The Suitability of GPS for Basic Area Navigation

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BIOGRAPHY

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Dignus-Jan Moelker received his M.Sc. in Electrical Engineering from Delft University in 1993, where he is currently working towards a Ph.D. degree. His current research interests are GNSS interference modelling and joint-domain techniques for GNSS interference and multipath mitigation.

Eric Theunissen has a M.Sc. in both Aerospace and Electrical Engineering and a Ph.D. for his research into advanced navigation displays. His current research takes place in the context of DELPHINS II, a program sponsored by the Dutch Technology Foundation STW, that studies integration of perspective flightpath displays into the flightdeck.

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Durk van Willigen heads a group that specialises in navigation performance of integrated navigation systems, such as MIAS (GPS and MLS) and Eurofix (GPS and Loran-C). This group is involved in radio-navigation systems simulation, both theoretically and experimentally in the International Research Centre for Simulation, Motion and Navigation (SIMONA).

Roland Rawlings is head of the navigation section in EUROCONTROL. He is responsible for ensuring that the future airspace concepts developed within the European ATC Harmonisation and Integration Programme (EATCHIP) are complemented by the necessary navigation developments. After graduating in Physics from London University, he worked for the Royal Aircraft Establishment in the UK where he was responsible for Navigation and Flight Management System research.

Mike Perry, a consultant in the navigation section in EUROCONTROL, is involved in the determination of quality of service of navigation systems and evaluation of RNAV route spacing in ECAC airspace. After graduating in Mathematics from Cambridge University he worked for Decca Navigator on the design and analysis of integrated navigation and flight management systems and was responsible for the satellite segment of integrated satellite positioning systems. He has also been involved in GPS digital receiver analysis and GPS/AFCS integration.

ABSTRACT

On behalf of EUROCONTROL, Delft University has investigated the technical suitability of GPS as a means of flying Basic Area Navigation Routes planned to be introduced in the ECAC area from 1998. Some operational aspects of GPS operation have been covered as well. In this area the work complemented other studies being carried out by EUROCONTROL, including RAIM availability determination [Hein97] and flight deck simulator studies of failure reversion. All studies together have provided the data required for a full safety analysis of the application of GPS. This paper provides a short overview of the most important findings of the study into the technical and operational suitability of GPS. The full report is available on the web; please check page http://wwwtvs.et.tudelft.nl/nav.htm for details.

1. INTRODUCTION

With effect from 29 January 1998 the first stage of the introduction of area navigation in the ECAC airspace will mandate the carriage of Basic Area Navigation (B-RNAV) equipment on the entire Air Traffic Service (ATS) route network. This will permit route structure changes to be in place allowing significant increases in airspace capacity. The requirements will be complemented by enabling RNAV application in the Terminal Airspace. This way, experience can be gained in the performance of RNAV in the terminal area and operational gains can be derived. Subject to full cost benefit analysis, the navigation programme is expected to develop towards requiring Area Navigation to be applied in all phases of flight and ultimately from Gate to Gate. Such further developments are not expected to be introduced before 2005 when it would be possible to consider removal of some elements of the ground navigation infrastructure such as VOR. If this does happen, area navigation equipment will need increased integrity and provide greater continuity of service than is available today, since manual reversion to non-RNAV operation will no longer be possible.

Minimum Aviation Systems Performance Specifications (MASPS) for RNAV systems capable of meeting the requirements for "sole means" operation have been developed jointly between US and European organisations [RNAV MASPS]. Equipment meeting such standards have been termed RNP(x)-RNAV. In time, the term B-RNAV will thus be replaced by RNP-5 RNAV. The requirements for both standards are listed in Table 1.

Surveys undertaken in 1996 indicated that 80% of the air transport fleet were equipped with conventional multisensor RNAV. A further proportion of the fleet (about 10%) were expected to be equipped by 1998. However, a small but significant proportion of aircraft will not be able to meet the timescale, comprising mainly General Aviation (GA) and older aircraft. For these aircraft the cost of ownership of such a multisensor RNAV is high compared with the value of the aircraft. Often, particularly in the case of GA aircraft, panel space restrictions even prevent installation of conventional multisensor RNAV in accordance with the JAA requirements [TGL-2].
GPS-based systems are seen as an alternative means of meeting the 1998 B-RNAV requirements due to their relatively low cost and their availability as single unit panel mount equipment. The availability of suitable systems in sufficient time to allow installation before the mandatory equipage date has also been an important factor in favour of the GPS solution, especially to those operators who have left their equipage decisions to a late stage in the RNAV implementation programme.

Investigating the use of GPS for B-RNAV raises both technical and operational issues. The technical suitability of GPS has to be addressed by analysing the expected accuracy, availability, continuity of service and integrity of the system. Operational aspects of the use of GPS equipment need to include consideration of the Pilot/Navigation System interface and the ability to continue navigating in case of a GPS system failure.

Following the information flow from satellite to pilot, as depicted in figure 1, this paper will highlight the expected performance of GPS-based RNAV and indicate the areas where problems might result. It will address all relevant aspects of GPS, including the signal in space, interference, positioning, integrity monitoring, navigation functionality and the man-machine interface.

2. PREMISES AND ASSUMPTIONS

As a first resource for GPS performance data, the Standard Positioning Service (SPS) signal specification [SPS] has been taken. Where necessary, the performance of SPS is compared with other sources from literature. GPS receivers will be certified according to [TSO-C129], and operate in the en-route mode. Furthermore, they will be required to obey the extra requirements from [TGL-2].

