User RAIM Integrity Testing with Upgraded German Galileo Test Range GATE

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BIOGRAPHIES

Dr. Guenter Heinrichs received a Dipl.-Ing. degree in Communications Engineering from the University of Applied Science Aachen in 1988, a Dipl.-Ing. degree in Data Processing Engineering and a Dr.-Ing. degree in Electrical Engineering from the University Paderborn in 1991 and 1995, respectively. In 1996 he joined the Satellite Navigation department of MAN Technologie AG in Augsburg, Germany, where he was responsible for system architectures and design, and digital signal and data processing of satellite navigation receiver systems. From 1999 to April 2002 he has served as the head and R&D manager of MAN Technologie's satellite navigation department. In May 2002 he joined IFEN GmbH, Poing, Germany, where he is currently the head of the customer applications department and business development.

Erwin Loehnert received a diploma in Aerospace Engineering in 1993 from the Munich University of Technology. In 1994 he joined the Institute of Navigation and Geodesy of the University of the Bundeswehr Munich as a Research Associate, working mainly for aerogravimetry and GPS/INS integration. In 2000 he joined IFEN GmbH as a Project Manager for Galileo studies and integrity determination. Since 2001 he is Head of the Mobile Solutions department, managing several projects and currently being the GATE manager.

Elmar Wittmann received a Dipl.-Ing. degree in Geodesy from the Munich University of Technology in 2000 and then joined the IFEN GmbH, where he is now working as a systems engineer in the field of GPS/Galileo satellite navigation and currently being the head of GATE customer operations.

ABSTRACT

GATE is the only Galileo test and development range worldwide where already today - years before the full operability of the Galileo system in space - navigation is possible with realistic Galileo signals on three frequencies simultaneously in an outdoor environment. Thus, GATE is an important intermediate step for Galileo on its way from the laboratory to the orbit in terms of realistic RF signal transmission. After its extension to a total number of eight transmits stations GATE is now supporting Galileo user integrity testing more effectively.

The paper will give an overview on the work that was performed in the frame of the latest system upgrade of the GATE test environment as well as the activities related to its certification as an open-air test infrastructure. It further will present results of user RAIM integrity and user interference mitigation tests obtained by test campaigns in the upgraded GATE test range by using commercially available Galileo receivers.

INTRODUCTION

The outdoor test range GATE operates following the same physical principles like Galileo and GPS to allow users finding their position, velocity and time (PVT). The receiver can determine its PVT by calculating the distance to the virtual satellite, emulated by a transmitter station, and finding the intersection point. Through its infrastructure, GATE is able to radiate the original navigation signals from Galileo satellites, to simulate natural influences like ionosphere or troposphere delays, to change characteristic parameters of signals and to adapt the signal strength as required, and thus to enable testing of standard respectively commercial receivers. GATE is capable of transmitting the Galileo OS (Open Service), the Galileo SoL (Safety of Life) Service on a functional basis, the Galileo CS (Commercial Service) default message) and a Galileo PRS (Public Regulated Service) noise/spectrum according to the latest Galileo SIS ICD version. Hence GATE allows for the usage of any unmodified commercial Galileo receiver which complies with this signal specification.

To enable RAIM integrity processing with fault detection and exclusion (RAIM FDE), at least six measurements are required. However, more measurements are often needed depending on the satellite geometry and to serve for higher robustness. For this reason the GATE test range with its former six transmit stations was extended by two further stations, now eight in total. In addition, GATE is now capable to emulate some basic configurable feared events scenarios on system/satellite level after the upgrade, thus supporting GPS and GATE/ Galileo dual constellation RAIM, individual user integrity test scenarios as well as test of receivers with different RAIM functionalities implemented.

The last step in the upgrade activities of GATE was its certification as an open-air test infrastructure. The successful completion of this certification process which was performed by the German certifier NavCert together with TÜV SÜD gave proof of the conformity of the test range with its specifications. Also its qualification for the execution of dedicated tests of Galileo Safety-of-Life (SoL) equipment could be successfully verified.

The test range is open to all users worldwide and has started commercial operations on August 1st in 2008. The official opening of the extended test range took place in February 2011. Since the beginning of this year IFEN GmbH is in charge of operating GATE at least until the end of 2013. The operation contract was awarded by the German Aerospace Center (DLR) who is the owner of the test range.

