Status Update on GPS Integrity Failure Modes and Effects Analysis

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BIOGRAPHIES

Karen Van Dyke is a project leader in the Center for Navigation. Ms. Van Dyke has conducted availability and integrity studies for aviation applications of GPS and its augmentation systems for all phases of flight. She was the project lead of a Volpe Center team which designed, developed, and implemented GPS outage reporting systems for both the U.S. Air Force and the FAA and this work has been extended to other countries around the world. Ms. Van Dyke received her BS and MS degrees in Electrical Engineering from the University of Massachusetts at Lowell and has served as President of the Institute of Navigation.

Karl Kovach is a Technical Director with ARINC Engineering Services, LLC in El Segundo, California. Karl has over 24 years in various aspects of the GPS program, including 3 years as the Air Force Officer-in-Charge of the GPS Control Segment when it was at Vandenberg AFB, California (1983-1986). He received his BS degree in Mechanical Engineering from the University of California at Los Angeles in 1978.

John W. Lavrakas is a Senior Staff Engineer for Overlook Systems Technologies, Inc. where he serves as Director of Operations Support for the Department of Defense GPS Support Center. Mr. Lavrakas has spent the last 22 years in GPS, supporting the development of the GPS Control Segment, GPS user equipment for military range applications, and developing and marketing GPS-based commercial asset location systems. Mr. Lavrakas has written numerous papers and articles on GPS, including those appearing in *GPS World* and *GPS Solutions* magazines. He is a graduate of Harvey Mudd College and the Claremont Graduate University with BS and MA degrees in mathematics.

ABSTRACT

GPS integrity anomalies have long been of great concern to the civil and military GPS communities for safety of life operations. The FAA, USCG, and their international counterparts have focused on how to accomplish integrity monitoring for safety of life services through the use of receiver autonomous integrity monitoring (RAIM), wide-area and local-area augmentation systems such as WAAS and LAAS, maritime differential GPS (DGPS) and nationwide differential GPS (NDGPS). The military is preparing to certify PPS RAIM receivers and is in the process of developing the Joint Precision Approach and Landing System (JPALS). Integrity failure modes need to be understood in order to develop a proper monitoring capability.

The main objectives of the GPS Integrity Failure Modes and Effects Analysis (IFMEA) project are to identify GPS integrity requirements, examine GPS failure data in order to identify integrity failure modes, examine the causes and effects of the failures, as well as their probability of occurrence, determine the impact of integrity anomalies on users, and recommend preventive actions. The IFMEA project is focused on integrity anomalies that are due to hardware and software failures in the satellite vehicles (SVs) and Operational Control Segment (OCS).

The IFMEA project will define algorithms to ensure proper detection of integrity anomalies and identify any design constraints or modifications to the GPS SV and OCS to either prevent failures that degrade integrity or provide protection from any adverse operational impact. Recommendations for modifications to the satellites primarily will be geared toward the GPS III program unless the GPS JPO decides they should be implemented on Block IIR-M or Block IIF satellites and associated control segment components.

This paper provides a status update on the current GPS IFMEA effort which is jointly funded by the Interagency GPS Executive Board (IGEB) and the GPS Joint Program Office (JPO). The benefits of this work are to gain a better understanding of integrity anomalies, their probability of occurrence, and how to monitor for them. This information is essential to the design of GPS augmentation system networks to support safety of life operations and will assist in meeting international commitments to describe GPS performance. The work performed under this study also will provide a technical basis to update the SPS Performance Standard and provide input to the PPS Performance Standard currently

under development. Finally it will help develop recommendations for improvements to future GPS satellites and the operational control segment.

INTRODUCTION

GPS integrity monitoring has always been of great importance to the civil GPS community for safety-of-life operations. Integrity is a measure of the trust which can be placed in the correctness of the information provided by the total system [1]. Integrity includes the ability of a system to provide timely and valid warnings to the user (alerts) when the system must not be used for the intended operation. Integrity warnings can be provided by various methods. Receiver Autonomous Integrity Monitoring (RAIM) Fault Detection (FD) and Fault Detection and Exclusion (FDE) algorithms are contained within some GPS receivers (mostly those certified for aviation). Other methods of integrity warning involve monitoring the GPS signal by a reference receiver (or a network of receivers) on the ground and broadcasting a message to users containing a differential correction for small errors or a “don’t use” message if the satellite is determined to be out of tolerance for the application. The FAA Wide Area and Local Area Augmentation Systems (WAAS and LAAS), Joint Precision Approach and Landing System (JPALS), USCG Maritime DGPS, and the Nationwide DGPS (NDGPS) are examples of such systems in the U.S., and equivalent systems are being developed internationally.

In order to properly design a GPS integrity warning system, an understanding of the failure modes (those that have been observed and potential integrity threats), as well as their probability of occurrence is required. Also, insight into how the failures manifest themselves is very important. For example, it is extremely helpful to know if the failure produces a step error or a ramp error and what the rate of the ramp error is. The effect of integrity anomalies on users also needs to be understood, including how large the effect is and how long it will last.

The GPS Program Management Directive (PMD) directs the GPS Joint Program Office (JPO) System Program Director to support US Space Command (now US Strategic Command) in establishing standards to measure, develop and maintain a means to monitor and report on Standard Positioning Service (SPS) and Precise Positioning Service (PPS) coverage. The Interagency GPS Executive Board (IGEB) recognized that a joint military and civilian Integrity Failure Modes and Effects Analysis (IFMEA) effort focused on anomalies would be an ideal way to satisfy much of this requirement, and so the IGEB provided the initial "seed" Stewardship funding for the first year of this IFMEA project in 2002.

OBJECTIVES

The main objectives of the IFMEA project are to identify and understand GPS integrity requirements, examine GPS failure data in order to identify integrity failure modes, examine the causes and effects of the failures as well as their probability of occurrence, determine the impact of integrity anomalies on users, and recommend preventive actions. The goal of the IFMEA project is to focus on integrity anomalies that are due to space vehicle (SV) and Operational Control Segment (OCS) failures.

One aspect of this project is to examine the longer term goals, since it is recognized that the IFMEA analyses must be updated as each new signal and system capability is developed. Each added signal has the potential to introduce new failure modes.

