



NLR-TP-99420

Analysis and validation of GNSS performance

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ACRONYMS			
		R&D	Research and Development
		RAIM	Receiver Autonomous Integrity Monitoring
ATC	Air Traffic Control		
B-RNAV	Basic Area Navigation	RNP	Required Navigation Performance
CAA	Civil Aviation Authority		
CAT 1	Precision approach with specified performance	RTCA	Radio Technical Commission for Aeronautics
EGNOS	European Geostationary Navigation Overlay Service	SA	Selective Availability
ESA	European Space Agency	SARPs	Standards and Recommended Practices
ESTEC	ESA Technology Centre		
ETG	European Tripartite Group	SBAS	Satellite Based Augmentation System
EU	European Union		
EUROCAE	European Organisation for Civil Aviation Equipment	SIS	Signal In Space
FTE	Flight Technical Error	SPS	Standard Positioning Service
GLONASS	Global Navigation Satellite System (Russian)	SRD	System Requirements Document
GMV	Grupo de Mecánica del Vuelo	TSP	Total System Performance
GNSS	Global Navigation Satellite System	WAAS	Wide Area Augmentation System
GPS	Global Positioning System		
GPV	GNSS Performance Validation study		
H/W	Hardware		
ICAO	International Civil Aviation Organisation		
ICD	Interface Control Document		
IGS	International GPS Service		
INS	Inertial Navigation System		
MOPS	Minimum Operational Performances		
MRD	Mission Requirements Document		
NLR	National Aerospace Laboratory		
NSE	Navigation System Error		

BIOGRAPHIES

Jeroen Vermeij obtained his MSc in Aerospace Engineering from Delft University of Technology in 1993. Since 1994, Vermeij has been working at the National Aerospace Laboratories (NLR) in Amsterdam, The Netherlands, participating in activities relating to air traffic management. Vermeij managed the EUROCONTROL project on GNSS Performance Validation.

Axel van den Berg obtained his MSc in Aerospace Engineering from Delft University of Technology in 1997. Since 1998, Van den Berg has been working at the National Aerospace Laboratories (NLR)



in Marknesse, The Netherlands. Van den Berg was involved in the GNSS Performance Validation study from the Space Systems department. Currently Van den Berg is co-ordinator of Satellite Navigation related activities at the NLR.

Rick Farnworth graduated with a BSc in Electronic Engineering from the University of Wales in 1988 and was awarded a PhD in 1992 for his work on Loran-C coverage prediction modelling. Farnworth then joined the United Kingdom CAA's National Air Traffic Services to work on R&D projects relating to the application of satellite navigation systems in civil aviation. Since February 1996 Farnworth has been working for EUROCONTROL at their Experimental Centre in France and is responsible for various R&D projects related to satellite navigation.

Edward Breeuwer obtained his MSc in Electrical Engineering from Delft University of Technology in 1992 and was awarded a PhD from this university in 1998 for his work on integrated navigation systems. Since October 1997 Breeuwer has been working at the Satellite Navigation Centre of Expertise of the EUROCONTROL Experimental Centre, participating in system research and development related activities focusing on implementation aspects of satellite navigation in civil aviation.

The GNSS Performance Validation Study has been performed during 1998 under contract to EUROCONTROL by a team lead by the Netherlands Aerospace Laboratory NLR and including the Spanish company Grupo de Mecánica del Vuelo GMV and specialised sections of the European Space Agency ESA/ESTEC and was completed in March 1999.

ABSTRACT

The GNSS Performance Validation (GPV) study has analysed the operational validation of the GNSS-1 concept from an aeronautical user point of view. The Total System Performance (TSP) has been divided into three topics: the Signal-in-Space (SIS), the onboard equipment and the dynamic system performance. This paper highlights the main findings of this study with regard to measurement, simulation and analysis of performances necessary for a legitimate operational validation. Secondly, this paper addresses the configuration options for a simulation environment which are required for particular validation tests.