The paper will give an overview on the work that was performed in the frame of the latest system upgrade of the GATE test environment as well as the activities related to its certification as an open-air test infrastructure. It further will present results of user RAIM integrity and user interference mitigation tests obtained by test campaigns in the upgraded GATE test range by using commercially available Galileo receivers.

GATE TEST RANGE OVERVIEW

The GATE test area is located in the region of Berchtesgaden in the very south-eastern part of Germany/Bavaria. Berchtesgaden is surrounded by high mountains that are rising up to over 2000 meters. The installation of the GATE transmitters on well exposed positions allows for the emission of the GATE signals with average elevation angles between 10 to 15 degrees from a user's point of view, when located within the GATE test area. The overall size of this area is approximately 65 km².

Consisting of the eight virtual „Galileo satellites" located on top of several mountains around the GATE test area in Berchtesgaden, a well suited topology is available to support different realistic GNSS testing scenarios. The Galileo signals are transmitted simultaneously on all three frequencies E1, E5ab and E6 compliant to the Galileo Open Service (OS) ICD specification. With the GATE "Virtual Satellite Mode" a realistic moving Galileo satellite constellation can be simulated, supporting commercial Galileo receivers without any modification. Two monitoring stations located within the test area are receiving and processing these signals. A central processing facility which constitutes the core of the GATE system is steering and controlling the signal transmission including the simulation of realistic ionosphere and troposphere errors. Due to its character as an outdoor test range with over-the-air signal transmission GATE also allows for the examination of real signal multipath and interference scenarios in the field.

An overview of the test range with its transmit and monitoring stations is depicted in the following figure.

Figure 1: Overview of the upgraded GATE test range

Apart from the testbed system infrastructure required for the generation and monitoring of the Galileo signals, GATE also provides adequate means to support professional user testing in the field: The GATE service office is located in the centre of the test area and a fully equipped measuring vehicle is available which includes a GPS-RTK/IMU based high-precision reference position unit and also serves as an installation platform for additional user equipment to be tested.


Figure 2: GATE service office and measuring vehicle

GATE EXTENSION ACTIVITIES

In addition to the six transmit stations of the primary GATE constellation the system was extended by two further stations in 2010. An in-depth analysis was initially performed to identify various locations particularly suited for the establishment of the two additional GTS with regard to their "visibility", i.e. the targeted signal receptability in wide parts of the test area. More than ten different potential installation sites have been investigated. The analysis was based on software simulations - using detailed terrain model data - as well as physical inspections of the potential installation sites, resulting in two favorite candidates. The locations that were finally selected allow for a particularly widespread signal coverage thanks to their exposed positions on the mountains "Rauhenkopf" (1.585 m altitude) and "Brettgabel" (1.840 m altitude). Both sites provide an acceptable accessibility for installation and maintenance activities. However, they did not feature any available infrastructure that could be used for the installation of the GTS, e.g. in terms of mounting platforms, power supply, communication links etc. Thus, the concept of the only existing autonomous GATE station so far, i.e. the GTS Gruenstein, was applied for the new stations: Two containers, each of them equipped with a number of solar panels, batteries and a dedicated GSM/WLAN communication infrastructure were installed (see Fig. 3) prior to the set-up of the signal transmission units. For each station the preparation of a solid foundation was required. Furthermore, considering the significant exposure to lightning in these alpine region, special attention was paid to the establishment of appropriate lightning protection systems. As both installation sites are only accessible via hiking trails the transportation of all construction materials and equipment was done by helicopters.

Figure 3: Additional autonomous GATE transmit stations GTS 7 & 8

Apart from the development and installation of the two additional transmit stations various further implementation and upgrade activities had to be performed in the framework of the test range extension. For instance an upgrade of the GATE processing facility (GPF) was required concerning the steering and monitoring of the additional signals. Also the monitoring and control facility software and the corresponding communication infrastructure in the GATE control center was adopted and extended accordingly. Thanks to the extension of the GATE test range a significantly increased signal coverage was obtained. An example of the number of GATE "satellites" actually received during a dynamic field test in the central area is depicted in Fig. 4. As it can be seen there in wide parts a minimum number of six signals is available, of course depending on the local environment such as buildings, vegetation etc.