The requirements for B-RNAV have been taken from [003-93]. For those system performance parameters that are not specified in that document for B-RNAV, the requirements from [RNAV MASPS] have been substituted. The Flight Technical Error (FTE) is expected to be at most 2 Nautical Miles (NMi), and is assumed to be independent of the Navigation Sensor Error (NSE), allowing the Total System Error (TSE) to be derived as

$$TSE^2 = FTE^2 + NSE^2$$

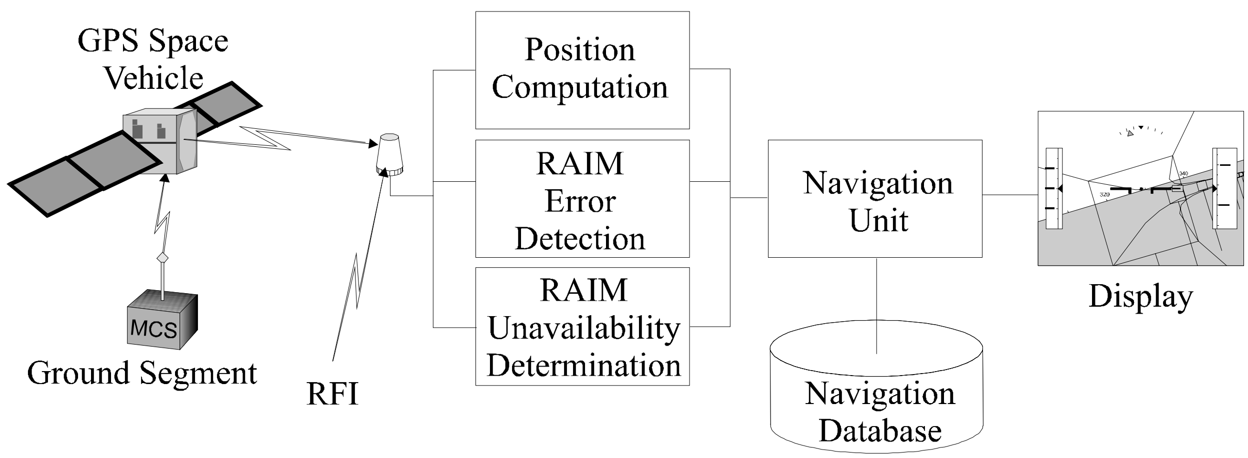

FIGURE 1. ***THE GPS SIGNAL FLOW***

Although this is pessimistic since the FTE has been shown to decrease substantially as the NSE decreases, the accuracy of GPS under normal operations is so much better than the required accuracy, that this will hardly make a difference in the performance evaluations.

3. GPS STANDARD POSITIONING SERVICE

The performance that civil users can expect of GPS is laid down in the Standard Positioning Service signal specification [SPS]. This document describes the signals that are available for civil use, for which the performance parameters are summarised in Table 2. The figures represent the performance that a civilian user is expected to experience, but are not guaranteed by the service provider.

As can be seen, the parameters that are specified are accuracy, reliability, availability and coverage. The requirements for B-RNAV are expressed in terms of accuracy, integrity and continuity of service. [SPS] does not provide any integrity figures, but its reliability parameter is closely related to the continuity of service. [003-93] defines continuity of service as “the portion of the time during which the system is capable of being used for navigation”. On the other hand, [SPS] defines reliability as “the percentage of time that the horizontal system error remains within a specified reliability threshold (500 meter horizontal), given the system availability”. The main difference lies in the conditions: the [SPS] definition conditions ‘reliability’ on the system being available, while [003-93] does not. This means that when the system is not available, this effects the B-RNAV continuity figure, but not SPS’s reliability figure.

4. RADIO FREQUENCY INTERFERENCE

4.1 Occurrence and effects

The reception of GPS is sometimes troubled by Radio Frequency Interference (RFI). A good overview of recorded occurrences has been provided in [RIN96]. RFI may originate from a large variety of sources that emit radio energy in or near to the GPS L1 frequency band, which complicates mitigation at the source.
RFI influences the received pseudoranges. When sufficiently strong, all pseudoranges measurements are lost and position determination by GPS will be impossible. Small levels of interference will slightly degrade the pseudorange accuracy (by at most 150 meters), which is of no relevance to the target accuracy for B-RNAV. This effect is hard to detect and little data on occurrences in the ECAC airspace is available. The published tests with commercial, not TSO-C129 compliant GPS receivers show considerable differences in performance degradation between receivers.

4.2 The TSO-C129 interference requirements

TSO-C129 requires that the performance of a GPS receiver is not affected by the presence of a prescribed level of interference. The interference for this test is of the continuous wave (CW) type because this waveform theoretically leads to worst case results. The required immunity varies with frequency, demanding the least rejection in the L1 band itself, more rejection near to this band and strongest rejection out-band. This so-called susceptibility mask is designed such that GPS receivers on aircraft with on board SATellite COMmunications (SATCOM) equipment will not suffer from its high emission levels.

4.3 Interference holes

Areas where unimpeded reception of GPS signals is impossible, so-called interference holes, are a potential hazard to the users of GPS. These holes are sometimes caused by ground based sources, which often makes the hole geographically fixed. Another possibility is that the source is airborne on the same or on other aircraft.
Examples of potential ground based sources are radio and television broadcast, VHF communications, Mobile Satellite Services (MSS) mobile earth stations, and radar and terrestrial microwave services. Examples of possible airborne sources are VHF transceiver equipment, SATCOM and Distance Measuring Equipment (DME).
At present, geographically fixed GPS interference holes are proven to exist, the size of these holes, however, is not exactly known. The available reports, which show problems all over Europe and particularly in Italy, make clear that TSO-C129 will not provide sufficient RFI immunity in the ECAC airspace. This is of no surprise, as TSO-C129 does not require additional in-band interference mitigation. The International Telecommunication Union allows levels of spurious emissions in the GPS L1 frequency band that are incompatible with GPS. TSO-C129 does however prevent unnecessary loss of signal by near- and out-band RFI. The same is true for airborne sources: in spite of TSO-C129, there still is a potential incompatibility between GPS and some airborne systems, such as DME and VHF transceivers.
Despite the ease with which interference holes can be detected, lack of good data about the performance of TSO-C129 GPS receivers in the European airspace is an indisputable fact. Moreover, not all incidents lead to public domain reports. Nevertheless, if the current situation continues, signal loss due to RFI with TSO-C129 certified receivers will undoubtedly occur.

