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CIVIL AVIATION INTEGRITY REQUIREMENTS
FOR THE
GLOBAL POSITIONING SYSTEM

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Civil Aviation Integrity Requirements for the Global Positioning System

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ABSTRACT

An Integrity Working Group was formed on April 22, 1986 by RTCA Special Committee-159 to investigate and report on civil integrity problems relating to the use of the Global Positioning System by civil aviation. Although the self-checking and warning features built into GPS are adequate to meet military integrity requirements and to allow safe operation of DoD aircraft, more stringent safety requirements must be met for GPS to receive FAA approval for use by civil aviation in the National Airspace System.

To establish integrity alarm limits and time-to-alarm requirements for GPS, the Integrity Working Group examined existing requirements already established for other navigation systems. A variety of GPS integrity monitoring techniques were then studied to determine for which phases of flight they would provide sufficient integrity to allow use of GPS by civil aviation. This paper summarizes the conclusions and recommendations of the Integrity Working Group.

INTRODUCTION

At the request of the Federal Aviation Administration (FAA), the Radio Technical Commission for Aeronautics (RTCA) established Special Committee-159 on September 20, 1985. The purpose of SC-159 was to prepare a Minimum Aviation System Performance Standard (MASPS) for the operation and use of the evolving Global Positioning System (GPS) in civil air navigation. To assist in preparing the MASPS, SC-159 formed an Integrity Working Group on April 22, 1986, chaired by the author, to investigate and report on civil integrity problems relating to GPS. The purpose of the Working Group was to establish GPS integrity monitoring requirements and to discuss suitable integrity monitoring techniques for civil aviation. The final report [1] was completed by the Working Group on June 3, 1987. This paper summarizes the Integrity Working Group recommendations to SC-159.

Integrity was defined by the Working Group as the ability of a system to provide timely warnings to users when the system should not be used for navigation. To assure the safety of aircraft, a timely warning is required any time the performance of the navigation system fails to meet the accuracy requirements applicable to the particular phase of flight of the aircraft. Consequently, integrity warning time and accuracy threshold requirements vary

with the phase of flight. Phases of flight considered by the Working Group were oceanic en route, domestic en route, terminal area and nonprecision approach.

A navigation system can receive FAA approval as either a sole-means navigation system or a supplemental navigation system for any phases of flight, depending on its capabilities. A sole-means navigation system is one that may be used on an aircraft without any other means of navigation available. Conversely, a supplemental navigation system may only be used when a sole-means system is available should the supplemental system be unable to continue navigation. Generally, the sole-means navigation system does not provide the same level of accuracy as the supplemental system, but is continuously available as a safe, alternative means of navigation. While integrity is obviously a requirement for sole-means approval, integrity warnings are also required for supplemental approval to assure the safety of the aircraft when the supplemental system is providing primary navigation.

The Global Positioning System was developed by the United States Department of Defense (DoD) to enhance the effectiveness of military missions and to reduce the proliferation of DoD radionavigation systems, thereby reducing costs. The extensive built-in self-checking and warning features of the GPS are adequate to meet military integrity requirements and to allow safe operation of DoD aircraft. However, more stringent safety requirements must be met for GPS to receive FAA approval for use by civil aviation in the National Airspace System (NAS).

For sole-means navigation, the FAA is not only concerned with the integrity of the GPS navigation solution, but also in the continuity of the GPS service. To satisfy this requirement, sufficient redundant signal coverage must be provided so that the failure of any single element of the system (e.g., any GPS satellite) does not cause an interruption of service. With the planned GPS constellation of 18 satellites and three spares, this requirement is not met since redundant satellite coverage is not continuously available.

For supplemental navigation, there is no requirement on the continuity of the GPS service. However, the navigation system must provide integrity warnings when out-of-tolerance conditions exist. Although the GPS satellites broadcast health and status information that indicate the system integrity, this data is not updated promptly enough to meet FAA requirements for timely warnings.

For GPS to be used for supplemental or sole-means navigation in the civil airspace, the Working Group concluded that conventional GPS navigation must be augmented to provide sufficient integrity and, in the case of sole-means navigation, increased redundancy and coverage. A wide variety of integrated systems, processing techniques and improvements to the GPS were discussed by the Integrity Working Group to achieve these ends.

BACKGROUND

GPS Navigation

GPS operates through passive triangulation to four satellites, providing highly accurate three-dimensional position, velocity and time. Two classes of service are available, the Standard Positioning Service (SPS) for civil applications, and the Precise Positioning Service (PPS) for military and other autho-

rized users. The PPS allows three-dimensional position to be determined to 16 m SEP (spherical error probable). In the interests of national security, the SPS accuracy is degraded to 100 m, 2 drms [2] through the introduction of artificial Selective Availability (SA) errors on the GPS satellite signals.

The GPS is partitioned into three segments: the Space Segment, which consists of the GPS satellites themselves; the Control Segment, which tracks and maintains the satellites; and the User Segment, which includes the receiver used to navigate from the satellite signals.

The Space Segment is currently planned to include a constellation of 18 GPS satellites with three active (broadcasting) spares. The satellites will be launched into 12 h orbits inclined at 55 degrees, at an altitude of 20,183 km (10,898 nmi). The orbits are chosen so that four satellites are continuously in view anywhere in the world. The full constellation of satellites is planned to be available in 1991.

The Control Segment consists of five monitor stations, a Master Control Station, and three ground antennas. Each monitor station passively tracks the GPS satellites, accumulates satellite and meteorological data, and transmits this information to the Master Control Station. The Master Control Station generates ephemeris and clock bias predictions and formulates the navigation message to be broadcast by the satellites. These messages are uploaded to the satellites, generally twice daily, using the ground antennas.

