GPS Availability for Aviation Applications: How Good Does it Need to Be?

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BIOGRAPHIES

Ian Mallett is head of Aerodrome and CNS/ATM Standards in the Civil Aviation Authority Australia. His projects have included the introduction of the Australian domestic primary means GPS approval and the use of GPS for nonprecision approaches. He has been on the ICAO RGCSP and the GNSS Panel since its inception in 1994 and was rapporteur of Working Group A on Operations. Ian joined the Royal Australian Air Forces as a pilot and flying instructor and has flown over 10,000 hours in a range of aircraft including the C130 Hercules and the Boeing 707 tanker. He is a graduate of the Canadian Forces Staff College.

Karen Van Dyke is a member of the technical staff of the Center for Navigation at the DOT/Volpe Center. Karen has conducted availability and integrity studies of GPS for all phases of flight including precision approach in support of RTCA SC-159. She served as the project lead for a Volpe Center team that designed, developed, and implemented a GPS outage reporting system for the U.S. Air Force and the FAA. This capability has been extended to Australia, Germany, and Chile to provide pilots with the status of GPS during pre-flight planning, as well as to Air Traffic Control. She received her BS and MS degrees in Electrical Engineering from the University of Massachusetts at Lowell. Ms. Van Dyke currently serves as the President of the Institute of Navigation.

ABSTRACT

The availability of GPS for airborne applications is driven by the accuracy, integrity, and continuity of the system. The International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPS) for GNSS spells out all of these requirements for each phase of flight. Continuity and availability requirements are provided as a range of values instead of one specific number. A range of values is given so there is flexibility for the intended operation, traffic density, complexity of airspace, and availability of alternative navigation aids.

Based on the requirements in the SARPS, availability for GNSS aviation applications is specified to range from 99% to 99.999%. For domestic U.S. airspace, the FAA has established a requirement of 99.999%. However, it is very difficult to satisfy this requirement without considerable augmentation. Also, what does this level of availability mean from an operational perspective since the associated outage duration is equivalent to a total of 5 min. of outage time per year? Are availability requirements for GPS being set more stringent than existing requirements for aviation navaids?

Individual countries need to determine what is acceptable for their airspace and this paper examines how this analysis is performed. In Australia, for example, general aviation pilots currently are allowed to fly with a single Automatic Direction Finder (ADF). Obviously, GPS can perform much better than this.

Other issues that are addressed in the paper include how the differences in performance requirements affect receiver design. If most of the GPS aviation receivers are manufactured in the U.S. under FAA specifications, what impact does this have on other countries who want to adopt FAA certification, but do not have requirements which are as stringent as the U.S.? Also, differences in requirements for high-end air transport vs. general aviation operations are examined.

Finally, the transition from supplemental use of GPS under TSO C129 to primary means with TSO C145/146 equipment and the benefits of gaining operational experience vs. satisfying stringent requirements are discussed.

BACKGROUND

It is interesting to think back to how our existing air navigation systems were approved. Most of them were based on operational judgment, not through analysis by international committees. It raises the question of whether the use of an ADF ever would be approved today.

In fact it is very difficult to determine what the availability requirements are for the current navaids. According to the 1999 U.S. Federal Radionavigation Plan (FRP) [1], a nondirectional beacon (NDB) is specified to provide 99% availability. VOR/DME is quoted as providing an availability which approaches 100%. However, this statement assumes that there is coverage from overlapping stations for en route navigation so it does not apply to NPA which is using one station. (Most likely the availability for a VOR NPA is on the order of 99%).

A single ADF or VOR fit currently is approved for instrument flight rule (IFR) operations and meets the ICAO classification of operations and airspace model requirements [2]. The question is does GPS provide an equivalent level of service? The obvious answer appears to be "yes", especially given that the accuracy of GPS has improved dramatically this year with the removal of Selective Availability (SA). For non-differential applications of GPS for en route through nonprecision approach operations, there is a direct correlation between an improvement in accuracy and an improvement in availability. This concept will be elaborated on further in the paper.

However, in determining whether GPS is capable of replacing current navaids, we must consider the performance of GPS with respect to the international requirements that have been set forth by ICAO.