Signal loss in itself will not lead to false data being provided and the pilot will be able to revert to manual navigation techniques. However, in the situation that the interference level exceeds the maximum tolerable RFI levels in TSO-C129, but is not strong enough to cause loss of signals, TSO-C129 lacks requirements for graceful performance degradation.

4.4 Eliminating interference holes

Apart from obvious solutions, such as requiring additional GPS receiver-based interference suppression on top of TSO-C129 and operational solutions as requiring back-up systems or restricting the use of GPS, several actions can be taken in the short term to reduce the RFI problem. These are discussed below for ground and airborne sources respectively.

4.4.1 Ground based sources

The frequency band containing GPS (L1) is designated for aeronautical radio-navigation on a primary basis. The GPS frequencies have been notified to the International Telecommunication Union (ITU). Consequently, the spectrum should be clear of harmful interference to GPS. The protection of the spectrum is a responsibility of the national administrations. These administrations usually take all practicable steps to ensure sufficient protection, including the avoidance of implementation of incompatible systems.

Despite this policy, European radio communications administrations have usually not been involved in tracking down interference sources. Consequently, systematic methods to track down the source have not been applied widely and counter activities have hardly ever been taken. Additionally, the indivudual state approach hampers European-wide co-ordination.

Therefore, better frequency monitoring and RFI incident reporting combined within a European-wide co-ordinated programme would offer a basis for significant reduction of RFI. Once identified, a source can be eliminated, for instance by employing emission filters or change of frequency.

4.4.2 Sources on aircraft

Sources on aircraft may disrupt the GPS receiver during all phases of flight, including en-route. It is extremely important that the probability of such an event is minimised by installation and testing. Many problems can be mitigated by proper antenna location and, if necessary, emission filters at the source that causes the harmful interference. Note however that even with proper installation, problems may occur later in the system life because of equipment ageing or malfunctioning.

Unfortunately, guidelines that ensure the necessary compatibility between the GPS receiver and the onboard emitters are not yet available.

4.5 Future interference sources

Mobile Satellite Services will use the frequency band from 1610 to 1660.5 MHz for high power transmissions from Mobile Earth Terminals (METs). Although of primary concern to GLONASS, which uses the nominal L1 frequency band from 1602 to 1616 MHz, spurious emissions might also affect GPS L1. This has been realised within the RTCA GNSS interference work group of special committee SC-159, which produced an MSS emission mask in [DO-235] on which it reached consensus with the MSS community. This mask is expected to provide sufficient protection for the GPS L1 band, and when it will be implemented, MSS is most unlikely to cause any significant problem in normal en-route operations.

Note that the receiver interference rejection mask in [DO-235] is approximately equivalent to that in [TSO-C129], which extends the relevance of the latter.

Because of the increasing demand for spectrum, especially for satellite communications, the pressure is growing to reallocate parts of the "aeronautical radio-navigation" spectrum to other services. It needs no argument that this places the long-term application of GPS to aviation at risk.

5. POSITIONING AND RAIM PERFORMANCE

Figure 2 shows how a receiver that is equipped with Receiver Autonomous Integrity Monitoring (RAIM) works. It uses the pseudoranges and constellation information that it receives to compute three types of information:

1. the unknown position
2. the possible presence of position errors (RAIM)
3. the detectability of position errors (RAIM availability)

The algorithms that are used to compute these data are not prescribed, and will therefore depend on the implementation chosen by the receiver manufacturer. Although different algorithms might be used in different receivers, the performance characteristics and limitations of all algorithms are determined by fundamental information theoretical considerations, and are not expected to depend to a great extent on the specific algorithmic implementation involved. We will therefore only use the algorithm of [DO-208] in our analysis.

5.1 Positioning accuracy

The B-RNAV requirements state that the horizontal accuracy should remain within 5 Nautical Miles 95% of the time. When a maximum FTE of 2 NMi is taken into account, assuming that the Navigation Sensor Error

(NSE) is uncorrelated with the FTE, the NSE should be within 4.5 NMi (8321 meters), where [SPS] guarantees a positioning error of 100 meters (both for 95% of the time). We can therefore conclude that GPS will easily meet the accuracy requirements of B-RNAV.

5.2 RAIM Error detection

Apart from a position computation algorithm, the receiver contains an integrity monitor that consists of two parts: an error detector and an error detectability monitor. The latter determines whether sufficient detection power is available to operate safely.

When there are more than four satellites in view, the measurements will never be completely consistent, and the position is computed by using a 'best fit' criterion. In that case, along with the position, a test statistic T can be obtained, that measures the goodness of fit, and thus the consistency of the measurements. A large value of T indicates that at least one measurement deviates substantially from its correct value. Therefore, when T surpasses a certain threshold, an error can be assumed present.

The basic principle of RAIM can best be formulated as a problem of hypothesis testing. We want to test which of the following two hypotheses is true: the 'no position error', or the 'position error' hypothesis:

H_0 *(no position error): position error* $\leq PE_{max}$
H_1 *(no position error): position error* $> PE_{max}$

As can be seen, a position error is defined as an error larger than PE_{max}, the maximum error that is allowed by the requirements. The decision on the presence of an error will be based on the value of the test statistic T by using the following error detection scheme:

$T \leq T_{Threshold} \Rightarrow H_0$ *is accepted*
$T > T_{Threshold} \Rightarrow H_1$ *is accepted*

It can happen that the wrong hypothesis is accepted. The two possible decision errors that can be made are called missed detection (accepting H_0 unjustly) and false detection (accepting H_1 unjustly). The missed and false detection rates determine how well position errors can be detected based on a decision involving T. Therefore, these rates are measures of RAIM performance.

When there is no measurement noise the relation between the test statistic T and the position error is linear. The slope of the linear relation differs for each failure mode and satellite geometry. The situation is sketched in Figure 3, where the noise is symbolised by a 'cloud' around this slope. The harder a certain failure is to detect, the steeper the slope becomes. On the other hand, some failures might have a very shallow slope, and will cause an alarm long before the position error exceeds PE_{max}.

