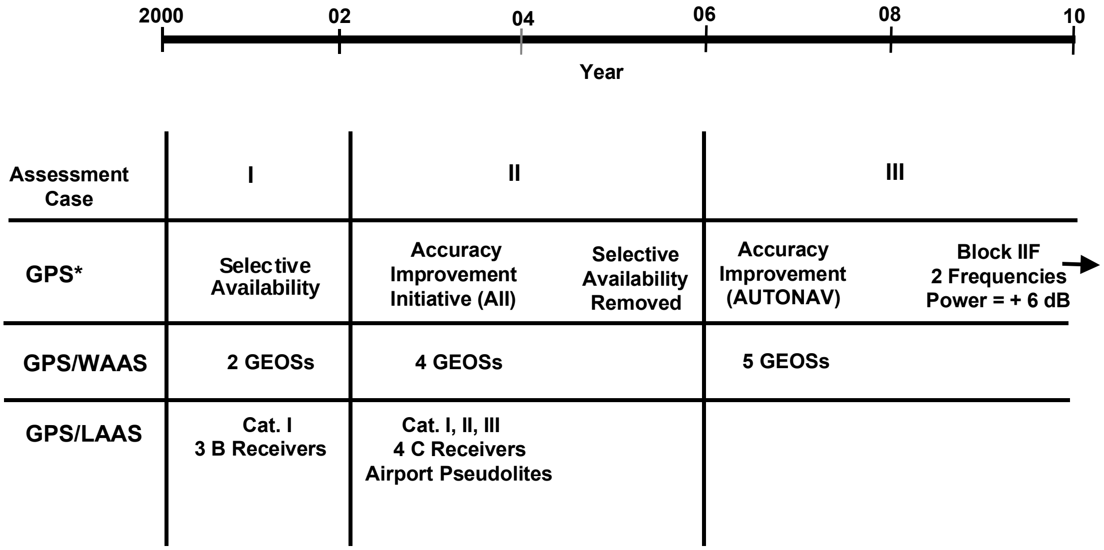
The following key assumptions were used in this study:

a. The current GPS constellation results were based on a 24-satellite constellation rather than the 27 available today. GPS signal-in-space ranging accuracy and satellite downing probabilities were derived from GPS OCS Performance Analysis and Reporting (GOSPAR) project studies. GPS satellite end-of-life failure rates and replacement strategy were based on current specifications. Performance was also analyzed with a 30-satellite GPS constellation.

b. GPS/WAAS analysis baseline assumed the 24-satellite GPS constellation and 2 GEOS at the current locations. Ionospheric correction and orbit determination errors were based on analysis of National Satellite Test Bed (NSTB) data (19 reference stations and Stanford algorithms). Ground system reliability was based on specifications using 25 reference stations, 2 master stations, and 2 geostationary uplink stations per GEOS. GEOS reliability was taken from the FAA-E-2892C WAAS specifications, except the mean times to repair (MTTRs) were varied to reflect different replacement strategies. Performance was also analyzed with 3, 4, and 5 GEOS.

c. GPS/LAAS accuracy models were based on the specifications given in RTCA/DO-245. Performance was analyzed with 24 and 30 GPS satellites, 4 GEOS, and 1 and 2 APLs.

The configuration variations considered in the study were generally set to represent the improvement timeline shown in Figure 3-4. It is understood that dates may not be accurate, but it was judged that the system capabilities shown in the figure represent realistic combinations of possible future improvements.



Assessment Case	I	II	III
GPS*	Selective Availability	Accuracy Improvement Initiative (AII) Selective Availability Removed	Accuracy Improvement (AUTONAV) Block IIF 2 Frequencies Power = + 6 dB
GPS/WAAS	2 GEOSs	4 GEOSs	5 GEOSs
GPS/LAAS	Cat. I 3 B Receivers	Cat. I, II, III 4 C Receivers Airport Pseudolites	

Figure 3-4 Notional Timeline for System Improvements

The initial evaluation timeframe (2000–2002) includes the current GPS with selective availability invoked, although the 24-satellite constellation discussed earlier was assumed rather than the actual 27-satellite constellation in place during late 1998. The current GPS Joint Project Office policy is to replace satellites on an as-needed basis, but there is no guarantee as to the number of satellites on orbit beyond the required 18. Current commitments, however, are that a minimum of 24 satellites will be maintained. The first timeframe also includes initial WAAS and LAAS capabilities.

The second evaluation timeframe (2002–2006) includes expected GPS improvements, the final LAAS configuration, and WAAS with 4 GEOS. The Accuracy Improvement Initiative (AII) will improve ranging accuracy by Master Control Station (MCS) filter improvements, inclusion of six additional ground stations, and an increased number of uploads per day. It is also expected that selective availability will be removed by 2006.

During the third evaluation timeframe (2006–2012), JHU/APL postulates a second civilian frequency and a 6-dB increase in satellite power. In addition, coded dual-frequency receivers will be available for WAAS. Finally, a 30-satellite GPS constellation was evaluated for timeframes II and III.

3.3 REQUIREMENTS EVALUATION

The diagram shown in Figure 3-5 illustrates the requirement evaluation process. Performance is conditionally evaluated for each measurement event. A measurement event is defined as a single GPS measurement of all satellites in view at a specific location and time. A measurement event may be further distinguished by, for example, the occurrence of a satellite downing and/or some other risk element. A given measurement event defines the set of available satellites, satellite geometry, and ranging accuracy.

Given the available satellites after scheduled and unscheduled downings, predictive availability is computed for an assumed ranging accuracy. The method used for each system configuration (GPS, GPS/WAAS, and GPS/LAAS) is detailed in Appendixes C through K. Note that it is also possible that a satellite will fail during the operation.

If the system is predicted to be available, accuracy, integrity, and continuity are then evaluated. Continuity depends on the integrity alert algorithm and estimated ranging errors. The probability that a loss of continuity occurs is computed as the probability that the alert threshold is exceeded.

As shown in Figure 3-5, a loss of integrity can occur only if either an alert is not declared or if the time-to-alert is exceeded. The loss of integrity is computed as the probability that the position error exceeds the alert limit, given one of these two events has occurred.

The probability distribution for true navigation error is computed, and the minimum value greater than 95 percent of all values is found. If this value is less than the required 95-percent accuracy, the accuracy requirement is passed. This is indicated by setting the conditional probability that accuracy is met equal to one.

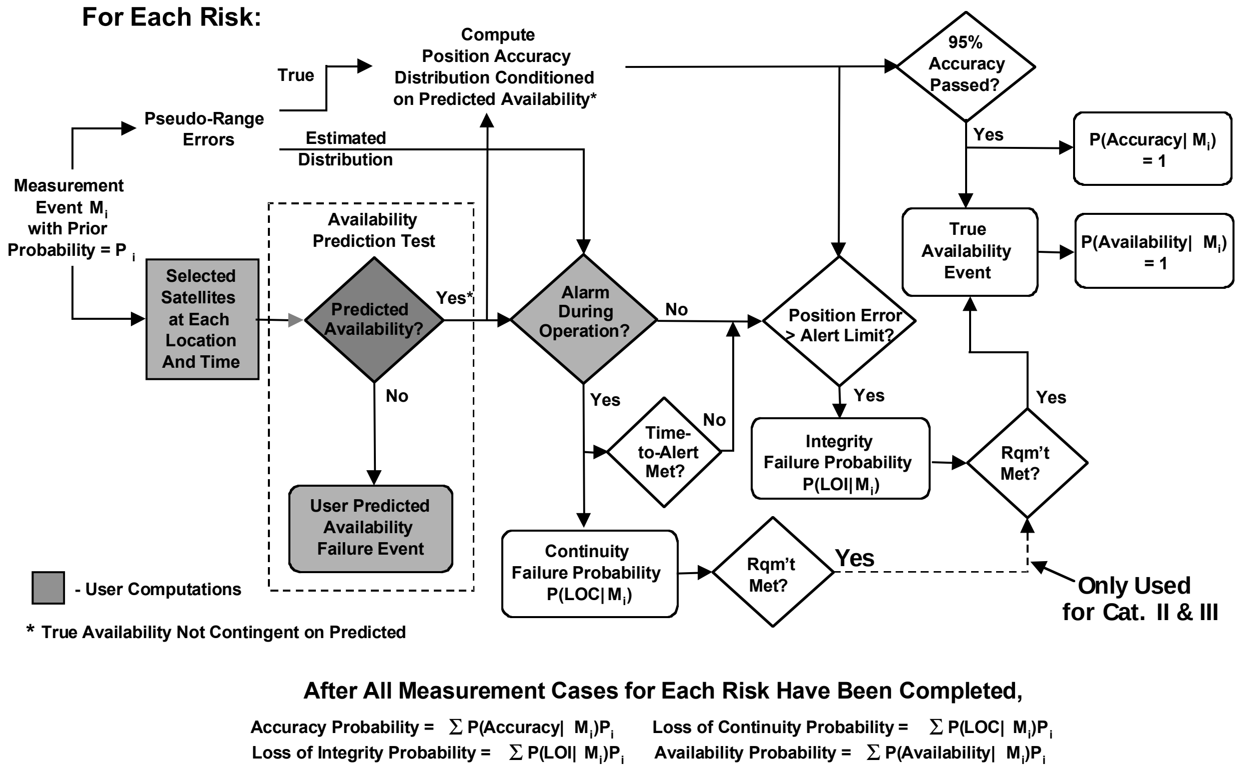


Figure 3-5 Requirement Evaluation Process

If the accuracy, integrity, and continuity requirements are all passed, a true availability event is declared. For each measurement event, the system is either truly available or not. This is also indicated by setting the conditional probability equal to one when availability is satisfied; otherwise, it is set equal to zero. Note that predicted availability is included in true availability because for any measurement event where predicted availability fails, the conditional true availability will be zero. As discussed earlier, true availability is also computed without continuity for oceanic through Category I service.

Finally, the total value of each performance measure is computed by summing the products of the prior probability of each measurement event, P(M_i), and the conditional probability for each performance measure.

Section 4

ANALYSIS RESULTS

The principal results are reported here for the most important configurations of the three systems: GPS without augmentation, GPS/WAAS, and GPS/LAAS,

4.1 GPS WITHOUT AUGMENTATION

GPS without augmentation is the SPS provided by the DOD. In addition, receiver autonomous integrity monitoring (RAIM), although an augmentation in the strict sense, is assumed to be an integral part of this system. GPS system performance models were mostly based on data provided by published GOSPAR analyses. User error models, including receiver noise, multipath effects, ionospheric compensation error and tropospheric compensation error, were also mostly derived from published literature. The simulation configuration, references, and models used to analyze this system are presented in Appendix C. The availability results for five GPS configurations are shown in Figure 4-1.