GNSS SARPS REQUIREMENTS

The ICAO Global Navigation Satellite System (GNSS) Panel recently completed the SARPS for use of GNSS for oceanic through Category I precision approach operations [3]. Table 1 provides the GNSS performance requirements from the SARPS for en route through nonprecision approach navigation which will be the focus of this paper. Note that both the continuity and availability requirements are given as a range of values with orders of magnitude difference between the low end values and the more stringent high end ones. In this paper we primarily concentrate on the availability requirement.

What do these numbers mean operationally? In order to place them in perspective, we have converted the availability requirement into the total allowable outage duration per day which would result. The minimum requirement is an availability of 99% which results in a total of 14.4 min. of outages per day. The most stringent requirement of 5 9's (99.999%) is only 5 min. of total outage time per year or 0.822 sec. per day (the latter number becomes meaningless since the outages would not be distributed this way).

The high end requirements for GNSS appear to be very stringent in comparison with the navaids in operation today. Also, take into consideration that there are some countries who can not maintain high availability due to vandalism of their ground-based navaids and would greatly welcome a system that was operational even 99% of the time. The required availability depends on the particular airspace and perhaps navaids will need to provide higher availability in the future as the amount and density of air traffic increases. Individual countries need to determine what is acceptable for their airspace, however no guidance is provided in the GNSS SARPS with respect to how to select which value to use.

Table 1 GNSS SARPS Performance Requirements

Phase of Flight	Accuracy	Horiz. Alert Limit	Integrity	Continuity	Availability
En Route	0.4 NM	2.0 NM	$1\text{-}10^{-7}$/hr	$1\text{-}10^{-4}$/hr - $1\text{-}10^{-8}$/hr	99% - 99.999%
Terminal	0.4 NM	1.0 NM	$1\text{-}10^{-7}$/hr	$1\text{-}10^{-4}$/hr - $1\text{-}10^{-8}$/hr	99% - 99.999%
NPA	220 m	0.3 NM	$1\text{-}10^{-7}$/hr	$1\text{-}10^{-4}$/hr - $1\text{-}10^{-8}$/hr	99% - 99.999%

HOW CAN THE GNSS SARPS REQUIREMENTS BE MET?

In this section we examine the ability of GPS and its augmentations to satisfy the requirements set forth in Table 1. Meeting the basic accuracy requirements is not a problem for GPS. However, achieving the integrity requirements with high availability can be a challenge. Table 2 outlines various GNSS options for meeting the availability requirement. These options range from standalone use of GPS which relies on Receiver Autonomous Integrity Monitoring (RAIM) and Fault Detection and Exclusion (FDE) algorithms for integrity monitoring, perhaps augmented by additional ranging signals from geostationary satellites or from the European Galileo system when it becomes operational. Other options are to take advantage of other navigation systems in conjunction with GPS such as an inertial navigation system (INS) or to use GNSS augmentation systems such as the satellite-based augmentation system (SBAS) or ground-based regional augmentation systems (GRAS).

Table 2 GNSS Options for Satisfying Aviation Availability Requirements

GNSS Options
Standalone GPS - Current System (No SA) - Modernized GPS
GPS/Ranging Geo SVs
GPS/Galileo
GPS/INS
SBAS
GRAS

The availability of RAIM and FDE for the Optimized 24 GPS constellation is provided in Table 3 for en route, terminal, and nonprecision approach phases of flight. A User Equivalent Range Error (UERE) of 6.6 m was assumed for the pseudorange error with SA removed which results in a horizontal position error of 19.8m 95% of the time, assuming an HDOP of 1.5. This estimate may be on the conservative side based on the observed performance of GPS since SA was removed, but the update to the GPS Signal Specification is not expected to be released until the end of 2000.

Barometric altimeter aiding also was incorporated in this analysis and a mask angle of 5 degrees was applied. RAIM requires a minimum of five visible satellites with sufficient geometry in order to detect an anomaly and is used for supplemental navigation, while FDE for primary means navigation requires a minimum of six visible satellites in order to detect and exclude an anomaly.