Figure 4: GATE signal availability in the central area

RAIM INTEGRITY TESTING WITH GATE

The goal of future or modernized GNSS (Global Navigation Satellite System) is not only to provide higher accuracy as comparable systems today but also to satisfy the safety critical needs of certain application areas like in the aeronautics, maritime or rail domain by providing a corresponding Safety-of-Life (SoL) service as it is planned for Galileo. Safety critical applications thus require a "trustable" position, denoted in GNSS as integrity. According to [1], a navigation system shall further deliver an alarm when the error in the computed user position exceeds an allowable threshold ("alarm limit"). This warning has to be issued to the user within a given period of time ("time to alarm") and with a given probability ("integrity risk"). Integrity is obtained by implementing appropriate mechanisms/algorithms at several levels. The integrity evaluation is typically performed either:

- at system level: the system provides integrity when it can detect errors and warn the users in a timely manner. In case of Galileo the Global Integrity Concept (GIC) etc.
- at user level: through receiver autonomous integrity monitoring (RAIM) etc.

The new approach for Galileo to provide integrity assumes that the integrity task is performed mainly on user level by applying RAIM algorithms within the user receiver. For RAIM integrity processing at user level a certain number of available satellites is required. To enable RAIM FD (Fault detection in RAIM), at least five measurements / satellites are required. RAIM FDE, i.e. fault detection in RAIM with the ability to exclude faulty data, requires at least six measurements. For a dual constellation scenario (GPS + GATE/Galileo/IOV), one additional satellite is required. In order to test meaningful integrity scenarios in GATE, two further considerations have to be taken into account:

- In GATE a so called "PRN change" is initiated from time to time in order to maintain a good horizontal DOP performance. To this end one satellite of the dynamic virtual constellation is replaced by another one more adequate in terms of the overall satellite geometry. This results in the temporary unavailability of one satellite which means that only the maximum number of satellites minus one can be used during this time.
- Due to the topography and shadowing effects by buildings and vegetation within the GATE test area, there are not always the maximum number of satellites (GATE transmit stations, GTS) visible.

Furthermore, even more measurements are often needed depending on the current satellite geometry and to serve for higher robustness. Thus, to perform robust RAIM FDE integrity tests within GATE at least eight satellites should be available. This was the main reason to extend the testbed by two additional GTS from six to eight transmit stations.

Note, that the GATE system provides no real RAIM capable GATE User Terminal (GUT). However, the standard GUT is principally capable to detect pseudorange errors – provided that they were induced by "large enough" feared Events (FE) – and to exclude the corrupted signal (again if large enough) for positioning by using implemented simple signal quality check algorithms.

The following Fig. 5 shows the GUT graphical user interface (GUI), which is used to command and control the GATE user receiver as well as to perform the positioning and graphical visualization of GATE data (viewer for position accuracy, coordinates, measurements, map, scatter plot etc.). Fig. 5 depicts a static GATE scenario, in which the PRN 26 signal was corrupted by the GPF with a FE on all three Galileo pseudoranges/frequencies E1, E5a and E5b. Because no signal quality checker is activated in the GUT software, the position calculated includes also the corrupted PRN 26 signal and thus a wrong position with an offset of about 440 meters (see red circles in Fig. 5) with respect to the true position is determined. The position drift due to PRN 26 can be clearly seen in the Scatter Plot.

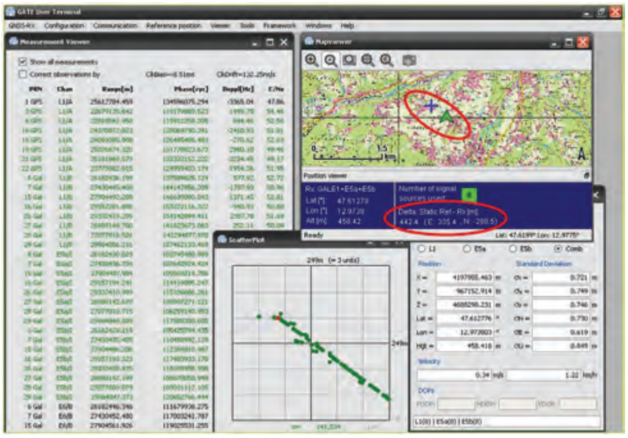

Figure 5: Wrong GUT position fix with corrupted PRN 26 (GUT signal quality checker turned OFF)

Fig. 6 shows the GUT position solution for the same GATE scenario as described above, but now with the GUT signal quality checker activated. The position fix is now fairly well and better than 1 meter with respect to the true position (see red circles in Fig. 6). As it can be further seen in Fig. 6 in the measurement and residual viewer is that the GUT signal quality checker detects and excludes the wrong/corrupted PRN 26 signal from the position solution, which is then correctly calculated by the remaining seven satellites.