BACKGROUND

The first implementation phase of Global Navigation Satellite Systems (GNSS) in Europe, called GNSS-1 (see Figure 1) consists of three main elements: the Global Positioning System (GPS), the Global Orbiting Navigation Satellite System (GLONASS) and regional Satellite Based Augmentation Systems (SBAS). The European Geostationary Navigation Overlay Service (EGNOS) is the SBAS covering the European region.

The European Tripartite Group (ETG) of the European Union (EU), the European Space Agency (ESA) and the European Organisation for the Safety of Air Navigation (EUROCONTROL) are managing the development of EGNOS. Within the ETG, EUROCONTROL is responsible for the operational validation of EGNOS.

The GNSS Performance Validation (GPV) study was performed under the authority of EUROCONTROL in order to assess all the aspects related to the operational validation

of the GNSS-1 concept. EUROCONTROL has now undertaken to set up the operational validation programme on the basis of the results of this study.

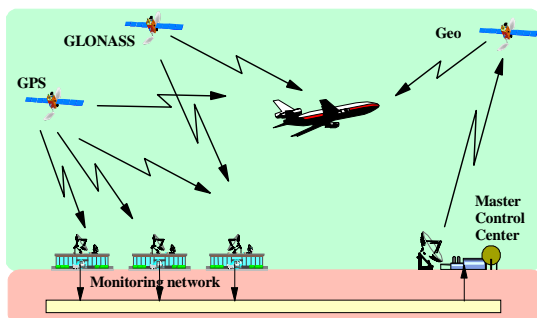


Figure 1: GNSS-1 system architecture

1 INTRODUCTION

In recent years substantial progress has been made towards the implementation of GNSS in European airspace. In this process, the following issues are being addressed:

- definition of operational requirements for GNSS-based navigation systems;
- validation of standards intended to support these requirements;
- validation of the performance of the total aircraft system with respect to the GNSS standards and the airspace requirements;
- definition of operational procedures for aircraft utilizing GNSS.

Although GPS has already been approved for use as a means of basic area navigation (B-RNAV), its use is limited. The introduction of a first generation GNSS through space-based, airborne, and possibly ground-based augmentation will provide a substantial increase in the capabilities of

systems based on GPS and GLONASS thereby permitting users to obtain benefits from GNSS in all phases of flight down to CAT I precision approach.

To allow the introduction of GNSS for these different operations in European airspace, a clear link needs to be established between the requirements set by the use of this airspace, and the Signal-in-Space and receiver specifications available for GPS, GLONASS and its augmentations. Airspace requirements on total aircraft performance are laid down in the manuals for Required Navigation Performance (RNP) of the International Civil Aviation Organization (ICAO); the GNSS Signal-in-Space requirements are currently being drafted by ICAO's GNSS Panel; while RTCA and EUROCAE are finalising the receiver requirements.

2 RNP PARAMETER DEFINITIONS

The basis of a validation effort is determined by the RNP parameters accuracy, integrity, continuity-of-service and availability. Unfortunately, several bodies - [GPS-SPS, 1995], [GLONASS-ICD, 1995], [ICAO SARPs, 1998], [RTCA/DO-229] - use different definitions of these parameters and their relation.

For example, the relation between the different RNP parameters in the GPS-SPS is specified the other way round compared to the ICAO documents. In the SARPs, the accuracy, or rather the horizontal and vertical alert limits, are used as baseline parameters, and thereafter the integrity and continuity risks are conditioned on these. On the other hand, in the GPS-SPS the accuracy of the Signal-in-Space is only determined once the signal is available and its integrity has been established. In

[Farnworth, 1998] some of these differences are illustrated for accuracy.

[EUROCONTROL, 1998] proposed a set of definitions, which has become applicable for the GNSS-1 mission requirements. Therefore these will form the basis for the validation of GNSS.

3 VALIDATION METHODS

Validation methods include analysis, modelling, simulation, static data collection and in-flight data collection.