Another aspect of the IFMEA project is to identify any design constraints or modifications to the GPS SV and OCS to either prevent failures that degrade integrity or provide protection from any adverse operational impact. Recommendations for potential modifications to the satellites are primarily being geared toward the GPS III program. It is probably too late to change the Block IIR-M satellites, and it is nearly too late to make any but the smallest self-contained changes to the Block IIF satellites.

The benefits of this work are obtaining a better understanding of GPS integrity anomalies, their probability of occurrence, and how to monitor for them. It also will provide a technical basis for future updates to the SPS and PPS Performance Standards and will help develop recommendations for improvements to future GPS satellites and the operational control segment. A further benefit is to help in designing integrity monitoring functions in GPS augmentations, in order to achieve aviation integrity requirements while maximizing availability and continuity. An overview of the IFMEA project is illustrated in Figure 1. It should be recognized that the IFMEA investigative work must be a multi-year effort to attain its goals, but also must transition to an ongoing effort once the processes are fully in place.

The approach for the IFMEA effort is to:

- Form a team of civil/military experts
- Review previous IFMEA studies
- Identify integrity requirements
- Develop and maintain a database of failure modes
- Analyze the data to develop the probability of individual failure modes
- Identify potential preventive actions

The first five tasks were the primary focus of the 2002 IFMEA effort.

The IFMEA project is closely related to two other IGEB projects funded in 2002: the Global Dual Monitoring System (GDMS) and the Civil Operations Evolution (COEP) project. The main objective of the GDMS project is to take advantage of all of the GPS signal-in-space (SIS) monitoring capabilities that currently exist in order to support integrity monitoring, various data collection activities, and assurance that requirements in the SPS and PPS Performance Standards are being achieved.

Current monitoring systems are somewhat stovepiped in that they were designed for a specific application. Some data sharing arrangements do exist between organizations and there are a few examples of collaborative networks in certain areas of expertise, but in most cases an organization has its own collection network to meet the requirements of the users it serves. Under the GDMS concept, organizations still will own their collection assets and they still will fulfill their own requirements, but by sharing their data they will simultaneously gain access to data collected by other organizations. This will leverage the individual costs into greater benefits to the community.

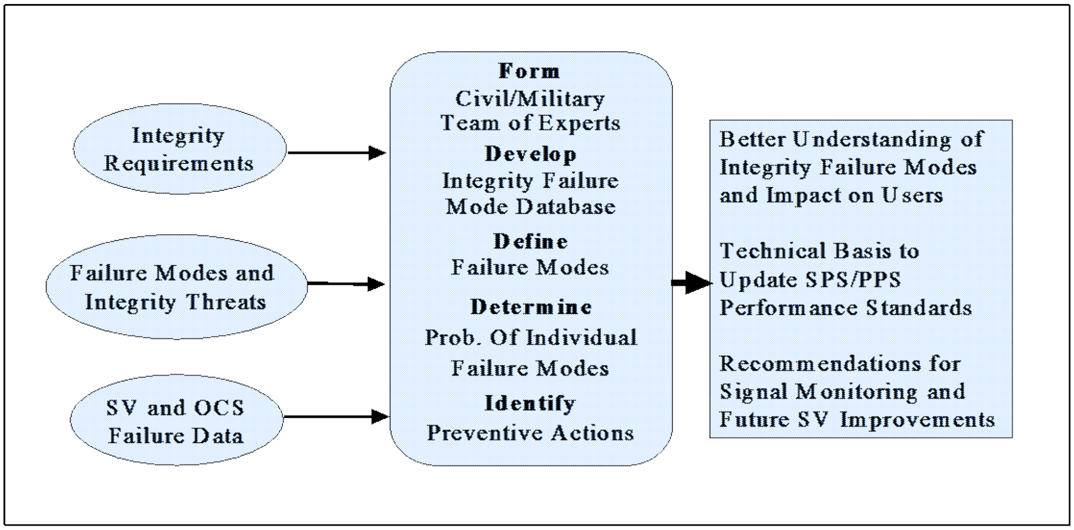

Figure 1 Overview of IFMEA Project

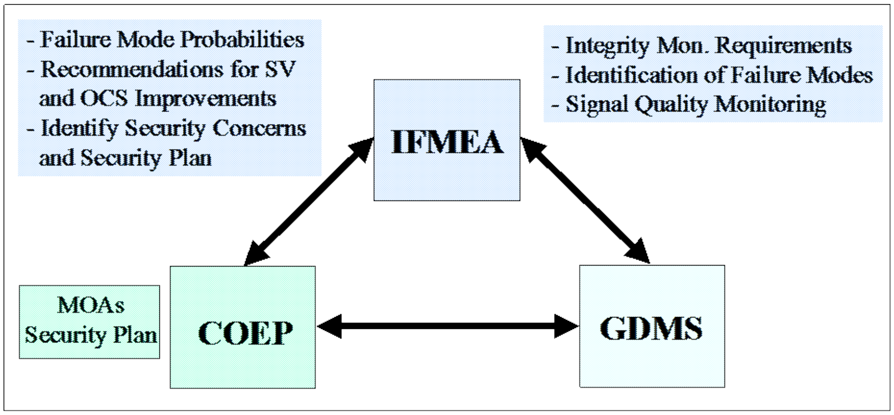

Figure 2 Relationship Between IFMEA, COEP, and GDMS

In order for a U.S. Government sponsored GPS monitoring system to ensure integrity monitoring of the GPS signal, an understanding of civil/military requirements is required, as well as knowledge of integrity failure modes in order to properly detect signal corruption, degradation, or system failure that could result in the loss of integrity.

The interface with the GPS Civil Operations Evolution Plan ensures that integrity definitions and parameters resulting from the IFMEA work are incorporated into appropriate GPS documents. For example, the GPS SPS and PPS performance standards may be updated based on the integrity failure mode probabilities identified through the IFMEA analysis. The COEP project also will ensure that security guidelines are adhered to for the public releasability of any IFMEA project data. The relationship between the three projects is shown in Figure 2.

BENEFITS

This IFMEA project will result in significant benefits to civilian and military users of GPS. The documentation and analysis of integrity failures will allow for the determination of the probability of individual failure modes which will help determine the probability of hazardously misleading information (PHMI) from GPS. The IFMEA analysis also will provide a technical basis to update the SPS Performance Standard. The SPS Performance Standard [2] currently allows for up to three major service failures per year, which appears to be very conservative based on how the GPS system has performed. Also, this document does not specify not to exceed (NTE) values for range rate or range acceleration error. Results from the IFMEA are needed before updates to this standard can be made. Results also will used in preparation of the PPS Performance Standard which currently is in development.

