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INTEGRITY MONITORING METHODS FOR THE GLOBAL POSITIONING SYSTEM

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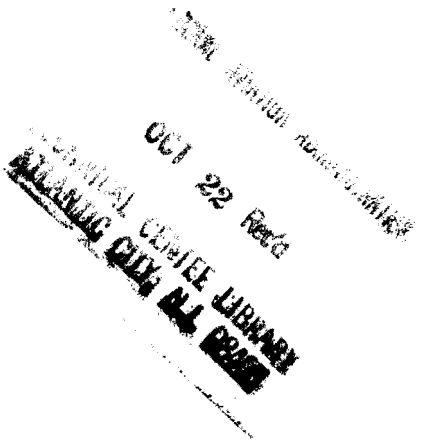

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1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this document is to present the parameters and characteristics intrinsic to a system which monitors the integrity of the Global Positioning System (GPS). Once the GPS integrity domain is defined and examined, specific recommendations for FAA feasibility testing are presented.

1.2 OBJECTIVES

The primary objective of this paper is to select the most viable method of monitoring GPS integrity and present the rationale involved in reaching this selection. This objective is approached through the following:

1. The global positioning concept and system are discussed. In this portion of the paper the reader is brought up to date with a brief history of GPS. A system overview will then examine the primary segments of GPS.

2. The next focus is on defining GPS integrity, the importance of it, why it is necessary, and what it means to the FAA.

3. The preponderance of the paper highlights the many integrity concepts and configurations, noting the advantages and disadvantages of each.

4. The final focus is on the conclusions and recommendations. At this juncture it is assumed that the reader has been equipped with the necessary tools to comprehend and hopefully concur with the logical sequence that led to the stated conclusions and recommendations.

2.0 BACKGROUND

2.1 GPS PROGRAM HISTORY

The US Air Force and the US Navy have had satellite programs that date back to the early 1960s. In April 1973 the US Deputy Secretary of Defense issued a memorandum directing the US Air Force to consolidate the existing satellite programs into a global, 24 hour, three-dimensional, all-weather navigation system. This system is named; Navigation by Satellite Timing and Ranging Global Positioning System (NAVSTAR GPS) or better known as, simply, GPS. The primary point of contact for GPS is the Joint Program Office (JPO) at Los Angeles Air Force Station (AFS), California, USA.JPO is governed by the US Air Force but is

staffed by personnel from the US Air Force, US Navy, US Army, US Marine Corps, US Coast Guard, US Defense Mapping Agency, Australia and NATO. The GPS JPO obtained approval to begin the concept validation phase (Phase I) in December 1973. During this phase, which took place in the mid to late 70s, prototype user and control equipment were tested and Block I satellites were deployed. In the early to mid 80s prototype equipment was modified, full scale development was taking place and system tests were conducted (Phase II). There are presently six operational Block I satellites in orbit. The present orbit configuration is such that full GPS service (four or more satellites accessible to the user) is available approximately four hours a day. Although this four hour window is limited, it is used extensively for debugging and early evaluation of the system. Block I satellites will be phased out and replaced by a constellation of 24 Block II satellites (Phase III). The Block II satellites are presently in production and will be deployed utilizing McDonnell-Douglas "Stretched Delta" Medium Launch Vehicles (MLV) and the Space Shuttle. The full constellation is expected to be in orbit in late 1992 to early 1993 (see Launch Schedule, Diagram 1).

The primary contractors for GPS are; Rockwell International for satellites and user equipment, General Dynamics for ground stations and user equipment, IBM for operational control systems, and McDonald-Douglas for satellite launch vehicles.

Presently, the bulk of development testing has been completed with promising results, but there remains two predominant deficiencies that must be rectified before the civilian aviation community can utilize GPS. The first deficiency, limited availability, would be satisfied with a full constellation of 24 satellites. The second problem lies with the lack of a system that monitors the integrity of GPS, which is a significant problem, and the focus of this paper.

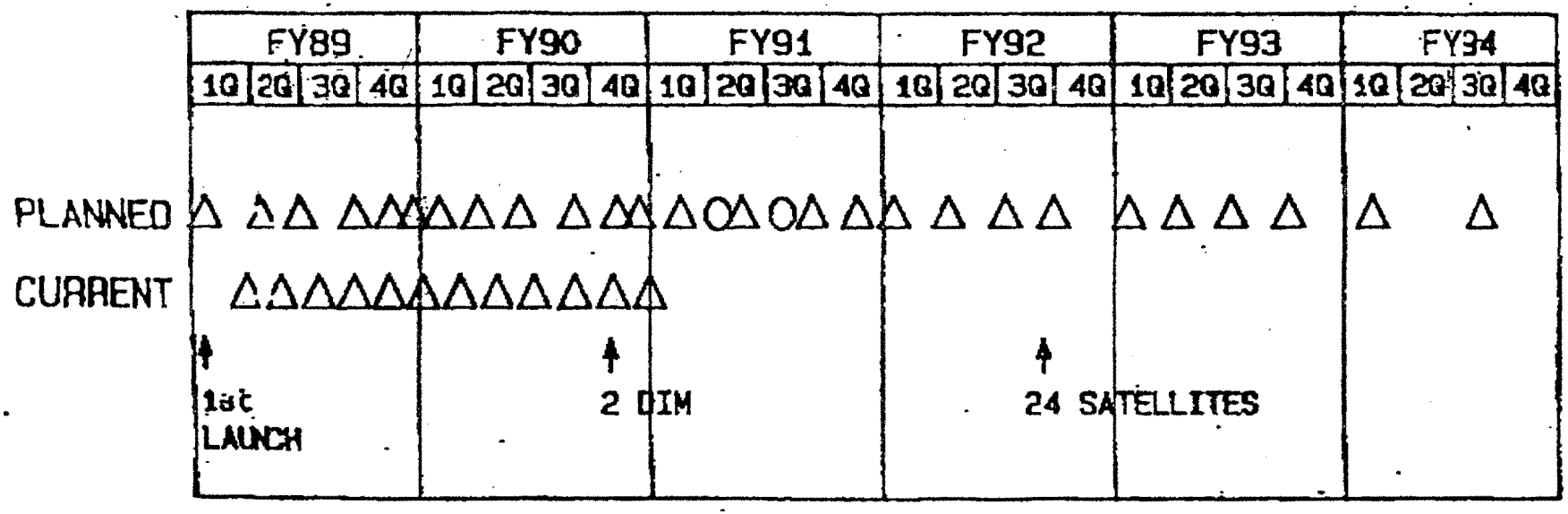
2.2 GPS SYSTEM SUMMARY

Navstar GPS is a highly accurate satellite based radio navigation system which provides three dimensional position, velocity and time. This system is designed to operate continuously (24-hour), globally and in all weather conditions. GPS is partitioned into three primary segments; space, control, and user.

