# Tools for GPS B-RNAV

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This paper discusses the design, development and operation of two tools intended for B-RNAV operations: the enhanced AUGUR system, which was commissioned by EUROCONTROL, and the Global Positioning System (GPS) Performance Monitoring System (GPMS), commissioned by National Air Traffic Services Ltd. (NATS). Both tools were implemented by STASYS Ltd., with support from Delft University on AUGUR algorithm issues. AUGUR, a Predictive GPS Receiver Autonomous Integrity Monitoring (RAIM) system, performs complex calculations and provides an easy-to-interpret Internet-based interface to aid aircraft operators with the use of GPS. Enhancements to AUGUR have been implemented to meet user requests and the requirements of a future Joint Aviation Authorities (JAA) Temporary Guidance Leaflet (TGL) on the airworthiness and operational approval for the use of Area Navigation (RNAV) systems in European airspace designated for Precision RNAV (P-RNAV) operations. The GPMS records output from a variety of GPS UE, has a real-time interface, performs simulations based on logged data, and permits remote analysis. The work carried out consisted of specifying a system to meet the safety study recommendations, choosing hardware, analysing interface requirements, and developing systems and software. These tools are now in place to help with GPS B-RNAV operations, and provide a layer of safety for both en-route flight and GPS-based non-precision approach operations in European airspace.

KEY WORDS

1. GPS. 2. Safety. 3. Integrity Monitoring

1. INTRODUCTION. There has been considerable effort made in the expectation of the exploitation of Global Navigation Satellite Systems (GNSS) for Air Transport Management. This paper discusses two tools: AUGUR, which performs predictive receiver autonomous integrity monitoring (RAIM) and was commissioned by EUROCONTROL; and the Global Positioning System Monitoring System (GPMS), commissioned by UK National Air Traffic Services (NATS) Ltd. Both tools were designed by STASYS Limited, with help for the RAIM algorithm from Delft University. The tools have been designed to meet an operational requirement concerning the use of GPS for current aviation operations. However, some of the lessons learned during their development will be of use for the development of GNSS applications for all modes. The objective of this paper is to give an overview of AUGUR and the GPMS, discussing the origins, design and capability of the two.

Aeronautical information is becoming increasingly complex, and thus new ways of dissemination are required. This paper aims to show that the Internet is a viable and suitable means of dissemination for certain aviation information, particularly GNSS-related information. As AUGUR is intended for aviation users, some of the communication links dedicated to aviation were considered as a means for data dissemination. However, as GNSS is multi-modal, a communications means that can reach all users within each mode is required. This paper begins with some background on the requirement for the tools, their functionality, design, and implemented and expected enhancements. It also shows some of the results obtainable via the GPMS, using the effect of Selective Availability (SA) removal as an example.

2. BACKGROUND. Four years ago, when aircraft operators were deciding upon which systems to install in order to meet the Basic Area Navigation (B-RNAV) mandatory carriage requirement for en-route operations,[1] there was a realisation by some that it was not economically viable to install the multi-sensor equipment available. There was a growing call by operators to be allowed to use GPS. When B-RNAV was originally conceived in 1990, GPS was not available. In fact, the equipment requirements of B-RNAV were based on empirical data obtained from VOR/DME units. When GPS user equipment (UE) suitable for aviation became available, they appeared to be a low-cost means of meeting the requirement. Thus the navigation division of EUROCONTROL (DED-4, now Airspace Management and Navigation (AMN)) initiated two parallel studies to determine the safety of such operations. These studies, which included experiments in an airline flight simulator, concluded (B-RNAV Safety Assessment Summary[2]) with a number of recommendations in order to mitigate the risk. Four of the recommended layers of safety were as follows:

(a) GPS UE meeting a certain standard was required. The US TSO-C129 standard was adopted, with the enhancements that the satellite health word and pseudorange step were both checked.
(b) All aircraft were still required to carry VOR/DME equipment as a reversionary mode, if the only means of meeting the B-RNAV requirement was by using GPS UE.
(c) Pre-flight predictions of Receiver Autonomous Integrity Monitoring (RAIM) Fault Detection (FD) availability were required for the route to be flown.
(d) The operational performance of GPS needed to be monitored, to ensure that it met its specifications.

Whilst GPS meets the accuracy requirements for en-route navigation, it does not meet the integrity requirements. The proposal to require users to perform a check on the expected RAIM availability was a step towards helping to meet these integrity requirements. TSO-C129 requires UE to perform RAIM, which involves using redundant measurements as a consistency check. The availability of RAIM requires the comparison of a derivative of the observation matrix against predetermined threshold values.