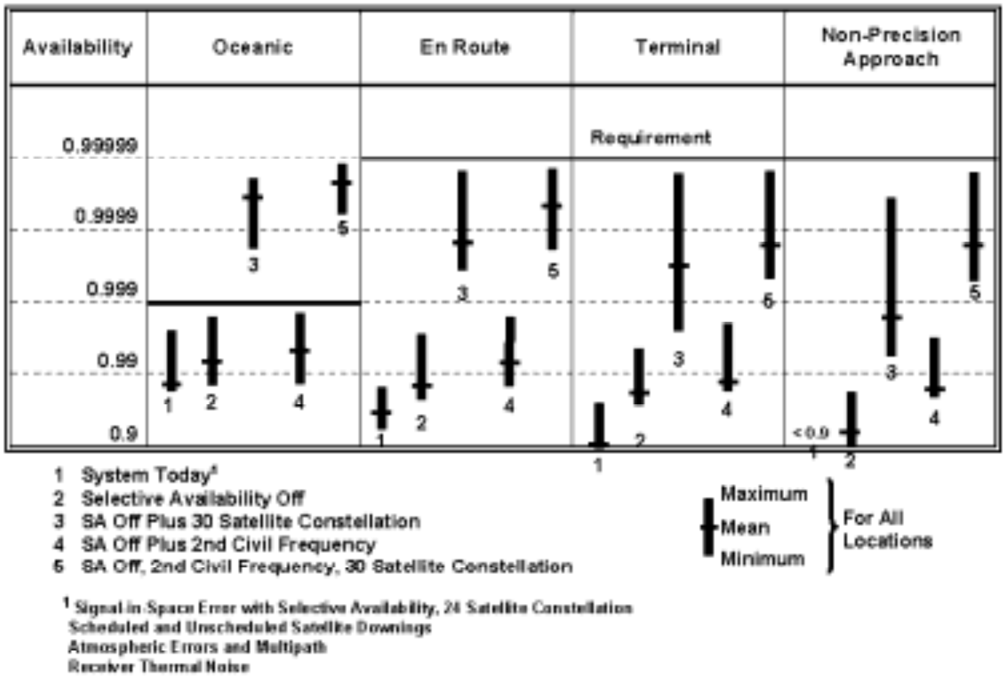


Figure 4-1 Analysis Results for GPS Without Augmentation

Each vertical bar represents the range of availability values determined for a specific service using a particular system configuration (number key below table). For example, the first bar within the oceanic column represents the range of availability considering all locations and times using the current GPS constellation (i.e., 24 satellites, selective availability on, no second frequency). The mean value is indicated by the horizontal line (i.e., the system's availability is less than 0.99). The performance of this system is seen to further degrade as more accurate service requirements are attempted (number 1 bar in successive columns). The number 2 bar represents the impact of turning selective availability off. While this definitely improves performance, the mean values continue to provide less than 0.99 availability (recall that the requirement for oceanic is 0.999 and for the other services it is 0.99999). The number 3 bars indicate the availability for a 30-satellite constellation with selective availability off. The numbers 4 and 5 bars indicate availability with selective availability off and with a second civil frequency for 24- and 30-satellite constellations, respectively. The analysis indicates that GPS without augmentation can only meet NAS oceanic requirements, and even then the constellation must be increased to 30 satellites. On the other hand, it should be noted that a considerable level of GPS service is already available to supplement existing capabilities, but it will not meet the availability objectives set for this study.

4.2 GPS/WAAS

A full "end-to-end" simulation was desirable with all the WAAS functions [Wide-Area Reference Sites (WRSs) functions, through the complex Wide-Area Master Site (WMS) processing and integrity functions, through the Geostationary Uplink Site (GUS) and GEOS links to the User], shown in Figure 4-2, being modeled. In principle, this model could be fully sensitive to all normal error sources and abnormal risks. Error distribution inputs could be validated by NSTB databases. However, the required extensive modeling/programming staffing was beyond the scope of this study.

A more efficient partial "middle-to-end" simulation was chosen, which models WMS estimation output errors developed from extensive NSTB databases as "satellite error models" to the existing GPS-only simulation, with added GEOS. User differential range error (UDRE) and grid ionospheric vertical error (GIVE) distributions were functionalized per satellite geometry with respect to WRS positions and abnormal conditions, such as peak solar sunspot activity. These models essentially replaced the detailed simulation of the WRSs and the WMS with less-extensive modifications to the GPS-only simulation. The UDRE and GIVE always produced horizontal and vertical upper bounds on the true position errors at the evaluation stations. Consequently, their use as truth models in the simulation will yield conservative results. The added value of this approach was that it was based on actual NSTB data experience using the Stanford orbit determination and ionospheric estimation algorithms. CONUS evaluations were produced from a 19-WRS database, while Alaska/Hawaii evaluations were based on an additional 5 WRSs in Alaska and 2 WRSs in Hawaii. Upper bounds for the reliability of the WAAS ground network were analytically calculated and the simulation results were modified, which modeled the GPS and GEOS geometry and reliability. These calculations assumed a full network of 25 WRSs, 2 WMSs, and 2 GUSs per GEOS. More details are included in Appendix D.

Figure 4-3 shows the main analysis results for GPS/WAAS. Availability is shown for six different system configurations (number key below table). Configuration #1 through #5 evaluations were at the eight CONUS sites plus Fairbanks (see Figure 3-3). Configuration #1 also was evaluated at the six non-CONUS sites for oceanic through nonprecision approach (NPA), resulting in better than 0.999 availability, except for Guam at NPA (0.998). Configurations #1, #2, and #3 represent the baseline results for GPS/WAAS. These results show that a GPS/WAAS configuration with 4 or 5 GEOS can meet the navigation performance requirements without any improvements to the 24 GPS satellites. The *IONO & OD* notation refers to assumed ionospheric and orbit determination processing algorithms at the WMS, those currently being used to support Stanford investigations and those being implemented by Raytheon (configurations #4 and #5). The bars labeled "Raytheon" in the figure were obtained by comparing Raytheon-published results (References 1 and 2) with corresponding Stanford results, yielding scaling factors on the NSTB/Stanford models. In both cases, however, the less conservative Stanford 15° restriction for valid ionospheric grid points [at least one WRS ionospheric pierce point (IPP) within a 15° great circle radius of the grid point] was assumed rather than the more conservative "three-of-four" restriction of the WAAS Specification (at least three out of four 5° quadrants surrounding the grid point must contain WRS IPPs). The three-of-four restriction significantly reduces availability and was not evaluated. JHU/APL believes that the NSTB database and Stanford processing results have tended to indicate adequate integrity of the Stanford processing and less conservative restriction (Reference 3). Further research is needed to validate this indication. If this is valid, the number of WRSs required for phase 2 may be reduced from the currently planned 48 stations.