2.2.1 SPACE SEGMENT

The space segment consists of a planned constellation of 21 operational and three active spare Block II satellites. The spares are provisioned to secure the probability of having 21 or more operational satellites at least 98% of the time. The

GPS BLOCK II LAUNCH SCHEDULE



Δ - DELTA II LAUNCH

O - STS LAUNCH/NASA MANIFEST

AS OF: 27 OCT 88

Diagram 1

probability of having 24 operational satellites is .70. The satellites will be placed in 11 hour 56 minute elliptical orbits at a distance of 10,900 nautical miles (20,200km) from the earths' center. There will be six orbital planes, four satellites per plane, with an inclination of 55 + or - 3 degrees with respect to the equator. JPO has contracted Rockwell International to deliver 28 Block II Satellites which should be a sufficient number to maintain the 24 satellite constellation. The Block II Satellites which are replacing the Block I Satellites have a mean mission life of six years and a design life of seven and one half years. The next generation satellite, the Block IIR, is already on the drawing board.

The launch schedule (Diagram 1) warrants discussion; as of January the first launch is scheduled to be mid February 89, but JPO states that the launch schedule changes almost daily. Two dimensional global coverage is established as indicated by 2 DIM, and STS Launch is better known as the Space Shuttle.

2.2.1.1 GPS SIGNAL STRUCTURE

The GPS signal is transmitted using spread spectrum techniques on two frequencies; L1 at 1575.42 MHz and L2 at 1227.60 MHz. Two types of signal spreading functions are utilized: Course/Acquisition (C/A) code and Precise (P) code on the L1 carrier and P-code only on the L2 carrier. The C/A code is one millisecond in length and each satellite is assigned a different C/A code chosen from a set of codes called; Gold Codes. The P code is a much longer 267 day code of which unique seven day segments are assigned to each GPS satellite. The C/A-code is available to all users but the P-code is only available to US military, NATO military, and DoD approved civilians. The P-code and the C/A-code is biphase shift key modulated with a Navigation Message (Nav-msg) which contains satellite ephemerides, system time, satellite clock behavior data, satellite status and health, and control segment information.

2.2.2 CONTROL SEGMENT

The control segment incorporates a network of five monitoring stations and one master control station. The Master Control Station (MCS) is collocated with a monitor station at Falcon Air Force Station in Colorado Springs, USA and is linked with the monitor stations via the Defense Satellite Communication System. The monitor stations passively track each satellite, collecting ranging data and satellite clock data which is then relayed to the MCS. This data is then processed such that the satellites' future ephemeris and clock drift can be predicted and then uploaded to each satellite for re-transmission in the Nav-msg. When the monitor stations detect a satellite drifting from its assigned orbit, the MCS uploads orbit correcting information to the satellite rocket boosters.

2.2.3 USER SEGMENT

GPS has the versatility to meet the needs of many users such as a navigation aid for space, air land and sea, attitude reference, time transfer, precise positioning, surveying, etc. The GPS user is passive, therefore GPS can facilitate an unlimited number of users. The GPS user segment usually consists of an L-band receiver, an L-band antenna, and a control-display unit.

2.3 GPS RECEIVER OPERATION

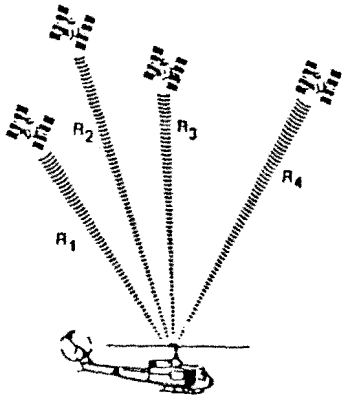
In order for the GPS receiver to operate it must acquire and track satellites and collect the Nav-msg data, this is done utilizing the following procedure: The receiver first attempts to acquire a satellite signal by determining which satellites are visible based on user entered present position, velocity, and time and receiver resident almanac data. If the receiver has no resident almanac data, a random sky search is conducted until a satellite is found.

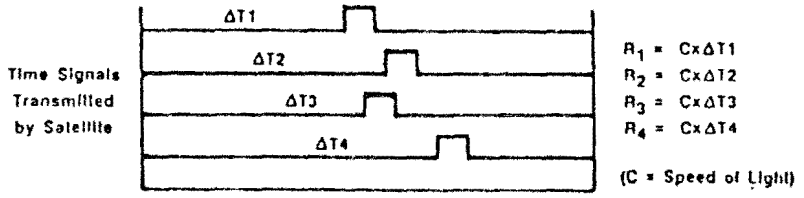
Once the signal is detected the receiver attempts to lock on or track the carrier. The receiver generates an L1 carrier frequency which differs from the satellite L1 due to a Doppler offset which is proportional to the relative velocity, along the line of sight, between the satellite and receiver. The receiver determines the relative velocity to four tracked satellites to calculate the users' velocity relative to Earth Centered Earth Fixed (ECEF) coordinates.

Once the carrier is tracked, and user velocity is determined, the superimposed C/A code is tracked for pseudorange measurements. In order to track the C/A code, the receiver generates a reference C/A code at user clock time t0, which it shifts in time until it correlates with in coming code generated at satellite clock t0. The amount of shift necessary to correlate codes is directly proportional to the pseudorange between the GPS receiver and satellite, based on the travel time intrinsic to signal transmission. The distance is referred to as pseudorange because there are known errors associated with this measurement. The most prominent of these errors is due to clock offset. It is very important that both the satellites and the GPS receivers share an accurate representation of GPS system time. The satellites utilize very accurate triply redundant atomic clocks but, due to the expense, the user receiver employs a less accurate crystal oscillator, thereby introducing a clock offset error. This error is compensated for by tracking four satellites and making four pseudorange measurements which allows four simultaneous equations with four unknowns to be solved.(see Diagram 2) The solving of these equations provide user position and GPS system time.

Once the carrier and code loops have locked onto the satellite

③ USER OBTAINS PSEUDO RANGE MEASUREMENTS
(R_1, R_2, R_3, R_4) TO 4 SATELLITES





④ USER SET PERFORMS THE NAV SOLUTION FOR POSITION

PSEUDO RANGES:

$(R_1) = C\,\Delta t_1$

$(R_2) = C\,\Delta t_2$

$(R_3) = C\,\Delta t_3$

$(R_4) = C\,\Delta t_4$

POSITION EQUATIONS:

$$(X_1 - (U_X))^2 + (Y_1 - (U_Y))^2 + (Z_1 - (U_Z))^2 = (R_1 - (C_B))^2$$

$$(X_2 - (U_X))^2 + (Y_2 - (U_Y))^2 + (Z_2 - (U_Z))^2 = (R_2 - (C_B))^2$$

$$(X_3 - (U_X))^2 + (Y_3 - (U_Y))^2 + (Z_3 - (U_Z))^2 = (R_3 - (C_B))^2$$

$$(X_4 - (U_X))^2 + (Y_4 - (U_Y))^2 + (Z_4 - (U_Z))^2 = (R_4 - (C_B))^2$$

R_i = PSEUDO RANGE (i = 1,2,3,4)

- PSEUDO RANGE INCLUDES ACTUAL DISTANCE BETWEEN SATELLITE AND USER PLUS SV CLOCK BIAS, USER CLOCK BIAS, ATMOSPHERIC DELAYS, AND RECEIVER NOISE
- SV CLOCK BIAS AND ATMOSPHERIC DELAYS ARE COMPENSATED FOR BY INCORPORATION OF DETERMINISTIC CORRECTIONS PRIOR TO INCLUSION INTO NAV SOLUTION

X_i, Y_i, Z_i = SATELLITE POSITION (i = 1, 2, 3, 4)

- SATELLITE POSITION BROADCAST IN NAVIGATION 50 Hz MESSAGE

RECEIVER SOLVES FOR:

- U_x, U_y, U_z = USER POSITION
- C_B = USER CLOCK BIAS

Diagram 2 Pseudoranging

signal, the Nav-msg can be demodulated from the C/A code to provide information for more accurate pseudorange calculation.