In general, data collection is the preferred method, since insufficient theoretical information is available to validate all parameters. Unfortunately, an immense amount of data will be required for full validation of the values of the integrity and continuity parameters. Therefore, data needs to be extrapolated in time as well as in space, based on required confidence levels. In addition, the collected data needs to be combined with available system knowledge to validate simulation models that can be used for statistical analysis.

For the different RNP parameters the required amount of samples and the sampling rate is determined. The sample rate is limited due to the fact that uncorrelated samples are required, while the amount of data to be collected depends on specific confidence levels. When models of the spatial and/or temporal behaviour of the data have been derived they can be extrapolated to minimise the effort needed for data collection.

Once models can be validated using collected data, simulation is essential for further system development and evaluating various operational scenarios.

4 GNSS PERFORMANCE BREAKDOWN

Approval of using GNSS-1 within the European airspace, a test and validation programme will need to demonstrate that an aircraft,

1. receiving GPS and/or GLONASS signals-in-space conforms to [GPS-SPS, 1995] and [GLONASS-ICD, 1995],
2. using EGNOS, RAIM or other augmentations, meets the SIS performance requirements,
3. is equipped with a receiver conforming to the Minimum Operational Performance Specifications (MOPS) [RTCA DO-229],
4. is able to meet the airspace requirements applicable for that phase of flight.

The basis of validation activities comprises the SIS and receiver performance specifications as developed by ICAO and RTCA/ EUROCAE. Validating the Signal-in-Space and the receiver to conform to these standards should ensure that an aircraft using compliant equipment is capable of meeting the operational requirements of the total aircraft system, see Figure 2. The proposed methodology for the GNSS performance validation process is described in [EUROCONTROL, 1999].

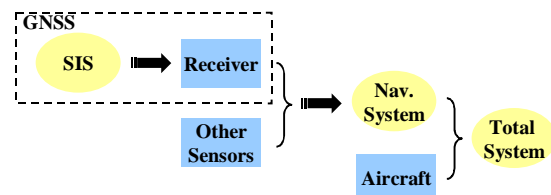


Figure 2: System components of GNSS

The first stage in the validation process is to ensure that the GNSS performance standards represent the European airspace requirements. This would include validation of the ICAO SARPs as well as Mission Requirements Documents (MRD) describing Europe's additional requirements.

The second stage is validating the performance of space-based signals, i.e. GPS, GLONASS and EGNOS, with respect to sections of the ICAO SARPs containing information extracted from GPS and GLONASS ICD documents and EGNOS and WAAS specifications.

The third stage is validating the performance of the receiver - either stand-alone or integrated with other sensors - with respect to the receiver standards (i.e. RTCA, MOPS).

The fourth stage is to validate whether the performance of the fully equipped aircraft using the proper signals-in-space is able to meet the requirements set for the airspace in which it is operating.

These validation activities will serve as a basis for certification of the ground, space and airborne equipment. This methodology should provide the European safety regulatory bodies with a framework allowing the validation of GNSS-based systems consisting of many widely dispersed elements which are operated and controlled outside national borders.

5 VALIDATION OF GNSS PERFORMANCE

5.1 Validation of the Signal-in-Space

In the near future, the received satellite signals-in-space which are part of a GNSS configuration (as shown in Figure 1), are

composed of GPS, GLONASS and SBAS (i.e. EGNOS for the European region).

Validation of the GPS and GLONASS SIS will need to focus on collecting statistical evidence of the behaviour of GPS and GLONASS, as detailed system specifications are not available for these systems. However, a large amount of SIS performance data is already available for these systems which have been operational, for quite some time.

For EGNOS, a specific SIS specification has been developed [EGNOS-SRD, 1998]. As a result, a more specific validation programme can be set up to check whether the system performance meets its specifications and is the responsibility of the developer of EGNOS, i.e. the European Space Agency (ESA). However, the European civil aviation community plays an active role in all the design reviews and system safety assessments.