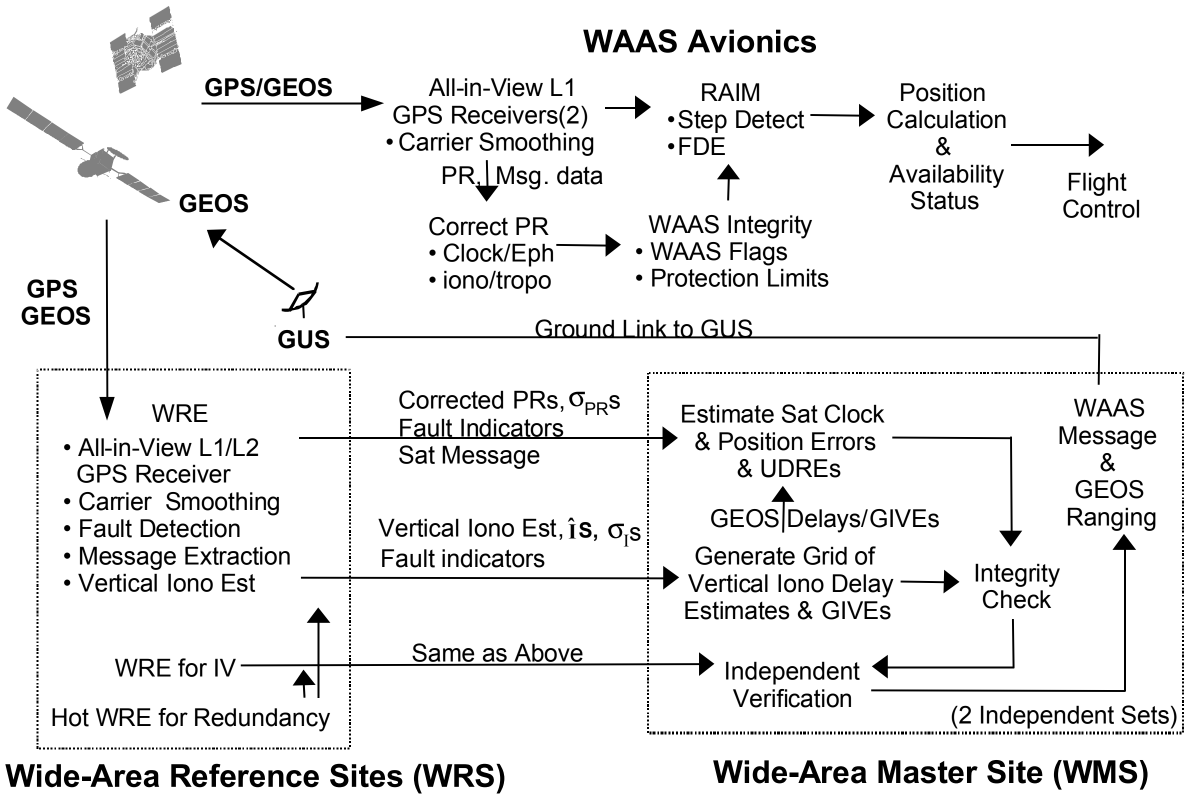


Figure 4-2 GPS/WAAS Functional Block Diagram

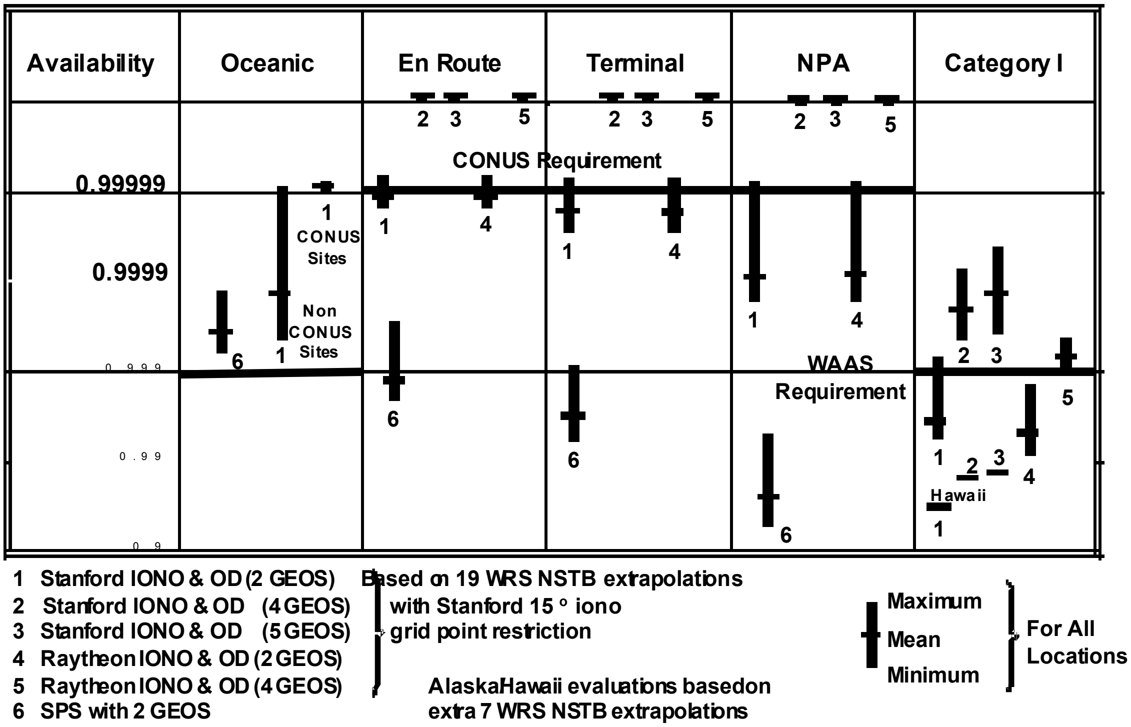


Figure 4-3 GPS/WAAS Analysis Results

The last configuration (#6) was added to evaluate if the oceanic requirement that was not met with the 24-satellite GPS constellation would be met by including ranging signal measurements from the current 2 GEOS. While this configuration does meet the necessary oceanic requirement, it can be seen that specifications for none of the other services can be met by this configuration. It can also be seen that the corresponding WAAS configuration (#1) can readily meet the oceanic requirements over CONUS and at all non-CONUS test sites. It will also be noted that none of the 2-GEOS configurations meet the 0.99999 requirement for en route through NPA or the 0.999 requirement for GPS/WAAS Category I service. The 4- and 5-GEOS configurations readily meet all service requirements except for Category I in Hawaii. The WRSs on CONUS and Alaska are too far from Hawaii to add much information to the essentially independent 2-WRS WAAS at Hawaii. GPS/LAAS must be used to achieve Category I availability greater than 0.999 at Hawaii. It should be noted that all requirements are met with a 24-satellite GPS constellation, without a second frequency, and with selective availability on (i.e., using the current GPS configuration).

The current WAAS GEOS implementation plan is unclear in that the number, location, suppliers, and replacement strategy have not been established. JHU/APL has assumed the following configuration placements: 2-GEOS configuration at Pacific Ocean Region (POR), Atlantic Ocean Region, West (AOR-W); 4-GEOS configuration at POR, AOR-W, 135W°, 75W°; 5-GEOS configuration at POR, AOR-W, 135W°, 75W°, 90W°; and 3-GEOS configuration at POR, AOR-W, 90W°. The importance of the replacement strategy is illustrated in Figure 4-4, by showing the availability for two different MTTR values. The 3-year GEOS MTTR (current WAAS specification in FAA-E-2892C) corresponds to having no spare in orbit, which would require procurement and launching. The 3-month MTTR assumes a more optimistic strategy and is clearly required to meet CONUS requirements.

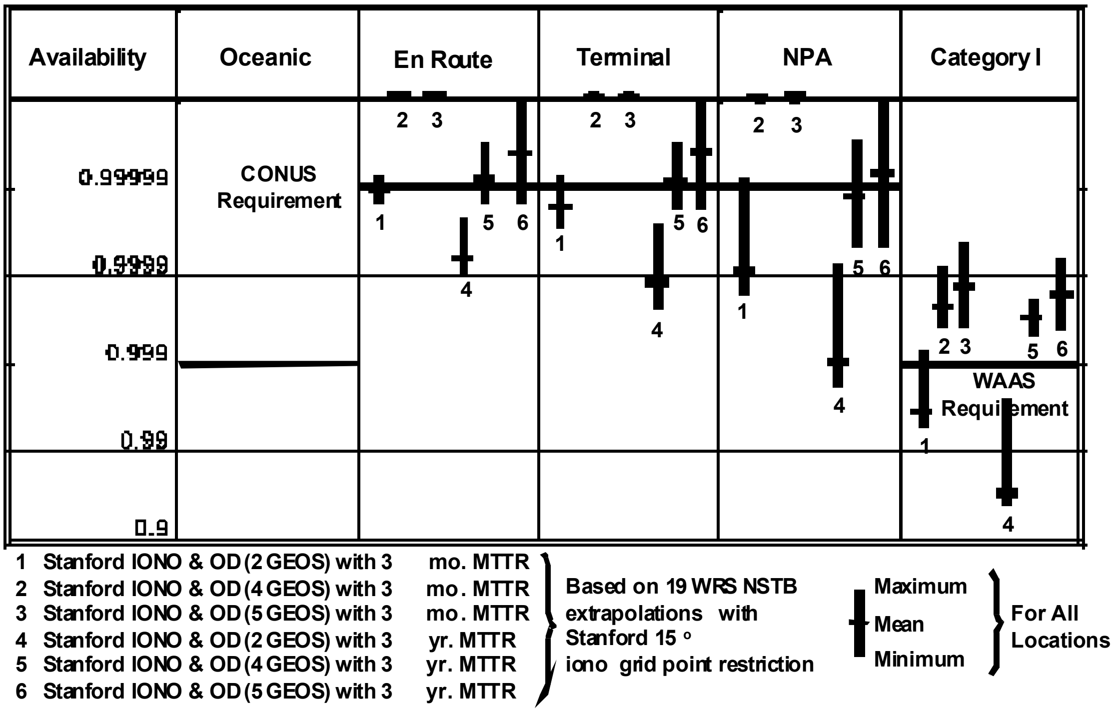


Figure 4-4 GPS/WAAS Results Versus Number of GEOS and Their MTTR

GPS/WAAS performance seems to be most sensitive to ionospheric processing (as indicated previously in the Stanford/Raytheon comparisons and the different grid point restrictions) and ionospheric phenomena, as shown in Figure 4-5. In all these cases, except for scintillation, the en route through NPA results were similar and passed the requirements. The solar maximum results were based on scaling the NSTB output ionospheric models, as suggested by Klobuchar, et al. (Reference 4). A conservative factor of 3 was used here. Clearly, the solar maximum results show serious degradation. An improvement in the ionospheric processing (such as tomography) and improvement in the measurements (more WRSs) will be needed to meet the WAAS specification for the solar maximum case. Further discussion appears in the WAAS risks section.

The scintillation results were based on Pullen, et al. (Reference 5) and Skone, et al. (Reference 6). Areas of moderate to strong scintillation were designated in the auroral region. IPPs that fell within these regions were checked to see if loss-of-lock occurred, affecting the availability of that measurement. As shown in Figure 4-5, scintillation will also degrade the nominal performance but not as seriously as solar max, affecting only the northern most sites, especially Fargo. Oceanic through NPA performance was minimally affected, with only Fargo dropping below the requirement at 0.99993 for NPA. The scintillation results and their implications are discussed more fully in the later section on WAAS risks.

The full spectrum of number of GEOS possibilities is explored in Figure 4-6. The 3-GEOS configuration meets the requirements. However, considering the potential degradation in performance due to abnormal ionospheric phenomena, as indicated previously, the 4-GEOS configuration represents the best choice for assured overall GPS/WAAS performance.

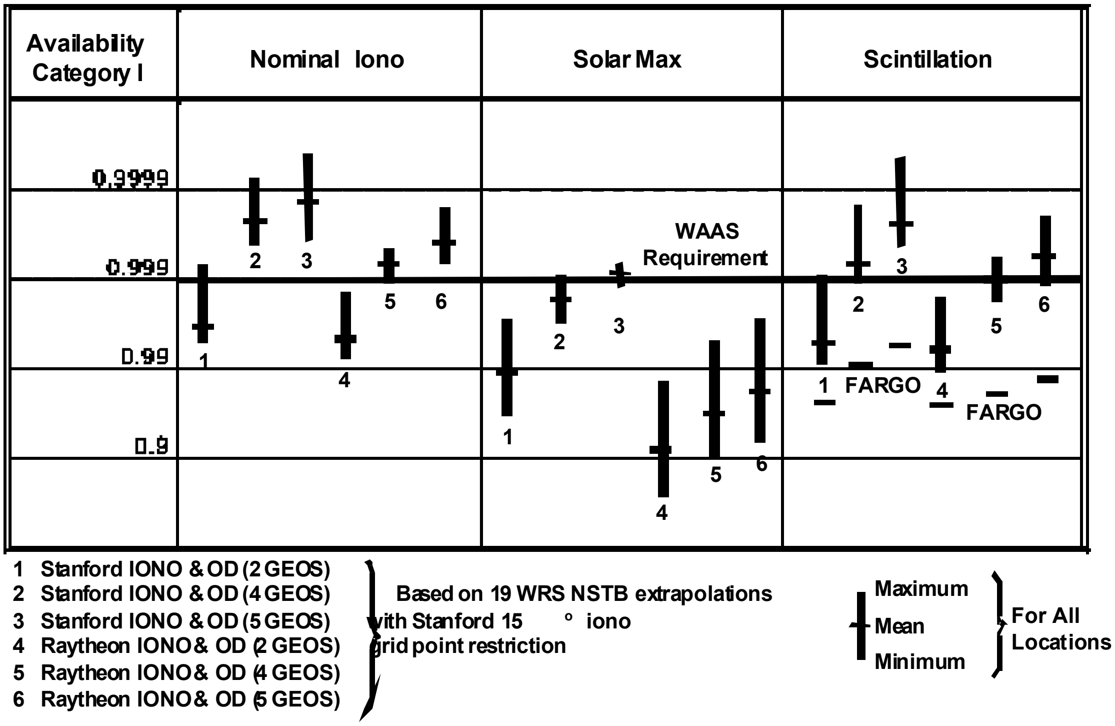


Figure 4-5 GPS/WAAS Results Versus Ionospheric and Orbit Determination Algorithms