A horizontal protection level (HPL) is computed and compared to the horizontal alert limit (HAL) shown in Table 1. Availability is the percentage of time that the HPL is lower than the HAL. Availability was sampled over a worldwide grid of latitude/longitude points every 5 degrees. The grid was sampled every 5 min. in time. Note that based on this sample time in this analysis, the min. duration for an outage is 5 min.

Table 3 GPS Availability With 24 SV Constellation

Phase of Flight	RAIM/ FDE Availability	Max. Outage Duration
En Route	99.999% / 99.959%	5 Min. / 20 Min.
Terminal	99.999% / 99.907%	5 Min. / 25 Min.
NPA	99.999% / 99.823%	5 Min. / 30 Min.

Table 3 demonstrates that a 24 satellite GPS constellation already satisfies a 5 9's availability of fault detection for en route through nonprecision approach and greater than 3 9's of availability for FDE for en route and terminal navigation with a 99.8% availability for NPA.

Unfortunately most GPS receivers certified under TSO C129 have the pseudorange error of 33.3m for the SA-on condition hard coded into them because the RTCA Minimum Operational Performance Standards (MOPS) DO-208 for supplemental use of GPS was developed long before the 1996 Presidential Decision Directive was released stating that SA would be turned off. However, the RTCA SC-159 WAAS MOPS (DO-229B), which also includes specifications for the RAIM and FDE algorithms, do include test procedures for the SA-off condition. TSO C145/146 will reference DO-229. It remains to be seen whether there will be an update to TSO C129 equipment to take advantage of the removal of SA.

As previously mentioned, there is a direct correlation between improvements in accuracy and improvements in availability. This is demonstrated by the results in Table 4, comparing the availability of FDE with SA on and after it is removed using the August 2000 constellation of 27 operational satellites. FDE availability is greatly improved and the maximum outage duration significantly reduced with Selective Availability turned off, especially for nonprecision approach operations where the maximum outage duration decreases from two hours to a maximum duration of 35 min.

Note that the availability numbers in Table 3 are based on an Optimal 24 satellite constellation, while the 27 satellites that are operational today have been rephased over time. Also, the extra three satellites (beyond the nominal 24) are positioned close to satellites expected to fail soon. This is the reason that the coverage is slightly worse for NPA with the current constellation even though there are more satellites in orbit.

Table 4 FDE Availability with August 2000 Constellation (27 SVs)

Phase of Flight	SA On / Max. Outage Duration	SA Off / Max. Outage Duration
En Route	99.806% / 30 Min.	99.977% / 20 Min.
Terminal	99.230% / 55 Min.	99.948% / 25 Min.
NPA	89.468% / 120 Min.	99.762% / 35 Min.

Figures 1 and 2 graphically demonstrate this improvement in availability by providing a composite of FDE coverage for NPA operations over a 24 hour period with SA on and off respectively, displaying the maximum outage duration at each location. The availability for terminal area and en route navigation are shown in Figures 3 and 4 which demonstrate the additional availability that can be achieved at higher alert limits.

Since FDE is a conditional probability, that is the receiver doesn't exclude a fault until one is detected, there is a proposal to relax the FDE requirements for NPA. The proposal is to allow nonprecision approaches when FDE is unavailable as long as RAIM is available for the approach and FDE is available for terminal area navigation [4]. If an outage were detected during an NPA, the aircraft then could revert to the terminal area and remain there for the duration of the FDE outage or divert to another airfield that is unaffected by the outage or which has a non-GPS navaid.