The User Segment consists of the GPS navigation sets used to receive the GPS satellite signals. To navigate with GPS, a minimum of four GPS satellites must be tracked by the receiver. From the four pseudoranges (range + receiver clock offset) to the GPS satellites, the receiver can determine three-dimensional position and GPS time. The delta-ranges (carrier doppler shifts) allow three-dimensional velocity to be also computed.

GPS Error Characteristics

The GPS navigation accuracy is a function of both the geometry of the four satellites being tracked and the precision of the pseudorange measurements made from the satellite signals. The position dilution of precision (PDOP) is the scaling effect of the satellite geometry between the satellite pseudorange measurement and the GPS three-dimensional position solution. The horizontal navigation accuracy provided by GPS can be computed by scaling the pseudorange measurement errors by the horizontal dilution of precision (HDOP). The horizontal 2 drms accuracy of the GPS navigation solution is computed using equation (1).

$$\text{Horizontal Navigation Accuracy} = 2 \times \text{HDOP} \times \sigma_{pr} \tag{1}$$

The standard deviation of SPS pseudorange measurement accuracy (σ_{pr}) is derived from a combination of different error sources. These can be grouped into four categories: satellite clock and ephemeris errors; propagation uncertainties due to atmospheric effects and reflected signals (multipath); receiver errors; and the artificial Selective Availablity (SA) errors introduced for purposes of national security.

The satellite clock and ephemeris errors for the production (Block II) GPS satellites are expected to be small, typically around 5 m, and so do not contribute

significantly to the SPS navigation errors. Propagation uncertainties are primarily a function of the accuracy of the atmospheric compensation models. The residual error after compensation can be as large as 20 to 30 m in extreme cases. However, errors on the order of 5 m at night and 10 to 15 m during the day are more typical. The measurement error introduced by a SPS receiver is on the order of 15 m. In most cases, this can be signficantly reduced through filtering.

The largest contributing error source for the SPS user is the SA errors deliberately introduced on the GPS satellite signals. Very little information has been released about the exact nature of the SA errors other than that they will be random and used to limit the SPS accuracy to 100 m, 2 drms. This is interpreted by the DoD, as in the Federal Radionavigation Plan, as a 95 percent figure. The SPS navigation errors may therefore be expected to exceed 100 m an appreciable fraction of the time [4]. Tracing backward from the 100 m, 2 drms figure, the magnitude of the Selective Availability error on the pseudorange signal will be about 30 m (RMS). When this is root-sum-squared with the other error sources it completely dominates the SPS error budget, resulting in a total error (σ_{pr}) of about 33 m.

The 18-satellite GPS constellation always provides a minimum of four satellites in view, with HDOP typically in the range 1.5 to 1.7. Scaling this HDOP by the pseudorange errors (σ_{pr}), as shown in equation (1), results in a total navigation accuracy of 100 m, 2 drms.

However, the 18-satellite constellation does not allow continuous world-wide navigation to this accuracy. Whenever the PDOP exceeds a threshold value of 6, the user is considered to be in an area of degraded performance where GPS is not capable of unaided navigation. These areas of degraded performance occur at regularly scheduled intervals at latitudes arround 35 degrees and 65 degrees in both hemispheres and generally last for around 20 min. Figure 1 shows where these regions occur with the 18-satellite GPS constellation.

By selectively placing the three GPS satellite spares, it is possible to remove these areas of degraded performance over a limited region, for example the continental United States. However, there is only a 75 percent probability of having all 21 satellites operational, while there is a 98 percent probability of at least 18 satellites being operational. As soon as a satellite failure occurs, the areas of degraded performance appear again over the United States. This coverage deficiency of the 18-satellite GPS constellation precludes the use of a stand-alone GPS receiver as a sole-means navigation system. Various methods of augmenting the GPS system were discussed by the Working Group to overcome this problem.

GPS System Integrity

The Global Positioning System has extensive built-in features and operating procedures to ensure the integrity of the navigation service. These include equipment redundancy, communication error detection codes, estimation and prediction consistency checks, and operator qualification verification [5].

The Block II GPS satellites are designed to perform extensive self-checking with the provision to discontinue the ranging signal if certain internal failures are detected. In addition, the signals and data transmitted to users are contin-
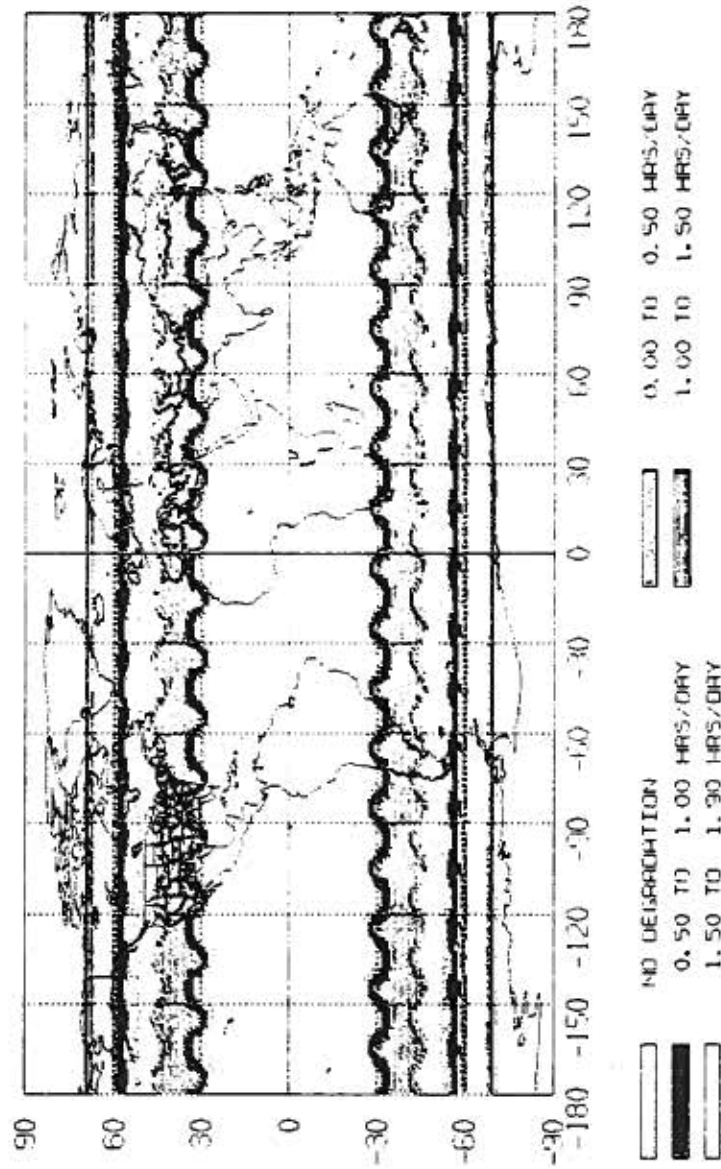
Fig. 1—*Areas of Degraded Performance with the 18-SatelliteConstellation [3]*