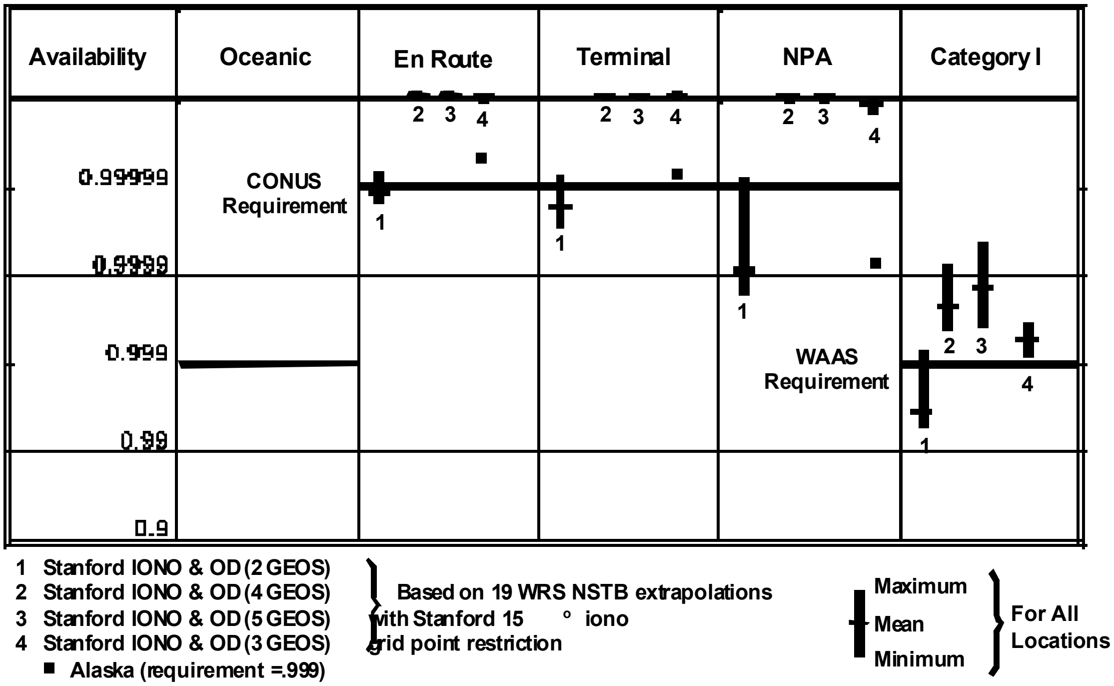


Figure 4-6 GPS/WAAS Results Versus GEOS Configuration Options

4.3 GPS/LAAS

System simulations and probabilistic risk assessments were conducted for a wide range of GPS/LAAS configuration options. Three classes of LAAS ground stations were considered. The first, referred to as a current LAAS station, was represented as having three ground antennas and receivers of the type commonly in use today for special Category I approach service. This is the type of station indicated for timeframe I (i.e., three modified choke-ring antennas with class B receivers). The second, referred to as an upgraded LAAS station, is based on the use of improved antennas and receivers to be used in timeframe II (i.e., four multipath limiting antennas and class C receivers). The third, referred to as a special LAAS station, includes an antenna configuration that further improves multipath performance and doubles the number of GPS receivers used in the upgraded station. This special configuration is expected to reduce the signal-in-space errors by a factor of 2. The analysis considered 24- and 30-GPS satellite constellations, with and without the 4 GEOS for additional ranging measurements, and 1 or 2 APLs. The results for six specific 24-satellite cases are shown in Figure 4-7.

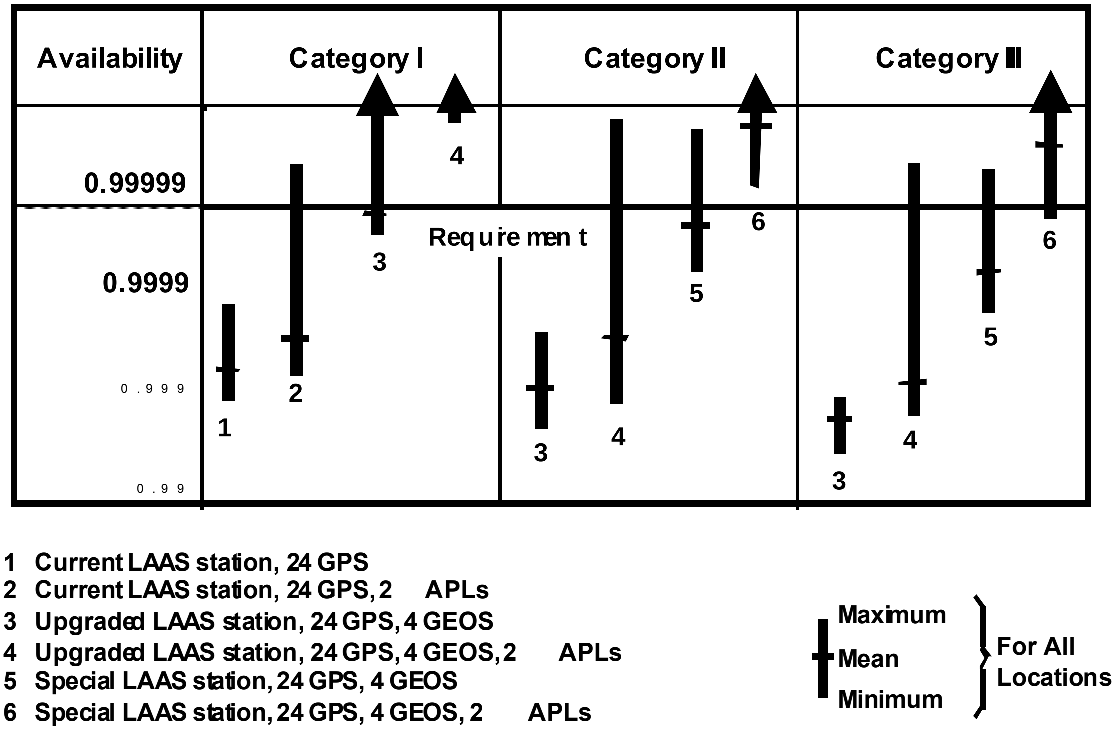


Figure 4-7 Analysis Results for Several GPS/LAAS Configurations

The configuration #1 (i.e., current capability) falls just short of meeting the minimum requirement set for GPS/WAAS Category I approaches, and it certainly cannot meet the 0.99999 availability requirement set for GPS/LAAS service. Configuration #2 shows the benefit of two APLs. While this provides considerable improvement, it will not meet all Category I requirements. The use of four GEOS shown in configuration #3 very nearly meets the most stringent Category I requirements, and the addition of APLs (configuration #4) pushes the mean availability beyond 0.999999. However, none of these configurations can meet Category II and III requirements. A 30-satellite GPS constellation with 2 APLs based on the upgraded LAAS station (not shown in the figure) was just able to meet the Category II requirement, but fell short of meeting Category III. Because of the limited time, the next case considered (also not shown in the figure) used the maximum geometry case considered; 30 GPS satellites, 4 GEOS, 2 APLs, and the upgraded LAAS station. That case met the Category II requirement and, with the exception of a few stations, the Category III requirement. The difficulty in meeting the high-availability numbers for Category II and III is primarily because of measurement accuracy limitations of the upgraded LAAS station. With specialized equipment, it is expected that the station errors can be reduced by a factor of 2. The case using this special LAAS station with 24 GPS satellites and 4 GEOS (configuration #5) continued to fall short of meeting the requirements. However, all requirements can be met with 4 GEOS and 2 APLs (configuration #6).

It was also determined that a special LAAS station used with a 30-satellite GPS constellation provided about the same performance as the best case shown in the Figure 4-7. These results indicate that the GPS and GPS/WAAS configuration choices should influence the decisions on LAAS configuration options. If it is unlikely that GPS will be upgraded to a 30-satellite constellation, the LAAS will need to depend on special station improvements, four GEOS, and APLs. However, if a 30-satellite GPS constellation and the 4-GEOS configuration were assured, LAAS could meet its requirements without special station improvements. In any event, the study indicates that given either a 30-satellite GPS constellation or a 4-GEOS commitment, GPS/LAAS can meet all NAS precision approach requirements. Further details of the GPS/LAAS analysis are discussed in Appendix E.

Section 5

RISKS

Risks were considered for GPS and for the two augmentation systems. GPS risks are central to all operations considered and they will be discussed first, followed by the WAAS and LAAS risks.

5.1 GPS RISKS

All performance analyses of GPS positioning assumed conservative models with regard to receiver thermal noise; multipath; ionosphere; troposphere; satellite ephemerides; unscheduled satellite failures; and for satellites being unavailable because they were scheduled for maintenance, repair, repositioning, training, or testing. The loss of GPS ground support functions (i.e., health of the operational and master control stations and their associated communications functions) were considered, and because of the very low probability of significant performance impact, these risks were not considered further. Signal emissions from other normal and expected transmissions were evaluated with regard to their potential to interfere with GPS signal reception. Finally, abnormally high levels of ionospheric errors and scintillation were evaluated and intentional interference was investigated. Of these, only the ionosphere and interference risks were found to be significant.

5.1.1 UNINTENTIONAL INTERFERENCE

There have been very few reports of GPS outages caused by unintentional interference, so this portion of the study was based on evaluating the impact of potential interference sources listed in RTCA/DO-235. Of these, only commercial very high frequency (VHF) radio, over-the-horizon (OTH) military radar, and broadcast television were considered possible interference threats requiring further analysis. Detailed characterizations of the military radar signals were not available for analysis, but it was determined that there are only a few widely dispersed systems and they use relatively narrow antenna beams. For these reasons, and because there have been no reported problems from these emissions, they are not considered a significant risk. However, further review is required to confirm this expectation.

A simulation was developed and run to determine the potential impact of commercial VHF and television transmissions on GPS reception. A standard link budget equation was used along with models of typical transmit and receive antennas, assumed distributions of transmitter radiated harmonic levels, and aircraft trajectories for en route and approach phases of flight. Simulation results, in the form of predicted maximum interference level contours, were then compared to the WAAS-specified interference levels to determine the likelihood of outage that would be experienced by a GPS receiver just meeting the specification. A detailed description of the evaluation is presented in Appendix I.

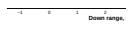
Information on actual commercial VHF transmitter out-of-band emissions was not readily available, so analysis was based on maximum transmit power and out-of-band emissions permitted by regulation. This is expected to yield a worst-case result. Even so, because of the low power involved, VHF transmitters pose no treat to aircraft en route. They are of concern only to aircraft on approach, where transmitters can be relatively close, and interference can arrive from near (instead of far below) the horizon where the aircraft body provides less attenuation.

VHF interference was analyzed by considering an aircraft on a typical approach path. Two types of interference sites were examined: one was assumed to be a mobile unit with its antenna 10 feet above ground, and the second was a fixed site with its antenna 100 feet above the ground. For both, transmit power was set at the maximum authorized level with out-of-band emissions at the Federal Communications Commission (FCC) limit. Contours of transmitter site locations that cause interference for the two cases are shown in Figure 5-1. (The origin of the range scale is the aircraft touchdown point.) They are shown for a receiver that just meets current WAAS specifications and for receivers with 10 and 20 dB more suppression capability. It can be seen that the 20-dB suppression improvement removes the mobile threat and forces a fixed site to locate close to the runway, if it is to be a threat. For a receiver operating at the WAAS specification level, these results suggest a significant amount of interference over a reasonably sized area. However, this result is offset by several factors:

a. Several currently available GPS receivers outperform the WAAS specification (by as much as 20 dB) for this type of interference.

b. Transmitters often don't transmit at the maximum allowed power.

c. It is expected that typical transmitter output harmonic levels are far lower (20 dB or more) than FCC regulations require.



Relative Interference – Fixed VHF Radio

Relative Interference – Mobile VHF Radio

Figure 5-1 Interference Zones for VHF Radio Transmitters

For these reasons, commercial VHF transmissions probably do not pose an operationally significant threat. However, consideration should be given to reducing the allowed out-of-band emission power (from 60 to 80 dB below carrier power) and on restricting siting of fixed VHF transmit antennas near runways. These two actions would eliminate the risk without requiring increased interference mitigation in GPS receivers.

Television stations can use very high power transmitters. This and the relatively lenient out-of-band suppression requirement makes television harmonic emissions a significant threat to GPS. The FCC requires out-of-band emissions be limited to levels 60 dB below the carrier power. This could allow, for example, a 5-MW transmitter operating within specifications to radiate 5 W in the L_1 band. Three television channels have harmonics that fall in the GPS L_1 band: channel 23 (second harmonic) and channels 66 and 67 (third harmonic). Field measurements made by JHU/APL and others indicate that out-of-band emissions of many stations are far lower than the permitted maximum level. However, some have been observed to do worse.

