GPS AVIATION OUTAGE PREDICTION AND REPORTING SYSTEMS

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ABSTRACT

Use of GPS for instrument flight rule (IFR) air navigation requires that the system have integrity. Integrity is the ability to detect when a satellite is out of tolerance and should not be used in the navigation solution and then warns the pilot in a timely manner. This capability currently is provided by a Receiver Autonomous Integrity Monitoring (RAIM) or Fault Detection and Exclusion (FDE) algorithm contained within the GPS receiver. All GPS receivers currently certified for air navigation under Technical Standard Order (TSO) C129 must have RAIM for supplemental navigation and FDE to serve as a primary means system.

In order for the receiver to perform RAIM, a minimum of five satellites with satisfactory geometry must be visible to the user and FDE requires a minimum of six visible satellites. Since the GPS constellation of 24 satellites was not designed to provide this type of performance, GPS RAIM/FDE is not available 100% of the time, even when all of the satellites are operational. Occasionally, satellites are taken out of service for maintenance, further degrading coverage.

There is a need to interpret the satellite status information and provide GPS outage information in a format which is meaningful to the pilot during the pre-flight planning process. In other words, it is not sufficient to only report to a pilot which satellite is out of service, but rather where and when the outages will occur. The location and duration of integrity outage periods can be predicted with the aid of computer analysis, however, and reported to pilots when the flight plan is filed.

This paper discusses systems that the FAA and the U.S. Air Force have implemented to disseminate GPS satellite outages, as well as airfield-specific GPS RAIM outages, to civilian and military pilots. These concepts are being adopted by other countries, such as Australia, and can easily be extended to GLONASS or a system which uses signals from both constellations.

However, in the implementation of such a system for reporting GPS outages for aviation, there are issues to address such as the format of the outage data disseminated, the standardization of GPS integrity algorithms, the large range of aircraft equipment which can be certified for Required Navigation Performance (RNP) requirements, and the training necessary for pilots and air traffic controllers. This paper also considers plans to disseminate outage information for satellite and ground-based GNSS augmentation systems of the future (i.e., SBAS and GBAS) which are beginning to be discussed in the ICAO GNSS Panel.

INTRODUCTION

GPS is a worldwide satellite radionavigation system which will be used extensively for air navigation. The FAA already has certified GPS as a supplemental navigation system for domestic en route, terminal, and nonprecision approach navigation, as well as for primary means oceanic use. Until satellite and ground-based GNSS augmentation systems (SBAS and GBAS) are implemented, GPS integrity will be provided by an algorithm within the receiver. This method is known as Receiver Autonomous Integrity Monitoring (RAIM).

According to the Federal Radionavigation Plan [1], DoD is required to provide a minimum of 48-hour advance notice of scheduled satellite outages to the USCG GPS Information Center and the FAA Notice to Airmen (NOTAM) system. There is a need to interpret the satellite status information and ***provide outage information in a format which is meaningful to the pilot***. In other words, it is not sufficient to only report to a pilot which satellite is out of service, but rather where and when the outages will occur.

This paper describes a system for reporting GPS outage information for supplemental air navigation, investigates issues associated with implementation of such a system, and examines methods of disseminating outages for future GNSS-based primary means navigation systems.

GPS AVAILABILITY

GPS differs from traditional land-based navigation systems due to the fact that the satellites and areas of degraded coverage are in constant motion. If a satellite fails or is taken out of service for maintenance, it is not intuitively known which areas may lose coverage, if any. Also, GPS does not have a built-in real-time monitoring system which will satisfy aviation requirements. GPS receivers certified for aviation must have integrity, which is the ability of the system to provide timely warnings to the user when the system is unreliable for navigation.

RAIM is an algorithm contained within the receiver which uses an overdetermined solution to perform a redundancy check. According to Technical Standard Order (TSO) C-129, GPS receivers certified for supplemental IFR navigation must have RAIM [2]. RAIM algorithms require a minimum of five visible satellites in order to detect a failure. Unfortunately, even with 24 operational satellites, there are occurrences when the geometry of the visible satellites prevents detection of a failure. Also, satellites occasionally need to be taken out of service for maintenance, further reducing the availability of RAIM. TSO C-129 requires that barometric altimeter aiding be employed for nonprecision approach (NPA) to improve the availability.