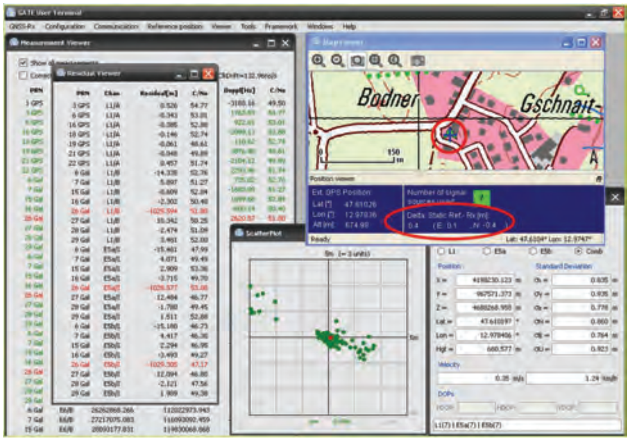

Figure 6: Correct GUT position fix with corrupted PRN 26 (GUT signal quality checker turned ON)

In the following, some functional integrity / RAIM test results are presented performed with an upgraded GATE testbed of eight stations and a RAIM capable Septentrio user receiver. As GATE is neither designed nor capable to validate the real Galileo satellite navigation system with actual integrity performance parameters (horizontal/ vertical alert limits, integrity risk, time to alarm etc.), the integrity test scenarios performed in GATE have to be regarded on a functional basis / qualitative level only. Fig. 7 shows the dual frequency E1/E5b user position, the position accuracy, the RAIM parameters and the planimetric plot (true offset of receiver position solution to the reference position) of a static integrity test (experiment I: normal operation with eight satellites) with the Septentrio user receiver performed in the GATE testbed close to the GATE office. Because GATE is specified only for a horizontal position accuracy of better than 10 meters (2 sigma) and not for the vertical due to its terrestrial nature, the integrity results presented are focused on the horizontal position and corresponding horizontal protection limits (HPL) and alert limits (HERL).

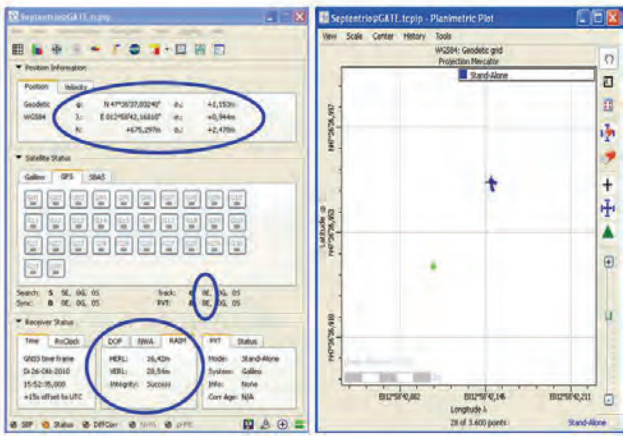

Figure 7: Position with RAIM parameters (HERL=16.42m) and planimetric plot

Fig. 8 depicts the receiver channels status with the GATE/Galileo satellites tracked on the SoL frequencies E1 and E5b for this experiment.

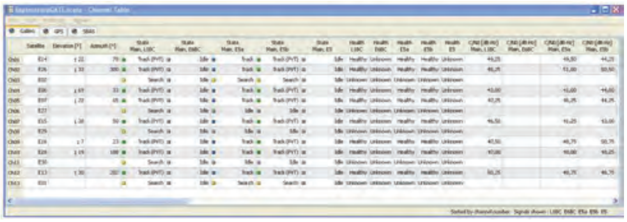

Figure 8: Receiver channels status, showing E1/E5b PVT solution

Fig. 9 shows the corresponding results of the horizontal protection limits (HPL). As it can be seen from the figure the resulting HPLs are around 7 meters, indicating "Normal Operation", detailed to 100% for "APV-I Operation and 100% for "CAT-I Operation" according to the limits set.