Not only are the harmonic levels a potential threat, no mechanism is in place for monitoring compliance. While stations operate nearly continuously, events do cause out-of-band emissions to change over time, such as degradation of transmit tubes with age and occasional maintenance (especially when it involves replacing the transmit tube, which occurs every couple of years).

We ran simulations of approach and en route scenarios using television transmit power distributions and antenna heights from the FCC database, distribution of carrier-harmonic power ratios from JHU/APL-collected field data, a typical television transmit antenna pattern, and a typical GPS receive antenna pattern. Figure 5-2 shows the probability of interference level that can be assumed whenever an en route general aviation aircraft is within radio line of sight of a channel 23, 66, or 67 television station (for a typical commercial flight at 30,000 feet, the risk of interference is zero). The two vertical lines indicate the current WAAS specification levels for interference from high-definition television (HDTV) (left applies to channel 66, right applies to channels 23 and 67). It can be seen that only channel 23 exceeds levels that receivers are designed to be tolerant of, and that occurs less than 1 percent of the time. It should be noted that only 4 dB of additional interference suppression would overcome this interference. Because the analysis is conservative and the WAAS specification is conservative, television emissions are not expected to be a problem for any en route aircraft.

The conditions possible during approach are shown in Figure 5-3, again based on HDTV transmissions. Two cases are shown: a worst case transmitter [i.e., one whose transmitted harmonic levels are in the top 1 percent (99 percentile) represented by the FCC database combined with the carrier-harmonic data we measured] and one that is in the 90 percentile. Contour levels are shown for interference levels relative to the WAAS requirement for non-precision approach (these levels are 3 dB higher than those used for the en route case).

The figure shows that if the worst-case transmitter were located inside the interference zone contour, it would cause interference at or above the level indicated by the depicted area. To avoid interference above the WAAS specification, the worst-case channel 23 transmitter would have to be located over 72 nmi away from the airport. However, for all but the worst 10 percent transmitters, the radius of the interference zone is reduced to 8 nmi. This suggests a combination of mitigation strategies.

By itself, television transmitter siting is not a practical means for preventing outages. However, adding only a modest amount (10 dB) of interference suppression (by increasing the WAAS specification levels and/or adding AJ processing in the receiver) reduces the threat radius down to a range where siting restrictions are easily enforceable for most (say, 90 percent) of the transmitters. The highest power transmitters can be handled by radio frequency interference (RFI) monitoring, both initially (during GPS approach certification) and after transmitter maintenance periods that can change out-of-band emissions levels (e.g., transmit tube replacement).

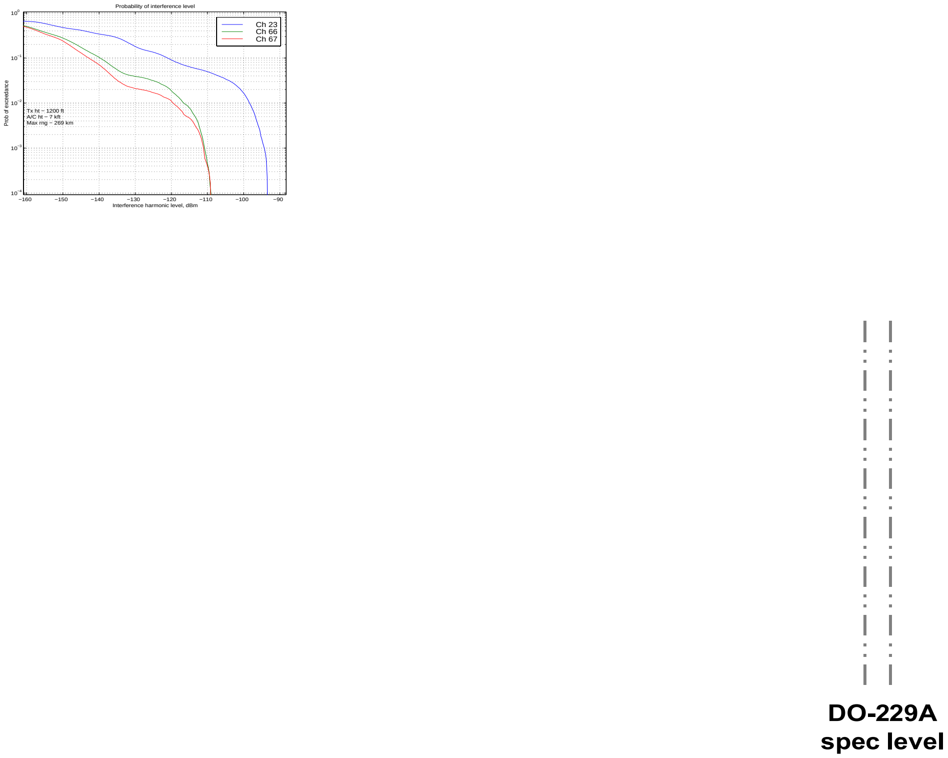
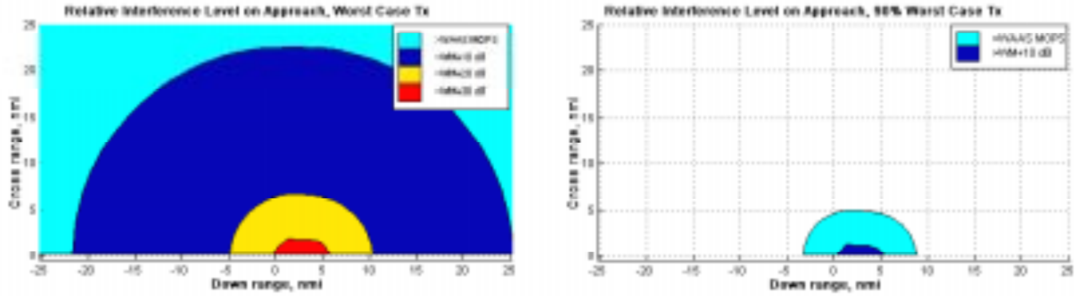


Figure 5-2 Probability of Receiving Interference Power at the Indicated Level



	All of TV Tx		90% of All TV Tx	
	Ch 23	Ch 66	Ch 23	Ch 66
Interference tolerance re WAAS MOPS	37 dB	24 dB	15 dB	1 dB

Notes for figures:

1. **Assumes worst (highest) 1 percent transmitted harmonic level. That is, 99 percent of channel 23 stations would not have this much impact.**
2. **Aircraft on standard approach.**
3. **TV station antenna at 600, 900, 1200 ft**
4. **Only 1 station considered here.**
5. **WAAS MOPS levels for non-precision approach.**

Figure 5-3 Computed Channels 23 and 66 Interference Zones

Note that the contours presented are based on a limited data set. Although they represent our best judgement with the available data, actual interference zones could be larger or smaller. In either case, television harmonics could deny GPS to aircraft on approach. Fortunately, it is clear that the risk of television interference can be made operationally insignificant by taking the simple mitigation steps described previously.

Acceptability of the unintentional interference risks was derived for the VHF radio and television broadcast. VHF radio interference was found to have no significant impact for en route operations and was therefore rated as acceptable for that case. In the terminal area there are no data characterizing the likelihood of occurrence, but an assumption was made it would be "reasonably probable." The impact of the risk was judged to be "minor" due to the intermittent and localized nature of outages caused by this source. As a result, application of the Hazard Risk Index shows the VHF interference risk is "acceptable but requires FAA review."

The risk due to television broadcast harmonics is "reasonably probable" en route but the impact is no effect because of the short duration of any outage. Thus, the television broadcast risk is acceptable for en route operations. In the terminal area, the impact was judged as "major" because of the significant outages that could occur. The television broadcast risk is therefore undesirable for terminal area operations. Recommended mitigations, however, would make this risk acceptable.

5.1.2 INTENTIONAL INTERFERENCE

Among potential risks to the GPS signal, the most problematic is that because of intentional interference. While the likelihood of such an event is impossible to predict, it can not be easily dismissed. It is well known that the GPS signal is very weak, and, assuming a standard GPS receiver, a small level of noise in the GPS band can disrupt reception over tens or even hundreds of miles. A modest level of jamming power can essentially stop GPS operations within a large area surrounding an airport. The result would be simultaneous loss of navigation by all aircraft and, therefore, a substantial increase in workload and a possible compromise of safety. To date the Department of Transportation (DOT) has not defined an intentional GPS interference threat to civil aviation nor specific circumstances that permit tolerable GPS outages. Thus, the approach taken in this study was to first define a plausible threat and then determine the level of interference suppression that eliminates GPS outage caused by that threat.

First, it was judged that the occurrence of a widespread GPS outage caused by intentional interference does not pose any direct safety risk because no flight operation is wholly dependent on GPS navigation. For example, if we consider the most critical case of a Category III precision approach, a sudden loss of the GPS signal would be known to the navigation system and might necessitate an abort, or in the final critical moments, use of the altimeter and possibly an inertial measurement unit (IMU). Thus, GPS outage because of jamming could have continuity impact, but loss of integrity is not an issue because accuracy degradation is relatively small before the signal is completely lost. The only potential risk to safety would result if the air traffic control system were not able to accommodate the disruption caused by interference. However, with validated procedures and proper training, this risk should be manageable. The only possible threat to integrity is spoofing where a phantom GPS satellite signal is generated to significantly increase navigation error, but this would require considerably greater expense and effort.

The possible sources of intentional GPS interference are (1) individuals or small groups ("hackers") who seek to create a nuisance by exploitation of a technological weakness or (2) a hostile organization or government that views the reliance of civil aviation on GPS as an opportunity for terrorist actions. It was the conclusion of this study that the latter source of interference is improbable because of the lack of incentive given the very low safety risk cited above. The hacker, on the other hand, may be satisfied with the more limited nuisance that is created. Interest could be expected to dwindle as the cost and difficulty increase.

To derive the hacker threat, estimates of jammer cost and size were developed versus jammer power. It was assumed that parts are the only cost, and the jammer is constructed of an inexpensive frequency source, solid-state transmitter, battery power supply, and an omni-directional antenna. The frequency source, in particular, is not readily obtainable, but must be specifically ordered from a manufacturer. Table 5-1 illustrates the relative size and costs. Note that cost increases proportionally with power output and depends on operating time. A 100-W jammer would cost approximately $300 and is about the size of a shoe box, while a 1000-W jammer would cost approximately $3000 and is approximately the size of a small suitcase. Volume and weight increase significantly as operating time is increased to 1 day. Based on these data, it was judged that a hacker threat might reasonably obtain a 100-W jammer and a 1000-W jammer becomes much less likely because of cost. Thus, a single 100-W broadband jammer was chosen as the baseline jammer type for this study. As shown below, interference suppression that is completely effective against a 100-W jammer would also provide reasonable protection against a 1000-W jammer. In addition, a broadband jammer would be simpler to construct than the narrowband jammer because of the less stringent requirement on frequency control. Depending on specific receiver design, the broadband jammer may also be more effective.