Figure 1 displays worldwide TSO C-129 RAIM coverage for NPA over a twelve hour period with the Optimized 24 GPS constellation. The coverage is computed every five degrees in latitude and longitude at five minute time intervals, applying a 7.5° mask angle as specified in the TSO. This figure contains an accumulation of outages over this time interval. Since the GPS satellites are in approximately twelve hour orbits, the coverage will repeat itself in the opposite hemisphere during the next twelve hours.

This figure demonstrates that even with 24 operational satellites, there are periods of up to 50 continuous minutes when GPS RAIM coverage is not available at some locations. These outages will occur in the same location every day, although the time of day will shift by four minutes per day. The number of visible GPS satellites increases as latitudes approach the equator, which explains the higher availability in that region.

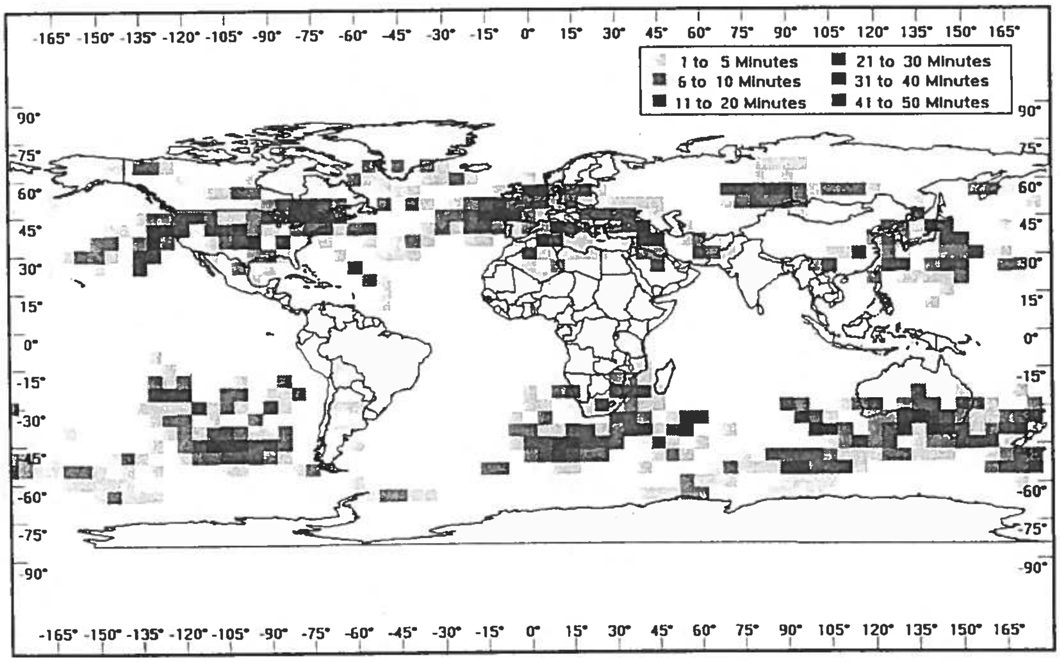


Figure 1 Worldwide GPS NPA RAIM Outages Over a 12 Hr. Period

GPS OUTAGE DISSEMINATION

As previously discussed, the U.S. Department of Defense (DoD) is required to provide a minimum of 48-hour advance notice of scheduled GPS satellite outages to the U.S. Coast Guard GPS Information Center and the FAA NOTAM System. The U.S. DoD needed to have this notification system in place before the GPS system could be declared operational.

GPS Notice to Airmen System

Since Oct. 28, 1993, satellite outages have been issued as international GPS Notices to Airmen (NOTAMs). Providing notification of GPS satellites outages was an initial step in establishing a GPS NOTAM system and disseminating GPS status to aviators. As shown in Figure 2, the GPS Master Control Station (MCS), which is located at Falcon Air Force Base in Colorado Springs, CO, faxes the satellite outages, known as Notice Advisory to NAVSTAR Users (NANUs), to the U.S. NOTAM Office (USNOF) at the FAA Air Traffic System Command Center. Scheduled outages are sent to the USNOF at least 48 hours ahead of the start of the outage and unscheduled outages are disseminated as soon as possible (generally within 30 minutes from the start time of the outage).