The IFMEA project will help improve the reliability of GPS in the future by providing recommendations for GPS SV and OCS design modification, as well as to integrity monitoring provided by civil/military augmentation systems and monitoring networks.

Finally, the analysis conducted through the IFMEA project, in conjunction with the benefits obtained from the GDMS and COEP projects, will increase user confidence in the ability of GPS satellites and OCS to satisfy commitments stated in the performance standards.

FORMATION OF IFMEA TEAM

The first task in the 2002 IFMEA project was to select a team of civilian and military experts who could provide a broad spectrum of capability to support the tasks outlined in this plan. The necessary GPS expertise related to integrity requirements and monitoring capabilities, identification of failure modes and their probability of occurrence, failure data that can be analyzed, and familiarity with the satellite design and operational control segment to determine potential integrity threats and mitigation techniques.

Table 1 provides a list of organizations who participated in the 2002 IFMEA project. Those with an asterisk next to them are ones that received IGEB Stewardship funding. However, many other organizations also participated in the IFMEA effort and should be recognized for their contributions. It should be noted that the level of effort provided by the GPS JPO and through voluntary participation exceeded funding provided by 2002 IGEB IFMEA funding.

Table 1 List of Organizations Participating in 2002 IFMEA Project

DOT/Volpe Center*	GPS JPO (CZC/CZE)
AJ Systems*	2SOPS
ARINC*	US Space Command
ARL:UT* (GDMS Project)	NIMA
Mitre CAASD*	Navy
Overlook Systems*	State Dept.
SAIC*	Aerospace Corp.
FAA	Boeing
USCG	Lockheed Martin
FHWA	Spectrum Astro
FRA	Northrop Grumman
Stanford University	Honeywell
	Rockwell Collins

* Received IGEB Stewardship Funding

REVIEW OF PREVIOUS IFMEA WORK

Two previous GPS IFMEA studies that have been conducted were reviewed to understand what was previously accomplished: a 1988 ARINC study and the 1991 IBM Integrity Study. These studies were mainly focused on the Block I satellites, but they are the basis for the current Standard Positioning Service (SPS) Performance Standard.

1988 ARINC Study

This study was initiated in 1986 based on the fact that the GPS Block I satellites were not very reliable. The study was conducted by ARINC for the GPS JPO (CZE) from 1986 to 1988. The results of this study are published in 1988 ION paper “Methodology and Calculation of a Preliminary Unconditional Integrity Value for GPS” by Karl Kovach [3].

The main achievements from this initial IFMEA study were a definition and framework for conducting integrity failure mode analysis. Also, it led to the development of Aberration Characterization Sheets (ACS) for each identified failure mode. This will be discussed more extensively in Section VI of this report. The preliminary estimate from the 1988 ARINC study was that the mean time between loss of integrity (MTBLOI) is 15.3 years.

1991 IBM Integrity Study

This study was performed in 1990 and completed in 1991 to determine if GPS could serve as a sole means system for DoD flight safety operations. The original view was that DoD did not need to worry about GPS integrity if GPS was integrated with INS, but this philosophy changed based on the results of the study.

Requirement Definition

"Identify an integrity architecture which provides service to all DoD users worldwide with a 99.97% confidence that horizontal accuracy will be within 100 meters or a warning will be provided in 10 seconds."

Solution Identification

- Consider modifications to control, space, user segments
- Assumptions
  - Global integrity solution
  - PPS service
  - DoD control, but compatibility with FAA/ICAO requirements (if possible)
- Removal of the signal in space constitutes a legitimate warning

Study Conclusions:

1: GPS is providing a robust positioning service that does not fail often.
2: When the current system does fail, the system is unable to respond in a timely manner to ensure navigation service integrity.
3: Several potential, technically feasible solutions to the GPS integrity problem exist.
4: Minimizing the probability of failure and the duration of a failure are the most effective methods of improving GPS integrity.
5: Due to the complexity of the GPS integrity problem, a single integrity architecture will not necessarily provide a complete solution.
6: The most cost effective architectures make maximum use of existing GPS resources, principally OCS resources. However, utilizing these resources, in general, does not serve to optimize the integrity response time.
7: Increasing the horizontal error threshold requirement only minimally improves Psafe, where Psafe is defined to be the probability that GPS will provide navigation service integrity.

Study Recommendations:

1: Make low-cost, easily-implemented improvements to the base system.
2: Implement OCS modifications that reduce the duration of system outages and enhance command and control capabilities.
3: Implement the manual SATZAP PRN command procedure.
4: Implement the horizontal error threshold requirement incrementally.
5: Continue evaluating system failure characteristics.
6: Implement the RAIM and Block IIR integrity architectures as long-term solutions.
7: Establish a policy stating that GPS will not be used as a non-precision approach aid if the Figure of Merit (FOM) is greater than one.
The study was published in six volumes. An overview of the applicability of each volume of the the 1991 IBM study to the current IFMEA effort is outlined in Table 2.

Table 2 Applicability of 1991 IBM Study to IFMEA Effort

IBM Study	Usefulness to Current IFMEA Work
Volume I Executive Summary and Overview	Good overview of the original study, defining many of the terms used and the scope of the work performed.
Volume II Design and Applications of a GPS Integrity Model	Description of what is needed to generate a failure mode attributes dataset.
Volume III Development of Candidate GPS Integrity Architectures	Some of these architectures are of interest, as well as the investigation conducted.
Volume IV Results of Preliminary GPS Failure Modes and Effects Analysis	Describes the FMEA performed on the Operational Control Segment in this study.
Volume V Candidate Integrity Architecture Requirements Support Assessment	Techniques used in evaluation of the candidate architectures are useful for IFMEA.
Volume VI Candidate Integrity architecture Cost and Schedule Analysis	Of historical interest, but not directly applicable to the IFMEA effort.