uously monitored by the Control Segment (with the exception of a small Pacific region west of Chili). However, a 15 to 20 min delay exists between the anomaly occurrence and the earliest indication of malfunction at the Control Segment. An additional hour is then generally required to deploy one of the ground antennas to the failed satellite and update the data transmitted to the user. The delay inherent in the Control Segment monitoring does not meet the FAA requirement of timely notification of system failures.

GPS Integrity Requirements

Under normal conditions, the GPS SPS will provide 100 m accuracy (2 drms) to civil users. However, in the unlikely event of a GPS failure occurring, additional precautions must be taken by civil aviation GPS navigation sets to detect failures before the navigation errors exceed the allowable error threshold for a particular phase of flight.

To establish integrity alarm limits and time-to-alarm requirements for different phases of flight, the Working Group examined existing requirements already established for other navigation systems. Documents referenced included the Department of Transportation Federal Aviation Administration Advisory Circular No. AC 90-45A, the Department of Defense and Department of Transportation Federal Radionavigation Plan (FRP) [20], and the Radio Technical Commission for Aeronautics Document No. RTCA/DO-180, "Minimum Operational Performance Standards for Airborne Area Navigation Equipment Using Multi-Sensor Inputs."

Requirements extracted from these documents are listed in Table 1. Where conflicting requirements occurred, the tighter or more stringent requirement was selected for GPS. Only horizontal navigation was considered because of problems with the compatibility of altitude reference system. Radial error alarm limits were selected as appropriate for GPS since the navigation errors are not dependent on the direction of the aircraft track.

Because of the superior navigation accuracy normally possible with GPS, and with a view towards possibly reducing aircraft separation and obstacle clearance criteria in the future, the Working Group also established a set of goals for GPS integrity criteria based primarily on information from the Federal Radionavigation Plan [20]. The goal criteria are listed in Table 2.

Table 1—GPS Integrity Requirements

Phase of Flight	Oceanic En Route	Domestic En Route	Terminal Area	Nonprecision Approach
Alarm Limit	12.6 nmi	1.5 nmi	1.1 nmi	0.3 nmi
Time-to-Alarm	120 s	60 s	15 s	10 s

Table 2—GPS Integrity Goals

Phase of Flight	Oceanic En Route	Domestic En Route	Terminal Area	Nonprecision Approach
Alarm Limit	5 km	1 km	500 m	100 m
Time-to-Alarm	30 s	30 s	10 s	6 s

The different integrity monitoring techniques addressed by the Working Group, were studied to determine under which phases of flight GPS failures could be detected within the required time-to-alarm before they exceeded the accuracy alarm limit.

INTEGRITY MONITORING TECHNIQUES

The integrity monitoring techniques considered by the Working Group can be divided into two categories, internal methods and external methods. The different techniques studied are listed in Table 3. With internal methods, the GPS integrity can be achieved using information provided by the aircraft sensors only. For example, redundant data inside the GPS receiver may be used, or aiding data supplied to the receiver from sensors such as a barometric altimeter or an inertial navigation system (INS). Using external methods, the GPS signals are monitored in real time through a network of ground monitoring stations. A variety of communication media were considered for disseminating the GPS integrity data to users.

The integrity monitoring techniques addressed were analyzed to determine over which phases of flight they would be suitable using the integrity criteria defined in Tables 1 and 2. If appropriate, the monitoring techniques also were studied to determine whether they supplied sufficient redundancy for GPS to be used for sole-means navigation.

Receiver Autonomous Integrity Monitoring

With Receiver Autonomous Integrity Monitoring (RAIM), the GPS receiver makes use of redundant information from the GPS satellites, or other sensors, as a check on the integrity of the navigation solution. A variety of different self-contained monitoring algorithms are possible [6, 7, 8].

Figure 2 illustrates a simple 'snapshot' approach to GPS failure detection. In this case five GPS satellites are visible. Depending on which four GPS satellites are used for navigation, there are five possible different navigation solutions as shown in Figure 2, Case 1. All five solutions are scattered due to the normal GPS system errors. However, in the case shown, all five navigation solutions lie within 100 m of the true location of the aircraft. If the differences between the five navigation solutions are compared, none will exceed 200 m, the normal error spread to be expected using the SPS.

