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A MULTI-SENSOR APPROACH TO ASSURING GPS INTEGRITY

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INTRODUCTION

The Global Positioning System (GPS) was developed by the United States Department of Defense (DoD) to enhance the effectiveness of military missions and to reduce the present proliferation of DoD radionavigation systems. 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).

Integrity is defined 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.

For GPS to be used for supplemental or sole–means navigation in the civil airspace, 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 GPS have been discussed by RTCA Special Committee–159 and other forums [1,2].

This paper discusses a multi–sensor approach to assuring the integrity of the GPS navigation solution. By integrating GPS data with data from other sensors on–board the aircraft, GPS failures can be detected with a high degree of reliability. The effectiveness of GPS/Baro–altitude, GPS/INS, GPS/Loran–C and GPS/Glonass integrated systems in assuring GPS integrity is discussed.

GPS INTEGRITY REQUIREMENTS

Under normal conditions, the GPS Standard Positioning Service (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 error exceed the allowable error threshold for a particular phase of flight.

In Table 1 the integrity requirements for existing radionavigation systems as determined by RTCA SC–159, are shown for different phases of flight. Since GPS can, in most cases, improve on the performance provided by existing radionavigations, or set of Integrity goals, shown in Table 2, were also defined by SC–159 based on the requirements for future radionavigation systems derived in the Federal Radionavigation Plan. These integrity criteria would provide the potential for reducing aircraft separation and obstacle clearance criteria in the future.

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

Non–Precision Approach

The most stringent requirement established for GPS integrity is the 100m alarm limit for a non–precision approach extracted from the Federal Radionavigation Plan [4]. To degrade the accuracy of the Standard Positioning Service, deliberate Selective Availability (SA) errors will be added to the GPS signals. Because of the planned level of the 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.

The 100 m accuracy requirement matches the best accuracies presently provided by a VOR installed at the runway threshold during non–precision approach. However, GPS integrity alarm limits must be set above 100 m in order to prevent frequent alarms from "natural" GPS effects such as Selective Availability. The significant impact on non–precision approached, as defined in the Terminal Instrument Procedures (TERPS) appears to be the size of the obstacle clearance areas (OCAs) and their effect on the minimum descent altitude (MDA). Obstacles in the OCAs will elevate the MDA. Consequently, the larger the OCAs, the greater the probability that the MDA will have to be elevated, thereby reducing the utility of the non–precision approach.

For a GPS monitor alarm limit of 200 m, study results [5] have shown that the proposed OCAs are approximately equal to those of a VOR installed in the vicinity of the runway threshold. However, for the majority of cases (approximately 70%), the OCAs for GPS non–precision approaches will be smaller than the equivalent OCAs for VOR approaches. The 100m integrity alarm limit for GPS non–precision approaches could therefore be relaxed while still providing equivalent or better performance to existing non–precision approach navigation aides.

GPS INTEGRITY MONITORING TECHNIQUES

The integrity monitoring techniques presently under consideration for GPS can be divided into two categories, internal methods and external methods. With internal methods, the GPS integrity can be achieved using information available inside the receiver, such as redundant satellite measurements or receiver clock information . Using external methods, the GPS signals are monitored in real time through a network of ground monitoring stations, and broadcast to a user through a GPS Integrity Channel (GIC).

GPS Integrity Channel

A concept for a GPS Integrity Channel network is shown in Figure 1 [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 rebroadcasts 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.

The FAA is presently considering implementing a GIC network to provide a GPS integrity service. Satellite carriers such as INMARSAT have expressed an interest in broadcasting the GIC data as an aeronautical service and have initiated implementation studies [6]. There is no doubt that a reliable GIC service could be developed that would meet the GPS integrity requirements and goals shown in Tables 1 and 2, including the 100 m non–precision approach alarm limit. However, the cost of developing and operating a GIC may prohibit its implementation.

Figure 1. GPS Integrity Channel Concept

Receiver Autonomous Integrity Monitoring

With Receiver Autonomous Integrity Monitoring (RAIM), the GPS receiver makes use of redundant information from the GPS satellites and as a check on the integrity of the navigation solution. A variety of different RAIM algorithms have been developed to make use of redundant satellite measurements which are described in references [7] to [16].

All of these algorithms rely on there being sufficient information from the redundant GPS satellite measurements to detect satellite failures. This equates to a satellite geometry requirement which is best illustrated using the simple 'snapshot' approach to GPS failure detection shown in Figure 2.

In the case illustrated, 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 and, 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.