The USNOF then issues an international GPS NOTAM in ICAO format under the KNMH identifier. An example GPS NOTAM is given below:

A) KNMH
B) 9710150350
C) 9710151550
E) GLOBAL POSITIONING SATELLITE PSEUDO RANDOM NOISE 05 U/S

This NOTAM states that GPS satellite PRN 5 will be out of service on Oct. 15 from 0350 GMT to 1550 GMT. Unfortunately, this information is essentially useless to a pilot unless there is a method to interpret its effects on flight plan availability. In other words, it is not sufficient to only report to a pilot that PRN 5 will be out of service for that period of time, but rather where and when any resulting outages will occur. There may be more than enough visible satellites to perform RAIM even with PRN 5 out of service or, on the other hand, this satellite may be critical to the navigation solution.

The Volpe National Transportation Systems Center, of the U.S. Department of Transportation Research and Special Programs Administration, has designed and developed a system for the United States Air Force Flight Standards Agency (AFFSA) to report GPS NOTAMs. This system, which was declared operational May 16, 1995, produces NOTAMs for GPS satellite outages and also provides airport specific military GPS NOTAMs for nonprecision approach that are based on RAIM outages lasting longer than twenty minutes. Reporting outages greater than twenty minutes is the requirement established by the United States Air Force based on the amount of fuel reserves that their aircraft carry. The start and end times of outages are determined to a one minute resolution. These outages are disseminated through the U.S. NOTAM system to military aviators via the Automated Weather Network (AWN).

An example of a NOTAM is given below for an outage at Los Angeles International airport. In the example, the outage lasts from 1933 to 2008 GMT on Nov. 8. The "GPS Only" explanation indicates that this outage is based solely on TSO C-129 criteria and the presumption is that GPS is not augmented by another navigation aid.

A) KLAX
B) 9711081933
C) 9711082008
E) GPS ONLY NPA NOT AVBL

These outages are disseminated through the U.S. NOTAM System to the National Communications Center (NATCOM). Data for military aviators is processed through the Aviation Weather Network (AWN) to the CONUS Meteorological Distribution System (COMEDS) and the Automated Weather Distribution System (AWDS), as shown in Figure 2.