Table 3—GPS Integrity Monitoring Techniques

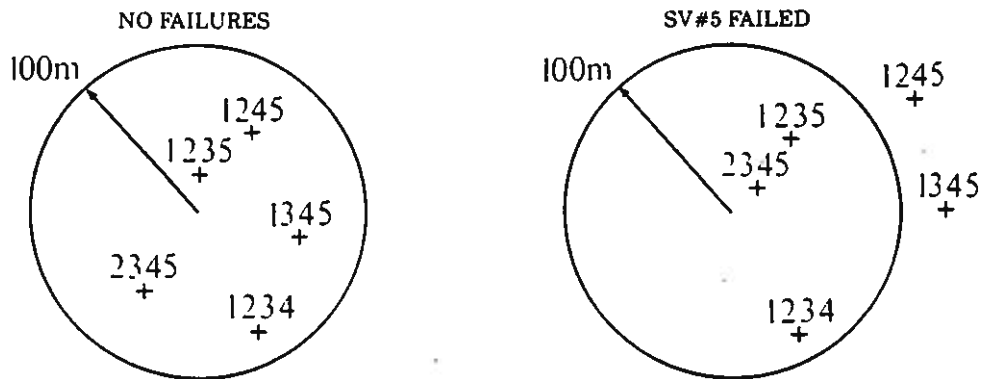| Internal Methods	External Methods
Receiver Autonomous	GPS Integrity Channel (GIC)
	—Ground-Based Communication
Integrated Systems	—Satellite Communication
—GPS/Baro-Altitude	
—GPS/INS/IRS/AHRS	Differential GPS
—GPS/LORAN-C	
—GPS/Omega	
—GPS/Multi-Sensor FMCS	
—GPS/VOR-DME/RNAV	

NO FAILURES

SV#5 FAILED

Fig. 2—Possible Navigation Solutions with Five GPS Satellites

In Figure 2, Case 2, a failure is assumed to have occurred in satellite #5 causing all the navigation solutions using this satellite to be in error by differing amounts. If the differences between the navigation solutions are now compared, some will exceed the expected 200 m allowable level, indicating that a satellite failure has occurred. Since one of the navigation solutions does not contain the failed satellite, this method always ensures that one solution is correct and must be near the true location of the aircraft.

For RAIM to be possible using this 'snapshot' approach, a navigation solution must always be possible, even when a satellite has failed. This reduces to a satellite geometry condition that all (N-1) subsets of satellites out of N visible satellites must give a PDOP sufficient to assure the navigation accuracy associated with the particular phase of flight of the aircraft [6].

The 'snapshot' approach can be improved by using Kalman Filter techniques [7] which take account of parameters such as doppler measurements and clock stability in the failure detection scheme. However, there is still insufficient redundancy provided by the 18-satellite GPS constellation to allow RAIM to be continuously effective. To provide continuous GPS integrity using this method, the satellite constellation must be augmented. Increasing the GPS constellation to 24 satellites would appear to provide sufficient redundancy for RAIM to be effective [6]. Augmenting the 18-satellite constellation with geostationary satellites would also provide sufficient redundancy. Two geostationary satellites located over the United States would provide integrity coverage over the Conterminous United States (CONUS). Five geostationary satellites would be sufficient to provide world-wide coverage.

The level of integrity that can be provided through RAIM under good geometry conditions is primarily a function of the Selective Availability errors. Simulations have shown that the minimum alarm level that can be set in the presence of Selective Availability, without an excessive alarm rate, is around 300 m [9]. From the integrity requirements listed in Tables 1 and 2, RAIM would be suitable to meet all the integrity requirements and goals, were sufficient satellite coverage available, except for the nonprecison approach goal of 100 m.

Integrated Systems

By integrating GPS with other navigation systems, it is possible to achieve highly accurate navigation performance while ensuring navigation integrity. In the interim period before GPS is fully operational, or to supplement the coverage provided by the 18-satellite constellation, integrated GPS navigation systems will prove effective for both supplemental and sole-means navigation. Integrating GPS with other navigation sensors provides additional redundant data that may be used for integrity monitoring. The additional data, in some cases, also increases the coverage provided by the GPS service and allows sole-means navigation to be possible for the hybrid navigation system.

Some of the navigation systems addressed already are certified for sole-means navigation for some phases of flight. GPS may obviously be used as a supplemental navigation system with these, using the navigation data from the sole-means system as a check on the integrity of the GPS navigation solution. This will allow errors to be detected before they exceed the allowable error limit for the particular phase of flight, should a failure occur. However, under normal operating conditions, the aircraft operator may take advantage of the superior navigation performance provided by GPS.

Baro-Altitude Aiding

The barometric altimeter has a long history as a cockpit instrument. In its modern form, the altitude can be provided digitally as an aiding sensor to the GPS receiver. Typically, the instrument errors of the barometric altimeter can be held within 200 ft. However, the barometric altimeter measures pressure altitude and thus is subject to meteorological vagaries in relating true altitude to pressure altitude. These differences can be quite large [10] and when not compensated for will dominate the intrinsic instrument errors. For example, it would not be unusual for pressure altitude to differ from true altitude by 1000 ft or more over long flights across the continent or ocean. Also, pressure altitude, even when corrected by a reporting station, can be in error by a few hundred feet at a different altitude or at a location a few tens of miles away.

The principle of baro-altitude aiding for integrity monitoring is similar to that described for RAIM, where the altitude data is used as an additional GPS satellite pseudorange measurement. This form of aiding is only applicable when less than five satellites are in view and RAIM alone cannot be effective. The baro-altitude aiding data is not as accurate as an additional pseudorange measurement from a GPS satellite, so the same level of integrity possible with RAIM cannot be ensured. However, the use of baro-altitude aiding does provide additional redundancy and increases the navigation coverage supplied by GPS.