IDENTIFICATION OF INTEGRITY REQUIREMENTS AND ASSUMPTIONS ON GPS PERFORMANCE

In order to properly conduct the IFMEA, an understanding of GPS integrity requirements and knowledge of what constitutes a failure is needed. It is recognized that the requirements are not the same for all users and applications. This task examined requirements for standalone use of GPS using internal receiver integrity monitoring, combined use of GPS/INS, and requirements for differential applications. The basis for these definitions were primarily the RTCA requirements and FAA input to the Interagency Forum for Operational Requirements (IFOR). In order for the requirements to not solely represent the aviation community, they were reviewed by the USCG, Federal Highway Administration (FHWA), and Federal Railroad Administration (FRA); however, no additions or changes were proposed to the identified requirements.

The purpose of this task was to assist in identifying what parameters need to be specified (e.g., signal waveform, navigation message values, range, range rate, and range acceleration errors, etc.), and determine how failures affect users. It is important to gain an understanding of the relationship between user requirements and the service that the GPS system provides. This information will help identify parameters that the user community would like to have defined in the SPS and PPS Performance Standards. Also, it became apparent that many assumptions on GPS performance have been made by the civil community in order to make use of the system in an operational environment. These assumptions are captured so that they can be reviewed and verified as to their validity.

Input on the following integrity monitoring requirements and assumptions also has been provided to the Global Dual Monitoring System team to assist in identifying the level of monitoring required.

Assumptions on GPS Integrity Performance Made In Analyses Supporting the Use of GPS as a Supplemental Means of Navigation in the U.S

The following assumptions regarding types of GPS anomalies, their probability of occurrence, and the OCS response time were made in analyses supporting the use of GPS as a supplemental means of navigation in the U.S.

Frequency of GPS Integrity Faults

The project defined the term "GPS integrity fault" to mean a GPS error inconsistent with the fault-free error distribution due to a fault condition when the satellite is marked "healthy" and which can lead to a position error larger than the maximum tolerable error for a given flight operation. In order for TSO C129/129a equipment RAIM algorithms to provide a probability of HMI of at most 10^{-7} in one hour, the frequency of GPS integrity faults can be at most 10^{-4} in one hour for the set of SVs in view of a single user .

Actual GPS performance, as measured by the FAA Technical Center and documented in Performance Analysis Network (PAN) reports (range domain errors, position domain errors, and service availability), has been observed to be much better than the assurance in the GPS SPS Performance Standard which, as previously stated, is fairly conservative.

Correlation of Error in the Pseudorange Residual Across Different SVs

An assumption used in analysis of RAIM is that the errors in pseudorange residuals of different SVs are uncorrelated, or that the error correlation is small enough not to degrade RAIM performance. This assumption applies both to the fault-free case and the faulted case. In the faulted case, the assumption may be better stated as follows: the probability of multiple GPS satellites having integrity faults simultaneously is small compared to the required probability of undetected HMI (10^{-7} in one hour).

OCS Response Time

The Operational Control Segment (OCS) response time is defined as the time required for the OCS to respond to a GPS integrity fault by setting the satellite to "unhealthy", taking the signal off the air, or fixing the problem, following the onset of an anomaly. The OCS response time, in combination with the frequency of integrity faults, determines the probability of simultaneous existence of GPS integrity faults on two or more satellites. The latter probability is not identical to the probability of onset of GPS integrity faults on two or more satellites during a given exposure time as defined above, which depends only on the frequency of integrity faults (and correlation across satellites, if any).

Most RAIM performance analyses are based on an assumption that only one GPS SV out of those in view of a single user has an integrity fault at any given time. Assuming independence of GPS integrity faults, the probability of simultaneous existence of two GPS integrity faults can be computed. If the OCS response time is about one hour or less, the probability of two or more GPS satellites having an integrity fault simultaneously is small (given the assumptions on frequency and independence).

Fraction of Time That a GPS SV Marked "Healthy" Has an Integrity Fault

The fraction of time that a GPS satellite integrity fault exists and affects a single user was assumed to be less than 3.7×10^{-4}. This assumption was taken from [4].

The 1993 and 1995 versions of the GPS SPS Signal Specification [5], as well as the GPS SPS Performance Standard [2], assure that the average fraction of time that a GPS satellite integrity fault exists and affects a user at a single location is 6.8×10^{-4} based on a worst-case response time to a major service failure of 6 hours. This is slightly worse than the assumption used in the analyses supporting the TSO C129 requirement [6,7]. Under "a favorable combination" of factors including OCS equipment availability, the OCS response time will be "on the order of 30-45 minutes." Since typical conditions are favorable (i.e., OCS equipment is in service the majority of the time), GPS performance should be better than assumed.

Range Error Rate Given that an SV Integrity Fault Exists

Another assumption that was made was on the size of the GPS range error rate when a GPS integrity fault occurs. It was assumed that a range error rate greater than 2164 meters per hour was "unlikely" in [8]. This assumption was based on [9] which reported that the largest range error rate observed as of that time was 2164 meters per hour.

Integrity-Related Assumptions Used in Analysis of Fix Displacement Tolerances

Analysis supporting Fix Displacement Tolerance (FDT) values used in defining en route, terminal, and NPA procedures is described in [10]. One rationale used assumptions on the fraction of time that a given number of GPS satellites would be operating and on the magnitude of the error in the pseudorange residual given that a GPS integrity fault exists. The magnitude of error in the pseudorange residual and the probability of occurrence from [10] is shown in Table 3.

Table 3 Probability of Magnitude of Error in Pseudorange Residual

X = Magnitude of Error in Pseudorange Residual	Probability that X is in the Specified Range
0 m < X < 150 m	0
150 m < X < 300 m	0.45
300 m < X < 450 m	0.24
450 m < X < 600 m	0.17
600 m < X < 750 m	0.08
750 m < X < 900 m	0.05

Assumptions Made in Analysis of the Use of GPS as a Primary Means of Navigation in Oceanic and Remote Airspace

Analysis supporting the use of GPS as a primary means of navigation in oceanic and remote airspace is documented in [11]. A number of assumptions made in this analysis already have been discussed, including the probability of one GPS integrity fault occurring in one hour and the probability of onset of two or more GPS integrity faults in one hour. One additional integrity-related assumption was that the probability is low that GPS position error exceeds 20 nautical miles when HDOP is small. This assumption was taken from [12].

