Journal of Global Positioning Systems (2007)
Vol.6, No.2: 108-118

Journal of Global Positioning Systems
2007

First Outdoor Positioning Results with Real Galileo Signals by Using the German Galileo Test and Development Environment - GATE

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Abstract. Under the leadership of IFEN GmbH, the Galileo Test and Development Environment GATE is being built up in southern Germany by a consortium of several German companies and institutes on behalf of the German Aerospace Center (DLR) with funding by the German Federal Ministry of Education and Research. The performance tests regarding the user positioning performance will cover various test scenarios for static and dynamic cases. The tests will be performed in all available GATE operation modes with GATE signals only and in combination with GPS. Preliminary test during system testing phase showed already impressive positioning performance with dedicated signals and services. The paper gives an overview on the variant test scenarios and setups and illustrates the detailed hardware setup. An introduction in the GATE Backend Receiver Software, which computes the position solution, is presented. It describes the test procedures and shows the test results. Finally an evaluation on the different GATE services with respect to the positioning performance is presented.

Keywords: Galileo, Pseudolites, GNSS

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1 Introduction

GATE is a ground-based realistic test environment for developers of receivers, applications and services for the future satellite navigation system Galileo. GATE is currently being built-up and as from beginning of October 2007 - several years before Galileo becomes fully operational - Galileo signals will be emitted by 6 earth-fixed transmitters in the area of Berchtesgaden, located in the southeast of Germany in the German Alps. This will provide the opportunity for receiver, application and service developers to perform realistic field-tests of hardware and software for Galileo at an early stage. In this way GATE will also support German and European products for Galileo entering the market. GATE is currently in the experimental operation phase, which will lead to full operational capability (FOC) soon.

While the motivation of the US ground-based ranging test bed Yuma in the 70's was to prove the concept of satellite navigation, no one doubts that Galileo will work from a conceptual point of view. However, it is still an ambitious technological project, introducing a signal structure far more sophisticated than the GPS C/A Code. In fact there are three major mission objectives to be covered by GATE – Signal Experiments, Receiver Testing and User applications.

2 GATE Infrastructure & Test Area

GATE System Architecture

Differing from real (navigation) satellite missions a differentiation of the GATE system into the typical sectors Space Segment, Ground Segment and User Segment is not adequate. A division of the GATE system into the following four segments was considered to be more appropriate:

- The Transmit Segment (GATS), consisting of six earth-fixed GATE Transmit Stations enclosing the service area.
- The Mission Segment (GAMS), consisting of two GATE Monitoring Stations (GMS) and the GATE Processing Facility (GPF) located within the test area. The GPF provides real-time estimation of the system parameters (e.g., transmitter clocks), generates navigation messages, steers the signal generators, and sustains the "virtual constellation and environment."
- The Control Segment (GCS) includes the GATE Monitoring & Control Facility (GMCF), the GATE Archiving & Data Server (GADS), and the GATE Time Facility (GTF).
- The Support Segment comprising the facilities and functionalities for preparing and supporting the

GATE missions. These are in particular the mobile GATE User Terminal (GUT) with the user receiver, the GATE Mission Support Facility (GMSF), and the GATE Signal Laboratory (GSL).

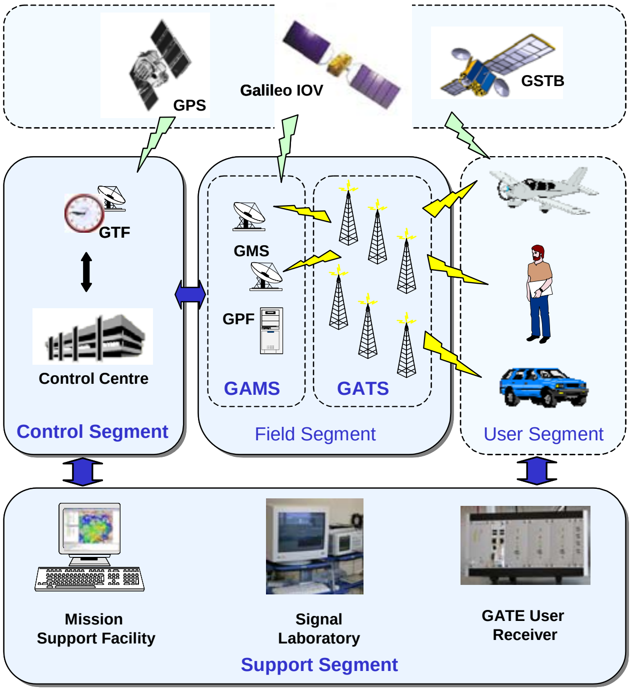


Fig.1 GATE Infrastructure Overview

Fig. 1 gives an general overview of the system architecture of the GATE infrastructure.