Further study is in progress, but it appears likely that baro-altitude aiding would allow the use of GPS as a sole-means navigation service for oceanic en route navigation with the 18-satellite constellation. Because of the limitations of the baro-altitude accuracy, the integrity provided will probably not be sufficient for other phases of flight.

GPS/Inertial Integrated Systems

Inertial navigation systems (INS) are relative, not absolute, position sensors and so the navigation accuracy deteriorates with time. The inertial errors are

generally characterized as a linear drift in position with a superimposed Schuler oscillation. In an integrated GPS/INS system the GPS data is used to calibrate the INS, while the INS is used to monitor the integrity of the GPS navigation. The INS cannot detect absolute position errors, but may be used to monitor against a slow drift occurring in the GPS navigation solution. In conjunction with RAIM, when five satellites are available, this is an effective technique for monitoring the GPS integrity throughout periods with poor satellite geometry. The problem then reduces to comparing the inertial drift rate to the GPS error rate over the period of time when RAIM is not effective with the 18 satellite constellation.

With the 18-satellite constellation, the maximum time that less than five satellites are in view is 63 minutes [11]. In Table 4, the integrity requirements and goals shown in Tables 1 and 2 are equated to drift rates over a 1 h period. To assure that the navigation error cannot exceed the alarm limit during the period that RAIM is not effective, the INS must detect error rates that exceed these limits.

From simulation results [12], a commercial 2 nmi/h INS integrated with a GPS receiver can meet the integrity requirements for en route oceanic and domestic phases of flight. The improved performance possible with an integrated GPS/INS system will also meet the integrity and redundancy requirements for the sole-means en route domestic phase of flight, and the goals established from future requirements for oceanic en route navigation. Inertial navigation is already a certified sole-means of navigation for oceanic en route phases of flight.

GPS/Loran-C

Integrating a GPS and a Loran-C receiver has the potential of providing a hybrid navigation system with superior performance than either system alone. Both GPS and Loran-C suffer to differing extents from a lack of coverage. The 18-satellite GPS constellation provides world-wide coverage with the exception of localized areas that appear at different times of day. The Loran-C network covers the majority of the United States with the exception of the mid-continent gap, which will be filled in the early 1990s. Both systems use ranging techniques for navigation; GPS pseudoranges from satellites and Loran-C time-differences (TD) from chains of ground transmitters. In principle, both the pseudoranges and TD measurements could be processed in an integrated solution using the redundant measurements for integrity monitoring similar to RAIM. Since the

Table 4—Error Rate Requirements for INS Integrity Monitoring

Phase of Flight	Oceanic En Route	Domestic En Route	Terminal Area	Nonprecision Approach
INTEGRITY REQUIREMENTS				
Drift Rate	6.4 m/s	0.8 m/s	0.6 m/s	0.15 m/s
Time-to-Detect	3720 s	3660 s	3615 s	3610 s
INTEGRITY GOALS				
Drift Rate	1.4 m/s	0.28 m/s	0.14 m/s	0.03 m/s
Time-to-Detect	3630 s	3630 s	3610 s	3606 s

nominal accuracy of Loran-C is 0.25 nmi, this hybrid navigation system will meet all the integrity requirements and goals listed in Tables 1 and 2, except for the nonprecision approach goal of 100 m. The extended coverage provided by this hybrid should allow sole-means navigation to be possible for en route domestic and terminal navigation phases of flight.

GPS/Omega

Like Loran-C, omega is a ground-based radionavigation service, although the omega coverage extends over most of the world. However, the omega navigation service only provides position to an accuracy of 2–4 nmi, which significantly limits the use of the omega ranges to monitor the GPS integrity or extend the GPS coverage. The only integrity requirements that can be met using omega data for monitoring are the oceanic en route requirements. Since omega already is certified as a sole-means of navigation for this phase of flight, an integrated GPS/omega receiver does not extend the range of operation of omega. The GPS navigation set may though be used as a supplemental navigation system for oceanic en route phases of flight.

GPS/Multi-Sensor FMCS

The integration of GPS into the Flight Management Control System (FMCS) can be viewed simply as the introduction of another radionavigation sensor. As such, the GPS receiver must meet the requirements established in RTCA/ DO-187, "Minimum Operational Performance Standards for Airborne Area Navigation Equipment using Multi-Sensor Inputs." The integrity requirements established in paragraph 2.2.1.11 of this document specify that the equipment should monitor itself for degraded performance and should annunciate degraded operation. This could be achieved by a variety of methods, for example RAIM. Following the guidance in DO-187 will allow supplemental use of GPS as a sensor input to an FMCS.

GPS/VOR/DME-RNAV

To make use of VOR/DME data to monitor the GPS navigation integrity, the raw range and bearing VOR/DME data must be converted into latitude and longitude data base coordinates. With the help of a navigation data base, a VOR/DME Area Navigation Computer (RNAV) can convert these polar coordinates to latitude and longitude, as described in RTCA/DO-180. The output of this RNAV computer can be used as a truth reference to monitor the integrity of the GPS navigation solution. This would allow supplemental use of GPS with an RNAV computer.

GPS Integrity Channel

With a GPS Integrity Channel (GIC), a ground-based GPS monitoring system is used to track the GPS signals and monitor the GPS satellite errors. Any excessive satellite errors are indicated on a GPS integrity message broadcast by a master control center to GPS users. The GIC network must be capable of disseminating integrity data for each monitored satellite signal, indicating the

phases of flight possible and alerting the pilot to out-of-tolerance conditions within the required time-to-alarm.