Assumptions Made in Analysis of the Use of GPS/WAAS Phase 1 for En Route Through LPV Flight Operations

Assumptions on GPS performance made in analyses supporting the use of WAAS fall into two groups. One group is a set of assumptions related to the fault detection and exclusion (FDE) function required in the WAAS MOPS (and therefore by TSO C145a/146a) [13,14,15] and the SBAS SARPs. WAAS user airborne equipment is required to implement FDE algorithms in case the WAAS broadcast message does not support the intended aircraft operation. Note that RAIM is called "fault detection" or FD in the WAAS MOPS and SBAS SARPs. The other group of assumptions are made in the analysis of the WAAS ground segment's ability to assure safety when the Horizontal Protection Level (HPL) computed using the WAAS broadcast message (called HPL_{WAAS}) is used to assure integrity.

FDE may be used on pseudorange residuals not corrected using WAAS information, or on pseudorange residuals corrected using WAAS information. An assumption or clarification that is more explicit in the development of WAAS user equipment than TSO C129 GPS user equipment is that in the absence of a fault condition, the GPS broadcast URA is the standard deviation of combined error in the GPS clock, ephemeris, and L1/L2 bias estimate (τ_{GD}) in the absence of a fault condition.

The other integrity-related assumptions supporting the use of FDE by WAAS user equipment on uncorrected pseudorange residuals (low correlation of errors and low probability of simultaneous integrity faults) are the same as those made in analyses of TSO C129/C129a equipment.

GPS integrity-related assumptions supporting the use of WAAS information are as follows [16].

Signal Deformations/Distortions ("Evil Waveforms")

The probability of signal deformations with characteristics in the GNSS SARPs [1], Attachment D, page D-17 is assumed to be less than 10^{-4} in one hour per SV. The OCS response time to signal deformations is not specified, but is assumed to be sufficiently small that the probability of a second signal deformation occurring before a previously existing one is resolved is small (on the order of 10^{-8} per hour). Note that LAAS algorithms, discussed later, may be based on an assumption of a shorter response time.

The probability of signal deformations with characteristics other than those of the SARPs is assumed to be much less than 10^{-7} in one hour for the set of satellites in view of a single user, if those signal deformations have the property that they could cause HMI to MOPS-compliant user equipment. Again, the response time should be short enough to assure that the probability of simultaneous signal deformations is small, if failure modes resulting in such signal deformations are possible.

Code/Carrier Divergence

The probability of code/carrier divergence (code minus carrier phase at the output of the SV antenna) greater than 6.1 meters is assumed to be less than 10^{-4} per hour per SV. It would be highly desirable to assure a smaller value in future phases of WAAS. The GPS OCS response time is assumed to be short enough that the code-carrier divergence does not persist over multiple "passes" of the satellite over the WAAS service volume.

GPS Ephemeris Errors

The onset of erroneous GPS ephemeris data is assumed to occur with a probability of 10^{-4}/hour for any single satellite. Erroneous GPS ephemeris data is ephemeris data whose error is not properly characterized by observed *a priori* error standard deviations in height, cross-track, and along-track directions (σ_{eph_h}=2.61, σ_{eph_c}=5.45, σ_{eph_l}=13.25). These values are based on historical observations of GPS performance [17,18]. In the future, it would be desirable if the standard deviation of GPS ephemeris error (in the absence of integrity faults) in each direction were reduced, e.g., 0.6 m height or radial error, 2 m cross-track error, and 3 m along-track error .

Signal Faults Causing Step Errors, Ramp Errors, or Acceleration Errors

The probability of a GPS signal fault causing any one of the following is assumed to be less than 10^{-4} per hour per SV:

- A step (discrete jump) error larger than 3.6 m
- A range acceleration error larger than 0.019 m/s^2

Note that WAAS integrity analyses are also based on an assumption that the probability of a GPS integrity fault causing an error not characterized by the GPS URA is 10^{-4} per hour per set of SVs in view. This is in contrast with the requirement on signal faults that cause steps, ramps, or range error accelerations larger than specified thresholds.

No assumption is made on OCS response time.

Absence of Common Mode Integrity Faults

It is assumed that there is no common mode failure that causes more than one of the following signal faults: signal deformation, code/carrier divergence, or step/ramp/acceleration error in the pseudorange residual.

Assumptions Made in Analysis of the Use of GPS/LAAS for CAT I Approach

GPS integrity-related assumptions made in analysis of LAAS integrity are as follows.

Signal Deformations/Distortions ("Evil Waveforms")

The probability of GPS signal deformations with characteristics in the GNSS SARPs [1], Attachment D, page D-17 is assumed to be less than 10^{-4} in one hour per SV, the same as the WAAS assumption. A desirable objective in a future GPS constellation is a probability of signal deformation of less than 10^{-7} per satellite per hour.

The probability of signal deformations with characteristics other than those of the SARPs is assumed to be much less than about 10^{-7} per CAT I approach for the set of satellites in view of a single user, if those signal deformations have the property that they could cause HMI to a MOPS-compliant user equipment. The probability of signal deformations with characteristics other than those of the SARPs is assumed to be less than 5×10^{-11} per CAT III approach for the set of satellites in view of a single user, if those signal deformations have the property that they could cause HMI to a MOPS-compliant user equipment. Again, the response time should be short if failure modes resulting in such signal deformations are possible.

Low Signal Power

The probability of GPS signal power less than 3 dB below the minimum required signal level is assumed to be less than 10^{-4} per hour per SV. However, if the probability exceeds this value, there is no impact on safety. The OCS response time is under discussion. A desirable OCS response time would be 30 seconds for a future GPS constellation.

Code/Carrier Divergence

The probability of code/carrier divergence (code minus carrier phase at the output of the SV antenna) greater than 0.02 meters/second (to be confirmed) is assumed to be less than 10^{-4} per hour per SV. A desirable objective would be that the probability of code/carrier divergence greater than 0.01 meters/second would be less than 10^{-7} per SV per hour in a future constellation.

Excessive Pseudorange Acceleration

The probability of an acceleration in pseudorange error greater than 19 mm/s^2 is assumed to be less than 10^{-4} per hour per SV. It is desirable to specify a tighter bound based on S/A off as an objective requirement for the future.