The one millisecond C/A code is relatively simple to acquire but the P code is 280 days in length. Although each satellite employs only a seven day segment of the 280 day P-code, this could create very lengthy lock on delays. This problem has been addressed by providing P code phase data in the Nav-msg, thereby minimizing the P code search window. A C/A code only receiver allows the user to navigate but a C/A - P code receiver provides a more accurate solution. Although the civilian community may someday employ the P-Code, this paper will focus on the present, C/A-Code only parameters.

3.0 SOLE AND SUPPLEMENTAL APPROVAL

When a new navigation system is developed, such as GPS, the FAA will analyze its' capabilities and may approve it as either a sole means navigation system or a supplemental navigation system. The issues that must be addressed prior to approval are coverage and integrity requirements. A sole means navigation system is one that has been approved to be utilized independently for specific phases of air navigation. In order for the FAA to approve GPS as a sole means of navigation the user must have a minimum of five satellites in view at all times, the satellites must be at least seven and one half degrees above the user horizon, and any combination of four of the user visible five satellites must give a Position Dilution of Precision (PDOP) of less than six at all times. In addition to the above stated coverage requirements, GPS must satisfy integrity requirements as stated in Table 1. The planned 24 satellite constellation provides a minimum of six satellites to users continuously and globally and therefore seems to satisfy the FAA coverage requirements for sole means approval. Unfortunately, there is only a 70% chance of maintaining a full 24 satellite constellation over time. There exists however, a 98% probability of maintaining 21 operational satellites but, this causes a PDOP greater than six over two percent of CONUS for a few minutes a day. This condition fails to support the 100% coverage requirement necessary for FAA sole means approval, although it will support supplemental coverage approval.

A supplemental navigation system is one that has been approved to be utilized for air navigation in alliance with a sole means navigation system. While it is apparent that integrity monitoring is a requirement for sole means approval, it is also a requirement for supplemental approval due to the potential that the supplemental navigation system is needed to provide primary navigation. GPS could be a sole means system if it addresses integrity issues and resolves coverage problems.

4.0 GPS SHORTCOMINGS/ERROR ANALYSIS

The global accuracy and coverage of GPS is unmatched by any existing navigation system, but the system is not without faults, both inherent and intentionally introduced. The errors discussed here will be those incurred by the civilian C/A code users.

4.1 SATELLITE EPHEMERIS AND CLOCK ERRORS

Satellite clock error is the difference between GPS system time and the satellite clock. GPS system time is maintained by the US Naval Observatory and the British Royal Observatory. Each Block II Satellite has triply redundant atomic clocks which can be calibrated via uplink stations. The typical satellite clock offset generates a pseudorange measurement error of less than two meters.

Ephemerides predict the satellite orbital position with respect to time. Ephemeris error is the geometric difference between the actual satellite location and that predicted in the Nav-msgs' ephemeris data. The typical ephemeris error will generate a pseudorange measurement error of less than two meters.

4.2 RECEIVER ERROR

Receiver errors are attributed to electrical n o i s e , computational errors and multipath errors. A good quality C/A code receiver should generate a pseudorange measurement error of less than 15 meters rms.

4.3 ATMOSPHERIC PROPAGATION ERRORS

GPS pseudorange measurements are made with the assumption that the satellite signal traveled at the speed of light in a vacuum. Of course, our atmosphere is not a vacuum. The signal is slowed and refracted largely due to the density of charged particles in the ionosphere and to a lesser extent the temperature, pressure, and humidity of the troposphere. The military user can eliminate these propagation errors through dual frequency delay comparison, but for the civilian user, a less accurate atmospheric model must suffice. Dr. Jorgensen of the Aerospace Corp. states that present models reduce the ionospheric effects by less than 60%. A typical pseudorange measurement error due to propagation delay is five meters at night, and 10 to 15 meters during the day at mid-latitudes.

4.4 SELECTIVE AVAILABILITY (S/A)

For purposes of security, the US DoD will intentionally introduce signal errors that will affect civilian C/A code users. The US DoD has promised to maintain the error at a level of 100m 2 distance root mean squared (drms) (100m 2drms = 76m spherical

error probability (SEP) = 40m circular error probability (CEP)) in the horizontal plane. This means that 95% of all positional fixes will be within a circle of radius 100 meters, centered at the desired position. The DoD controlled intentional error is pseudorandom and possibly implemented through satellite clock and/or ephemeris dithering. S/A dominates the civilian error budget and puts the 100 m 2drms GPS integrity goal for nonprecision approach in jeopardy. If a GPS signal monitoring system set an alarm threshold at 100 meters 2drms as indicated in Table 1, the probability for alarm will be a significant 5 : 100. Clearly, a higher alarm threshold or reducing the S/A error is needed. Some higher alarm limits and their respective probability for alarm are displayed below.

Alarm setting	Probability for alarm
150 m	1 : 10,000
200 m	1 : 10,000,000

S/A can cause a pseudorange measurement error of 30 to 35 meters.

4.5 DILUTION OF PRECISION

Dilution of Precision (DOP) measures the uncertainty of position based on satellite geometry relevant to the user. DOP acts as an error multiplier therefore, the higher the DOP the worse the user accuracy will become. There are several DOPs relevant to the GPS community; Vertical (VDOP), Horizontal (HDOP), Time (TDOP), Position (PDOP), and Geometric (GDOP). The results of Phase II testing in the US revealed that a PDOP<=6 or HDOP<=4 provided a reliable navigation solution.

5.0 GPS INTEGRITY

The FAA has three major concerns that must be addressed before GPS is approved for use in the US civil airspace. These concerns are reliability, accuracy and integrity; the latter of these is the focus of this report.

When GPS was initially configured, it did not rely on an independent monitoring system for integrity. Extensive integrity checks were developed as part of the GPS. These integrity features include; equipment redundancy, communication error detection with retransmissions, estimation and prediction consistency tests, and operator qualification verification. In addition, each space vehicle maintains 14 days of prediction data to guard against momentary faults in the control segment. The GPS signal is also continuously monitored by the Control Segment to assure a highly reliable system. If the Control Segment detects a signal anomaly, which can take 15-20 minutes, it uplinks new data to correct the problem. The uplink process can

take up to an additional 100 minutes.

Integrity is defined as the ability of a system to produce time sensitive warnings indicating a system anomaly. As defined, a system that monitors integrity, must embrace timely warnings. This point is underscored due to the GPS Control Segments' inability to issue such warnings. The time presently needed for the GPS Control Segment to detect and correct a problem is typically 15 minutes to two hours. This time frame is wholly inadequate for use in the US domestic airspace, where timely warning of a system malfunction is critical. The need to develop a more rapid integrity system for the civilian aviation community is highlighted by this lengthy time frame. A variety of integrity methods and configurations have been proposed for GPS use. These methods can be categorized as either internal or external to the aircraft.