Studies by the Working Group [13] indicate that the GPS integrity may be determined relatively easily within the required time-to-alarm using a network of ground monitoring stations. The problem then remains of how to disseminate the data to the GPS users. The Integrity Working Group performed preliminary studies on both ground-based and satellite communication links for broadcasting the GIC message. This work is being continued by a GIC Working Group established by SC-159 to prepare a standard format for broadcasting GIC data.

Ground-Based Communications

Several methods of broadcasting GIC data using existing ground-based radio facilities were discussed by the Working Group [14]. The most attractive system considered was the use of aeronautical nondirectional beacons (NDBs) as a transmission medium. As stated in the U.S. Federal Radionavigation Plan [20], NDBs will remain a part of the radionavigation system well into the next century. It is expected that there will be 728 federal and 855 non-federal NDBs in the United States by the year 2000 [15]. The NDB coverage extends over most of the United States and Canada. However, there are some areas (mostly the mountainous regions of the Western U.S. and Alaska) that do not receive service.

It would be possible to modify existing NDB stations to include the GIC data message modulated on the NDB signal without interfering with navigation operation [16]. Although the NDB range of operation for data transmission greatly exceeds the navigation range, the Working Group concluded that the existing NDB coverage would need to be extended to provide continuous coverage over CONUS suitable for a GIC integrity data link. The relatively low cost of operating and maintaining an NDB GIC link would make it an attractive alternative to a satellite based system were sufficient signal coverage made available.

Satellite Communication

A concept for a GPS Integrity network is shown in Figure 3. The GPS signals are monitored at ground-based stations linked through a ground communication network to a master control station. The master station uplinks the GIC data to geostationary satellites, which then rebroadcast it to users in the area covered. To provide redundant integrity coverage over CONUS, two geostationary satellites are required. Five geostationary satellites would provide redundant world-wide coverage.

A variety of communication alternatives for the satellite broadcasts were discussed by the Working Group. Of concern to the group was the proliferation of systems (navigation, communication, etc.) within the aircraft. Ideally, a GIC communication link would be sufficiently similar to the GPS signals that the GIC data could be received and interpreted directly by the GPS receiver itself.

Presently the GPS has 37 C/A codes reserved for use by the GPS satellites and ground transmitters. However, there are 1024 possible C/A codes that can be tracked by GPS receivers. If a geostationary satellite were to broadcast the GIC data modulated on the L1 frequency using an unassigned C/A code, the
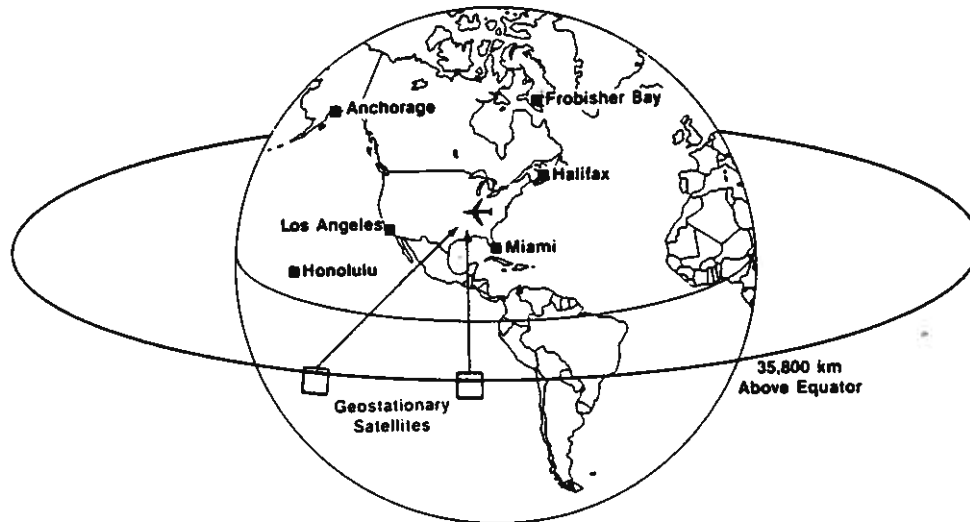
Fig. 3—Satellite GPS Integrity Network

GPS receiver could track that signal and demodulate the integrity data internally. Because of the cross-correlation properties of the C/A codes, this integrity service would not interfere with the GPS navigation service.

In addition, it was suggested that the GPS-like signal broadcast by the geostationary satellite could also be used for navigation. In this case, not only is integrity ensured but the GPS satellite coverage is also enhanced. Providing two geostationary satellites over CONUS would supply sufficient redundancy to meet the FAA requirement for sole-means navigation, i.e., the service should not be interrupted by a single satellite failure. Sufficient spare bits are included in the existing GPS data format to provide a limited indication of the GPS satellites' integrity. It would also be possible to broadcast the navigation signal in phase quadrature with the integrity signal. This would provide a 50 Hz independent data channel for the GIC data.

A number of candidate satellite systems were discussed for broadcasting the GIC and GPS navigation messages. Block II GPS satellites could be modified to broadcast the GIC data and to operate in geostationary orbit. A more inexpensive option considered was to piggy-back a GPS signal repeater on a geostationary satellite such as the GOES weather observation satellite [17]. The GPS-like signal would be generated by a ground-based master control station, accounting for the propagation delays in the uplink to the geostationary satellite. The signal would then be transmitted to the satellite where it would be down converted by the signal repeater to the L1 frequency and rebroadcast to users. This approach increases the complexity of the master control station but significantly simplifies the satellite payload.