5.3 RAIM tuning

It is up to the manufacturer to tune the error detection algorithm by choice of a certain threshold $T_{Threshold}$. In literature, two methods exist to determine the decision threshold: by fixing the false detection rate (advised in [DO-208]), or by fixing the missed detection rate. These two ways of determining a threshold lead to different receiver behaviour and performance.
Fixing the false detection rate implies making $T_{Threshold}$ as low as the continuity of service specification allows. On the other hand, fixing the missed detection rate makes $T_{Threshold}$ as high as the missed detection rate allows.
When the satellite geometry provides better performance than the minimum required level, receiver manufacturers have the choice to exploit this to improve either the missed detection rate, or the false detection rate. Of course, they could also balance the benefits by choosing a threshold somewhere in between the extremes that are obtained using the two discussed criteria. For our analysis, we assume that a TSO-C129 certified receiver is used with 'worse case tuning': when considering missed detection rates, we will assume tuning according to the fixed missed detection rate criteria, when considering continuity, fixed false detection rate tuning will be assumed.
Receivers will also have to determine if RAIM can be

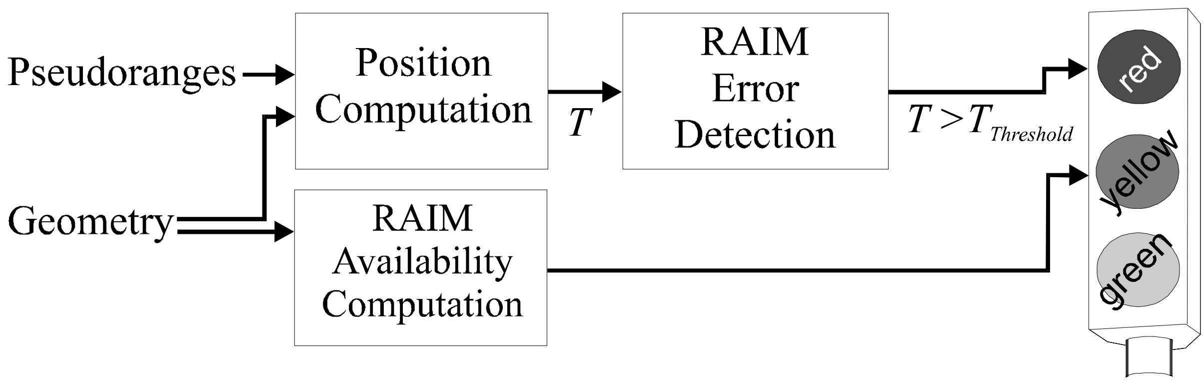

FIGURE 2. ***COMPONENTS OF A RAIM EQUIPPED RECEIVER***

considered available. If the requirements for missed and false detection rates cannot be met simultaneously, RAIM is unavailable. Unfortunately, [TSO-C129] lacks RAIM availability requirements (this has been fixed in the revised TSO-C129A). This allows receiver designers to sacrifice availability in order to meet the requirements on integrity and continuity of service.

5.4 Failure modes

[SPS] states that for the 24 satellite constellation at most three major service failures per year will occur for the whole GPS system. Different, usually higher failure rates are given throughout literature [Durand90], possibly because the SPS considers only 'major' failures. Note that [DO-208], the basis of [TSO-C129], assumes only 1.33 failures a year!

Using the assumption of three failures a year, the failure rate of one single satellite equals $1.4 \cdot 10^{-5}$ per hour. When there are n satellites in view, this means that there is a probability of $n \cdot (1.4 \cdot 10^{-5})$ per hour that a malfunctioning satellite is in view. The probability of having two failing satellites in view simultaneously is $n(n-1) \cdot (2.7 \cdot 10^{-8})$ per hour, and can therefore be neglected considering the [RNAV MASPS] integrity requirement of 10^{-5} missed detections per hour.
It is important to note that other failure modes exist, although the probability of occurrence of these failure modes is hard (if not impossible) to quantify. First, the space segment of GPS contains a single point of failure in the Master Control Segment (MCS). It can never be excluded that the MCS induces large errors in GPS that will remain undetected by RAIM. Furthermore, RFI can cause errors in one or multiple pseudoranges. While this will never lead to large position errors, it can effect system availability and continuity by causing false detections, or by causing the receiver to loose lock on one or multiple satellites. Note that such effects can also occur when banking of the aircraft causes blocking of the line of sight to satellites.
Receiver hard- and software failures are another cause of concern. It has been reported that large amounts of RFI can cause receivers to stop navigating completely. Such events have also been reported to occur under other circumstances, causing the receiver software to enter a loop from which it is unable to exit, or from which exit takes an appreciable time [Asbury94][Sharkey96]. Often, re-initialisation or power down is necessary to recover from such a failure. [Schänzer97] states that after 8 years of experience in flight and vehicle experiments, including about 600 flight hours, the total experienced GPS failure rate has been around 0.01 per hour, which is orders of magnitude worse than the values for single satellite failures only. We can conclude that satellite failures may not be the dominating error source in GPS. Whilst the TSO-C129 equipment standard is intended to provide reliable operation, the tests specified are insufficient to confirm conformance to the standard with a sufficiently high reliability. For a short inventory of the shortcomings