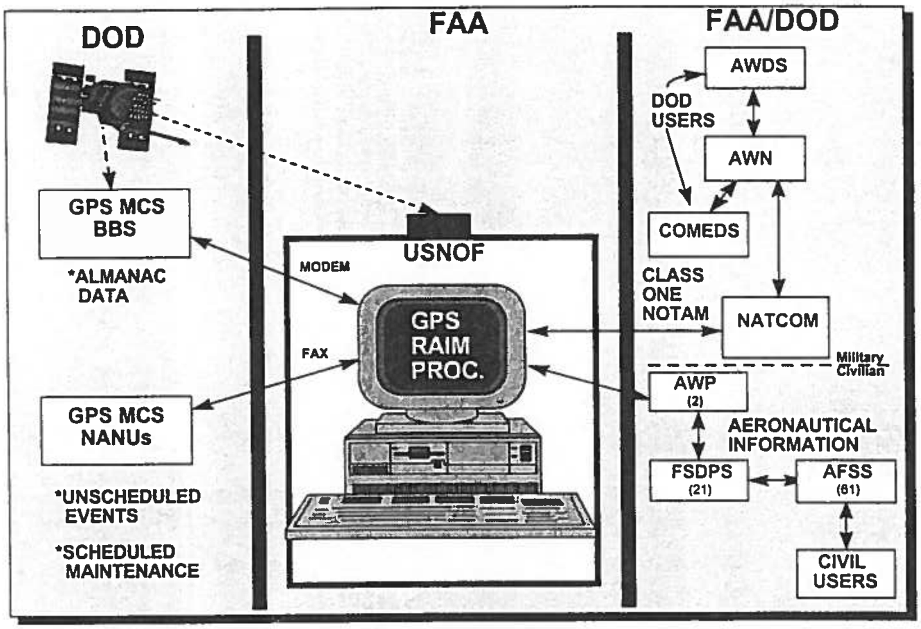


Figure 2 United States GPS RAIM Outage Reporting System

FAA GPS Aeronautical Information System

The Volpe Center also developed a GPS aeronautical information system, based on the Satellite Operational Implementation Team (SOIT) requirements. The FAA system uses the same GPS RAIM processor as the DoD NOTAM system to compute aeronautical information. The FAA data distribution differs from the DoD system in that information is disseminated through their two Automated Weather Processors to the 21 Flight Service Data Processing Systems (FSDPS) and then to the 61 Automated Flight Service Stations (AFSS), as shown in Figure 2. GPS RAIM availability for the next 48 hours is calculated once per day for all airfields in the database and is distributed to the 61 AFSSs. If a change in the satellite constellation occurs due to an unscheduled outage, RAIM is recalculated for the airfields and the databases at the AFSSs are updated. Upon request by a pilot, the AFSS furnishes GPS availability for an NPA at a destination airfield. The FAA GPS aeronautical information system was declared operational November 2, 1995.

IMPLEMENTATION ISSUES

Implementation of the system described above and plans to implement similar systems in other countries have raised several issues. One of the first issues which arises when considering to implement such a system is whether the aviation authority should be responsible for disseminating GPS RAIM outages. After all, TSO C-129 requires a predictive RAIM capability in GPS receivers for the nonprecision approach phase of flight. Therefore, satellite outage information could be used as an input to receivers in order to predict GPS RAIM coverage at specified destinations. This method, however, forces the pilot to go to the cockpit of the plane to perform the RAIM prediction and so it does not qualify as pre-flight planning. There also are other problems with this procedure:

1) Not all GPS receivers have a satellite deselection capability. Hence, if a GPS NOTAM states that in 30 minutes a satellite will be taken out of service for maintenance, there is no means to incorporate this fact into the receiver RAIM prediction.

2) According to the TSO, the receiver must perform the RAIM prediction for +/- 15 minutes of the estimated time of arrival (ETA). If RAIM is unavailable at any point during this time interval (longer than 5 minutes), most receivers display the message "RAIM NOT AVAILABLE", but do not divulge the duration of the outage. Therefore, even if the outage is very short, the receiver will indicate that RAIM is unavailable for an NPA.

NOTAM vs. Aeronautical Information

Airfield-specific GPS RAIM expected outages can be provided more accurately and efficiently through standard briefing practices which also are more convenient for pilots and Air Traffic Control. The question that the U.S. SOIT addressed was whether to issue RAIM outages via the NOTAM system or through another means of distribution. The U.S. NOTAM system is a jointly operated military/civilian facility located at Air Traffic System Command Center. Before the SOIT took this issue under consideration, the U.S. Air Force already had established a requirement to report all airport specific GPS RAIM outages lasting longer than 20 minutes in a NOTAM format. The basis for this requirement was the amount of fuel reserves that U.S. military aircraft carry. The FAA decision to report all GPS RAIM outages lasting longer than five minutes was based on requirements in the TSO and input from pilot associations.

The current U.S. NOTAM system consists of antiquated equipment, both in terms of computer hardware and communication lines. As a result, any increase in the number of NOTAMs beyond the normal daily load (e.g., due to snow storms) causes the system to approach saturation. When applying RAIM for nonprecision approach, some locations can experience more than one outage during a day and, if satellites are taken out of service for maintenance, the number and duration of the outages significantly increases.

An analysis was performed which demonstrated that for the database of airfields for which the FAA wanted to report GPS RAIM availability, the number of GPS NOTAMs would exceed considerably the capacity of the NOTAM system. Since GPS is an area navigation system, the number of reportable outages is directly tied to the number and location of airfields within the database. Even if the minimum outage duration requiring a report were increased to twenty minutes, the current NOTAM system still would have difficulties handling the load [3].