Table 5-1 Estimated Jammer Characteristics

Power (W)	**Operating Time**					
	1 Hour			**1 Day**		
	Cost ($)	Weight (lb)	Volume (cu. in.)	Cost ($)	Weight (lb)	Volume (cu. in.)
10	50	1	50	60	11	250
100	300	3	500	409	112	2500
1000	3000	10	5000	4090	1100	25000

To illustrate the impact of a 100-W jammer on GPS signal reception, Figure 5-4 shows the area over which a 100-W jammer would cause a GPS receiver to lose track of the GPS signal. In this analysis, it was assumed the receiver could track a GPS signal up to a jammer-to-signal ratio of 30 dB. This value is typical of current technology and is consistent with the WAAS RTCA/DO-229 specification for broadband noise. The left portion of the figure shows the effect if the aircraft antenna gain were unity in all directions. In fact, an aircraft antenna pattern would have some decreased gain in the direction of the jammer because the jammer is expected to be below the aircraft and the aircraft provides some degree of shading. The right portion of the figure illustrates the reduction in effective area if the antenna gain were –10 dB (one-tenth) in the direction of the jammer. Circles are also shown to represent the horizon line-of-sight limits for aircraft operating at 30,000, 15,000, and 3000 feet. Thus, the jammer would not affect an aircraft flying at 30,000 feet until it is within the horizon circle, a radius of approximately 215 nmi from the jammer.

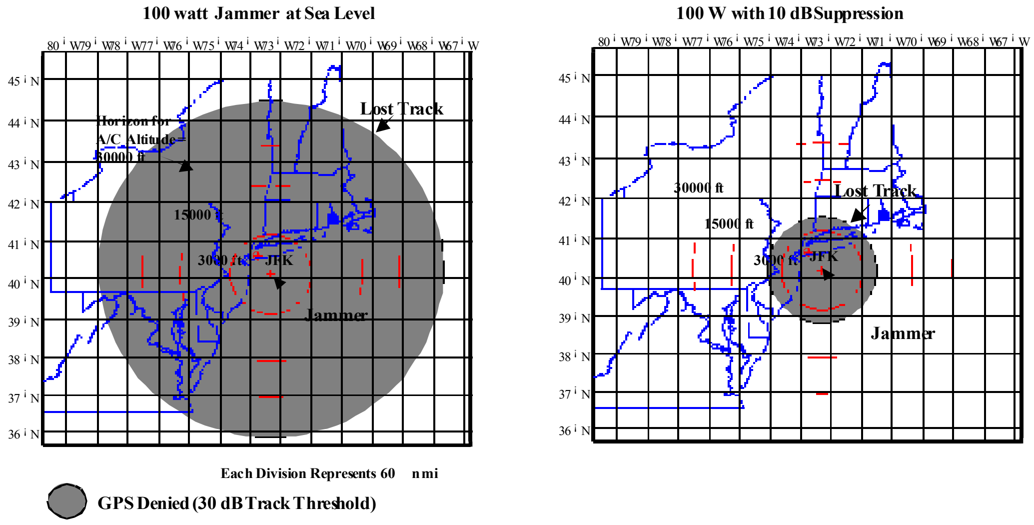


Figure 5-4 Outage Area Caused by 100-W Jammer

The effect of a further reduction in jamming signal because of either aircraft antenna pattern or other interference suppression is shown in Figure 5-5. The left portion of the figure shows the impact of 20 dB of additional suppression, and the right side shows a plot of jammer power versus corresponding denial range. Thus, for example, if the effectiveness of a 100-W jammer is to be reduced to less than a 1-nmi radius an additional 50 dB of interference suppression is required.

To analyze the potential impact of jamming in the terminal area, a scenario illustrated in Figure 5-6 was developed. A nominal aircraft trajectory was assumed, and a 100-W jammer was randomly placed at ground level within a 30-nmi radius of the landing point. Other maximum jammer distances were evaluated, but the 30 nmi value was found to be an approximate “worst case” after accounting for line-of-sight limits because of the horizon and range effects. The scenario also assumed a smooth Earth so that the benefit of terrain masking was not included. A baseline aircraft GPS antenna pattern was also included in the simulation model. The antenna pattern is discussed further in Appendix I.

An example trajectory is shown in Figure 5-7 where jammer-to-signal power ratio (J/S) is plotted as a function of range to touchdown for an aircraft making an approach and landing at JFK airport. The jammer is located approximately 20 nmi from the airport under the flight path. The plot illustrates that the J/S value after attenuation by the antenna is always greater than a typical receiver tracking threshold value of 30 dB. Thus, in this example, GPS would not be available throughout the entire approach and landing trajectory. The plot also serves to illustrate that an additional 32 dB of interference suppression would eliminate the GPS outage.

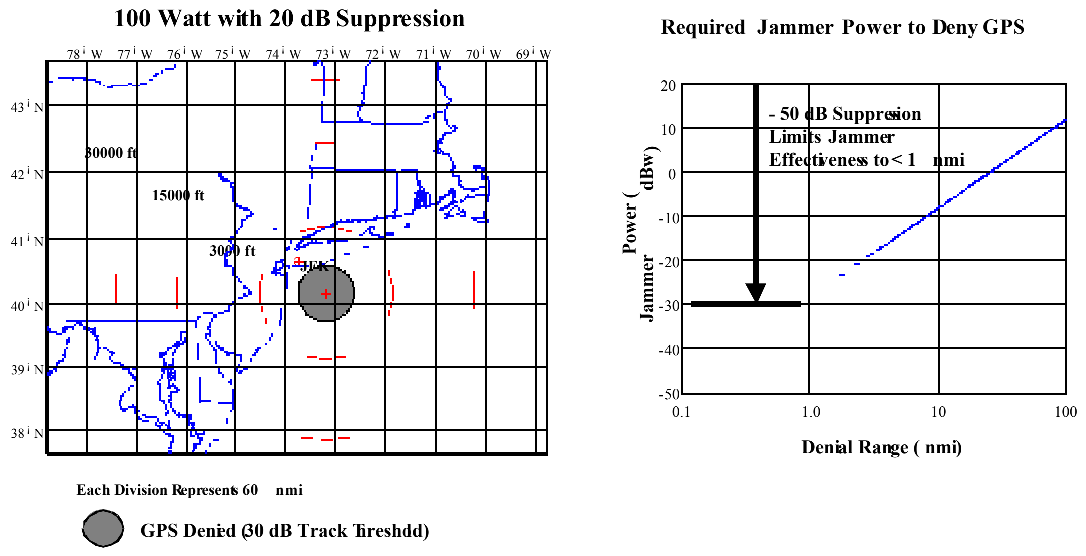


Figure 5-5 A 100-W Jammer with Additional Interference Suppression

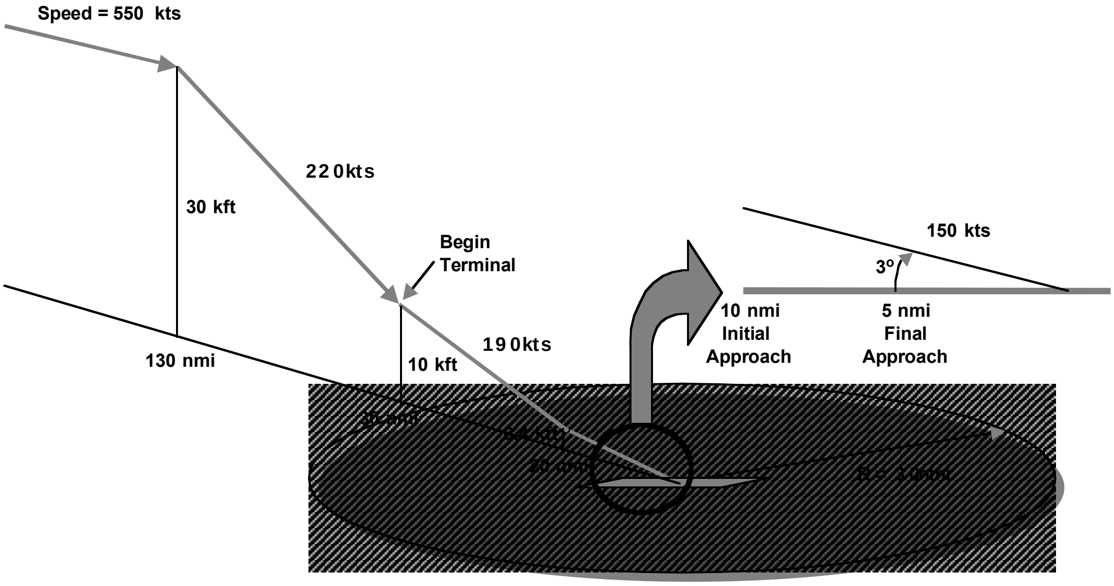


Figure 5-6 Terminal Area Scenario

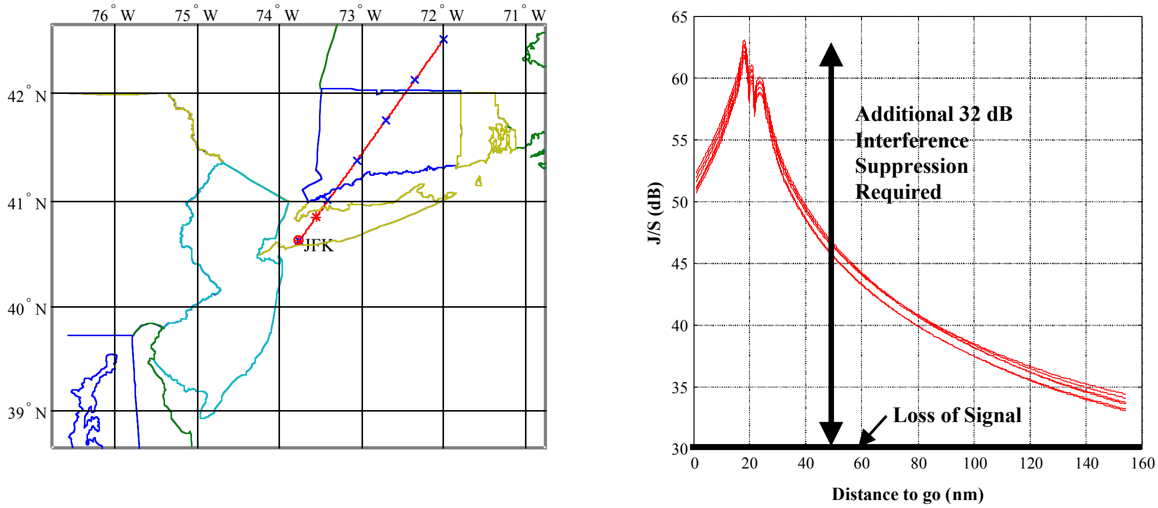
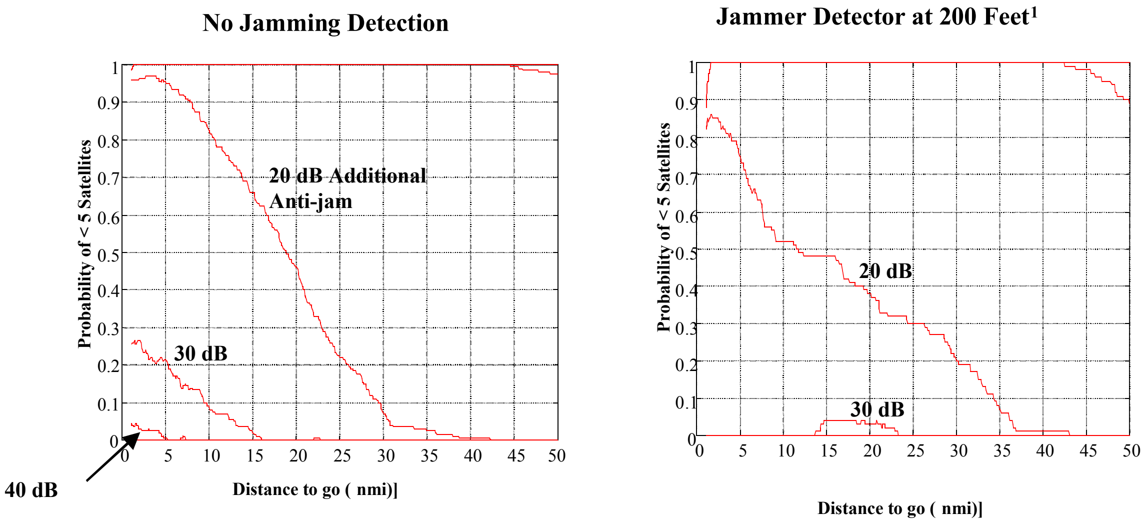