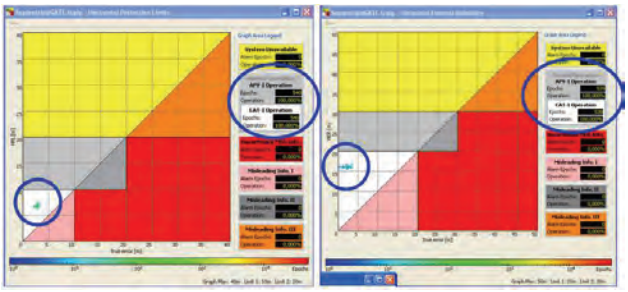

Figure 9: Experiment I: Horizontal protection and alert limits, showing "HPL/HERL normal operation"

In the experiment II (see Fig. 10), one single satellite out of the eight satellites was removed from the position solution (PVT). The HERL increased from 16.42 m to a value of 40.60m resulting to HERL "system unavailable".

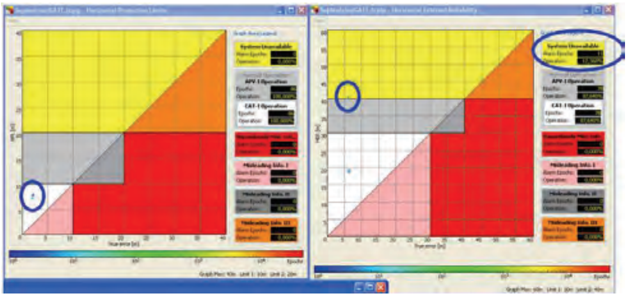

Figure 10: Experiment II: HERL of 40.60m, leading to "HERL system unavailable"

Finally, in the "integrity" experiment III, a feared event (FE) was introduced in this way that the steering algorithm of the GATE processing facility was de-activated for a single satellite (PRN 25 in the test), which causes the virtual satellite to drift slowly away (see Fig. 11).

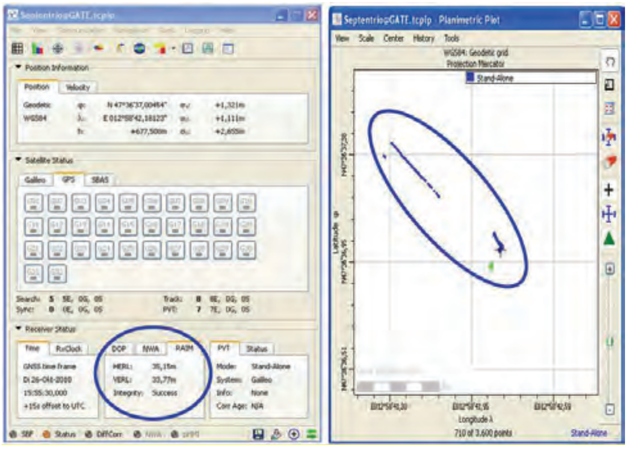

Figure 11: Exp. III: Position with RAIM parameters (HERL=35.15m) and planimetric plot, indicating user postion drift due to induced PRN 25 FE

This position drift results after some time into a Hazardously Misleading Information for several epochs (see HPL plot in Fig. 12 with corresponding 22 alarm epochs). Furthermore, due to the increased HERL value of 35.15m, an "HERL system unavailable" is raised.

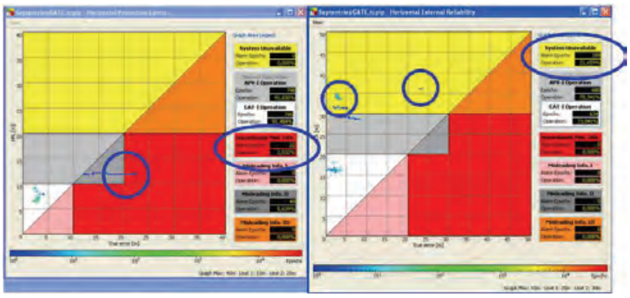

Figure 12: Experiment III: HPL Plot, indicating "Hazardously Misleading Information", HERL of 35.15m, leading to "HERL system unavailable"

Because a RAIM algorithm is implemented in the Septentrio test receiver, this receiver is capable to detect and to exclude (FDE) the feared event corrupted signal PRN 25 and finally it rejects this signal from the internal PVT solution (see Fig. 13).