The internal methods can be partitioned further into methods self-contained internal to the receiver and those methods that utilize inputs from additional aircraft equipment. Self-contained or Receiver Autonomous Integrity Monitoring (RAIM) is a method in which the GPS receiver calculates multiple navigation solutions from a constellation of five or more user visible satellites without reference to any sensors other than the receiver itself. These solutions, which utilize four satellites apiece, are compared to detect a solution anomaly which would indicate a GPS system failure. The integrity method that employs inputs from other aircraft equipment may take the form of a integrated GPS/INS, GPS/OMEGA, GPS/Loran-C, GPS/AHRS or among others, GPS/Barometric Altimeter.

The external integrity methods utilize a network of ground monitoring stations that assess the GPS signal and conveys the findings to the user via ground based radiobeacons or geostationary satellites.

Although the full GPS constellation is several years from implementation, integrity requirements have already been established by the Radio Technical Commission for Aeronautics (RTCA) special committee 159 (SC-159). SC-159 examined the present RNAV equipment requirements as dictated by numerous aeronautical community standards. The committee also examined time to alarm requirements as put forth by VOR nonprecision standards. It was found that accuracy requirements were dependent upon the phase of flight (oceanic en route, domestic en route, terminal areas, nonprecision approach), and as such, established GPS integrity criteria.

Table 1 Integrity Criteria
Present Requirements

	En Route		Terminal	Nonprecision
	Ocean	Domestic	Area	Approach
Alarm Limit*	23.34 km	2.78 km	2.04 km	0.56 km
Time to Alarm	120 sec	60 sec	15 sec	10 sec

Goals for Integrity Criteria

	En Route		Terminal	Nonprecision
	Ocean	Domestic	Area	Approach
Alarm Limit*	5,000 m	1,000 m	500 m	100 m
Time to Alarm	30 sec	30 sec	10 sec	6 sec

* radial horizontal position error

Due to the superior accuracy of GPS as compared to existing navigation systems, SC-159 recognized the potential of reducing aircraft separation along some air traffic routes and reducing obstacle clearance requirements. This reduction promotes significant user cost and efficiency benefits. Reduction in separation standards demand more stringent integrity requirements, so SC-159 established a set of system accuracy requirements and integrity goals as shown in Table 1.

6.0 INTEGRITY OPTIONS

6.1 GPS INTEGRITY CHANNEL (GIC)

The objective of the GIC system is to broadcast GPS integrity data to the user via data link from a ground monitoring network. The GIC system consists of a sparse network of ground stations that monitor the GPS signal and send the findings to a Master Control Station (MCS). The MCS compiles this data to determine the health of the GPS signals. The results of this analysis are then broadcast to the GPS user via one way data link. The standard GPS receiver must have the appropriate hardware/software to receive and process this integrity data.

The RTCA GIC working group noted the following as operational requirements for the GIC system:

1. The GIC system shall provide protection against unacceptable signal-derived position errors (SPEs).

2. A positive indication of satellite usability shall be provided by the GIC system for each healthy satellite in view of the GIC network. A non-positive (negative or absent indication does not necessarily mean that the GPS integrity has been compromised;