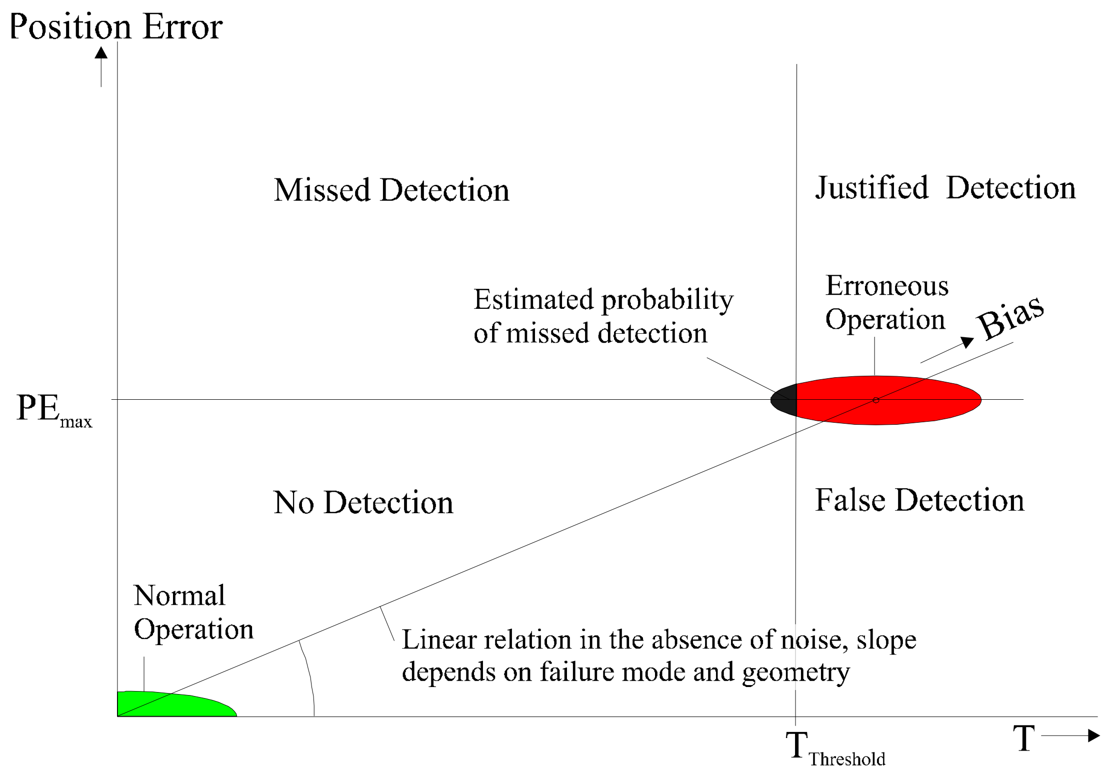

FIGURE 3. ***THE RELATION BETWEEN TEST STATISTIC AND POSITION ERROR***

of the TSO RAIM tests see Appendix A.

5.5 Integrity

Because no existing multisensor RNAV has been certificated against defined integrity standards, such requirements are not defined in [003-93] for B-RNAV. The hazard analysis for B-RNAV has taken due account of the lack of such requirements in its evaluation of RNAV route spacing. However, to provide a target value for the present studies, the GPS system has been compared with the requirements set out in the RNAV MASPS, allowing at most 10^{-5} missed detections per hour. The maximum allowed position error is defined in the MASPS by a containment surface of 10 NMi, that is, twice the 95% accuracy. Assuming that the FTE is independent of position errors, even an FTE as high as 2 NMi still allows a maximum GPS position output error close to 10 NMi.

TSO-C129 receivers are tuned to allow at most $3.8 \cdot 10^{-8}$ missed position error detections per hour, considering single satellite failures only. It defines a position error as any error exceeding 2 NMi. The expected integrity performance of the TSO-C129 receiver is therefore much better than required for B-RNAV, even if satellite failure rates would be considerably higher than assumed in [TSO-C129] or [SPS].

It is hard to predict to what extent other error sources, especially the receiver itself, will contribute to the missed detection rate. All that can be confirmed is that the gap between the requirements and the expected performance based on satellite failures alone leaves significant room to allow for non-perfect receivers. More data of both satellite and overall system errors will have to be collected before the integrity of GPS can be proved beyond reasonable doubt.

5.6 Continuity of service

[003-93] requires that the loss of navigation function for B-RNAV is at most 10^{-4} per flight hour. Continuity of service is affected by both true and false detections: in both cases, the user cannot continue using the system. TSO-C129 receivers are tuned to detect about 99.9% of all occurring satellite failures. This means that almost all satellite failures will be detected and thus affect the continuity of service. We have seen that we can expect a satellite failure rate of $n \cdot (1.4 \cdot 10^{-5})$ per hour when n satellites are in view. Therefore, the continuity requirement for B-RNAV can not be met when more than 7 satellites are used in a position fix.

Moreover, the continuity requirement for TSO-C129 receivers is much less stringent than the one for B-RNAV, $2 \cdot 10^{-3}$ per hour, permitting the TSO-C129 receiver to use a much lower RAIM threshold than would be optimal for B-RNAV, providing higher integrity at the cost of a lower continuity. The user cannot expect to get performance better than this, and reality might even be worse, as the TSO-C129 standard neglects both receiver errors and ‘unusual’ signal errors, for example caused by interference. The B-RNAV continuity of service requirement is therefore not met by GPS and any deficiency will need to be met by the use of manual VOR/DME/ADF operation. For pilots that fly GPS, loss of area navigation capability will surely not remain a ‘once in a lifetime experience’.

6. FROM POSITIONING TO NAVIGATION

Up to this point the paper discussed the quality of the position that GPS provides. Except for a positioning sensor, a B-RNAV capable navigation system will also contain some kind of navigation computer and a database containing waypoints and a flightplan. When aircraft are not equipped with an RNAV capable Flight Management System (FMS), the GPS receiver will have to provide the navigation functionality and contains the database. Hence, we should compare the B-RNAV requirements to the receiver specifications [TSO-C129] on issues related to this navigation capabilities.

Such a comparison reveals that a TSO-C129 certified GPS receiver complies with most - but not all - of the B-RNAV functional requirements. The functions that are not mandated or not fully complied to are:

- Possibility to verify a correctly loaded database
- Ability to provide range, bearing, time and ground speed to any waypoint
- Ability to predict the availability of RAIM for the whole flight

Additionally, whilst the turn performance of a TSO-ed GPS receiver will meet the B-RNAV requirement when operating with an Automatic Flight Control System (AFCS) [DO-208], the basic requirement for operation without AFCS relies on guidelines given in [DO-208] which are just one method shown by the FAA to be capable of working. There is no guarantee that the method adopted by a pilot will enable the required performance to be achieved. However, this limitation is true of all the simpler RNAV systems not feeding an AFCS and this limitation has been taken into account in defining the route spacing criteria.