Consequently, the SOIT issued a decision paper which recommended that GPS satellite outages continue to be disseminated as NOTAMs, but that airport specific GPS RAIM outages, based on TSO C-129 criteria, should be distributed as aeronautical information [4]. The SOIT decision paper served as the basis for the U.S. position paper on GPS NOTAMs and Aeronautical Information that was presented to ICAO in November, 1995 [5]. Aeronautical information differs from a NOTAM because it is disseminated through the Aviation Weather Processors (AWPs) to the Automated Flight Service Stations (AFSS), thereby circumventing the NOTAM system. Aeronautical information also does not have the same regulatory standing as a NOTAM, raising some questions regarding the legal implications of issuing these outages.

There are other drawbacks to the FAA GPS aeronautical information system configuration. Since the civilian GPS RAIM data are not disseminated through the NOTAM system, other users such as the airlines and the Direct User Access Terminals (DUATS), that allows pilots to file flight plans by computer, do not have access to this information. Also, there are approximately 20 U.S. Flight Service Stations which are not automated and since they only have access to the NOTAM system, they cannot receive the aeronautical information.

The Air Force does not have the option of disseminating GPS RAIM outages as aeronautical information since their distribution system is set up only to handle data which are in a NOTAM format. On the other hand, the military GPS RAIM reporting requirements are less stringent than the civilian, both in terms of the number of airfields in their database and the minimum outage duration. As a result, military outages can be accommodated by the U.S. NOTAM system. The FAA currently is in the process of upgrading its NOTAM system and is attempting to address concerns over GPS aeronautical information.

Australia has faced a different set of problems over this same issue. Although the Australian NOTAM system can physically accommodate the GPS outages, their Air Traffic Services (ATS) have received many complaints from pilots who felt that there are too many NOTAMs on the system and that they were given NOTAMs which were irrelevant to their flight plans. Since it is the goal of ATS to reduce the number NOTAMs on the system, they have decided to implement a GPS Aeronautical Information System similar to the FAA.

Standardization of Integrity Algorithms

Since the TSO only specifies the baseline criteria that the GPS receiver must satisfy to be certified, the receiver may actually perform better than the specification. For example, the TSO allows use of a reduced mask angle if all other performance criteria are met. Therefore, the RAIM algorithm in the receiver may have a higher availability than TSO C129 criteria. The FAA and Air Force have decided to base GPS outage predictions on the more conservative TSO C129 criteria for pre-flight planning.

Figure 3 contains a map of the GPS NPA RAIM coverage over Australia and New Zealand based on TSO C129 criteria with the specified 7.5° mask angle. The RAIM availability in this figure was computed with one degree spacing of latitude and longitude at five minute intervals over a 24 hour period. As shown in this figure, southern Australia can experience outages lasting up to 50 minutes per day. With the mask angle lowered to 5°, as shown in Figure 4, outages are reduced to a maximum of 20 min. The number of outages and their duration naturally will increase if less than the full constellation of satellites are available. As demonstrated in these figures, however, there can be quite a discrepancy regarding from what is reported and what is observed if the mask angle of the prediction program and the GPS receiver do not agree.