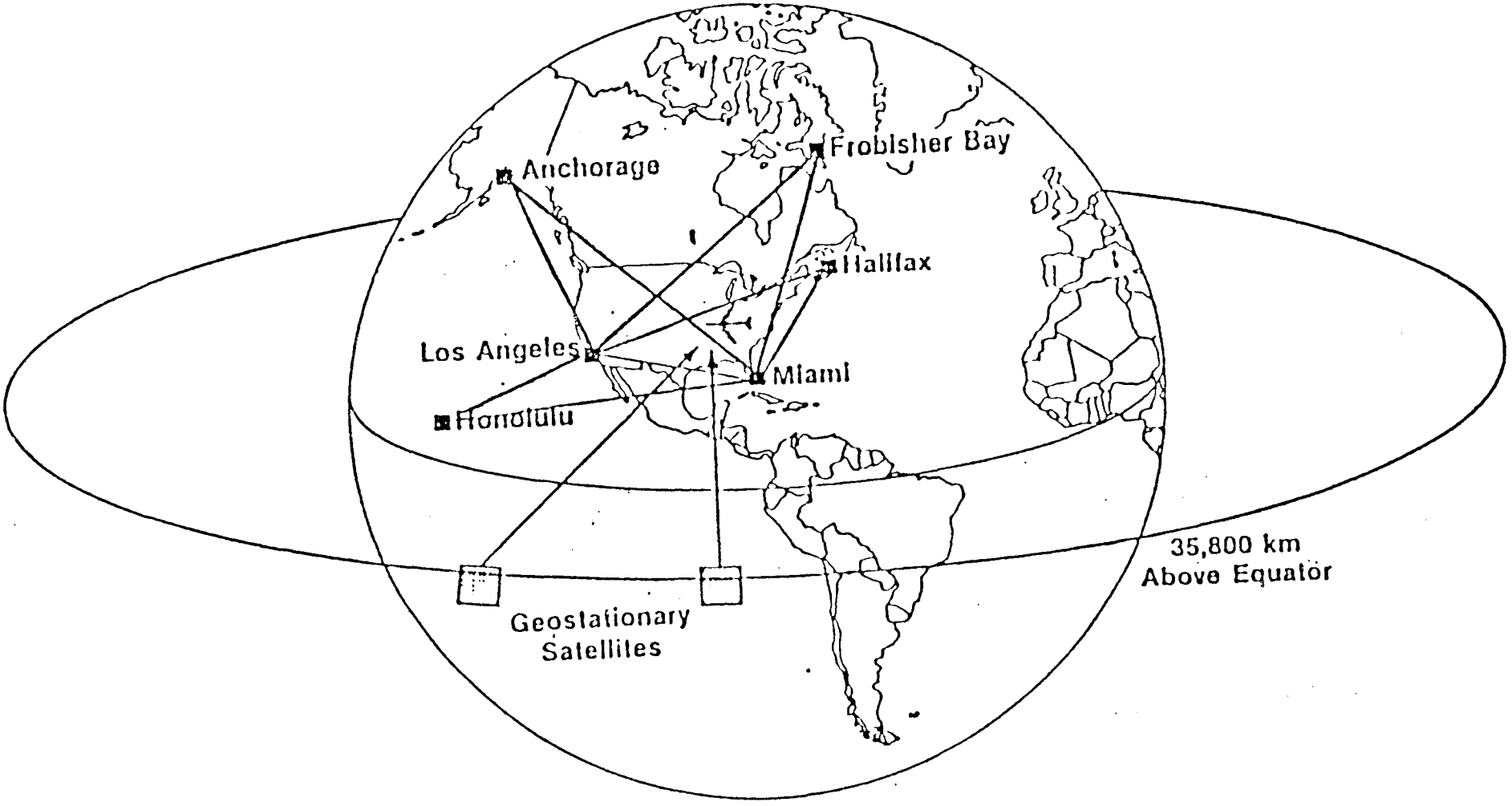


Diagram 3 GPS Integrity Network for North America

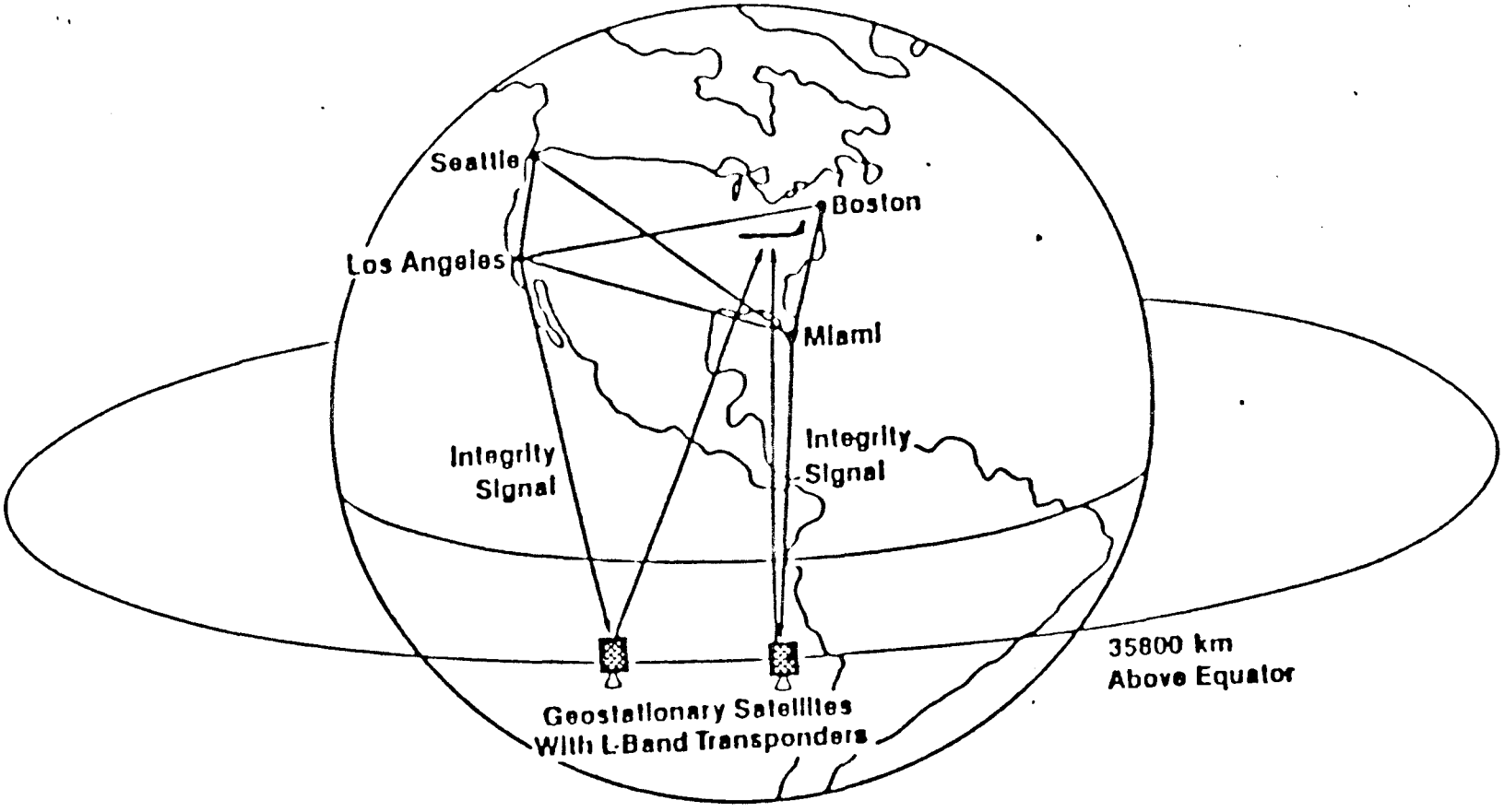


Diagram 4 GPS Integrity Network for CONUS

however. the satellite shall not be used by the receiver without a positive indication of usability.

3. The GIC system shall set an integrity alarm when satellites fail that are indicated healthy by the satellite data, or when the GIC network fails such that satellites may not be monitored.

4. The GIC system shall be capable of meeting the most stringent time-to-alarm requirement, which is 10 seconds for nonprecision approaches in the U.S..

5. The GIC system shall ensure GPS integrity whenever there is an acceptable GPS satellite geometry anywhere in the designated area of operation. The GPS receiver shall be required to determine if the satellite geometry is acceptable for the satellites being tracked (i.e., good HDOP). If the HDOP exceeds the acceptable level, the receiver shall also automatically deselect satellites that are indicating bad health or poor user range accuracy in the navigation data.

6. For sole means navigation, the GIC availability requirement approaches 100%. The GIC must therefore be designed to be fully redundant. For supplemental navigation, the availability requirement is less, but should be set high enough that GIC system component failures do not frequently cause alarm.

6.1.1 GROUND NETWORK

The purpose of the GIC ground network is to monitor GPS signals, evaluate the signal integrity, compile the results at a central location(s), and broadcast this information to the user in a timely fashion. The ground network will consist of a sparse network of ground monitor stations and a central processing or master station. The system will provide the redundancy necessary to maintain acceptable performance in the event of any one failure. A typical ground monitor station is expected to consist of a GPS User Set at a known fixed location, an accurate clock, a communication link and possibly some additional processing equipment. The ground monitor station will process all available GPS C/A-code signals on a continuous bases to determine signal integrity. This information is then sent via land lines, satellite link or possibly another technique, to a master control station (MCS). The MCS will process and evaluate the data to determine the health of the constellation as a whole or on a per satellite basis. Existing FAA facilities are likely locations for MCSs, possibly co-located with ground monitor stations.

The ground network is configured based on the geographical area

it must monitor. If North America is used as an example of an area to be monitored, the ground network would be configured such that it would be capable of monitoring every satellite the GPS North American user might employ in a nav solution (see Diagram 3). If the area to be monitored is very large, (i.e. North America) the computational burden of the master control station seems enormous. Upon initial examination an algorithm to compute accuracy estimates for a grid of points over several points in time using all potential satellite combinations would be needed. This algorithm would employ several hundred or thousand 4 X 4 matrix inversion computations. Fortunately, A. Brown developed an algorithm called Horizontal Absolute Sum Error (HASE). HASE generates an upper bound measure of uncertainty which is relatively insensitive to satellite selection algorithms, thus greatly reducing the ground station processing burden.

6.1.2 GROUND-TO-USER LINK

Once the master control station has collected and processed the integrity data, a message must be conveyed to the user. Two GIC broadcast vehicles methods have been examined; pseudolite, and geostationary satellite.

6.1.2.1 PSEUDOLITE

A pseudo satellite or pseudolite is a ground based station that transmits a satellite-like signal. A pseudolite could be configured to transmit a GPS-like signal that includes integrity data, and be GPS time synchronized. Under these conditions, it could then be used for a pseudorange measurement as well as an integrity link. If the vertical angle between the user and pseudolite is sufficient, the aircrafts' vertical uncertainty could be reduced. Due to low elevation satellites being used most in an airborne navigation solution, a high level of vertical uncertainty usually exists. However, with three satellites overhead and one pseudolite below the VDOP and PDOP could be improved. Pseudolites could also reduce or eliminate terrain shadowing when appropriately positioned.

If a pseudolite transmitted a GPS-like signal, the high frequency carrier would greatly limit its' useful range. If a high power signal was used to increase its' range, it would jam the user receiver due to its' closeness relative to the satellites' distance. Due to these inherent problems, a great many pseudolites would be necessary to cover a large area such as CONUS. The use of pulse transmissions may address the jamming problem, but pseudolite range is still quite limited.