With the exception of the RAIM prediction function, all the deficiencies above can be overcome by pilot procedures. It is the intention of EUROCONTROL to provide means (probably by the use of the World Wide Web) by which the RAIM prediction can be made available on request.

7. MAN MACHINE INTERFACE

Finally, the data that is provided for navigating will have to be presented to the pilot. In this section, we discuss what can be expected from airborne GPS equipment in respect of data presentation, as well as other relevant Man Machine Interface (MMI) aspects of introducing GPS for B-RNAV.

The data provided by GPS equipment varies from basic position data in an alphanumerical format to moving map graphic displays that can present geographic information, a depiction of the flightplan, and a presentation of cross-track deviation and track angle error. Furthermore, the functionality ranges from a number of basic capabilities to functions comparable to those found in today's flight management systems.

GPS equipment can be integrated in various ways in existing flightdecks. The level of integration determines the way the MMI changes. When GPS is only used as a sensor that provides data to an existing integrated navigation system, the resulting changes in the total MMI may be minor. However, when additional displays and control are integrated into the flightdeck, as is the case with standalone GPS equipment, this may have a more profound impact on the navigation, guidance, and control tasks. The potential reduction in task complexity and the resulting reduction in workload can contribute to safety by reducing certain types of errors. Yet, as has been frequently noticed with the introduction of new technology, other types of errors may be introduced.

Designers and the regulatory authorities use the lessons learned from the past in order to anticipate the potential errors that may occur when introducing GPS for B-RNAV navigation. It is this, inter alia, that led to the original TSO-C129 and experience in the operation of equipment meeting the original standard that led to the subsequent issue of C129A. Many of the issues that are related to the application of GPS based RNAV are common to all RNAV operations. It is therefore necessary to identify potential human errors, caused by the task changes due to the introduction of RNAV. This identification by itself, however, does not provide any information about the likelihood that errors will occur. Such information can be extracted from human factors research data in this area and an analysis of similar or related events that have previously occurred. An analysis of such failure modes was undertaken as part of a Hazard Identification for the safety studies undertaken on the application of GPS for B-RNAV. The identification made use of the output of the present study as part of its analysis.

The tasks influenced by the introduction of GPS equipment are navigation, guidance, and control. Navigation is the determination of the position of the aircraft and the desired course. It comprises the interaction[1] with the GPS equipment to enter waypoints and select the mode that provides the required guidance[2]. The resulting guidance aids the pilot in making the necessary control[3] inputs. In the following sections, the potential for human error is addressed. They contain an analysis of the task dictated information requirements and current certification guidelines for airborne GPS equipment [TSO-C129] [TGL-2] and [N8110.60]. The results have been classified into the categories control, navigation, and interaction, each of which will be briefly discussed. Particular attention will be paid to desirable functionality that has not been laid down in the current requirements.

7.1 Control

The pilot's manual control task can be divided into two types of control functions:

1. Stabilisation: establishing an equilibrium state of aircraft motion and stabilise aircraft motion after disturbances. This requires data about angular motion, so-called inner-loop data.
2. Guidance: manoeuvring the aircraft along the desired trajectory. This requires data about position and orientation errors, so-called outer-loop data.

[TSO-C129] and [TGL-2] define criteria, directly or by reference, against which the presentation methods of both inner- and outer-loop data are to be assessed. This in itself will not result in consistency of data presentation formats. Whilst this is considered necessary to avoid the regulations inhibiting genuine technical innovation, the danger exists that different presentation methods may lead to confusion and incorrect situation awareness where a pilot transfers between aircraft using different RNAV systems. This differs from displays of conventional navigation aids where a standard display methodology for VOR/ADF has developed by tradition.

Figures 4a to 4g present different possibilities for the presentation of position and orientation errors. Figures 4d and 4e are simplified navigation display formats. The track-up format in Figure 4d is typically used during navigation, whereas the North-up format in Figure 4e better supports planning. The other figures show potential symbolic formats. In Figures 4a, 4b, 4c, 4f, and 4g, the frame of reference for the depiction the cross track error (XTE) is determined by the fly-to principle used in today's Course Deviation Indicator (CDI). [TSO-C129] does not specify a frame of reference for the depiction of the Track Angle Error (TAE). Figures 4b and 4c use a fly-to presentation for the depiction of the TAE while 4f and 4g employ a fly-from frame of reference. All these presentation formats are allowed by the TSO-C129 standard. To prevent proliferation of different data presentation methods for the situation awareness data, additional requirements that reduce the number of potential options for the selection of reference frames are clearly desirable.

Whilst the turn performance limits are specified, [TSO-C129] does not address the means by which this is achieved. Specifically, since an Automatic Flight Control System (AFCS) is not demanded in [TGL-2], the data required by a pilot to support turn anticipation need to be considered. At present, manufacturers have a lot of freedom regarding the presentation and the danger exists that certain formats which present outer-loop data can change the pilot's control strategy in such a way that inner-loop feedback is neglected. Good human factors considerations in the design of the display system can mitigate this, but the design and installation services used for the RNAV upgrade will probably not have such resources available.

7.2 Navigation

Due to the high performance of GPS when it is functioning well, pilots might see GPS as a perfect system. Overconfidence and confirmation bias may unnecessarily delay the pilot's decision to revert to the alternative means of navigation. Therefore, it is important to identify the most likely factors that might cause a pilot to postpone reversion, and to address the associated problems in training to make the pilot aware of the GPS system deficiencies. However, the mitigation in this instance is that the warning limit is well inside of the navigation performance limits and delays could be tolerated without impact on the system safety.

To ease reversion to alternative means of navigation, the MMI of GPS should minimise the pilot’s effort needed to crosscheck the data with the alternative means of navigation. The display should serve as a kind of ‘external memory’ to support the mental transformation that the pilot has to make when switching reference frames, thus reducing workload. By providing such assisting information, the risk of control blunders can be reduced.