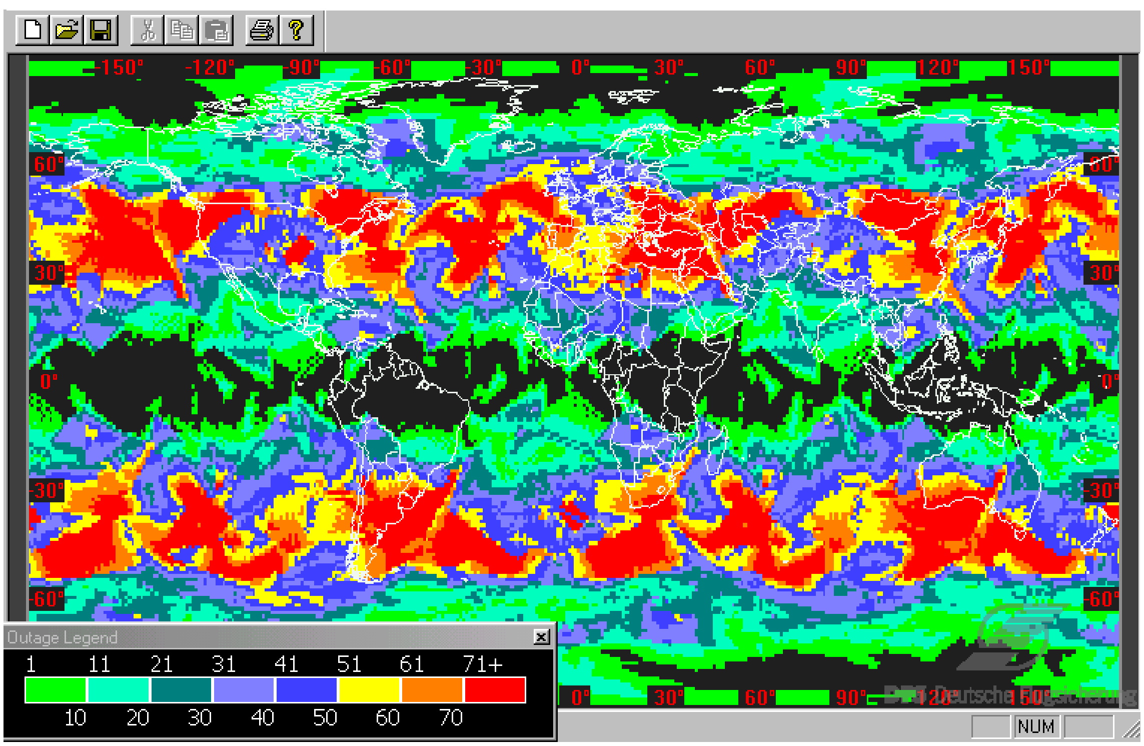

Figure 1 Worldwide GPS NPA FDE Coverage August 2000 (Assumes SA On)