When validating the performance of the SIS, the focus will have to be on those elements that determine the accuracy of the individual range and range rate measurements to the GPS, GLONASS and geostationary satellites. This can only be accomplished while using a receiver. Therefore, the range accuracy is determined by two main factors: the satellite and the user.

The main satellite signal-in-space parameters are clock and ephemeris data. Both may be subject to unintentional and intentional degradation. Unintentional degradation of the clock is due to the instability of the on-board frequency standard, while ephemeris errors are caused by incorrect ephemeris prediction and model implementation, which could result from e.g. space vehicle acceleration



uncertainty. Intentional degradation of the SIS, called Selective Availability, is currently only applied to the GPS satellite clocks, however it may be phased out in the near future.

User errors can be divided into the inability to model the signal group delays in the ionosphere and troposphere, multi-path and receiver noise which strictly speaking are not elements of the SIS).

It is very difficult to distinguish between SIS and receiver performance. It should be taken into account that when measuring SIS performance one will always include receiver induced errors.

Accuracy validation will require data collection over an interval resulting in statistics representative of any time and location in the coverage area. The GPS SARPs specify a data collection period of at least 4-hours during a 24 hour period. On the other hand, no requirements currently exist for GLONASS. Unfortunately, the data collected over such a period will prove to be not very useful as most data will be highly correlated and the 4-hour averages will differ substantially on a day-to-day basis. The current rule-of-thumb for GPS is a 200-second correlation interval for Selective Availability. Data already collected [GPV3100, 1998] confirm that this is the right order of magnitude. Data collected for GLONASS (which does not employ SA) indicate a correlation interval of 600 seconds for the ionospheric errors on the range measurements.

Validation of integrity and availability statistics based on data collection is difficult due to the rarity of outages and integrity failures. Long term ground and in-flight data collection efforts will, therefore,

be necessary. Ground data are already being collected in the IGS network, although only for GPS. In-flight data collection has already started in the SAPPHIRE project [Tiemeyer et al., 1998].

As mentioned before, the GNSS SIS specification is based on the fault-free receiver concept. Therefore, to validate the GNSS SIS against SARP requirements, multiple receivers will have to be used in order to isolate specific receiver-dependent failures from the measurements. In addition, the results will have to be calibrated for the nominal accuracy and time-to-alarm budgets.

When considering SIS performance of a single satellite, the continuity-of-service parameter is of little relevance, as it basically is a service parameter related to specific aircraft operations.

5.2 Validation of receiver performance

RTCA and EUROCAE provide detailed testing procedures for validating receiver performance, e.g. [RTCA/DO-229]. General receiver tests are specified as well as tests for receivers intended for specific phases of flight, in particular the approach phase. The general receiver performance tests include:

- (Re)-Acquisition,
- Satellite selection,
- Signal processing,
- Message processing,
- Receiver integrity.

Specific receiver tests are related to integrity monitoring during precision approaches.

A detailed assessment of these tests showed that these tests alone would not be

sufficient for a proper validation of the receiver performance. Especially for multi-path and integrated architectures additional tests are required, and have been proposed [EUROCONTROL, 1999].

Integrating 2 or 3 uncoupled GNSS/INS elements is recommended following a fault tree assessment of different integration options. This integration option is preferred both with regard to performance and level of complexity.

5.3 Validation of total system performance

After the assessment of the GNSS navigation system error (NSE), the total system error (TSE) needs to be validated to include the aircraft performance based on GNSS signals. The flight technical error (FTE) will be influenced by the behaviour of the NSE which has to be carefully analysed in order to be able to validate the Total System Performance (TSP).

Due to the high costs of an extensive flight test program, simulations need to be performed to the maximum extent. The models used for the simulation must, however, be validated by means of static and in-flight data collection.

Flight trials are effective to validate the available software models resulting in an overall system performance evaluation on a temporal as well as a spatial basis. An exhaustive validation of all potential scenarios each with probable parameter combinations using flight trials would be impractical. If the different contributions to the performance are conveniently identified and modelled, the flight trials will serve to validate the correctness of those models and to determine the safety margins which must be applied to guarantee specific service

performance with system performance models.