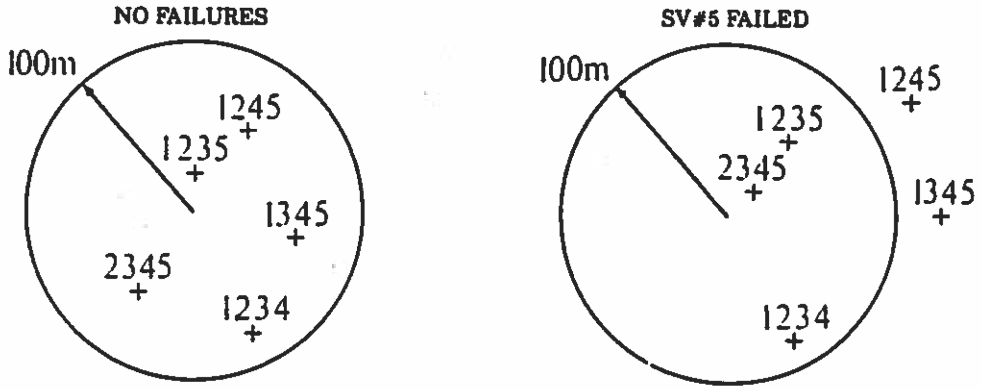


Figure 2. Possible Navigation Solutions with Five GPS Satellites

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 on solution is correct and must be near the true location of the aircraft.

For RAIM to be effective 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.

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 [8]. From the integrity requirements listed in Tables 1 and 2, RAIM would be suitable to meet all the integrity requirements and goals, if sufficient satellite coverage is available, except for the non–precision approach goal of 100 m. However, from previous discussions, this non–precision approach alarm limit could be relaxed without significantly affecting performance. This would permit RAIM to meet all integrity requirements, providing that sufficient redundant satellites are available.

RAIM Coverage

The effectiveness of RAIM is dictated by the satellite geometry of the GPS constellation. GPS will transition to the 21 + 3 satellite constellation in the mid 1990s which will consist of four satellites in each of six planes as shown in Table 3 [17]. The constellation will be maintained so that at least 21 satellites are always fully operational, and that the coverage provided by the constellation does not fall below a constellation value of 0.9960. The constellation value (CV) represents the fraction of space and time that at least four satellites are visible at a 5^0 elevation angle with a PDOP below ten. The constellation values for the 21 + 3 GPS satellite constellation assuming one, two, three and four satellite failures are shown in Table 4.

Table 4 also illustrates the percentage of time that RAIM is available. To assure integrity using self–contained means, good geometry must be provided by the constellation for each N–1 subset of visible satellites. From Table 4, if one satellite is deleted from the 21 + 3 constellation, the CV varies from 1.000 (no degradation.) to 0.9997 (0.03% degradation) depending on the satellite deleted. Assuming that RAIM can function adequately when the integrity geometry provides a PDOP<10, the redundancy in the 21 + 3 satellite constellation can be used to detect a satellite failure greater than 0.03% of the time.

If the constellation is degraded to a 21 satellite constellation (3 satellite failures), the integrity monitoring geometry is significantly poorer. With only 21 satellites available it is impossible to detect the fourth satellite failure 5.3% of the time. This assumes worst case conditions, i.e., that the worst possible satellites have been removed from the constellation leaving the poorest navigation and integrity coverage.

Table 3. 21 + 3 Primary Satellite Constellation

EPOCH = 1989. 11. 26. 0. 0. 0.0
$a = 26609$ km $e = 0$ $i = 55^0$ $w = 0^0$

Plane	Ω (degrees	M (degrees)
A1	325.730284°	190.96°
A2	325.730284°	220.48°
A3	325.730284°	330.17°
A4	325.730284°	83.58°
B1	25.7302839°	249.90°
B2	25.7302839°	352.12°
B3	25.7302839°	25.25°
B4	25.7302839°	124.10°
C1	85.7302839°	286.20°
C2	85.7302839°	48.94°
C3	85.7302839°	155.08°
C4	85.7302839°	183.71°
D1	145.730284°	312.30°
D2	145.730284°	340.93°
D3	145.730284°	87.06°
D4	145.730284°	209.81°
E1	205.730284°	11.90°
E2	205.730284°	110.76°
E3	205.730284°	143.88°
E4	205.730284°	246.11°
F1	265.730284°	52.42°
F2	265.730284°	165.83°
F3	265.730284°	275.52°
F4	265.730284°	305.04°

Table 4. Robustness of the 21 + 3 Satellite Constellation

# SV'S DELETED	BEST C.V.	AVERAGE C.V.	WORST C.V.
1	1.0000	.9999	.9997
2	1.0000	.9993	.9961
3	.9998	.9969	.9769
4	.9997	.9905	.9475

MULTI–SENSOR INTEGRITY MONITORING

Although RAIM algorithms have been shown to be highly effective most of the time in detecting satellite failures, and are relatively inexpensive to implement in the existing receiver designs, the 21+3 GPS satellite constellation does not provide sufficient geometry to provide continuous RAIM coverage. A GPS Integrity Channel could be implemented that would provide a continuous, highly effective GPS integrity monitoring service. However, this service would require a significant investment in ground equipment, a satellite communications link, and customized receivers for all aircraft subscribing to the service.