Erroneous Ephemeris

The probability of erroneous ephemeris information depends on the nature of the ephemeris information. The following causes have been identified:

- Unintentional SV maneuver that causes an ephemeris error larger than 200 m
- Intentional SV maneuver that causes an ephemeris error larger than 200 m for which OCS fails to issue a Notice Advisory to NAVSTAR Users (NANU).
- Intentional SV maneuver that causes an ephemeris error larger than 200 m for which OCS fails to set the ephemeris health word to "unhealthy"
- Intentional SV maneuver that causes an ephemeris error larger than 200 m for which the OCS issues a NANU and sets the ephemeris health word to "unhealthy" but fails to update the ephemeris information after setting the health word to "healthy"
- All other causes of erroneous ephemeris information with an error larger than 200 m

The currently assumed probability of errors larger than 30 m or 4.42 × URA is 10^{-4}/hr per set of SVs in view.

Desirable probabilities for future GPS constellations for unintentional maneuvers causing an ephemeris error larger than 200 m (threshold) or 100 m (objective) are assumed to be negligible.

Desirable probabilities for future GPS constellations for intentional maneuvers causing an ephemeris error larger than 200 m (threshold) or 100 m (objective) for which the OCS fails to set the ephemeris health word to "Unhealthy" are 10^{-7} per SV per hour (threshold) and 10^{-10} per SV per hour (objective).

Desirable probabilities for future GPS constellations for intentional maneuvers causing an ephemeris error larger than 200 m (threshold) or 100 m (objective) for which the OCS issues a NANU and sets the SV's ephemeris health word to "Unhealthy" during the maneuver, but fails to update the ephemeris information after setting the SV to "Healthy" are less than 10^{-7} per SV per hour (threshold) and 10^{-10} per SV per hour (objective).

A desirable probability for future GPS constellations for all other causes of ephemeris errors larger than 100 meters is under discussion. If it is not feasible to detect and respond to ephemeris errors of 100 m, 200 m is an acceptable threshold.

OCS Response Time

The OCS response time for LAAS is under discussion. A desirable OCS response time would be 15 minutes, or even 6 seconds, if possible, for a future GPS constellation. However for backward compatibility purposes, a response time on the order of one hour may be acceptable.

Assumptions Made in Analysis of the Use of GPS Integrated with Inertial Systems for En Route through NPA Operations

The probabilities of step and ramp errors in the GPS pseudorange residual were estimated to have values shown in Table 4 are taken from the WAAS MOPS, Appendix R, Table R-2 [15]. The assumed probabilities, also shown, are more conservative than the predicted values. If smaller probabilities of the various fault modes could be assured, significant benefits in availability will result.

IFMEA DATA COLLECTION AND ANALYSIS

This task focused on the collection, organization, and analysis of current GPS production and operational failure data, and any previous FMEA data that is available. Historical GPS failure data is being collected and assembled for evaluation from civilian and military agencies. The agencies who are currently evaluating GPS failures and have processes for monitoring and recording GPS integrity anomalies need to be identified.

The following resources for data collection were identified and the IFMEA team has access to these data:

- Satellite Operations Squadron Data
  - Real-time PPS range performance using measurements and Kalman filter states
  - Real-time SV bus performance using telemetry data
  - Daily PPS clock performance using NIMA data

- SV Contractors
  - Daily & long term trending using SV telemetry

- GPS Support Center
  - Daily GPS user performance assessments
  - Dual Frequency PPS users

The goal is to develop a centralized integrity failure mode database that compiles information from many different data sources and allows for identification and analysis of individual failure modes. A format for this database needs to be agreed upon. Potential failure modes that have not been observed (known as integrity threats) also need to be identified. The failure data needs to be evaluated for impact to integrity, based on performance needs of both civilian and military users. Fault-free/nominal conditions need to be characterized in concert with the faulted case. This sets the threshold to define a "fault" or "failure." These thresholds must be set to account for low false-alarms and missed-detection probabilities.

Table 4 Probabilities of Ramp and Step Errors from WAAS MOPS Appendix R

Predicted Fault Type	Predicted Probability	MOPS-Assigned (Assumed) Probability
Ramp 0.01 m/s	2×10^{-7}/hour/SV	1×10^{-6}/hour/SV
Ramp 0.1 m/s	1×10^{-7}/hour/SV	1×10^{-6}/hour/SV
Ramp 0.5 m/s	3×10^{-7}/hour/SV	1×10^{-6}/hour/SV
Ramp 1 m/s	10×10^{-7}/hour/SV	3.5×10^{-6}/hour/SV
Ramp 5 m/s	12×10^{-7}/hour/SV	4.1×10^{-6}/hour/SV
Step 300 m	1×10^{-7}/hour/SV	1×10^{-6}/hour/SV
Step 3000 m	34×10^{-7}/hour/SV	NA

This database will be maintained and used throughout the evaluation period and this should transition to an ongoing process. The goal is to continuously maintain and update this database as new features are added to GPS. The nominal thresholds for fault-free performance identified in the integrity requirements task will be used to determine the probability of exceeding this threshold. Analysis of the probability of occurrence of each identified failure mode will lead to better definition of the Probability of Hazardously Misleading Information (PHMI), which is a key statistic, crucial to safety-of-life use of GPS, as well as for military weapons delivery.

ABERRATION CHARACTERIZATION SHEETS

A prioritized list of all significant failures that have known or potential effect on integrity will be maintained.

Existing failure mode definitions will form the basis of this list, with additional failure mode definitions being added as they are identified. The team will establish the priorities. If possible, preventive action for the failure modes will be identified. The starting point for this effort was the previous aberration characterization sheets (ACS) which identifies each integrity failure mode, its cause, impact, and probability of occurrence. The parameters that comprise an ACS sheet are shown in Figure 3.

ACS sheets for anomalies were developed and maintained from the first IFMEA study in 1988 through 1998. These sheets are publicly available. The goal for the current IFMEA is to update them through the GPS Block IIF program and then develop a process whereby they can be continuously maintained by the GPS JPO.

The Aberration Characterization Sheets consist of four major types of aberrations. Table 5 shows the breakdown of the types of aberrations that need to be accounted for and updated in the ACS sheets for the GPS Block IIR, IIR-M, and IIF satellites.

It should be noted that GPS satellites already perform onboard monitoring for detection of anomalies. Different types of alerts are provided based on the type of fault that is detected. Examples of these alerts are:

- Non Standard Code
- Default Nav Data (alternating 1's and 0's)
- URA Alert Flag (Bit 18 of HOW)

Onboard monitoring is a key factor in meeting the current failure rate of 10^{-5}/hr/signal-in-space (SIS). The effects of onboard monitoring is documented in the ACS Sheets. Monitoring on the satellites will be a powerful technique to meet a future failure rate of 10^{-8}/hr/SIS.