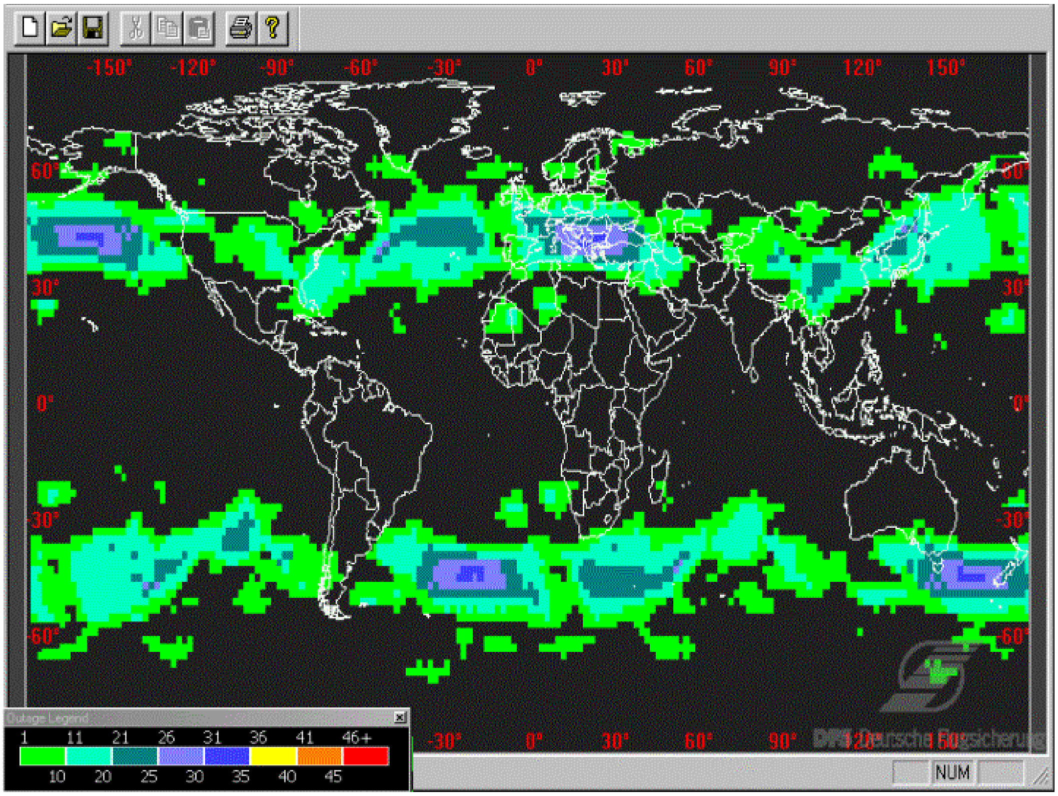

Figure 2 Worldwide GPS NPA FDE Coverage August 2000 (SA Off)

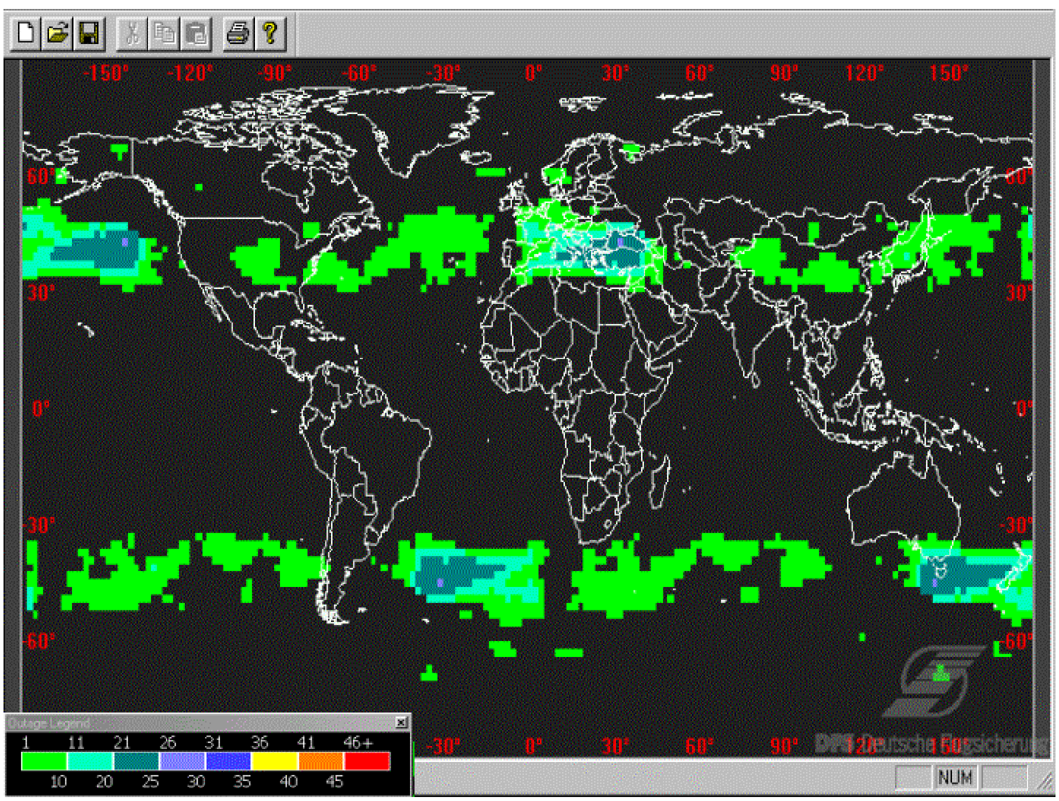

Figure 3 Worldwide GPS Terminal Area FDE Coverage August 2000 (SA Off)