A more cost–effective solution to the GPS integrity problem, which is addressed in this paper, is to integrate GPS with other sensors on–board the aircraft to continuously monitor the health and error levels on the GPS satellite signals. This multi–sensor approach has the potential of solving both the GPS integrity and coverage problems while requiring minimum capital outlay for development. In the following sections, GPS/Baro–altitude, GPS/INS, GPS/Loran–C and GPS/Glonass multi–sensor systems are considered from the integrity point of view.

GPS/Baro–Altitude

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 [19] 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. Instead of using a fifth satellite to validate the integrity of the GPS navigation solution, the baro–altitude data is used as though it were a redundant satellite range measurement [18]. The baro–altitude aiding will therefore allow integrity checking to continue when less than five satellites are in view and RAIM alone cannot be effective.

The integrity level alarm limit that can be assured using baro–altitude aiding is a function of the satellite geometry and the accuracy of the baro–altitude measurement compared with a GPS pseudo–range measurement. For some phases of flight, the imprecision in the baro–altitude measurement is not significant enough to degrade the effectiveness of the integrity monitoring. For example, during oceanic en–route navigation the existing integrity alarm limit is only 12.6 nmi. Simulations have shown [18] that baro–altitude aiding can increase the RAIM coverage to 100% for oceanic en–route navigation.

However, baro–altitude aiding is less effective for other phases of flight and is particularly poor for terminal navigation. During the terminal phase, the aircraft is descending in altitude and the offset between baro–altitude and geometric altitude can change significantly due to variations in temperature and pressure from standard atmospheric conditions. During this phase, the barometric altitude errors can erroneously indicate satellite failures causing an unsatisfactory probability of false alarm.

In conclusion, baro–altitude aiding shows promise for assuring GPS integrity for oceanic en–route navigation (100% availability), and to a certain extent domestic navigation (99.8%

availability). However, for terminal and non–precision approach, the barometric altitude accuracy is not sufficient to provide a reliable indication of GPS integrity.

GPS/INS

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.

From simulation results [20], 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.

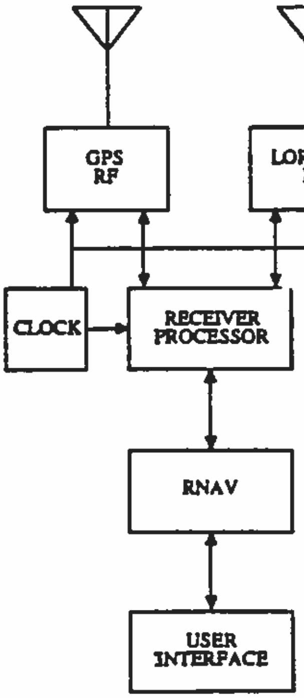
GPS/Loran–C

It is possible to improve the coverage and integrity of both Loran–C and GPS by integrating the two systems together. Currently Loran–C Master station transmitters are synchronized to UTC within ± 2.5 μs. Secondary stations are held within ± 50 ns of the Controlling Standard Time Difference (CSTD) measured by the System Area Monitor (SAM). The main disadvantage of the current Loran–C timing procedure is that the time of transmission of the Secondary station varies when propagation delays to the SAM vary. This results in an uneven error distribution with relatively large errors in areas not close to the LOP defined by the CSTD. A concept under consideration to improve the accuracy and coverage of Loran–C is to synchronize all Loran–C transmitters using GPS time [22,23]. This would significantly increase coverage for Loran–C cross–chaining users and would also increase reliability as a failing Master station would not result in an unusable chain.

If the Loran–C system was synchronized to GPS time, a hybrid Loran–C/GPS receiver, such as that illustrated in Figure 3 would be able to provide a highly accurate and reliable navigation solution. In this design the time of the Loran–C transmitters is synchronized to he same time reference as the GPS satellites and the Loran–C receiver timing is also synchronized to the GPS receiver time. Studies need to be completed on how well the relative timing of the Loran–C and GPS receivers can be maintained. If the relative timing errors between the receivers can be maintained within a nominal level, it is possible to compute a hybrid navigation solution using pseudo–ranges from both the GPS satellites and Loran–C transmitters.

The combined geometry of the Loran–C and GPS hybrid solution is extremely robust and would allow for failures to be detected in individual Loran–C or GPS transmitters using RAIM algorithms [21]. The level of integrity that could be provided by this hybrid solution still needs to be verified through simulation. However, it appears likely that a hybrid GPS/Loran–C system could meet all the existing integrity requirements for en–route, terminal and non–precision approach throughout CONUS. Integrity coverage would only be lacking when Loran–C transmitters were not in range, for example during en–route oceanic navigation.