Another approach considered was to use leased channels on mobile-service satellites or on commercial fixed service satellites [18]. This approach has merit in the short term as an inexpensive method of supplying GIC data. In fact,

Inmarsat recently announced that they plan to offer a GPS integrity service to their users [19]. However, aircraft would be required to carry communication equipment in addition to the GPS navigation sets to use this type of GIC service. Certification problems may also arise with a navigation service (GPS) that is dependent on a communication service for integrity.

Differential GPS

The use of differential GPS provides both integrity and improved GPS navigation accuracy. The differential GPS concept is similar to a GPS integrity monitoring network. The GPS satellite signals are monitored at surveyed locations to determine the satellite health and signal errors. The differential GPS message differs from GIC data in that error corrections are also broadcast in addition to the satellite integrity data. This allows an out-of-tolerance signal to be still used for navigation once the error correction has been applied.

A standard differential GPS data format was prepared by RTCM Special Committee-104 [16] that allows common errors between the monitor station and the user to be eliminated. This improves the GPS navigation accuracy to 5 to 20 m, 2 drms as the SA errors can be completely removed from the navigation solution when the data is transmitted in a timely manner. Using differential GPS, it is therefore possible to meet the FRP goal of a 100 m alarm limit for nonprecision approach. However, differential GPS does not increase the satellite coverage and so sole-means navigation would still be precluded by the FAA requirement for redundant satellite coverage.

CONCLUSIONS

Sole-Means Navigation

For GPS to be certifiable as a sole-means navigation system, the integrity of the navigation solution must be assured should system failures occur. Also, sufficient redundancy must be built into the system to allow navigation to continue in the event of a single satellite failure.

The navigation integrity can be provided internally through Receiver Autonomous Integrity Monitoring or externally by using a GPS Integrity Channel. With RAIM, the GPS receiver makes use of redundant navigation data for self-checking purposes. Redundant satellite data may be used, as permitted by user-satellite geometry, or aiding data from other sensors on-board the aircraft such as baro-altitude, Loran-C or an inertial navigation system. With a GIC, a network of ground monitoring stations continuously tracks the satellites and broadcasts an integrity message indicating the health of the GPS satellites. Both of these integrity monitoring techniques can meet all the integrity requirements and goals shown in Tables 1 and 2, except for the nonprecision approach goal of 100 m.

The FAA coverage requirement, that the loss of a single satellite should not cause an interruption of service, is not met by the 18 + 3 GPS satellite constellation. Even without a satellite failure occurring, there are significant periods of time when unaided navigation is not possible with this constellation. Table 5 summarizes the methods of augmenting the GPS system that the Working Group considered were suitable for sole-means navigation with GPS.

Table 5—Potential Sole-Means GPS Navigation Systems

GPS Navigation System	Phases of Flight Integrity Level	Oceanic En Route		Domestic En Route		Terminal Area		Nonprecision Approach	
		Req	Goal	Req	Goal	Req	Goal	Req	Goal
18 Satellites + 5 geo-stationary—GIC or 24 Satellite Constellation—RAIM		x	x	x	x	x	x	x	
18 Satellites + 2 geo-stationary over CONUS—GIC				x	x	x	x	x	
GPS/Baro-Altitude—RAIM		x							
GPS/INS —RAIM		x	x	x					
GPS/Loran-C —RAIM				x	x	x	x	x	

If the satellite constellation were increased to 24 satellites, sufficient redundancy would be provided to allow navigation to continue in the event of a satellite failure and also to determine that a failure has occurred using RAIM. This would allow GPS to be certified as a sole-means navigation system for all phases of flight world-wide, except possibly nonprecision approach. Adding two geostationary satellites over the United States would provide sufficient redundancy to meet the FAA coverage requirement over CONUS. Integrity could also be supplied by broadcasting GIC data through the geostationary satellites. Five geostationary satellites could provide the same service world-wide.

The GPS system redundancy can also be increased by integrating the receiver with other sensors on board the aircraft. By including aiding data from a barometric altimeter, a GPS receiver can meet the integrity and coverage requirements for oceanic en route navigation. An integrated GPS/INS can meet not only the oceanic en route requirements (for which the INS is already certified) but also the tighter oceanic en route goals and the domestic en route integrity and coverage requirements. An integrated GPS/Loran-C receiver can meet all the integrity requirements and goals except for the 100 m nonprecision approach goal.

Nonprecision Approach

Because of the planned level of the Selective Availability (SA) errors, the GPS navigation errors will exceed 100 m approximately 5 percent of the time, averaged globally over 24 hours. Since the SA errors change only slowly with time, the navigation error may stay outside the 100 m limit for a number of minutes [4]. The Federal Radionavigation Plan (FRP) [20] established a 100 m accuracy requirement for future nonprecision approach systems as a VOR near the runway threshold supplies 100 m accuracy (95 percent) at 0.7 nmi from the VOR. This means that during the approach, the VOR can be expected to be within this accuracy 95 percent of the time. However, with GPS, if the SA errors cause the navigation accuracy to exceed 100 m at the beginning of the flight, the same navigation error will apply for the next few minutes. In the

worst case condition, the 100 m alarm limit could be exceeded 100 percent of the time throughout the approach. Essentially, the GPS 100 m, 95 percent accuracy limit set by the SA errors means that only 95 percent of the time can an approach be made using GPS that will compare in accuracy to a VOR nonprecision approach when the VOR is located at the airport.

The Working Group concluded that the SA errors would preclude GPS meeting the nonprecision approach standards established in the FRP, unless the SA errors are reduced or GPS is operated in the differential mode.

Supplemental Navigation

In the near term, the most promising application for GPS is as a supplemental navigation system. During the constellation build-up phase, sole-means navigation will not be possible due to insufficient satellite coverage. However, as a supplemental navigation system, the excellent navigation accuracy provided by GPS may be used whenever sufficient satellites are in view to allow navigation.