Again, training is going to be important as well. Much of the information needed to support cross-referencing (such as range/bearing crosscuts to reversionary aids) could be pre-drawn on charts as part of the flight planning carried out by the pilot. For large companies, a service could be provided by which the required data could be made available to the crew. In addition, investigation is underway to see how it could be incorporated in the standard charting facilities.

7.3 Interaction

Regarding the functions which are mandated, adequate care has been taken in [TSO-C129] to limit their potential complexity by restricting the maximum number of actions which are allowed.

A potential danger that remains is the addition of all kinds

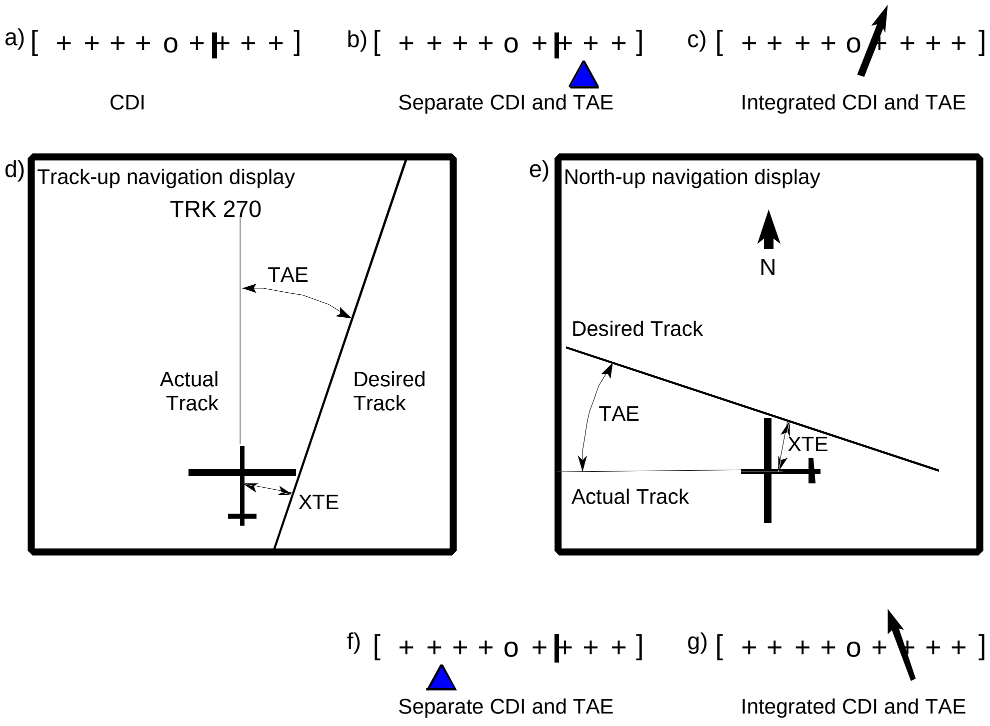

FIGURE 4. ***DIFFERENT METHODS TO PRESENT POSITION AND ORIENTATION ERROR***

of not required but ‘nice to have’ functionality that possibly demands more interactions, placing a higher load on working memory. Furthermore, the complexity of such additional functionality may act as an ‘attention sink’ and lead to absorption of the pilot’s attention. Finally, it may well provoke unintended use.
The same problem has also been observed with the use of flight management systems in commercial aircraft [FAA96] and the issue is therefore a general RNAV problem rather than a specific GPS issue. At present, no requirements protect against the integration of additional functionality. Note that current GPS receivers already illustrate a trend towards an increasing amount of features.

8. CONCLUSION AND RECOMMENDATIONS

The study has shown that the space segment of GPS is expected to meet all but one of the technical requirements for the application in B-RNAV. Only the continuity of service is expected to be below the requirements and hence an alternative system supporting reversionary operation will remain required. VOR/DME and ADF can provide such reversion.
The total system integrity of GPS is hard to quantify, as only limited data is available on certain failure modes. Because the expected integrity of the GPS space segment is much higher than the required total system integrity, there is room to accommodate a certain amount of other failures, such as receiver hard- and software failures and interference related problems. It is yet unclear how likely these types of failures are to occur, but there are indications that they might well be the dominating error sources at this point in time.

Interference holes from ground based sources definitely exist in the European airspace. TSO-C129 certified GPS receivers are not expected to function properly in these holes. Lack of good data, monitoring and incident reporting makes it difficult to predict the full extent of this problem. This, and the time-scales required for completion of a European-wide co-ordination prevents rapid mitigation. Onboard emitters are another important source of interference. Installation and testing guidelines that ensure compatibility of GPS equipment with such onboard emitters are needed but not yet available.

The introduction of GPS equipment has the potential to increase safety by reducing task-demanding load for the navigation task. However, it has to be appreciated that the capabilities provided by RNAV can present a distraction from other safety critical issues. This can be of particular importance to GPS systems since the high nominal system accuracy invites application into phases of flight where RNAV was not previously used.

Current GPS equipment certification requirements mandate certain functionality to be implemented and certain data to be presented. They do not protect against the dangers resulting from additional features, such as unintended use and attention absorption. Moreover, the data presentation requirements lack sufficient consistency and leave room for various types of data presentation. Some potential formats conflict with existing methods and are likely to cause confusion.
It is impossible to anticipate all new designs and new functionality that will be introduced and it is not wise to simply prohibit them. New developments should be evaluated for their compatibility with the existing ones, their compatibility with the task requirements, and for their potential impact on overall task strategy. It is important that, as part of this evaluation, the possibilities for unintended use and task interference are covered as well.

NOTES

[1]The interaction between the pilot and the GPS equipment is determined by the functionality, the displays, and the controls. In the U.S., the pilot-system interface characteristics of GPS receivers are certified according to [TSO-C129], [DO-208], and [AC20-138]. Furthermore, a ‘*Human Factors and Operations Checklist for Standalone GPS Receivers (TSO C-129 CLASS A)*’ has been developed by VOLPE National Transportation Systems Centre for the FAA [FAA96]. This checklist allows evaluation of the interaction and of the quality of the displays and controls.