6.1.2.2 GEOSTATIONARY SATELLITE(S)

Due to the liabilities of the pseudolites and the assets of a

satellite, the latter seems more feasible for the GIC integrity broadcast over large geographical areas such as CONUS. A pseudolite may be applicable in small designated areas. The geostationary satellite would be employed as a broad-band repeater, in other words, an uplink frequency from the master control station to the satellite would be converted in frequency at the satellite and downlinked to the user. The FAA is presently evaluating several satellite service providers to establish potential services, time frames, and integrity broadcast methods.

6.1.2.2.1 SATELLITE GPS-LIKE SIGNAL

A broadcast method that shows promise is a GPS-like spread spectrum signal centered at 1575.42 MHz that will employ the unused Gold Codes. This signal would be transmitted from a master control station to a "bent pipe" transponder on a geostationary satellite and then down to the user. There are several significant advantages to the GPS-like signal.

1. Modifications necessary to presently envisioned receivers will be minimized. This approach eliminates the need for an additional GPS front end (antenna and interface).
2. The GPS frequency band is protected.
3. This approach also addresses the periods of degraded GPS service in that the integrity satellite can be synchronized with GPS and used as an additional satellite for ranging.

Presently, there are no satellite transponders that operate in this frequency band. INMARSAT recently met with FAA officials to address this problem, and as a consequence, INMARSAT is actively investigating potential transponder designs that would operate at the GPS frequency. George Kanal of INMARSAT speculates that these GPS transponders could be part of INMARSATs Phase III satellite(s) payload, due to be placed in orbit in 1994.

INMARSAT is also working on a signal that is very similar to the GPS C/A-code except it is centered at 1542 MHz. INMARSAT employs a high gain antenna and a 33 MHz mixer to receive and multiply the signal, and then feeds it into the GPS receiver. The advantage of this scheme is that 1542 MHz service presently exists. The disadvantages are the lack of global coverage in this frequency band and the need for an additional GPS receiver front end.

6.1.2.2.2 SATELLITE L-BAND AMSS SIGNAL (NARROW BAND)

A growing problem for satellite communication is frequency allocations. The merits of satellite communication are becoming more and more apparent, and consequently, the demand for

frequency spectrum is on the rise. In respect to this problem, it would be ideal to employ a previously allocated frequency band that isn't fully utilized. There exists an anomaly in the Aeronautical Mobile Satellite Service (AMS(R)S) bands that meets these requirements. The AMS(R)S bands are a pair of frequency bands reserved for aeronautical mobile satellite data links. The satellite-to-user band (1549-1560 MHz) is paired with the user-to-satellite band (1649.5-1660.5 MHz), but the Radio Astronomy band overlaps at 1659.5-1660.5 MHz. Due to the overlapping in the user-to-satellite band, its' paired mate (1559-1560 MHz) in the satellite-to-user band is undesirable for two-way data link operations. On the flip side, 1559-1560 MHz would be suitable for a one-way data link such as a GIC, Presently there are no transponders that utilize 1559 MHz, but INMARSAT and the American Mobile Satellite Consortium have plans to provide service to this frequency band.

Due to the closeness of 1559 MHz to GPS L1 frequency, an additional GPS receiver front end may not be necessary but, it seems likely that the existing front end would need modification.

6.1.2.2.3 SATELLITE C-BAND SIGNAL

There are many GIC questions that need to be addressed before a long term integrity method can be chosen. Three dimensional GPS coverage is expected by 1992, so it is imperative that these questions be examined immediately. A sub-division of John Chance Associates called STARFIX, has the potential to provide a wealth of GIC answers. STARFIX presently has ten ground reference stations, a master control station, dedicated phone lines to link the two, a C-band satellite link and a receiver equipment set. FAA personnel have met with STARFIX personnel in late January 89 to discuss the logistics involved to test the GIC concept. It was concluded that a GIC concept validation test could be conducted for approximately $250K ($150K for STARFIX + $100K for FAA costs) (see Diagram 5).

The STARFIX network clearly provides a near term GIC test bed. Unfortunately, due to STARFIXs' use of the unprotected C-band satellite link, it is possible for airborne receivers to experience noise from ground-based transmissions. Employing the C-band for GIC transmissions would also require a separate receiver front end although, a combined C\L-band antenna could be designed. Due to these liabilities, STARFIX is undesirable as a long term GIC solution.

6.1.2.3 DATA FORMATS

The integrity ground monitoring network has the ability to gather a great deal of data. The data must be processed and incorporated into a specific format to be broadcast to the user. This section presents seven data formats as put forth by SC-159:

ESTIMATED GIC TEST OPERATION COSTS

11 January, 1989

Prepared by:

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Ground Network Equipment Costs

1.	STARFIX Base Station data link – STARFIX Lease: $500/mo each	5 stations	$2,500 /mo
2.	10 Channel Differential GPS Receiver – Trimble Lease: $5,000/mo each Purchase: $28,000 each	3 receivers	$15,000 /mo
3.	Master Site office space, base station link and support Lease: $1,000/mo		$1,000 /mo
	Total Lease: 5 stations		$18,000 /mo

Satellite Communication Link

4	50 Hz satellite link and STARFIX receiver	$650 /day

Differential Software

5.	Δ–NAV Differential GPS Software Software modifications will be quoted by TAU on request	3 systems	$20,000

TOTAL COST	Ground Network – 6 months		$108,000
	Satellite Link – 30 days		$19,500
	Δ–NAV Software		$20,000
		TOTAL	$147,500

Diagram 5

1. A **System Use Indication** is a simple go (GPS accuracy is acceptable) or no-go (GPS accuracy exceeds acceptable error limit) user notification. The ground network determines if GPS will meet a predetermined accuracy requirement in a designated area. A simple flag or audible tone could suffice for a no-go alarm. This data format is the only one presented in this paper that does not require a data link into a GPS user set.

2. **System Use Indication by Phase of Flight** is very similar to the previous format with the distinction of an accuracy level for each phase of flight. The aircraft would be fitted with a flag for each phase of flight.

3. With the **Satellite Use Indication**, the ground monitoring network evaluates <u>each</u> satellite signal to determine whether use of that satellite would cause an unacceptably large error. This method allows the user to omit a "bad" satellite from the navigation solution and continue using GPS if there exists a "good" satellite to take its place.

4. **Satellite Use Indication by Phase of Flight** is analogous to the previous format with the exception that this format will indicate a go/no-go with respect to phase of flight per satellite.

5. **Satellite Error Magnitude Indication** is a method whereby the ground network determines and transmits the absolute value of the range error for each satellite. Incorporating this format data into a satellite selection algorithm, the GPS avionics could determine if the position error exceeds a phase of flight threshold, and if so, set a flag. This format allows the GPS receiver to select the satellite combination that minimizes position error. There are two advantages to this format; it would reduce false alarms and it would provide the flexibility needed for the wide range of receiver architectures and satellite selection algorithms.