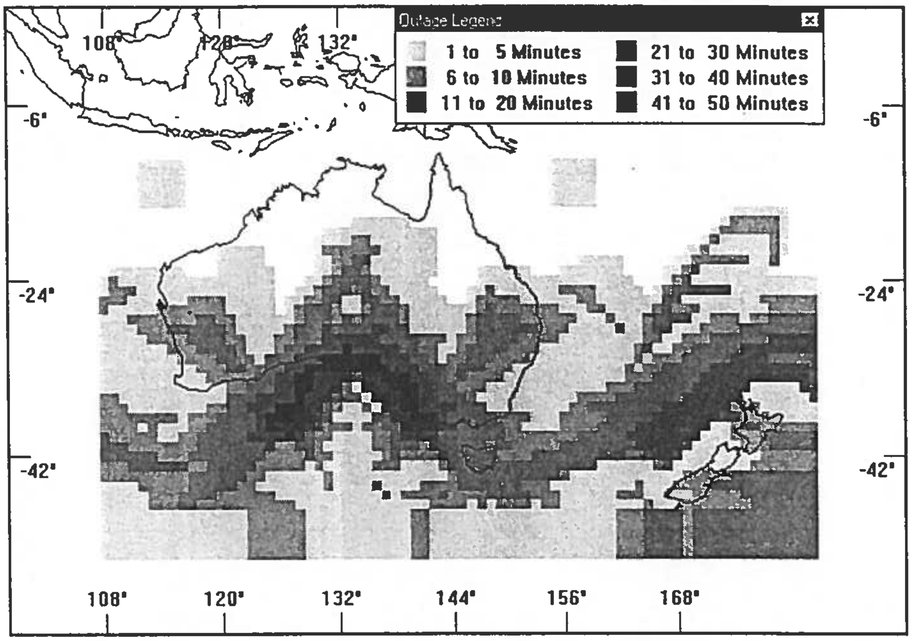


Figure 3 GPS NPA Availability with a 7.5° Mask Angle

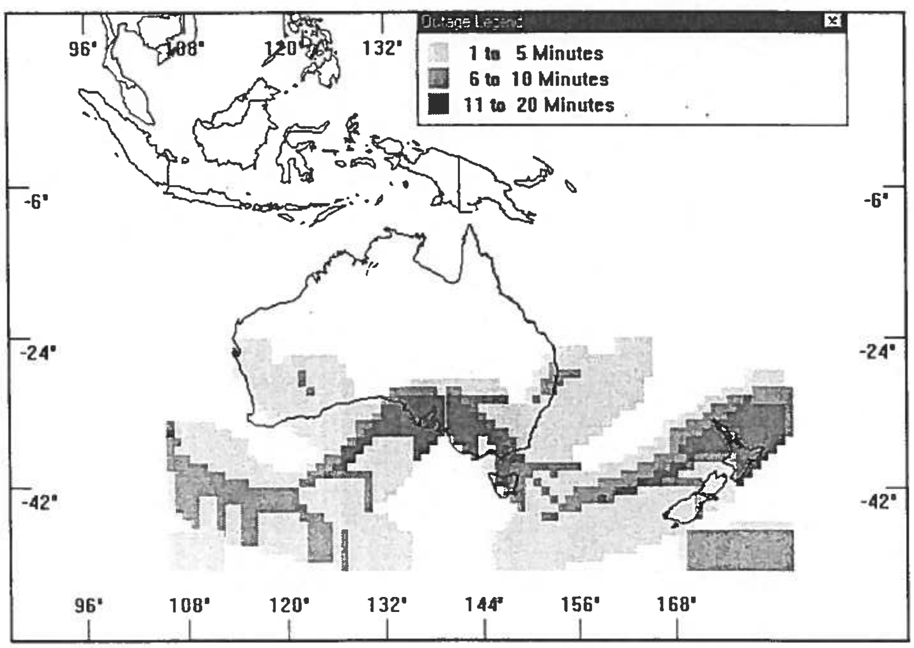


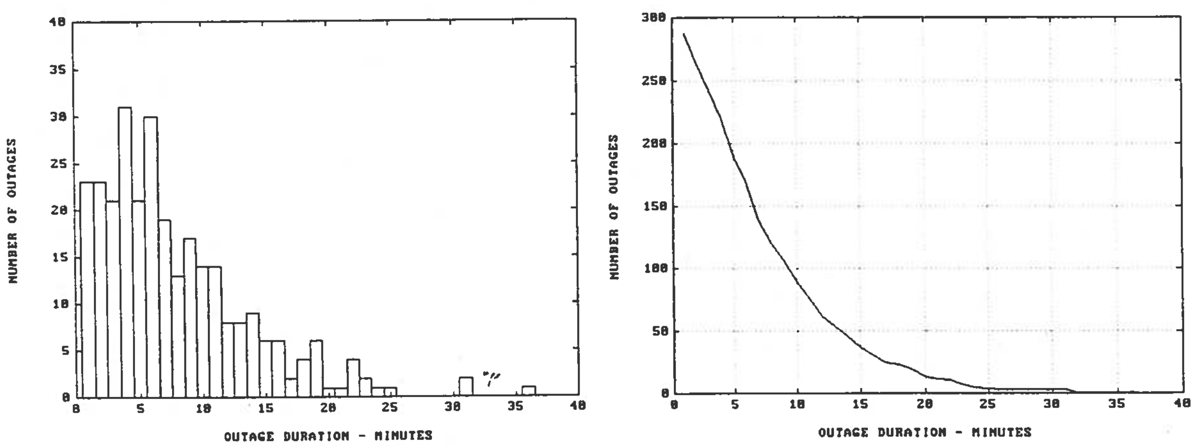
Figure 4 GPS NPA Availability with a 5° Mask Angle