A subgroup of the IFMEA team was established to meet on a weekly basis to work through the Block IIR design data available from Lockheed Martin. This information will identify integrity anomalies and their theoretical probability of occurrence and the observed anomaly data will allow for identification of the actual probability of occurrence. The Block IIR ACS is expected to be complete in the spring of 2003 and then will be reviewed at the GPS JPO to ensure that there is no sensitive material that can't be released to the public. The goal of the IFMEA team is to have unclassified ACS material publicly available to the entire international GPS community. Once the security review is completed, the update to the ACS sheets will be released to the public. The subgroup then will continue its efforts in analyzing the GPS IIR-M and IIF satellite data.

SECURITY CONSIDERATIONS

Given the goal stated in the previous section to make the Aberration Characterization Sheets publicly available, an understanding of security classifications is required. The COEP project heavily assisted the IFMEA project in this area. There are four categories of unclassified material:

Unclassified: Unrestricted data generally available in the public domain.

For Official Use Only: Sensitive, but unclassified. Data restricted in use by the source of the data.

Proprietary/Competition Sensitive: Restricted data that would give that company an edge based on uniqueness, usually information developed by that company

ITAR: All unclassified restricted data is subject to export control by the State Dept. before being released to foreign nationals.

Table 5 Updates Required to ACS Sheets for Block IIR, IIR-M, and IIF Satellites

System	Block IIR	Block IIR-M	Block IIF
System Allocated SIS Aberrations			
Space Segment Allocated SIS Aberrations	X	X	X
Control Segment Allocated SIS Aberrations		X	X
User Segment Allocated SIS Aberrations			

Sample
ABERRATION CHARACTERIZATION SHEET (ACS)
X.X.X

ABERRATION NAME: Name Assigned to Aberration	
SEGMENT ALLOCATION: System, Space, Control, User	
SHORT DESCRIPTION: What is the aberration?	
PROXIMATE CAUSE(S): What most directly causes the aberration?	
PRECIPITATING EVENT(S): What is the ultimate source of the aberration?	
PROBABILITY OF OCCURRENCE: **Per day, per year, per SV, per constellation, per upload**	**EFFECT/MAGNITUDE:** **Effect on signal: Off, nil, ramp, step, noise, sinusoid, m, m/sec, m/sec squared**
DETECT RESPONSIBILITY: **System, Space, Control, User, mix, none** **When an aberration occurs, who is responsible for determining that it happened?**	**UNDETECTED PROBABILITY: Per day, per year, per SV, per constellation, per upload** **Probability that the aberration goes undetected.**
POST-DETECT EFFECT/MAGNITUDE: **Off, nil, ramp, step, noise, sinusoid, m, m/sec, m/sec squared** **What happens after the aberration has been detected?**	**UNDETECTED DURATION:** **Time until aberration is detected and user notified.**
REPRESENTATIVE OCCURRENCES (IF ANY): **Based on observed data obtained through IFMEA data collection effort**	
REMARKS: **Remarks and free text**	

Figure 3 Sample Aberration Characterization Sheet

GPS areas of sensitivity that may be classified are:

- Selective Availability: range errors, pseudorange errors, precise ephemeredes
- SAASM
- NAVWAR
- Accuracy: Total PPS UE

DEVELOPMENT OF FUTURE IFMEA WORK PROGRAM

The goal is for this project to be an on-going effort and the IFMEA database and associated analyses must be updated as each new signal and system capability is developed. Each added signal has the potential to introduce new failure modes. The baseline requirements and plans for GPS IFMEA were defined in CY'02.

This project will result in significant benefits to civilian and military users of GPS. Potential benefits include documentation of a joint definition of GPS integrity parameters, which could then be incorporated into appropriate system and acquisition documents. Both civilian and military users also will have a better understanding of GPS integrity failures, as well as the potential causes and operational impact of failures.

The documentation and analysis of integrity failures will allow for the identification of the probability of individual failure modes which will help determine the probability of hazardously misleading information (PHMI) from GPS. The IFMEA analysis also will provide a technical basis to update the SPS and PPS performance standards. The SPS Performance Standard currently allows for up to three major service failures per year which appears to be very conservative based on how the GPS system has performed. Also, this document does not specify not to exceed (NTE) values for range rate or range acceleration error. Results from the IFMEA are needed before updates to these standards can be made.

The IFMEA project will help improve the reliability of GPS in the future by providing recommendations for GPS SV and OCS design modification, as well as to integrity monitoring provided by civil/military augmentation systems and monitoring networks. Finally, the analysis conducted through the IFMEA project, in conjunction with the benefits obtained from the GDMS and COEP projects, will increase user confidence in ability of GPS satellites and OCS to satisfy requirements stated in the performance standards.
The signal quality monitoring work will be based on analyses that have been performed by the FAA and their support contractors on integrity monitoring for the GPS Wide Area and Local Area Augmentation Systems (WAAS and LAAS).

The following methodology will be applied in identifying the appropriate monitoring scheme for each fault mode:

1. Analyze both nominal and "faulted" data for each fault mode. Characterize the statistics of the data for each case. Also quantify the user errors resulting from the faults.
2. Define the threat model. Identify the relevant fault parameters and place reasonable and/or conservative bounds on the span of those parameters. (Note that this is where correlations between fault modes may be identified and analytically integrated.)
3. Identify methods for detecting anomalous (faulted) data. Define acceptable and unacceptable performance for various user categories; set thresholds according to minimum detectable limits.
4. Using the threat model, analytically determine the set of failures that can escape detection.
5. Determine the effect each of the undetectable faults may have on user performance.
6. Iterate this process as necessary to achieve acceptable performance.

Providing sufficient integrity monitoring ensures that the fault can be detected and the user notified, but the long-term goal is to remove known failure modes from future satellites and/or the OCS, if possible, through design improvements. Recommendations for design changes and/or constraints based on the type of failure mode will be made where possible.