Figure 13: Receiver channels status, showing E1/E5b PVT solution and the rejected (FE corrupted) PRN 25 signal

FUNCTIONAL INTEGRITY TESTING USING GATE I/NAV MESSAGE CONFIGURABILTY

In order to support functional integrity testing effectively, four new functionalities/commands for the GATE Processing Facility (GPF) to control the I/NAV integrity data broadcasted by the GATE system are available as following:

"CmdAlertSisma",

"CmdAlertSat",

"CmdSetSisma" and

"CmdResetSisma"

The first two commands allow for triggering integrity alert pages (either SISMA or Satellite Alert) according to the GATE/Galileo signal in space specification. The last two commands can be used to modify the integrity table content/values for each satellite, e.g. indicating the SISMA quality value, "satellite not OK for use" or "satellite not monitored", which are broadcast from the system to the user.

At the start of a GATE VSM test scenario, the SISMA values indicated by the integrity flag (IF) are set to 1 (highest quality) by default for all satellites.

During a functional integrity scenario, a satellite alert "CmdAlertSat" command may be initiated by the GATE operator at GMCF level, e.g. with the parameters "7,0;" and "13,0;" which are then processed by the GPF, fed into the I/NAV message stream and then transmitted via the GATE SIS to the GATE testbed and user terminal, respectively. At the GUT GUI it will invoke the pop-up of the information window "Integrity Alert", indicating a "NOK" for satellites PRN 7 and 13 (see Fig. 14 and Fig. 15).

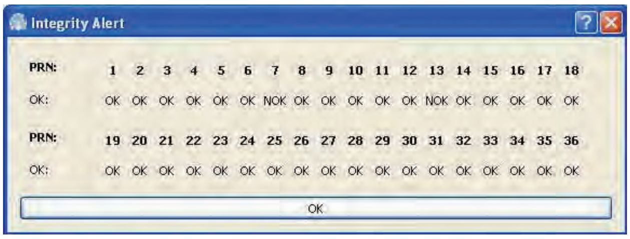

Figure 14: GUT GUI Integrity Alert Window showing initiated "NOK" for PRN 7 and 13

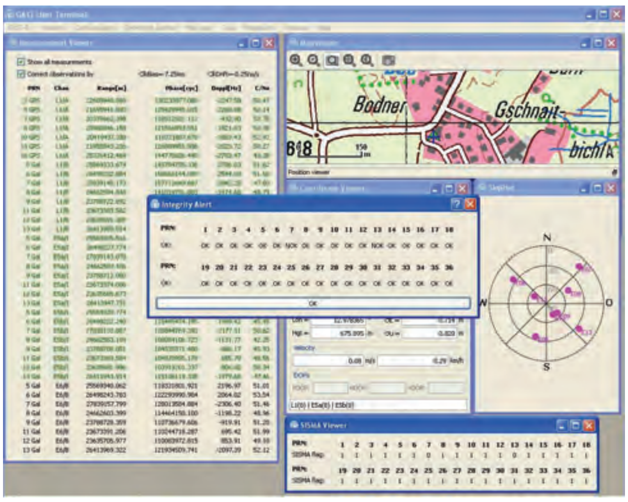

Figure 15: GUT GUI with Integrity Alert Window and SISMA Viewer indicating "NOK" for PRN 7 and 13

Depending on the settings of the "Functional SoL Receiver" parameter of the GUT Configure Positioning window (see Fig. 16), different GUT positioning methodologies will be performed. If the Functional SoL Receiver box is not activated, the GUT will just show the integrity information (see Fig. 15), but not react on it, i.e. positioning will be done with all signals available, including the ones with IF flag. However, if the SoL receiver functionality is activated (see Fig. 16), then the GUT will automatically exclude the signals with "NOK" on E1 and/or E5b frequency from the positioning algorithm.

Figure 16: GUT Configure Positioning Window with activated SoL receiver functionality

After a functional integrity test was performed, any integrity commands which were configured can be reset, either individually for each satellite (CmdSetSisma), or for all signals simultaneously (CmdResetSisma), without the need of a system restart.