The GPS navigation integrity may be ensured either through cross-checking with the sole-means navigation system or through making use of the integrity monitoring techniques suggested for sole-means GPS navigation. Table 6 lists the supplemental GPS applications that were considered by the Integrity Working Group.

RECOMMENDATIONS

The Integrity Working Group made the following recommendations to the SC-159 committee in their final report [1].

Expanded GPS Constellation

As recommended by the Working Group, a letter was drafted by the RTCA to the Department of Defense urging that the GPS constellation be expanded to 24 satellites. The 24-satellite constellation would provide continuous coverage and sufficient integrity for civil navigation world-wide, except possibly for nonprecision approach.

Reduction in the Effect of Selective Availability

Analyses by the Working Group showed that the presently specified level of selective availability is unacceptable to meet the nonprecision alarm limit goal of 100 m. The Working Group recommended that a joint committee be formed with FAA and DoD personnel to: (a) determine the appropriate alarm limit required for nonprecision approach; (b) determine the SA level and bounds consistent with this requirement; and (c) study the effects of the planned SA errors on GPS integrity. The acceptability of reduced level of SA to the DoD should also be assessed.

Table 6—Supplemental GPS Navigation Systems

GPS/Multi-Sensor FMCS	GPS/VOR/DME-RNAV
GPS/Omega	GPS/INS
GPS/Loran-C	

GPS Integrity Channel (GIC) Working Group

As recommended by the Integrity Working Group, on September 9, 1987, SC-159 formed a GPS Integrity Channel Working Group. This group was tasked to prepare a standard GIC data format for communicating the integrity of the GPS navigation solution. The group will consider civil GPS user requirements, monitoring/communication system requirements, GIC data message formats and suitable GIC communication media.

Topics for Further Study

The Working Group recommended that studies should continue on Receiver Autonomous Integrity Monitoring techniques, GPS/Loran-C integration techniques and the use of Baro-Altitude aiding for integrity monitoring.

REFERENCES

1. SC-159 Integrity Working Group, Radio Technical Commission for Aeronautics *Report of the SC-159 Integrity Working Group*, RTCA Paper No. 220-87/SC159-95, May 1987.
2. Kalafus R., and Chin G., *Measures of Accuracy in the Navstar/GPS: 2 dRMS vs CEP*, ION National Technical Meeting Proceedings, Long Beach, California, January 1986.
3. Jorgensen P., *Achieving GPS Integrity and Eliminating Areas of Degraded Performance*, NAVIGATION, Winter 1987–88, pp. 297–306.
4. Brown R. G., *Selective Availability Simulations*, Radio Technical Commission for Aeronautics, RTCA Paper No. 19-87/SC159-73.
5. Francisco S., *Operational Control Segment of the Global Positioning System*, Radio Technical Commission for Aeronautics, RTCA Paper No. 117-86/SC159-16.
6. Brown A., and Jessop, R., *Receiver Autonomous Integrity Monitoring using the 24-Satellite GPS Constellation*, Radio Technical Commission for Aeronautics, RTCA Paper No. 279-87/SC159-102.
7. Brown R. G., *GPS Failure Detection by Autonomous Means within the Cockpit*, Radio Technical Commission for Aeronautics, RTCA Paper No. 247-86/SC159-26.
8. Lee Y., *Analysis of Range and Position Comparison Methods as a Means to Provide GPS Integrity in the User Receiver*, Radio Technical Commission for Aeronautics, RTCA Paper No. 248-86/SC159-27.
9. Brown R. G., *Self-Contained GPS Integrity: Trade-Off Between Selective Availability and Radial Error to be Protected Against*, Radio Technical Commission for Aeronautics, RTCA Paper No. 408-87/SC159-119.
10. Brown A., *Integrity Monitoring of GPS using a Barometric Altimeter*, Radio Technical Commission for Aeronautics, RTCA Paper No. 405-87/SC159-117.
11. Kalafus R., *Durations of Periods with Less than Five Satellites in View*, Radio Technical Commission for Aeronautics, RTCA Paper No. 488-86/SC159-59.
12. Brennen M., *GPS Monitoring using IRS or INS*, Radio Technical Commission for Aeronautics, RTCA Paper No. 461-86/SC159-50.
13. Jorgensen P., *A Suggested Approach for Integrity Monitoring Stations*, Radio Technical Commission for Aeronautics, RTCA Paper No. 18-87/SC159-72.
14. White F., *Communications Methods for Disseminating GPS Integrity Data to Aircraft Using Planned Capability*, Radio Technical Commission for Aeronautics, RTCA Paper No. 303-86/SC159-33.
15. Scull D., *Communications Link for Differential GPS Monitor Stations*, Radio Technical Commission for Aeronautics, RTCA Paper No. 457-86/SC159-46.

16. Special Committee 104, Radio Technical Commission for Maritime Services, *Recommendations of Special Committee 104: Differential Navstar/GPS Service,* November 1985.
17. Ford Aerospace and STI, *Implementation of a GPS Type Payload on a Geostationary Satellite,* Radio Technical Commission for Aeronautics, RTCA Paper No. 246-86/SC159-25.
18. Braff R., *GPS Signal Integrity Briefing for RTCA SC-159,* Radio Technical Commission for Aeronautics, RTCA Paper No. 114-86/SC159-14.
19. *Inmarsat Moves to Provide Satellite Navigation Services,* Aeronautical Satellite News, September 1986, p. 1.
20. U.S. Department of Transportation, *Federal Radionavigation Plan (FRP),* DOT-TSC-RSPA 84.8, 1984.