There are two levels of RAIM; the level of RAIM required for GPS use for B-RNAV is to detect faults, FD. The level required by FAA's Oceanic and Remote operations approval, Notice 8110.60,[3] Fault Detection and Exclusion (FDE), was considered not to be necessary.

There are a number of RAIM algorithms. The intention of AUGUR is to imitate the behaviour of operational UE, or to give a more conservative result. Research by Bastiaan Ober at Delft University showed the Minimal Detectable Bias (MDB) algorithm to be the most suitable. At that time, not all UE possessed a ready means of performing a pre-flight RAIM availability check for an entire route, and there was no large-scale monitoring of GPS. Thus the AUGUR and GPMS tools were commissioned.

3. AUGUR FEATURES. The Joint Aviation Authorities (JAA) recognised the output of the EUROCONTROL safety work, and produced guidance material for operators.[4] This guidance material gave requirements for the pre-flight RAIM prediction, and AUGUR was designed to meet these requirements. AUGUR, as far as it is available over the Internet, was originally comprised of four modes, *STATUS*, *VISIBILITY*, *AREA* and *ROUTE*. A new 5th mode, Non-Precision Approach (*NPA*), will be discussed later. The modes make use of the graphical capabilities of the Internet, but there are also text outputs and re-use of downloaded bitmaps, to speed up use.

*STATUS* gives a graphical and text view of the number of operational satellites in the GPS constellation over the selected time period. This number is taken from the total number of satellites indicated as being healthy in the almanac, minus any indicated as being unavailable by the Notice Advisories to Navstar Users (NANUs). The information conveyed by *STATUS* is also available via an automated telephone system.

*VISIBILITY* mode shows a sky plot of operational satellites and one of the more unique views is the *AREA* mode. This gives a weather map-type view of periods of RAIM availability greater than 5 minutes over a fixed time period, which is currently fixed at 3 hours. Colour coding has now been added to indicate length of contiguous outage. This plot requires some 16 million point RAIM calculations to be performed each day.

The fourth mode, *ROUTE*, is one that calculates RAIM availability for a specific route, input again by identifiers. It gives predictions for plus and minus 15 minutes about the nominal time at first waypoint.

4. AUGUR DESIGN. The interface has been designed with the intention of requiring minimal user input. As well as making it easy to use, this facilitates use of the Internet, which is not suitable for high degrees of interaction. Sufficient information for an operator to meet the JAA TGL-2 requirements in most instances can be obtained by a single key press.

The tool makes use of almanacs and Notice Advisories to NAVSTAR Users (NANUs) provided by the US Coast Guard, the official source of data dissemination to civil users for GPS information. AUGUR also incorporates a database of all navaid and waypoint identifiers in ECAC airspace.

Due to the large number of RAIM availability calculations required, powerful hardware is needed, and as the intention here is to provide a service, a mirror site exists in order to provide back-up in the event of a failure at the primary site. This is an operational tool, and therefore the software was designed in a quality environment, complying to the TICK IT British standard. In order to handle a large number of enquiries, there is also a dedicated communications link to this machine.

5. AUGUR ENHANCEMENTS. Since AUGUR became operational, there have been a number of requests from users. This has led to a number of changes, some of which have already been implemented.

The difficulty of conveying the time-varying data for the large geographic area has been tackled by reducing the time periods for which the Area RAIM availability is pre-calculated from six hours to three hours. Also, more colours have been used for the *AREA* mode colour coding. The number of colours used remain limited, so that those users with older PCs/software can continue to access this web page

The almanac is now obtained directly from a receiver, with the almanac received from the USCG used as a back-up. There have been a number of requests to expand the geographic coverage; however, although there is sufficient spare computing/storage capacity, the expanded area has yet to be defined in detail.

The Non-Precision Approach mode is available for airports, and uses the same algorithm used by *AREA* and *ROUTE* modes, only now with the TSO-C129 RAIM availability thresholds for en-route. The *NPA* mode, and its associated 4-letter airport identifier database, have recently become operational. Figure 1 shows the output screen for AUGUR *NPA* Mode.

6. GPMS FEATURES. The second tool is the Global Positioning Monitoring System (GPMS). The GPS B-RNAV safety studies recognised the need for the service provided by GPS to be monitored, in much the same way as the output of any other navigation aid must be monitored to ensure that its performance meets that expected. Also, the study recognised that its findings required substantiating, and this was not possible with the performance data available at that time.