6. **Satellite Error Indication** coincides to the previous format with the addition of direction, opposed to just magnitude. This permits the GPS avionics to determine the actual signal-derived position error (radial error minus receiver error). Due to the satellite errors being defined in both magnitude and direction, there may be a temptation to improve the position fix by subtracting out these errors. Although this could be implemented logistically, the FAA prefers to maintain a clear separation between an integrity system and a system it is monitoring.

7. A **Differential Message** is a data format that contains pseudorange error corrections intended to be incorporated in the navigation solution to improve accuracy. With the advent of Selective Availability degrading civilian accuracy, this format

would be a true benefit, especially for nonprecision approaches. This integrity monitoring system differs from the others discussed in two respects; this technique employs integrity data that incorporates corrections to improve overall accuracy, and the data is limited to the local area. The differential method can reduce or eliminate S/A, atmospheric delay, ephemeris and satellite clock errors. The accuracy of differential GPS can be 5 to 20 meters drms. Unfortunately, as mentioned in the previous format option, a clear separation must be maintained between the integrity system and the system it is monitoring.

The FAA is presently examining a FAA/NASA agreement for future differential work. Although this work is not focused on the integrity aspects of GPS, the results of this work may provide integrity and/or coverage solutions.

6.2 RECEIVER AUTONOMOUS INTEGRITY MONITORING (RAIM)

As the acronym indicates, RAIM is a method of integrity monitoring that does not reference any sensor other than the receiver itself. A GPS receiver utilizing a RAIM algorithm would calculate redundant navigation solutions and then compare these solutions to detect a measurement anomaly that exceeds a specified error threshold. There presently exists several RAIM algorithms from unpretentious maximal separation schemes to elaborate Kalman Filter and detection strategy. For the unaided GPS receiver to calculate redundant solutions there must exist a minimum of five or more satellites with good geometry (GDOP) visible to the user. With the above constellation (five or more satellites with good GDOP visible to the user) a RAIM receiver can determine that a single satellite is contributing an error that exceeds a specified threshold; this is called <u>detection</u>. Six or more user visible satellites with favorable geometry provide enough data to determine <u>which</u> satellite is in error; this is called satellite <u>isolation</u>. Satellite isolation would prove to be a great benefit because a user could remove the erroneous satellite from the users' navigation solution and continue GPS use with confidence. For example, if the user was conducting a nonprecision approach and only detection was possible, the user would have to perform a missed approach but, if isolation was possible the user would omit the erroneous satellite and continue the approach. A RAIM simulation assuming a 24 satellite constellation performed by Dr. Alison Brown indicated that failure isolation was possible 87.6% of the time at an alarm limit of 400 meters and 97.6% at 800 meters.

RAIMs ability to perform competently under the planned 24 satellite constellation will be ascertained by the setting of three thresholds; accuracy, time to alarm, and false alarm rate. The accuracy and time to alarm criteria for GPS integrity monitoring is shown in Table 1, the false alarm rate has yet to be formally established.

Computer generated simulations indicate that the 100 m 2drms nonprecision approach goal is not obtainable by RAIM methods, however, the present requirement of 0.30 nautical miles for nonprecision approach is. If the radial error alarm threshold is set at 300 meters, the probability of S/A inducing an error greater than this is 10E-16 At this level, S/A induced errors are essentially excluded so that true satellite errors can be focused on. This focus in the RAIM simulations revealed that true satellite error detection probabilities approach 100% if the radial error threshold is set at 300 meters. These results provide an optimistic view of RAIM, unfortunately, into each scenario a little RAIM must fall. As discussed in section 3.2.5 Dilution of Precision, there also exists satellite geometries which make failure detection quite difficult. These "integrity outages" will occur approximately six to seven percent per day. A potential solution to these outages that has shown promise in computer simulations, is clock coasting. Clock coasting employs a user clock as the fourth satellite thereby relaxing the satellite geometry requirements. Well designed crystal oscillators can provide a clock drift of 10E-9 which corresponds to a position error of 100 meters after six minutes. Simulations indicate that clock coasting addresses the problem of integrity outages but falls short of solving it, clearly, this integrity outage must be further investigated before final judgments on RAIM are made.

6.2.1 RAIM ADVANTAGES

RAIM computer simulations on a 24 satellite constellation show promise. The receiver has access to the most information on the integrity of GPS signals therefore integrity monitoring is best performed in the receiver. RAIM has the potential to provide the minimum time to detect and annunciate an alarm condition. RAIM has the ability to isolate the erroneous satellite thereby allowing the aircraft to continue the accurate use of GPS by omitting it from the navigation solution. RAIMs greatest ally is likely to be its very modest cost and ease of implementation. Software augmentation in the GPS receiver is the primary implementation cost with the potential of modest receiver hardware changes as well. The utilization of RAIM would also eliminate the need for a relatively expensive independent ground monitoring system. As previously mentioned RAIM suffers from lack of coverage problems but, an agreement with USSRs' GLONASS may present a solution.(see Section 6.3.6 GPS/GLONASS)

6.2.2 RAIM DISADVANTAGES

The RAIM test results in this paper assume a 24 satellite constellation and are computer generated. The 24 satellite constellation has a probability of .70 that there will be 24 fully operational satellites over time, and reality is sometimes harsh on computer generated results. The "integrity outages"

present the most difficult hurtle for RAIM to clear, it is a problem that must be solved before RAIM can be considered a viable integrity option. The accuracy of 100 m 2drms for nonprecision approach seems far out of reach of RAIM capabilities. RAIMs primary competitor in the integrity arena is GIC which can achieve the 100 m 2drms goal when utilizing differential techniques.

6.3 INTEGRATED/HYBRID SYSTEMS

GPS user equipment can be utilized in many configurations. Its' use can range from a simple stand alone GPS receiver to one that is integrated with INS, barometric altimeter and an accurate time source. A GPS receiver has an internal Kalman Filter which can generally incorporate external aiding data into the navigation solution. Both the aiding source, which supplies the GPS Kalman Filter with navigation data, and the GPS receiver together form an integrated system. In a hybrid system, the best assets of each contributing system are combined. In such a system, there is usually a Kalman Filter for each contributing system and a Kalman Filter to combine the resulting data. Integrated/Hybrid systems have the potential to produce a more accurate and robust solution as compared to GPS or other navigation systems alone.

6.3.1 GPS/BAROMETRIC ALTIMETER

An airborne GPS receiver can accept data from a barometric altimeter as a Kalman Filter measurement. Altimeter errors are calibrated when the receiver is tracking four satellites. During the constellation build-up, when potentially less than four satellites are in view, the altimeter is expected to supply altitude information which can be converted to an X, Y, Z orthogonal ECEF system. When the full constellation is in place, the altimeter can provide the additional position data to enhance the RAIM integrity technique. A typical quantization error of 100 feet combined with the standard atmosphere matching error of 200 feet or less, promotes the barometric altimeter as a fairly accurate instrument. Unfortunately, this instrument is subject to meteorological anomalies, or more specifically, pressure anomalies. This problem can create errors of more than 1000 feet during long flights.

It can be concluded that data from a barometric altimeter would provide a useful integrity check where accuracy requirements are not severe such as en route and terminal. The nonprecision approach requirements seem too stringent for a barometric altimeter.