Figure 5-7 Example Jammer-to-Signal Ratio During Approach

Given the more general scenario defined by Figure 5-6 in which the jammer is randomly located, the probability of GPS outage versus distance to the landing point was computed using Monte-Carlo simulation. GPS outage was defined as the tracking of less than five satellites. Figure 5-8 shows the resulting probability values for different levels of interference suppression beyond that provided by the assumed baseline antenna pattern. In addition, the right-hand plot shows the result of placing a jammer detector at the airport and then making the assumption that all jammer locations are forced to be outside the line-of-sight horizon limit for a jammer located at ground level. For a detector at 200 feet, this limit is 17.4 nmi. Appendix J contains further discussion of the jammer detection option. Note that without the jammer detector, 50 dB of interference suppression eliminates GPS outage, and with the jammer detector 40 dB is sufficient. Also note that if the jammer power were 1000 W instead of 100 W, this would effectively reduce the interference suppression by 10 dB, so the 40-dB curve would apply if 50 dB of suppression were being used. Figure 5-9 indicates the impact of a 1000-W jammer would be relatively minor.

The impact of an airborne emitter in the airport area is shown in Figure 5-9 for a jammer located at 5000 and 20,000 feet. It can be seen that the jamming effectiveness is not largely enhanced relative to the levels shown in Figure 5-8. On the other hand, a jammer at altitude can be detected from a much greater range, which implies that the jamming detection process benefits more than the jammer.

Acceptability of the intentional interference risk was derived by judging the likelihood to be “reasonably probable,” given the study threat scenario. The impact of this risk was conservatively judged to be “hazardous” because of the very widespread outage that can result and the potential impact on safety without appropriate air traffic control procedures. As a result, application of the Hazard Risk Index shows this risk is rated as “unacceptable” or at least, undesirable if the impact were judged to be only major. The recommended mitigations would make the risk acceptable.



[1] Plot Shows Impact of Jammer Beyond 17.4 nmi Detection Range

Figure 5-8 GPS Outage Due to 100-W Jammer at Ground Level

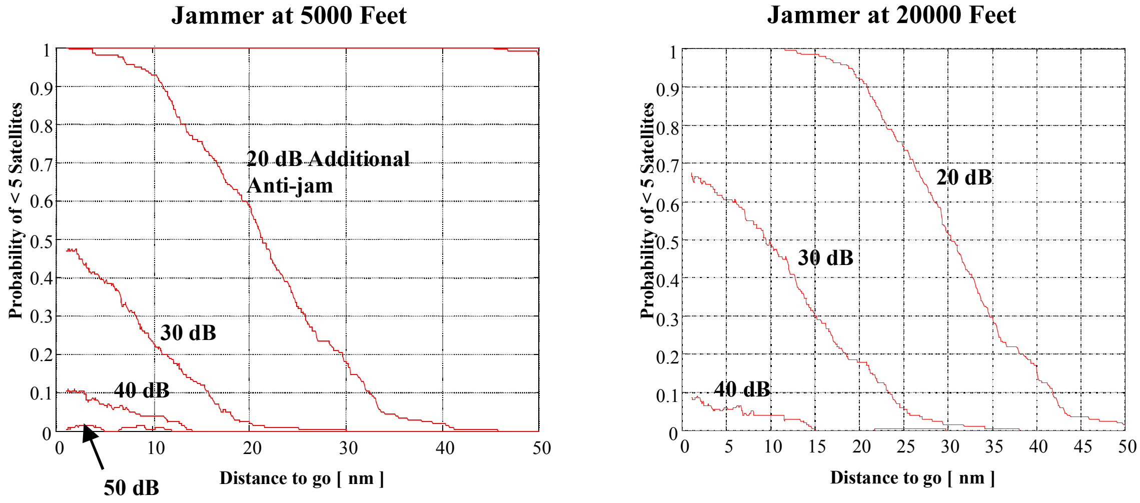


Figure 5-9 GPS Outage Caused by 100-W Airborne Emitter

5.1.3 INTERFERENCE MITIGATION

It will be necessary to establish methods and procedures for interference detection and location as discussed in Appendix J. Unintentional interference will need to be monitored and corrected, and persons maliciously producing intentional interference will need to be rigorously pursued and prosecuted. Beyond that, numerous technology options exist that provide additional GPS interference suppression to mitigate the risks of both unintentional and intentional interference. They fall into the general categories of GPS signal-in-space improvements, user antenna design and installation, coupling of the GPS receiver with other sensors, and receiver signal processing. Examples of user based techniques are given in Table 5-2. Estimated component costs are used to indicate relative complexity. They do not include the impact of nonrecurring engineering or the cost of integration.

Table 5-2 Example GPS Interference Suppression Technologies

Technology	Max Gain[1]	Number of Emitters	Estimated Cost	Remarks
IMU Receiver Code Loop Aiding	**10 dB**	**N/A**	**$10 – 40 K**	**Cost depends on accuracy; higher cost represents 1 nmi/hr quality**
Adaptive Controlled Radiation Pattern Antennas (CRPA)	**35 dB**	**~(# elements –1), but Depends on geometry**	**$2 – 20 K**	**Less capable systems available now; higher end systems not in production for a few years**
Low-Elevation Antenna Nuller (LEAN)	**35 dB**	**Any Number Near Horizon**	**$3 K**	**Still in development; need to assess impact on satellite tracking**
Signal Polarization Cancellation Antenna	**31 dB**	**14 dB for 4 Broadband**	**$3 – 5 K**	**L1 C/A available**
Reference Canceller	**50 dB**	**Any Number Near Horizon**	**-**	**In development; need to assess impact on satellite tracking**
Adaptive Filtering or Narrowband Frequency Excision (FX)	**50 dB**	**3-20 Narrowband**	**<$100**	**Ineffective against broadband interference**
Combined FX & Nonlinear Adaptive Processing (FXNONAP)	**40 dB**	**20 Narrowband, up to 3 Broadband**	**<$100**	**NONAP deployed in sub fleet; FXNONAP still in development**
Direct Measurement Processing	**20 dB**	**N/A**	**-**	**In development**

[1] **Actual performance highly dependent on scenario**

The most beneficial signal-in-space improvement with regard to intentional interference is an increase in satellite power. Recent proposals have suggested an increase of 6 dB. While this increase falls far short of that needed to counter the scenario examined in this report, any increase benefits the user because J/S would be lowered independent of user-interferer geometry and the specific suppression techniques applied by the user. Furthermore, the performance of some AJ techniques is improved with increased satellite power. A second civil frequency would provide additional benefit in the case of unintentional interference, because the likelihood of unintentional interferers appearing at both frequencies simultaneously should be considerably less than occurrence of interference at one frequency.

The interference suppression approach that has been most actively pursued in the GPS community is design of the user GPS antenna. As already noted, a standard antenna provides a degree of interference suppression in cases where the interferer is below the aircraft body, a situation that is most commonly expected.

Appropriate selection of antenna location on the aircraft body and inclusion of additional treatments such as a skin embedded choke ring might further enhance interference suppression because of body masking. These techniques, however, must at the same time ensure visibility of GPS satellites to a 5° mask angle. It should also be noted that too little antenna gain below an aircraft could preclude the use of APLs for GPS/LAAS operations. These requirements will need to be considered together.

The potentially most effective antenna technique is adaptive nulling of interfering signals by use of multiple antenna elements. A number of manufacturers have developed systems of this type, mostly for military application. These antennas can also be used to increase gain in a satellite direction. There are, however, several limitations to these systems. The most fundamental is that the number of nulls is limited to one less than the number of antenna elements. Packaging and cost limit the number of elements. Systems have been developed that have from two to seven antenna elements. Thus, the performance of a nulling antenna will typically degrade as the number of interference sources increases and, moreover, can degrade as a function of the geometric relationship between the antenna and interferer locations. Another factor to consider is the possibility that the antenna not only nulls interference, but might also null the GPS signals because of both "sympathetic" nulls[1] and in satellite directions close to interferer directions. When installed on wide-body aircraft, the effectiveness of these antennas against sources beneath the aircraft body also needs to be assessed. The dynamic response of the nulling antenna must also be considered because the null direction must rotate to counter the relative motion between the aircraft and interference source.

The integration of other sensors with the GPS receiver is another technique that is commonly pursued by military systems to provide additional interference mitigation. In particular, an IMU can be used to provide aiding signals to the GPS signal carrier and code tracking loops in the receiver, allowing tracking bandwidth to be lowered. As a result, received noise is filtered to add approximately 10 to 15 dB of additional suppression. In the event GPS is jammed, the IMU continues to provide a navigation solution for a time period determined by the quality of the IMU and the accuracy requirement. Integration with an altimeter also provides benefit because, in effect, another ranging source is available.

The most basic signal processing techniques are only effective against narrowband sources and must be directly integrated with the receiver hardware. More advanced techniques that are under development have some additional capability against broadband sources. One promising approach is sometimes referred to as direct measurement processing where the traditional cascaded receiver tracking loops are replaced with a vector measurement process that more directly couples the IMU and the navigation Kalman filter with the fundamental GPS signal measurements.

It is clear that no single technique will achieve the recommended interference suppression value of 50 dB using current technology. An example combination of techniques is as follows. First, optimize the effectiveness of body shading. This will require the direct measurement of underbody antenna patterns. This might increase the assumed baseline value by 5 to 20 dB. Second, the greatest gain will come from nulling antenna technology, which could provide another 25 to 35 dB of suppression. Finally, integration with an IMU, where available, would add another 10 to 15 dB. Thus, a possible total is 40 to 70 dB, although the upper value is subject to verification of the combined effects of body shading and the operation of the nulling antenna. Advanced signal processing could be included to further increase gain, if needed.