The GPMS is a Personal Computer (PC)-based tool providing monitoring and data logging functionality primarily for aviation regulatory applications, using the output of two GPS UE: a Javad Legacy, and a Novatel MiLLennium. The GPMS can be operated remotely. Data analysis of constellation performance and viewing of quantities is in real time, and is performed via a Windows interface.

It analyses the GPS output and compares it with the GPS Signal Specification,[5] and thus meets the requirements of the GPS Performance Monitoring System described in Annex C of this specification. It also meets the requirements stated for a GPS Performance Monitoring System as recommended in EUROCONTROL's Safety Assessment for the use of GPS for B-RNAV

The tool is for unmanned, uninterrupted operational use, and so there is substantial redundancy in the architecture. There is sufficient data storage capacity to store the large volumes of output obtained from GPS for approximately ten days. Control of logging rate for each parameter group allows the user to make efficient use of the available memory and communications link availability.

7. GPMS CHALLENGES. This particular implementation of a monitoring system faced a number of unique challenges. The GPMS was designed to meet the recommendations of EUROCONTROL's Basic Area Navigation (B-RNAV) safety study, and to operate in a remote location, leading to it having the ability to:

(a) Be unmanned.
(b) Operate autonomously and continuously in the event of component failure through built-in redundancy. It has to analyse data, but also store raw data.

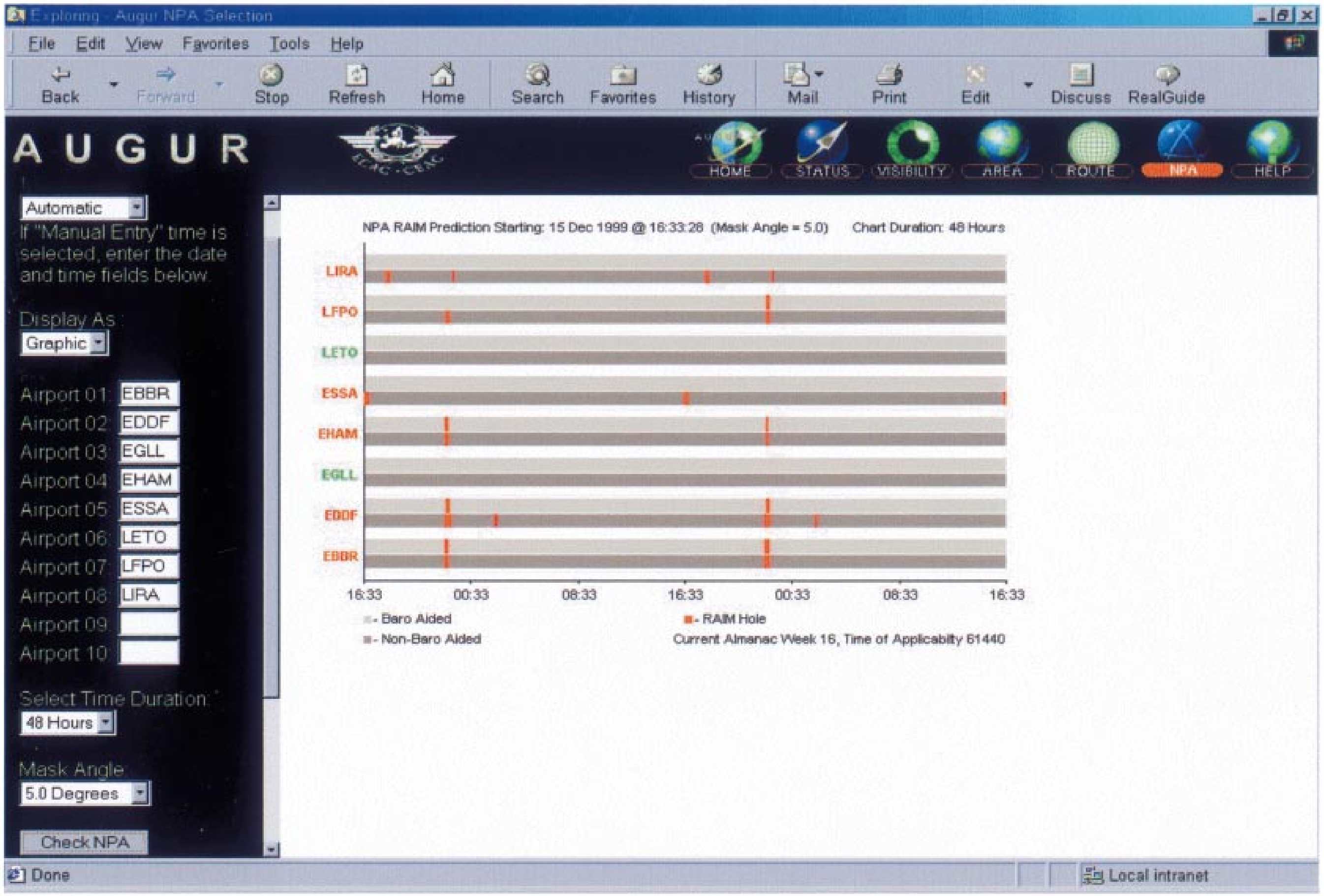


Figure 1. AUGUR NPA mode output.