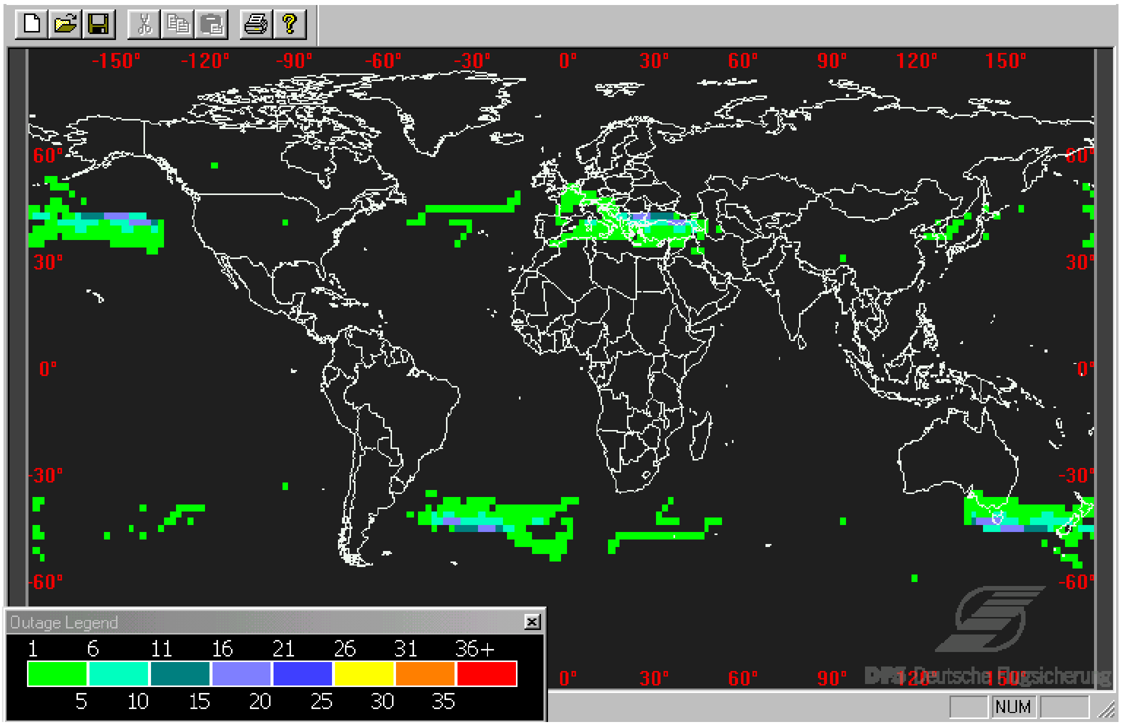

Figure 4 Worldwide GPS En Route FDE Coverage August 2000 (SA Off)

Geostationary satellites used to support SBAS operations also will provide a GPS ranging signal. These signals can be used to augment RAIM and FDE availability. Table 5 presents the results of an availability analysis performed over the CONUS using the three geostationary satellites visible over the U.S. (AOR-E, AOR-W, and POR). The results demonstrate that RAIM is available 100% of the time and the availability of FDE has increased by a '9' for all phases of flight.

Table 5 GPS Availability with 3 Geos (Ranging)

Phase of Flight	RAIM/ FDE Availability	Max. Outage Duration
En Route	100% / 99.998%	0 Min. / 5 Min.
Terminal	100% / 99.996%	0 Min. / 5 Min.
NPA	100% / 99.976%	0 Min. / 20 Min.

GPS availability also was examined for a thirty satellite GPS constellation [5]. The results, shown in Table 6, demonstrate that GPS could even satisfy 5 9's of FDE availability for en route through NPA. Although we may never have 30 GPS satellites, there are implications for the type of service a receiver using both the GPS and Galileo constellations may achieve.

Since Galileo is expected to become operational in the 2008 time frame, the potential capability of these two systems should be considered. Two constellations, each consisting of 24 or more satellites, would allow satellites to be taken out of service for routine maintenance without impacting availability.

Table 6 GPS Availability With 30 SV Constellation

Phase of Flight	RAIM/ FDE Availability	Max. Outage Duration
En Route	100% / 100%	No Outages
Terminal	100% / 100%	No Outages
NPA	100% / 99.999%	0 Min. / 5 Min.

RAIM and FDE are designed to complement SBAS and GRAS systems outside of their service areas. However, depending on how stringent the availability requirements become, these augmentation systems also may want to take advantage of the availability provided by RAIM and FDE in satisfying the higher level requirement.