As previously discussed, the work in CY'02 focused on failure modes related to the C/A code on L1 and the P(Y) code on L1 and L2. This work will continue to complete the failure characterization sheets, identifying each integrity failure mode and its theoretical and observed failure rate. However, the effort in CY'03 will be extended to include the L2C and L5 signals that may introduce new failure modes that have not yet been identified given that it is a new signal design. Since satellites with these signals have yet to be launched and it will take years for sufficient data to be collected to develop failure mode statistics, this work will be performed by conducting a fault-tree analysis. The GPS JPO is relying on the results of the fault-tree methodology to improve future design of both satellites and the OCS.

The CY'03 effort also will continue with the integrity data collection activities. The goal is to transition the database collection activity over to the JPO and OCS in CY'04 once the process is well established.

SUMMARY AND CONCLUSIONS

The IFMEA project will result in significant benefits to civilian and military users of GPS. Potential benefits include documentation of a joint definition of GPS integrity parameters, which could then be incorporated into appropriate system and acquisition documents. Both civilian and military users also will have a better understanding of GPS integrity failures, as well as the potential causes and operational impact of failures.

The IFMEA project will help improve the reliability of GPS in the future by providing recommendations for GPS

SV and OCS design modification, as well as to integrity monitoring provided by civil/military augmentation systems and monitoring networks.

Finally, the analysis conducted through the IFMEA project, in conjunction with the benefits obtained from the GDMS and COEP projects, will increase user confidence in ability of GPS satellites and OCS to satisfy requirements stated in the performance standards.

The 2002 IFMEA project met its goals of:

- Forming a team of civil/military experts
- Reviewing previous IFMEA studies
- Identifying integrity requirements
- Developing and maintain a database of failure modes
- Analyzing the data to develop the probability of individual failure modes

Aberration characterization sheets are being developed to capture all of the anomalies and their theoretical and observed probabilities of occurrence. It is the goal of this project to make as much information included in the ACS sheets as publicly available as possible. It is expected that an update to the ACS sheets will be made available in spring 2003.

The documentation and analysis of integrity failures will allow for the identification of the probability of individual failure modes which will help determine the probability of hazardously misleading information (PHMI) from GPS. The IFMEA analysis also will provide a technical basis to update the SPS and PPS performance standards. The SPS Performance Standard currently allows for up to three major service failures per year which appears to be very conservative based on how the GPS system has performed. Also, this document does not specify not to exceed (NTE) values for range rate or range acceleration error. Results from the IFMEA are needed before updates to these standards can be made.

Finally, the analysis conducted through the IFMEA project, in conjunction with the benefits obtained from the GDMS and COEP projects, will increase user confidence in ability of GPS satellites and OCS to satisfy requirements stated in the performance standards.

The CY'03 effort also will continue with the integrity data collection activities. The goal is to transition the database collection activity over to the JPO and OCS in CY'04 once the process is well established.

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REFERENCES

1. International Civil Aviation Organization (ICAO) Annex 10, Volume I (Radio Navigation Aids), "Aeronautical Telecommunications," Fifth Edition, July 1996, Amendment 77, November 2002. The GNSS standards and recommended practices (SARPs) are contained in Section 3.7 and subsections, Appendix B, and Attachment D.

2. U.S. Department of Defense, *GPS Standard Positioning Service Performance Standard*, October 2001.

3. Kovach, K. "Methodology and Calculation of a Preliminary Unconditional Integrity Value for GPS", ION GPS 1988.

4. Conley, R., and A. Wilfong, "The Design and Application of a GPS Integrity Model," *Proceedings of ION GPS-91 Satellite Division Conference*, Albuquerque, NM, September 1991.

5. U.S. Department of Defense, *GPS Standard Positioning Service Signal Specification*, originally published 5 November 1993, updated June 1995.

6. "Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS)," Technical Standard Order (TSO) C-129, 10 December 1992, U.S. Federal Aviation Administration, Washington, D.C.

7. "Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS)," Technical Standard Order (TSO) C-129a, 20 February 1996, U.S. Federal Aviation Administration, Washington, D.C.

8. Fernow, J.P., and Lee, Y.C., "Analyses Supporting FAA Decision Made During the Development of Supplemental GPS Avionics Requirements," *NAVIGATION, Journal of the Institute of Navigation*, Vol. 41, Number 4, Winter 1994-1995, pp. 463-477, The Institute of Navigation, Alexandria VA.

9. Kovach, K., and R. Conley, "SATZAP: A Novel Approach to GPS Integrity," *NAVIGATION, Journal of the Institute of Navigation*, Vol. 38, No. 2, Summer 1991, The Institute of Navigation, Alexandria VA.

10. Lee, Young C., and R. Sexton, "Analysis of Fix Displacement Tolerances for the Development of Instrument Procedures Criteria for GPS," Proceedings of the National Technical Meeting of the ION, 21-23 January 1998, Long Beach, California.

11. Lee, Young C., and J. Fernow, "Description of Requirements Analyses to Support Development of an FAA Position on Use of GPS as a Primary Means of Navigation in Oceanic and Remote Airspace," *Air Traffic Control Quarterly*, Vol. 2, No. 4, 1994, p. 287.

12. Shelton, W.L., of Falcon Air Force Base, Letter to Joseph Dorfler of FAA Satellite Program Office, 3 June 1994.

13. "Airborne Navigation Sensors Using the Global Positioning System (GPS) Augmented by the Wide Area Augmentation System (WAAS)," TSO C145a, 19 September 2002, U.S. Federal Aviation Administration, Washington, D.C.

14. "Stand-Alone Airborne Navigation Equipment Using the Global Positioning System (GPS) Augmented by the Wide Area Augmentation System (WAAS)," TSO C146a, 19 September 2002, U.S. Federal Aviation Administration, Washington, D.C.

15. *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment*, RTCA Document No. DO-229C, 28 November 2001, prepared by RTCA Special Committee (SC) 159.

16. GPS Performance Assumptions Made in WAAS Analyses, correspondence with H. L. Habereder of Raytheon Company, 7 January 2003.

17. Jefferson, D.C. and Bar-Sever, Y.E., "Accuracy and Consistency of Broadcast GPS Ephemeris Data," Proceedings of ION GPS 2000, 19-22 September 2000, Salt Lake City, Utah.

18. Warren, D.L.M., and J. F. Raquet, "Broadcast vs. Precise GPS Ephemerides: A Historical Perspective," Proceedings of the ION Technical Meeting, 28-30 January 2002, San Diego CA

.