6.3.2 GPS/INS

INS can provide velocity aiding to GPS code tracking loops to

ensure high GPS performance, even during high dynamics, and high EMI environments. During favorable satellite geometry the INS could be calibrated to remove position, velocity and tilt errors within the INS. The ability of an inertial navigation system to monitor the integrity of GPS is limited to error rate or drift of the inertial device. Due to this characteristic, slow drift satellite failures could not be detected by an INS. In addition to this, the ability of the INS to accurately monitor error thresholds will diminish over time without an update from GPS. To display the ability of INS to monitor GPS integrity, the table of GPS accuracy requirements (Table 1) has been converted to minimum update rate requirements for an INS/GPS system.

Table 2
Update Requirements For INS/GPS Systems

Phase of flight	Employing a 0.8nmi/hr(.41m/s) drift INS	
	Accuracy (meter)	T(min update rate) (minute)
Requirement		
En Route Ocean	23,340	949
En Route Domestic	2780	113
Terminal	2040	83
Nonprecision	560	23
Goal		
En Route Ocean	5000	203
En Route Domestic	1000	40
Terminal	500	20
Nonprecision	100	4

The objective of Table 2 is to convey the minimum INS update rate that will still allow the INS to detect satellite errors that exceed the error threshold per phase of flight. Table 2 assumes a zero error at the start of the update period. JPO states that with the 21 + 3 satellite constellation there will be no periods of degraded performance over CONUS. By configuring an INS with a GPS, a more robust and dynamic navigational unit is created but, it should be noted that INS lacks the independence from GPS to become a GPS integrity monitor. It should also be noted that an INS can cost over $100K.

6.3.3 GPS/OMEGA

Due to the limited coverage of GPS during constellation build-up, combining GPS and Omega has the potential for a interim coverage solution. OMEGAs' accuracy is approximately 2 - 4 nautical miles and as such only meets integrity requirements for oceanic navigation. OMEGA is available now on a near global

scale and it has been approved for sole means navigation. The down side of OMEGA is its inability to satisfy all but en route ocean integrity requirements, its sole means approval is for oceanic flight only, and there presently exists more suitable navigational solutions (i.e. GPS/INS) to the interim coverage problem.

6.3.4 GPS/LORAN-C

Combining GPS and LORAN-C presents an additional interim solution to the present limited GPS coverage. The LORAN-C receiver can be calibrated for local and daily effects when the GPS receiver is tracking the necessary satellites to produce an accurate solution. When satellite coverage becomes unfavorable the LORAN-C receiver switches to a stand alone system. From the integrity stand-point GPS measurements can be employed as a check on LORAN-C measurements and vice versa.

This combination of equipment is less costly than a GPS/INS or GPS/AHRS, and it extends both LORAN-C and GPS coverage. The accuracy of LORAN-C (approximately 0.25 nautical miles) satisfies all requirements and goals of Table 1 except the nonprecision approach goal. The gap in Loran-C coverage over midwest CONUS is expected to be filled in the near future. Although this configuration seems promising, it should be noted that LORAN-C has limited coverage worldwide.

6.3.5 GPS/VOR/DME

VOR/DME could be coupled with GPS in a similar manner as with LORAN-C/GPS. To combine the outputs from GPS (position in latitude and longitude),and VOR/DME (range and bearing to or from the station (polar coordinates)) an Area Navigation Computer must be employed to convert the polar coordinates to latitude/longitude coordinates. VOR/DME CONUS coverage approaches 100% at low altitudes but, its' coverage is far from global.

6.3.6 GPS/GLONASS

The Global Navigational Satellite System or GLONASS is a system presently being developed in the USSR. GLONASS, which is similar to the US DoDs' GPS, is expected to possess a 21 + 3 satellite constellation by 1992 - 1995. Due to the similarities of GLONASS and GPS, the benefits of a working relationship has been recognized. Personnel from the US and USSR have been meeting to examine the logistics of a combined system. Although a relationship is speculative at this time, a combined system could consist of a 42 + 6 satellite constellation. A constellation of this magnitude has the ability to solve all coverage deficiencies and would enhance RAIM capabilities.

7.0 SATELLITE SIGNAL SIMULATOR (SSS)

The US civil aviation community looks to the FAA for GPS certification. GPS and GPS integrity monitoring presents many parameters that must be tested and evaluated before certification can be obtained. This certification process makes significant demands of the FAAs' manpower and financial budgets. To lessen the time and financial burden, the FAA is presently in the process of procuring a SSS. The SSS has the ability to generate multiple GPS signals. These signals can be manipulated to simulate both a static and dynamic atmosphere. The FAA is presently examining the SSS potential for the test and evaluation of:

1. integrity alarm parameters
2. GPS receiver performance
3. GIC data formats (section 6.1.2.3)
4. RAIM algorithms (section 6.2)

8.0 CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. Integrated/Hybrid navigation systems incorporating GPS provides a more robust unit and increases the potential of GPS as a supplementary navigation system.

2. The GIC integrity option discussed in section 6.1, when employing two geostationary satellites will provide the needed coverage and integrity to promote sole means approval over CONUS.

3. Based on the integrity options discussed, a system can be developed that satisfies all the requirements of Section 6.1 and all the integrity requirements and goals of Table 1 except for the nonprecision approach goal.

4. When the DoD implements Selective Availability Errors, the 100 m 2drms nonprecision approach goal can not be met unless differential techniques are employed.

5. STARFIX contains the major mechanisms necessary for a GIC proof of concept demonstration.

RECOMMENDATIONS

1. The most important recommendation is to move quickly. Now that a satellite launch is scheduled for once every 2 - 4 months the full constellation is only a few years away. Many questions must be addressed before GPS can be fully approved for the civil aviation community. It is recommended that the FAA pursue GIC concept validation tests employing the services and assets of STARFIX (see section 6.1.2.2.3). The STARFIXs' configuration and Trimbles' reference station equipment presents an all inclusive package for a GIC test-bed. If the FAA moves quickly to initiate tests, the results could be made available to the SC - 159 MOPS committee.

2. STARFIX only addresses the near term testing needs of GPS integrity. The recommendation for a long term integrity monitoring method is for a GIC. The recommended GIC system concept would utilize two geostationary satellites for the ground-to-user data link. The ground network would be similar to Diagram 3 and 4, employing dedicated redundant phone lines for communication between master stations and monitor stations. The preferred data format would be the Satellite Error Indication as discussed in Section 6.1.2.3. The GPS-like signal centered at L1 (1575.42 MHz) is the signal option with the greatest potential. The signal option is a very important link in the GIC chain. Due to the lengthy lead time associated with satellite work, an effort must begin immediately. INMARSAT presently has an interest in working with the FAA in the areas of both narrow and wide band signal formats. It is recommended that the FAA pursue a working relationship with INMARSAT to test and evaluate GIC signal options.

3. It is recommended that further tests be conducted using RAIM techniques. The GPS receiver has access to the most information on the integrity of GPS signals therefore integrity monitoring is best performed in the receiver. As discussed in Section 6.2.2, there are significant periods of time when RAIM can not detect satellite failures but, because of the strong advantages of RAIM, further examination is warranted. Due to the satellite coverage problems, RAIM is less desirable than a GIC unless one of the following occurs:

    1. GPS and GLONASS satellites are utilized for RAIM calculations
    2. A significant RAIM algorithm advance that solves the coverage problem is made.

The FAA expects the delivery of a Satellite Signal Simulator in 1990 which would facilitate RAIM testing.