OBSERVATIONS

As discussed in the previous section, GPS today exceeds the performance of most existing navaids, therefore the requirements for GPS appear to be set too tight. However, as the airspace becomes more congested, availability requirements may need to become more stringent. The question is do we need to meet those requirements now or can we transition toward them over time as necessary?

We have shown that additional satellites greatly benefit availability and the constellation will become robust to satellites taken out of service for routine maintenance. These additional satellites may become available through the European Galileo system, ranging signals on geostationary satellites used to support SBAS operations or perhaps additional GPS satellites in the constellation.

Also, it would appear that requirements on augmentation systems perhaps could be relaxed for en route through NPA operations, taking advantage of the high availability of RAIM and FDE to satisfy the overall availability requirement.

Finally, with the accuracy improvements expected through the GPS modernization effort and the high accuracy expected from Galileo (horizontal and vertical positioning errors sub 3 meters 95%), the next logical step in this analysis would be to examine the ability of unaugmented GPS to meet approach with vertical guidance (APV) requirements.

ISSUES

The selection of availability requirements for GNSS is crucial for implementation decisions to be made by aviation authorities around the world. The ICAO GNSS SARPS do provide guidance on the values to be used, but currently offer little advice on how a state should select values within the range provided. This selection will determine what level of augmentation (if any) to GNSS is needed. In addition, the SARPS were constructed to allow GNSS to provide a sole means service. If it is determined that a backup system is required due to GNSS interference concerns, then can availability requirements for GNSS and its augmentations be relaxed? This paper most likely raises more questions than it answers.

The ICAO Classification of Operations allows a distinction in requirements between commercial air transport, aerial work, and general aviation operations [2].
These classifications are already used to define the navigation capability and equipment carriage requirements. There is already, for example, considerable differences between air transport and general aviation navigation carriage requirements.

The range of GNSS options will only serve to add complexity to these differences. Large transport aircraft fitted with such systems as the FANS package already meet the enroute through NPA requirements for most operations so, paradoxically, the ability to provide the GNSS answer for general aviation at a reasonable cost may govern the rate of transition to a full GNSS based architecture and the timescale for the removal of ground-based aids.

Early certified GPS aviation receivers (TSO C129) were not designed to provide a sole means of navigation, yet many of these receivers are being widely fitted, especially for general aviation aircraft. Even with the improved level of service of GPS with the planned revised to the Signal Specification, the need to have the improved RAIM capabilities and FDE, as provided by the TSO C145 receivers and probably dedicated prediction services would appear necessary for GPS-based operations.

Achieving user acceptance of any updated GPS requirements will require incentives such as the ability to remove existing equipment such as the ADFs , VORs and DMEs.

As is currently the case with inertial navigation based approvals, the limiting factor in the approval may not be the navigation capability of the equipment, but rather its mean time between failure (MTBF). There has been little published material on this issue and that which is available appears to have some rather conflicting results. Can the industry demonstrate that the TSO C129/145 receivers have at least the MTBF values of the ADF that is now approved as the only IFR navigation aid for some operations?

There also are operational issues to contend with such as provision of outage prediction and Notice to Airmen (NOTAM) systems plus the institutional and legal questions which arise from using these systems.

CONCLUSIONS

In conclusion, it appears that GPS may already be able to provide a level of service that is acceptable for some areas of the world. Application of the ICAO SARPS requirements may even be excessive for some airspace needs. Also, there is a need to review the need for a backup system to GNSS. If a backup system is required, perhaps availability requirements for GNSS could be relaxed.

Institutional issues, such as the determination of navigation parameters to be used, the receiver acceptability and supporting RAIM/FDE prediction capabilities and NOTAM systems, rather than the quality of the GPS signal in space, would now appear as the main areas to be addressed.

The ability to provide a satisfactory GPS solution for general aviation appears to be a limiting factor for transition to GPS-based operations. Hopefully certified aviation equipment that provides increased availability with SA off will become available soon in order to take advantage of the increase in availability. This, combined with some realistic determination of the operational navigational requirements may well allow GPS to provide the navigation solution for general aviation. The world is waiting!

REFERENCES

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[5] Kelley, C.W., “Transition to a 30 Satellite GPS Constellation”, Proceedings of the Institute of Navigation National Technical Meeting Jan. 1998.