Reportable Outage Duration

Another issue which needs to be considered in implementing an outage reporting system is the minimum outage duration to report to the pilot. As previously discussed, the FAA decided to report all outages lasting longer than five minutes. Other countries seem to be following this approach.

However, the choice of this criteria has a significant impact on the number of outages which are reported. To demonstrate this impact, an analysis was performed for a database of Australian airfields having an instrument approach (197 in total). The data was sampled at one minute intervals over a 24 hour period. An outage was declared if there were fewer than five visible satellites or the horizontal protection level exceeded the NPA horizontal alert limit of 0.3 nautical miles.

Figure 5a displays a histogram of the number of GPS RAIM outages vs. the outage duration with all 24 satellites operational. This figure demonstrates that outages can last up to 36 minutes at a location. A cumulative distribution of the outages vs. time is given in Figure 5b. For a database of 197 airfields and all 24 satellites operational, there are 190 outages lasting 5 minutes or longer, 37 outages lasting 15 minutes or longer, and 13 outages lasting 20 minutes or longer. Figure 5b provides insight into the number of NOTAMs that would be issued over a 24 hour period, depending on the time at which the outage duration threshold is set.



a b

Figure 5 Histogram of Outages and Cumulative Distribution - 24 GPS SVs

Pilot & Air Traffic Training/Education

The FAA aeronautical information system operates by AFSS briefers furnishing GPS availability for an NPA at a destination airfield to a pilot upon request. The FAA has been attempting to make it clear to pilots that they must specifically ask for this information or they will not receive it. It has been difficult to make this process widely known since GPS already had been approved for NPA before the aeronautical information system became operational. As a result, many pilots have been flying NPAs without requesting GPS

RAIM availability during flight planning. Also, since AFSS briefers receive so few requests for this information, many have forgotten the procedures to access it.

As will be discussed further in the next section, this task will only become more difficult in the future as the world transitions to RNP, an airspace requirement that is independent of the aircraft navigation equipment. There will be many options for satisfying the RNP criteria for a particular phase of flight, ranging from an aircraft-based augmentation system (ABAS) using the RAIM/FDE algorithms in existence today with GPS, perhaps augmented by GLONASS or geostationary satellites, and/or combined with an inertial navigation system (INS), to satellite and ground-based augmentation systems, which also will have various levels of augmentation.

As a result, it will be very difficult for the air traffic controller to know of any system outages and their impact on the airspace system. It also will be very important for the pilot to understand the navigation equipment in his aircraft and its level of performance.

FUTURE GNSS OUTAGE REPORTING

As the use of GPS transitions from a supplemental air navigation system to a primary means system and encompasses GNSS, outage reporting of these systems must evolve as well. For use of GPS as a supplemental system, outage reporting has focused on the nonprecision approach phase of flight since that is the most critical and most likely to experience outages.

Accommodating Additional Phases of Flight

Predicting en route GPS RAIM outages is more difficult than for a nonprecision approach. Although an outage of significant duration may exist at a location, an aircraft could fly across this area and experience only a fraction of the outage. A graphical representation of the aircraft along the route flying at a typical airspeed might be a more appropriate method of predicting en route coverage. An example of this capability is shown in Figure 6, which displays the phase of flight that GPS RAIM can support over a route from Perth to Canberra. This capability would be useful for a country, such as Australia, which already has implemented a domestic en route primary means system predicated on GPS.

This type of a prediction capability also is required for primary means oceanic. Currently, receivers manufacturers who sell equipment for primary means oceanic navigation are providing prediction software along with their receivers which allow input of a satellite outage from the US NOTAM system or the USCG navigation information service.