(c) Permanently log data from two GPS RPU 24 hours a day, 7 days a week. It must also automatically manage large amounts of data within an Oracle database.
(d) Operate from a remote site only accessible via a standard telephone line. Use of this link meant that a network approach was not possible, but it did give flexibility for the GPS RPU to be housed anywhere.
(e) Provide a remote real-time view which raised a number of challenges, due to the low capacity and unpredictable behaviour of a standard telephone line.
(f) Monitor a comprehensive range of data concerning the GPS constellation from a variety of equipment and convert it into a common format.
(g) Simultaneously interface to different GPS RPU and continuously log the available data for post-analysis and graphical display.

The latter two challenges were particularly difficult in the absence of a common interface definition of the type used in military applications (such as MIL-STD 1553B database Interface Control Document 059). Now that a common format has been devised, the operator has no need for learning the vagaries of each RPU CDU and command language. An example of this harmonisation is that one RPU outputs the ionospheric correction, whereas the other only provides the values given via the almanac/ephemeris. The GPMS computes the correction using these latter values, thus providing the output from both RPU in a format that enables comparison.

The uniquely wide range of parameters required at the same instant causes the RPU interfaces to be worked at the limits of their capacity.

8. GPMS ARCHITECTURE. The system architecture is divided in two: a remote site (currently Greenford) and a local site (currently Spectrum House, Gatwick).

The remote site houses the GPS RPU and associated antennas, and the logging server/database. As this site is unmanned, and not easily accessible, there needed to be substantial redundancy to enable continuous operation. Many systems and software work well, but few are designed for continuous operation and zero intervention. The design made use of the same commercial-off-the-shelf (COTS) packages used by many for working at home, but special modifications were found to be required. In case of communications failure, the GPMS is able to operate continuously, with its 42-Gigabyte data storage capacity giving approximately 10 days of continuous operation.

The local site consists of a PC with the download software, analysis software and data storage capability. It dials up the remote site, and then can download data, or view the real-time reports. This download is normally performed automatically at regular intervals, thereby obviating the need for an operator to spend time waiting for all data to be downloaded since the last time logged in.

9. GPMS INTERFACE. At both sites, there is a comprehensive Windows interface for control and analysis of constellation performance. Aspects of GPMS control include: remote connection and disconnection of each RPU, remote reset for each RPU.

Aspects of the constellation performance available for analysis are:

(a) time histories of a comprehensive list of parameters, harmonised for both RPU, using a graphics engine able to plot approximately 6000 data points

(b) real-time reports of information from the RPU in a harmonised format
(c) simulations of the satellite constellation to enable calculation of RAIM, satellite selection, and satellite visibility about a fixed location
(d) an X, Y scatter plot of RPU horizontal position, and a plot to allow comparisons of satellite health as stated in one part of the navigation message compared to that stated in NANUs.

A comprehensive *Help* feature, based on the COTS help program, is available to describe all features of the program. The control of the system is performed by two initialisation files, and these allow, amongst other facilities, control over data download and logging rates.

10. GPMS TIME HISTORY/REPORTS. The time history function allows the operator to call a variety of recorded quantities from the database and display each on an individual plot graph against a specified time period. Only one plot quantity can be included on each graph but up to 32 SV can be included on the same graph, if applicable. Plots are displayed separately for each RPU. Up to six plot graphs can be created at any one time. All six can be displayed at the same time and arranged adjacent to each other to allow the operator to compare results.

The quantities have been categorised into the following. Ephemeris (including almanac), Constellation, Navigation, Performance (statistics), Status, and Measurements. Ephemeris gives all orbital parameters broadcast in the navigation message. Constellation gives quantities relating to the SV constellation aspects of the navigation solution; for example, RAIM availability (calculated from measurements) and DOPs. Navigation gives quantities output by the RPU navigation solution; for example, geodetic position. Performance gives statistics on the performance of the SV constellation as defined by Reference 4; such as, availability. Status gives quantities such as an RPU's estimation of the presence of jammers. Measurement gives access to the observables as measured; for example, pseudorange and carrier-to-noise ratio.