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[1] By virtue of the adaptive nulling algorithm, a null might be placed in a direction other than the direction of the interference source

5.1.4 IONOSPHERIC PROPAGATION

Naturally, ionospheric signal refraction acts on all GPS signals. Current authorized users can correct for this effect by using the two signal frequencies provided for the precise positioning service (PPS), and eventually a dual frequency capability will be provided for the current SPS. Because the refraction effect is inversely proportional to the square of the transmit frequency, a two-frequency user can compute the first order refraction from the difference in time of arrival of the two signals. The process used virtually eliminates the refraction error, because higher order terms are exceedingly small at the GPS frequencies. Current civil use is based on the single-frequency SPS service now provided by GPS. These users make a correction to the GPS measurement data that is based on a model that considers location, time of day, approximate time within the solar cycle (i.e., the total effect varies with solar activity with an approximate 11-year cycle), and line-of-sight elevation angle (i.e., length of the refraction path). The experienced based model for this error indicates that the model corrections have an uncertainty equal to half the total delay.

For this study, a statistical distribution was developed to match the large historical database available for this error term. This distribution was used with the above noted model parameters to determine the errors used in the performance simulations. For the GPS-only runs, where only oceanic through non-precision approach flight phases were evaluated, two separate cases were tested. The baseline case considered the total distribution (i.e., looked at the long-term statistical nature of this error over the full solar activity cycle). The second case was restricted to the high solar activity period (i.e., to characterize the short-term worst-case condition). In either case, the impact for the phases of flight considered was not significant. The GPS/WAAS and GPS/LAAS implications are discussed later.

5.1.5 IONOSPHERIC SCINTILLATION

Ionospheric scintillation is the result of nonuniform electron distributions trapped by and moving in the Earth’s magnetic field. The general model for ionospheric refraction is based on a model that assumes a relatively smooth distribution with no particularly dense regions. However, at certain times and locations the densities can be high enough or the temporal and spatial gradients large enough to diminish GPS signals below receiver thresholds. When that happens, some satellite signals will be lost to the user with the corresponding reduction in positioning accuracy. Ionospheric scintillation is most severe in equatorial regions and in the auroral region. The most likely means by which ionospheric scintillation affects GPS users in the continental United States is in viewing GPS satellites through these regions. The auroral region covers the northern part of Canada between 65° and 72° N *geomagnetic* latitude and the equatorial region covers zones at 15° ± 10° N and at 15° ± 10° S geomagnetic latitude. Only the northern equatorial zone is seen from the United States and only by two of the locations included in the study. Scintillation will most likely coincide with auroral storms (known as “Auroral-E ionization,” or AEI), and, in these conditions, the southern edge of the auroral oval may dip down into continental United States. AEI is most likely to occur during evening hours (1900–2400 local time). Within this disturbed region, pierce points with a local time between 2000–2200 are considered to be susceptible to “strong” scintillation, whereas pierce points with local times between 1900–2000 or 2200–2400 are considered to be susceptible to “moderate” scintillation. Within both of these zones, scintillation is “patchy,” such that an average of 30 percent of the pierce points are affected.

A conservative model was used to test the overall impact of including this effect in the normal system availability analysis. The best SPS case considered in this study (i.e., 30 GPS satellites, SA off, and dual frequency available) was tested with this model. The oceanic availability dropped from 0.999996 to 0.988; en route availability dropped from 0.99994 to 0.988; terminal availability dropped from 0.9999 to 0.988; and NPA availability dropped from 0.9998 to 0.998. The availability numbers with scintillation were only different beyond the third significant figure. Because this effect seriously degrades availability, it is a risk factor. Occurrence of the risk was determined to be “reasonably probable” (i.e., between 10^{-2} and 10^{-5}) and our assessment of consequences is that it is “minor.” Using the hazard risk index, this risk is characterized as “acceptable with FAA review.” The GPS/WAAS and GPS/LAAS implications are discussed later.

5.2 WAAS RISKS

The set of potential risks affecting WAAS are the same as for GPS, except for additional risks associated with the WAAS ground system and the GEOS. Most of these are statistically characterized in the GPS/WAAS simulation model and results discussed previously. Intentional and unintentional interference on the WAAS user avionics is the same as discussed in the previous section for GPS only. However, interference to the WAAS (ground system and GEOS) and ionospheric abnormalities are unique to WAAS and will be discussed in the following subsections.

5.2.1 INTERFERENCE (Reference 7)

Unintentional interference to the ground system is less likely than for the user avionics because of ground shielding. Intentional interference at a WRS would be detected in the integrity checks, with no safety effects. Losing an entire WRS has no impact on en route performance and minor impact on precision approach performance. Geographic dispersion of the WRSs mitigates any attack via WRS jamming. Data communications between the WRSs, WMSs, and GUSs is by a ground-based system, with integrity checks to assure data validity. The timing signal from the U.S. Naval Observatory (USNO) can be jammed but the WMS cesium reference keeps accurate time for extended periods. This, along with geographic dispersion of redundant WMSs minimizes any effects of WMS jamming. The GUS uplink to the GEO is difficult to overpower (16-m dish), and the GUS signal-in-space monitor would instantly recognize the difference between the transmitted and received signals. This, along with geographic dispersion of redundant GUSs and GEOS, minimizes any effects of GUS and/or GEOS jamming. Consequently, the probability of interference to the WAAS infrastructure is judged to be insignificant and would not result in an integrity failure.

5.2.2 IONOSPHERIC PROPAGATION (Reference 8)

Because WAAS accuracy for Category I precision approach is considerably higher than for NPA through Oceanic operations, the effects of ionospheric abnormalities on WAAS are potentially more significant than described in the GPS-only section. Three types of resulting phenomena will be considered (increased total electron content, increased geomagnetic storms, and increased scintillation), which are all related to the peak of the 11-year solar cycle (next peak in 2000–2001). First, the general increase in the total electron content (TEC) over nominal conditions is well modeled and should be corrected out. This would correspond to the largely prevailing “quiet conditions” at the solar maximum part of the cycle. However, geomagnetic storms become more frequent and intense during the solar maximum period with about two medium-to-severe storms expected per month. About half of these will produce ionospheric disturbances (large temporal and spatial gradients) over CONUS that will last for 2 to 3 hours. Consequently, no more than 36 hours per year (about 0.4 percent of a solar maximum year) will present solar maximum disturbance problems, which was modeled in the simulation evaluations labeled “solar max” in Figure 4-5. In that case, only the Category I performance failed the requirement. Because this could result in integrity failures, it was deemed a “major” consequence with a “reasonably probable” occurrence, resulting in an “undesirable” risk assessment. Mitigation of this risk is being accomplished by an extensive research program conducted by the FAA over the next few years using NSTB and Phase I WRS site data to validate the severity of this effect and develop better modeling and processing techniques [such as tomography (Reference 9)] with more WRSs, if needed.

5.2.3 IONOSPHERIC SCINTILLATION

The third phenomenon that increases near the peak of the solar cycle is the “flickering” effect, called scintillation, described in the previous section. Not only is the WAAS user affected as in the GPS-only case, but the WRS receivers as well (especially the less robust L_2 channel; this was not simulated in our WAAS simulation) (Reference 5). Using the simulation model as described in the GPS/WAAS performance section, the results in Figure 4-5 show some degradation for the northern most CONUS sites, but not as serious as the solar maximum case. Because serious scintillation occurrence for CONUS is a few tens of hours in every 11-year cycle (~$2x10^{-4}$; “reasonably probable”), with a “minor” consequence (no safety factor), this risk was judged “acceptable,” with FAA review. The main mitigation of these effects is to use more robust receivers at the WRSs and especially in the user avionics.

5.3 LAAS RISKS

Naturally, all the signal risks that impact GPS signals will affect LAAS performance. In particular, the interference as experienced at the aircraft will impact GPS/LAAS performance. The only additional interference potential is with the VHF data link between the ground station and the aircraft. Also, because the ground station and the data link represent single points of failure, their reliabilities must meet the LAAS ground station specifications. Assuming careful design, station reliability should not present a significant risk. The ionospheric propagation issues that apply to GPS and GPS/WAAS performance are not a factor for GPS/LAAS. The residual ionospheric errors in the local area differential processing of the GPS/LAAS are not a significant factor at any time in the solar activity cycle. The only ionospheric issue for GPS/LAAS is scintillation.

5.3.1 IONOSPHERIC SCINTILLATION

The same model conditions used for the GPS simulations were applied to GPS/LAAS simulations. The case that was selected for evaluating the scintillation effect was the 24-satellite GPS constellation with 4 GEOS and 2 APLs. With the scintillation applied, the mean availability for Category I service dropped from above 0.99999 to 0.991; it dropped from above 0.99999 to 0.989 for both Category II and III service. This is again, by the hazard risk process, defined as “acceptable with FAA review.”

Appendix A

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Appendix B

LIST OF ACRONYMS AND ABBREVIATIONS

AC	Advisory Circular
AEI	Auroral-E Ionization
AII	Accuracy Improvement Initiative
AOPA	Aircraft Owners and Pilots Association
AOR-W	Atlantic Ocean Region, West
APL	Airport Pseudolites
ATA	Air Transport Association
CONUS	Continental United States
CRPA	Controlled Radiation Pattern Antennas
DOD	Department of Defense
DOT	Department of Transportation
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FM	Frequency Modulation
FX	Frequency Excision
FXNONAP	FX and Nonlinear Adaptive Processing
GEOS	Geostationary Satellite
GIVE	Grid Ionospheric Vertical Error
GOSPAR	GPS OCS Performance Analysis and Reporting
GPS	Global Positioning System
GUS	Geostationary Uplink Site

HDTV	High Definition Television
HRI	Hazard Risk Index
ICAO	International Civil Aviation Organization
IMU	Inertial Measurement Unit
IONO	Ionospheric Determination Processing Algorithm
IPP	Ionospheric Pierce Point
JHU/APL	Johns Hopkins University Applied Physics Laboratory
J/S	Jammer-to-Signal Power Ratio
LAAS	Local Area Augmentation System
LEAN	Low-Elevation Antenna Nuller
MASPS	Minimum Aviation System Performance Standards
MCS	Master Control Station
MOPS	Minimum Operational Performance Standards
MTTR	Mean Time to Repair
NAS	National Airspace System
NPA	Nonprecision Approach
NSTB	National Satellite Test Bed
OCS	Operational Control Segment
OD	Orbit Determination Processing Algorithms
OTH	Over the Horizon
POR	Pacific Ocean Region
PPS	Precision Positioning Service
RAIM	Receiver Autonomous Integrity Monitoring
RF	Radio Frequency
RFI	Radio Frequency Interference
RTCA	Requirements and Technical Concepts for Aviation

RTCA, Inc.	A not-for profit organization
SOW	Statement of Work
SPS	Standard Positioning Service
TEC	Total Electron Content
UDRE	User Differential Range Error
UHF	Ultra-High Frequency
USNO	U.S. Naval Observatory
VHF	Very High Frequency
WAAS	Wide Area Augmentation System
WMS	Wide-Area Master Site
WRE	Wide-Area Reference Equipment
WRS	Wide-Area Reference Sites