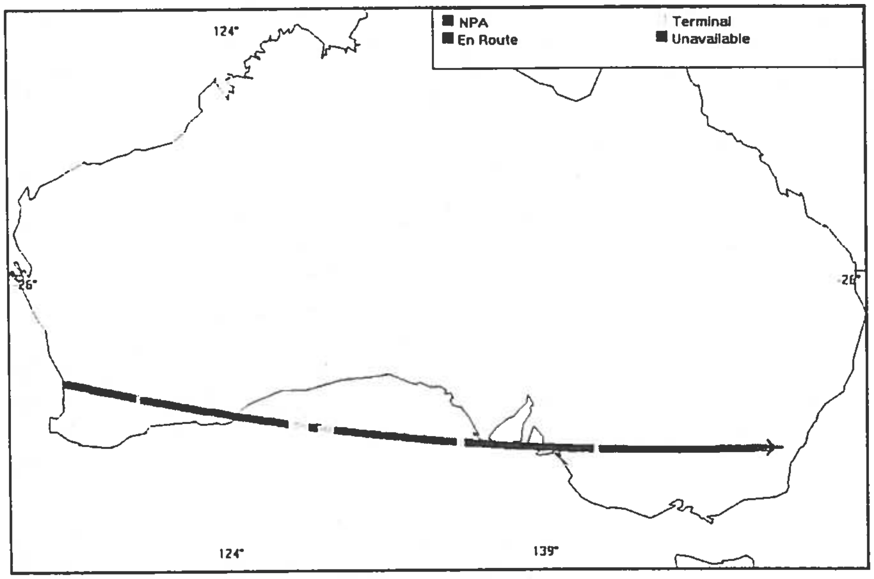


Figure 6 Flight Plan Specific GPS RAIM Coverage

Augmentation Systems

Outage reporting for satellite-based augmentation systems requires a more complicated coverage model which needs to incorporate not only the geometry of the GPS satellites, but geostationary and GLONASS satellites, as well as the number and placement of the reference stations, and effects of the ionosphere. Since the ionosphere is very difficult to predict in advance, SBAS outage predictions may be based mainly on satellite geometry characteristics and the network architecture. Such a prediction would satisfy operations through nonprecision approach, but without an accurate estimate of ionospheric conditions it would be difficult to determine the availability of a Category I precision approach.

In addition, it is important to have interoperability between the SBAS systems for standardized outage reporting; the three planned systems: WAAS, EGNOS, MSAS and any other systems which may be developed. As mentioned previously, aircraft using these systems may have different levels of augmentation, such as the use of an INS, adding another dimension to the availability determination.

Outage reporting for ground-based augmentation systems used for Category I/II/III precision approach will be need to be specific to each airfield since the system availability is a function of satellite geometry, pseudolites, and the number of ground reference receivers. This information could be disseminated through a NOTAM, but again there is the potential for discrepancy between the NOTAM and the aircraft navigation system availability if the aircraft has additional augmentation systems on board.

SUMMARY/CONCLUSIONS

Disseminating GPS NOTAMs for nonprecision approaches is an important step in meeting the flight planning needs of pilots using GPS. Hopefully additional phases of flight can be accommodated in the future. Since GNSS is an area navigation system, the best method of providing GNSS outage information may be a graphics display, similar to that used to convey weather information.

However, outage reporting in the future with GNSS-based systems will be much different than in the past, where there were standard navigation systems used for each phase of flight, and it was clear whether or not they were operating and available for use. There will be many GNSS aircraft-specific navigation system options for satisfying the RNP criteria for a particular phase of flight, including aircraft, space, and ground-based augmentation systems with different levels of augmentation in each category.

The method of outage notification for these systems raises many questions. For example, should availability determination be relegated to the airlines' dispatch services since they will know the navigation system equipage of each aircraft, with only satellite outages provided as NOTAMs to be used as inputs to prediction programs? If so, then how will general aviation be notified of outages? Will air traffic control be aware of potential GNSS outage areas and the fact that some aircraft may be affected while others won't? These issues are very complicated and will need to be resolved by international authorities before GNSS-based systems are certified for primary means use.

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