6 SIMULATION ENVIRONMENT FOR VALIDATION

The previous sections indicate that merely real measurements would not suffice or be far too expensive for the operational validation of the GNSS-1 concept. Simulations are essential to reduce the time required for validation, to cover special “worst-case” conditions and to reduce the cost of an operational validation campaign.

Therefore, dedicated simulation environments should be established specifically for these tasks. Three different levels of simulation environments have been proposed.

6.1 Receiver validation environment

This would require a set-up including a GNSS signal generator, constellation and aircraft dynamic models to provide inputs for a physical receiver. Figure 3 depicts the environment. Aspects relating to acquisition, tracking, interference and multi-path could be covered within this environment.

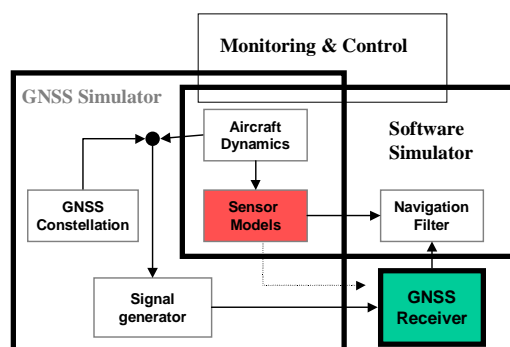


Figure 3: Receiver validation environment

6.2 TSP validation environment

The TSP environment requires a closed loop in which the navigation output is fed back through a guidance module into the aircraft dynamics models which in turn provides the input for the signal generator. Figure 4 illustrates the set-up.

For this set-up the receiver validation environment (i.e. physical receiver in the loop) could be augmented by a guidance model or even a complete flight simulator to incorporate the human factor. However, some dedicated fast-time simulations require an all-software simulator.

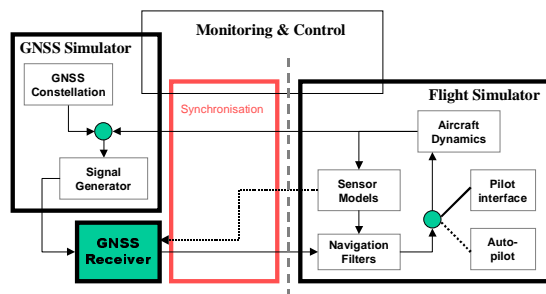


Figure 4: TSP validation environment

6.3 Operational validation environment

The operational environment (Figure 5) focuses on the aircraft's surroundings (e.g. multiple aircraft, ATC and special terminal conditions). In this case the performance of a physical receiver is less important. Integrating a software module with a coupled flight and ATC simulator to determine the navigation performance is likely to provide the best results.

One should bear in mind that the simulation environments provide the most realistic performance when as many H/W components as possible are incorporated.

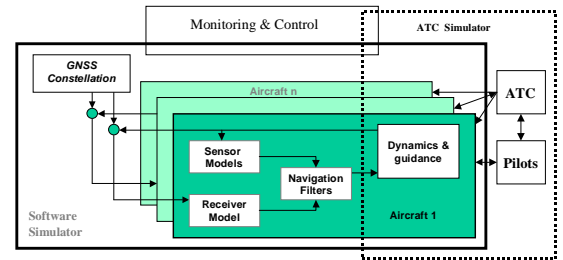


Figure 5: Operational validation

7 CONCLUSIONS

The main conclusions from the GPV study are as follows:

- SIS validation can be based mainly on real measurements. Failure analysis and simulation tools are required to cover special conditions,
- Available receiver tests (i.e. MOPS) are not sufficient, especially with regard to multi-path and integrated receivers. Additional tests have been proposed,
- Receiver, TSP and operational validation require extensive simulation. Simulation environments have been proposed,
- Simulation environments present the additional complication of validating the models,
- Flight trials should support model validation and should always be considered as the ultimate proof.



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