USE OF GATE FOR ESA GNSS EVOLUTION PROGRAMME

GATE will be used as test environment for the HISTB (High Integrity Safety critical regional augmentation Test-Bed) project and the MLUTB (Multi-Constellation Regional System Land User Test-Bed) project, launched in the framework of the ESA`s European GNSS Evolution Programme, 2nd phase.

MLUTB started in December 2010, Kick-off for the GATE experimentation activities in the frame of HISTB was in September this year. Both projects will undertake extensive test campaigns in GATE in 2012.

The aim of HISTB which will be based on the existing SPEED (Support Platform for EGNOS Evolutions and Demonstrations) is to facilitate the running of experiments and use cases relating to high-integrity aeronautical performance. A number of experiments will be performed to this end in the course of various experimentation cycles, also including tests within the GATE testbed. In the context of integrity testing there is one particularly relevant use case focusing on "user integrity advanced concepts". The objective of this use case is to assess the detection capabilities of ARAIM user algorithm under satellite feared event conditions. For this purpose the GATE processing facility will be modified for more sophisticated feared event scenarios, allowing for higher flexibility in manipulating the pseudoranges of GATE signals.

GATE CERTIFICATION

The test range upgrade and extension activities also included the certification of the GATE system and its operation. The certification process has been performed by the independent company NavCert GmbH together with the independent third-party certifier TÜV SÜD. The general requirements for the competence of testing and calibration laboratories (ISO/IEC 17025) served as a basis for the certification process and resulted in a set of operational and technical certification requirements generated for the GATE test range. The compliance of the testbed with the specifications e.g. in terms of the system performance and functionality has been validated by means of a comprehensive test campaign complemented by a technical review process. The tests in Berchtesgaden included for instance several static and dynamic tests in the different GATE operation modes, the analysis of the transmitted signals regarding e.g. signal spectrum and power, the performance of integrity tests etc.

Regarding the compliance of the GATE operation with the related quality management standards several audits were performed including a review process focusing on the operational aspects, particularly with regard to the procedures applied for the GATE customer operation.

The successful completion of this certification process resulted in the issuing of the formal certificate approving the following GATE features:

- Conformance of the GATE signal characteristics and signal quality to the Galileo specification (Galileo OS SIS ICD 1.1) including the simultaneous usability of all Galileo frequencies E1, E5a, E5b and E6.
- Conformance of the GATE test range to DIN EN ISO / IEC 17025 standard as a Galileo open-air test laboratory with eight transmit stations and a covered area of about 65 km².
- Feasibility of Galileo receiver integrity testing (RAIM) for Safety-of-Life (SoL) applications in GATE.

The official certification mark for GATE is depicted below.

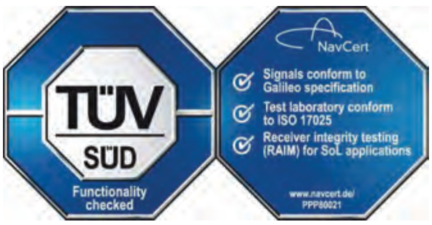

Figure 17: GATE certification mark

CONCLUSION AND OUTLOOK

After its latest upgrade the GATE test range is now featuring eight transmit stations thus not only allowing for realistic Galileo positioning tests but also supporting user integrity testing more effectively. In February 2011 the extended testbed was officially (re-)opened. It can be booked by any user worldwide for testing Galileo receiver equipment and applications under realistic outdoor conditions.

The paper presented the high flexibility and configurability of GATE with respect to functional integrity test scenarios and results of a dedicated functional RAIM test with GATE were presented. It was further outlined that GATE will serve as outdoor test facility for extensive GPS/Galileo test campaigns for the projects HISTB and MLUTB in the frame of ESA's European GNSS Evolution Programme.

Regarding the upcoming availability of the first Galileo IOV satellite batch scheduled for October 2011, and a second batch in 2012, a combined use of the eight GATE signals together with the Galileo IOV SVs will result in a further enhanced constellation of up to twelve visible "Galileo satellites", reflecting a complete Galileo FOC constellation.

Further up-to-date information about GATE can be found on the official homepage www.gate-testbed.com

ACKNOWLEDGMENTS

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