The real-time reports are sub-divided into four: Performance, Summary, Measurement, and Status. These categories give real-time values of a subset of the quantities given in the time histories, with the addition that the measured accuracy is stated in a number of different measures. This access to the behaviour of such a wide variety of parameters also makes the GPMS a useful educational tool.

11. GPMS SV CONSTELLATION. The SV Constellation function gives access to the following plots, most of which are based on a simulation of the satellite constellation based on the logged almanac. *Position Scatter* is particularly useful to see horizontal scatter of the RPU's navigation solution over a selected time period. *RAIM Availability* (calculated from orbital simulation based on almanac) gives an area plot of accumulated RAIM unavailability (of greater than a specified duration). *SV Health* permits comparison of the two different measures of satellite health in NANUs and in the Navigation Message. *Visible SV ID* helps time history plotting, as it indicates which satellites were available for a given time period (i.e. for which satellites certain quantities will be available for a given time period). *SV Selection* evaluates permutations of the relative geometry between the user position and the SV to give the best four, based on PDOP. *SV Visibility* gives a sky plot of visible satellites about a given location for a given time period.

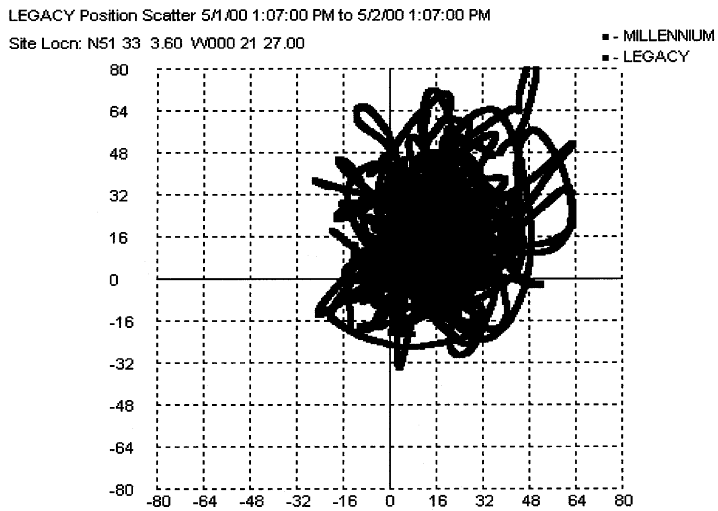


Figure 2. GPMS position scatter – SA On.

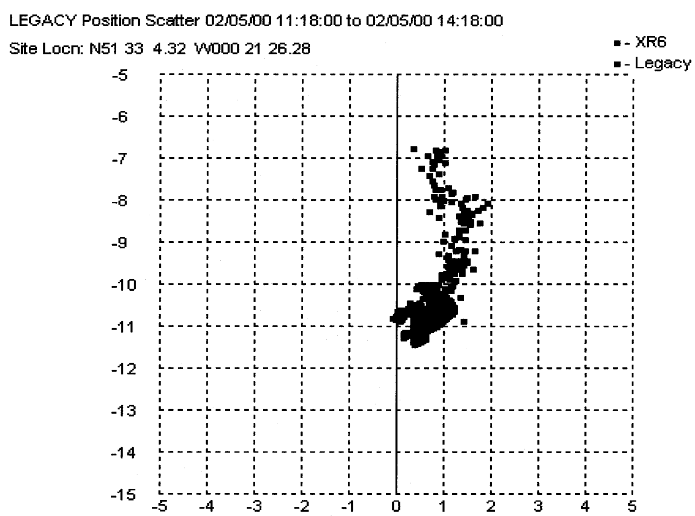


Figure 3. GPMS position scatter – SA Off.

12. GPMS RESULTS. The two plots at Figures 2 and 3 give an example of the capability of the GPMS. Figure 2 shows the scatter of GPS horizontal position the day before SA was removed. Figure 3 shows the scatter the day after. These plots can be easily produced at the GPMS remote station.

13. CONCLUSION. Two tools have been developed to meet a current operational requirement for European aviation concerning GPS. AUGUR, accessible to all at no cost via the Internet (www.augur.ecacnav.com), meets JAA requirements for RAIM availability prediction for operations where GPS is the sole means of meeting the B-RNAV mandatory carriage requirement. The GPMS, primarily

intended for air traffic service providers, permits comprehensive analysis of GPS as a navigation service. It is likely that, following the recent decision to remove SA, the GPS B-RNAV safety assessment will be revisited, and it is expected that the GPMS will play a major role in any new safety assessment.

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https://doi.org/10.1017/S0373463300001016 Published online by Cambridge University Press