Figure 3. Hybrid GPS/Loran—C Receiver



GPS/Glonass

The USSR has developed a global satellite navigation system designated Glonass which is planned to become operational in the 1990's. Details on the Glonass satellite orbital and signal structure are already available in the literature [25, 26]. In summary, Glonass satellites transmit spread—spectrum signals at two L—band carrier frequencies around 1250 and 1600 MHz designated L_2 and L_1. A high—precision code at 5.11 Mbits/s is transmitted on both frequencies, with a lower—precision code at 0.511 Mbits/s on L_1 only. These codes are modulated with binary data at 50 baud which contain a precise ephemeris for the transmitting satellite, low—precision almanacs for all satellites currently operating and system parameters for integration and coordination of measurements. These measurements essentially consist in timing the arrival of a known reference from the satellite against a ground—based reference. Four time—difference measurements to four suitably located satellites provide the user with enough data to compute his own position.

Glonass satellites do not all transmit on the same carrier frequency but instead each satellite has its own carrier frequency within the allocated frequency band of 1597—1617 MHz. The separation between individual transmission frequencies is an integer multiple of 9/16 MHz at L_1 and 7/16 MHz at L_2. The system is capable of operating with up to 36 channels, but decoded signals show that only 24 channels are planned for full operations [26]. The orbital structure chosen also supports this view with an operational configuration of 24 satellites with 8 satellites in each of 3 orbital planes.

With the current Soviet GLASNOST policy, there has been a concerted effort by the US FAA, a special committee on Future Air Navigation Systems (FANS) within the International Civil Aviation Organization (ICAO), and the Soviet Ministry of Communications to begin discussions about the cooperative use of GPS and the Soviet Global Orbiting Navigation Satellite System (GLONASS) for civil aviation uses.

One potential solution to the GPS integrity problem is the development of a GPS/Glonass hybrid receiver. Test results have demonstrated that the navigation accuracy provided by the Glonass system is very similar to that available with GPS [26]. The combined geometry provided by the 21+3 GPS satellite constellation and the 24 satellite Glonass constellation provides more than sufficient redundancy for RAIM algorithms to be effective in detecting failures in either GPS or Glonass satellites [27].

Some issues still to be resolved in the development of a hybrid GPS/Glonass receiver are: the errors introduced due to differences in the timing and datum references between the systems; and the relative time synchronization errors between a Glonass and GPS receiver operating off a common clock, as illustrated for the Loran–C receiver shown in Figure 3. The FAA are presently sponsoring study programs to develop an integrated GPS/Glonass receiver and to investigate methods of linking the two systems together with a common timing and geodetic reference.

However, preliminary results have indicated that a hybrid GPS/Glonass receiver could likely meet the integrity requirements and goals established for all phases of flight and would prove a viable global sole–means navigation system.

CONCLUSIONS

In Table 5, the integrity requirements that can be met by the multi–sensor GPS systems under consideration are illustrated. A GPS receiver integrated with a barometric altimeter or/and an INS can provide sufficient self–checking and redundancy internally to meet the requirements for an en–route oceanic or domestic sole–means navigation system. A GPS/Loran–C integrated system would provide sufficient integrity and redundancy to meet the requirements of an en–route domestic, terminal or non–precision approach sole–means navigation system wherever there is adequate Loran–C transmitter coverage.

The most promising multi–sensor system considered is a GPS/Glonass integrated receiver which has the potential of providing a global sole–means navigation system suitable for all phases of flight. As illustrated in Table 5, none of the multi–sensor systems considered can meet the 100 m alarm limit set as a goal for non–precision approach systems in the FRP. As previously discussed, however, this alarm limit could be relaxed to a level that can be achieved by GPS without significantly affecting performance.

In conclusion, integrated GPS systems can provide sufficient internal failure detection and redundancy to allow a multi–sensor GPS system to be certifiable for sole–means navigation. The multi–sensor approach to integrity monitoring can therefore provide a cost–effective alternative to other integrity monitoring systems under consideration for GPS such as a GPS Integrity Channel.

Table 5. Multi–Sensor GPS Integrity Monitoring

Phase of Flight	Oceanic En-Route		Domestic En-Route		Terminal Area		Non-precision Approach	
Alarm Limit	Req. 12.6 nmi	Goal 5 km	Req. 1.5 nmi	Goal 1 km	Req. 1.1 nmi	Goal 500 m	Req. 0.3 nmi	Goal 100 m
GPS/Baro	X	X	X	-	-	-	-	-
GPS/INS	X	X	X	-	-	-	-	-
GPS/Loran-C	-	-	X	X	X	X	X	-
GPS/Glonass	X	X	X	X	X	X	X	-

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