[2]Guidance is the determination of a trajectory from a current position and velocity to a desired position and velocity.

[3]Control is the determination of commands to the vehicle actuators to implement the desired trajectory, preserving a stable feedback loop.

DISCLAIMER

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APPENDIX A. TSO-C129 RAIM TESTS

This section discusses the testing of the RAIM functionality that [TSO-C129] requires. We will show why these tests should be considered insufficient to support a high trust in the receiver. Note that the problems reported in [Sharkey96] are also concerning TSO certified receivers.

A.1 Description of tests required by TSO-C129

Testing of the RAIM function of receivers is done with two types of tests: off-line software simulation and on-line bench test. In both cases, satellite noise is modelled as a superposition of an SA-like process and a white noise term, that in the off-line tests is slightly larger because it has to include the receiver noise as well. The simulations are preceded by selecting 1152 space-time points, of which only those that would be considered 'available' according to the receivers 'availability determination' algorithm are used. These geometries are labelled 'admissible'. The subset of the 10 worst admissible geometries will be called the 'marginal geometries'. Admissible and marginal geometry sets are formed for each phase of flight for which the receiver has to be certified.

The software tests are only performed for the phase of flight with the highest integrity requirements. For all 10 marginal geometries, 500 experiments are done with a ramp error of 5 m/s on the worst case satellite (on which failures are hardest to detect). At most 5 missed detections are allowed to occur during these 5000 runs. For all admissible geometries 100 experiments are done with no satellite errors present. The total number of alarms is not allowed to exceed 1.2%. At most 1 alarm for any admissible geometry is allowed.

The on-line bench tests are performed for all phases of flight for which the receiver should be certified. For all 10 marginal geometries, 10 good geometries and for each phase of flight, only one (!) experiment is done, with a ramp error of 5 m/s on the worst case satellite. No missed detections are allowed. Using the same geometries, one experiment is done with no satellite error present. Only one sample is taken each time, and no false alarms are allowed to occur. On-line bench tests are also done to verify the selection of admissible geometries: the receiver should identify 10 'just inadmissible' geometries as unavailable for each phase of flight.

The tests that are described in [TSO-C129] are not very extensive. Receivers that fail the tests once are allowed to be retested 'because it is recognised that the tests involve a relatively small number of samples, statistically'. This lack of statistical significance is just one of the many problems that are insufficiently addressed in the standard. We will end this section with a list of problems that have been identified, and that surely justify the conclusion that [TSO-C129] provides insufficient guarantee that a receiver will meet the RAIM performance standards for which it is designed.

A.1.1 Lack of confidence

Both the off-line and the on-line tests have a low confidence level. This means that the real probabilities of missed and false detection might be higher than the ones specified in the TSO requirements. In Table 3 we have summarised some values of missed detection probabilities in case of a satellite failure ($P_{MD|failure}$) with a 99%, 99.9% and 99.99% confidence respectively. This figures should be interpreted as follows (taking the first value as an example): when the $P_{MD|failure}$ of a receiver exceeds 0.0026, the chances that this receiver passes the TSO-C129 off-line tests is at most 1%. The target value of $P_{MD|failure}$ specified in the TSO is 0.001. However, B-RNAV allows 263 times more undetected failures, implying a target value of 0.263. In these figures, all tests have been taken into account. The on-line test figures resulting from testing with the 10 marginal geometries only would be 0.37, 0.50 and 0.60 respectively. Note that the off-line tests for the en-route are not always mandatory, see A.1.4.

A.1.2 Lack of randomisation

All simulated satellite errors are 5 m/s ramp errors. This allows detection algorithms to be optimised for this type of failures only. Only single satellite failures are considered.

A.1.3 Low availability of low integrity receivers

Receivers are allowed to disregard bad geometries. As no availability parameters are specified, they are allowed to disregard as many satellite geometries as necessary in order to pass all RAIM tests. To avoid this, the revised TSO-C129A specifies an availability of 95% of all of the 21 satellite optimal constellations.

A.1.4 Lack of completeness

Software tests for en-route do not have to be performed when the equipment is also used for non-precision approaches. This means that the specific threshold selection of the error detector is only tested in the on-line bench tests, that has an extremely low statistical significance, see A.1.1.

A.1.5 Lack of global validity

The geometries that are tested are taken from a set of 1152 possible geometries. The worst geometry among these, that should just be sufficient to get the required RAIM performance, is not exactly the worst geometry that should be minimally acceptable. [Easton95] shows that receivers that pass the tests with the given 1152 points, sometimes fail when this set is extended with other points.

	B-RNAV	RNP-5 RNAV	TSO-C129 (en route)
TSE Accuracy (95%)	5 NMi	5 NMi	0.124 NMi
Missed Detection Rate	-	10^{-5} / hour	$3.8 \cdot 10^{-8}$ / hour
Alarm rate	10^{-4} / hour	10^{-5} / hour	$2 \cdot 10^{-3}$ / hour
Maximum Position Error	-	-	2 NMi
RAIM Availability	-	-	-

TABLE 1. B-RNAV AND TSO-C129 EN ROUTE MODE REQUIREMENTS

	Performance	Conditioned on:
Horizontal Accuracy	≤ 100 m 95% ≤ 300 m 99.99%	coverage, availability and reliability
Reliability	≥ 99.79%	coverage and availability
Availability	≥ 83.92%	coverage
Coverage	≥ 96.9%	≥ 4 satellites in view, PDOP ≤ 6, 5° mask angle, 24 satellites constellation

TABLE 2. SUMMARY OF THE STANDARD POSITIONING SERVICE PERFORMANCE

	Off line tests			On line tests		
Confidence	99 %	99.9 %	99.99 %	99 %	99.9 %	99.99 %
$P_{MD\|failure}$	<0.0026	<0.0033	<0.0039	<0.21	<0.29	<0.37

TABLE 3. MISSED DETECTION PROBABILITIES FOR DIFFERENT CONFIDENCE LEVELS