The ground-based transmitters, which are part of the GATE Transmit Segment (GATS), will emit all frequencies foreseen for Galileo. Therefore they have to be flexible in signal generation and adaptive to changes in signal structure. As GATE is a real-time system it is necessary to feed the navigation message in real-time to the transmitters. They are also equipped with stable atomic clocks. The following Fig. 2 shows the six envisaged transmitter locations, as well as the transmitter rack and the corresponding transmit antenna.

The GATE Signal Generators developed by Astrium GmbH are designed to generate simultaneously the Galileo navigation signals in the E5, E6 and L1 band. As shown on the left photo in FIG. 2, its major building blocks are the Control Computer, a Rubidium Reference Clock Unit and three (mostly identical) Signal Generation Units, one for each Galileo frequency band, followed by an RF amplifier section. With exception of the Voltage controlled Oscillator (VCO) for the generation of the RF carrier frequency, the Signal Generation Units are based on identical hardware providing a high degree of freedom to be configured by software according to the different channel setup requirements.

Fig. 2 GATE Transmitter Locations and Transmitter Rack GATE Infrastructure Overview

The GATE Mission Segment (GAMS) monitors the navigation signals by using two GATE Monitoring Stations (GMS), performs the time synchronisation of all system clocks and generates navigation messages and steering commands to be sent to the six transmitters. The tasks denoted above are mainly performed by the two GAMS core elements, the GATE Processing Facility (GPF) and the GATE Monitor Receiver (GMRx), both developed by IFEN GmbH.

The GATE Control Segment (GCS) includes all the functionality and facilities that are required for the mission control and operation. The main tasks it has to perform are to monitor and control the entire GATE system, to host and operate the control centre, which serves as operational node of GATE including e.g. the mission planning, to host and provide the GATE system time, and to archive the GATE mission data.

The main tasks of the GATE Support Segment (GSS) finally comprise the appropriate preparation, i.e. simulation and planning, of the GATE experiments with dedicated software tools, as well as the provision of the GATE User Terminals equipped with a combined Galileo/GPS receiver.

GATE Test Area Berchtesgaden / Germany

The GATE test area is located in the region of Berchtesgaden in the very south-eastern part of Germany / Bavaria. The service area is depicted in the maps shown in FIG. 8 below. The GATE test area, which is roughly limited by the imaginary connection lines between the signal transmitters, has a size of about 65 km², while the GATE core test area, as marked in Fig. 3 below on the right hand side, is about 25 km². The two monitoring stations are located at an exposed position quite centric within the GATE test area. As it can be seen from FIG. 3 below, Berchtesgaden is surrounded by high mountains rising up to over 2000 m. The establishment 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 located within the GATE test area.

Fig. 3 GATE Service Area Berchtesgaden/Germany (core test area marked in red, transmitters marked as red dots) and view into the GATE test area

Five GTSs will be set up using already existing infrastructure, e.g. TV or mobile phone masts. Additionally, only one completely autonomous GTS has to be established. Within this context, the German Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway (BNetzA) has already approved the usage of the requested frequency bands E5a/b, E6 and L1 for the transmission of the GATE signals in the area of Berchtesgaden.

GATE Field Installation

With the set-up of the autonomous station at the mountain Gruenstein the in-field installation of the testbed has recently been started. The container for accommodating the transmit equipment was installed by helicopter at a location close to the mountain top. The solar panels for the autonomous power supply were finally mounted on the top of the container. Fig. 4 shows the GTS container with the view into the valley.

Fig. 4 Transmit Station at the Gruenstein mountain and Helicopter transport of GTS rack

The first two transmit units were installed subsequently at the locations Gruenstein and Stoehrhaus. First tests of remotely accessing and controlling the transmit station were performed successfully. The set up of the transmit equipment on the remaining stations has taken place in January and February 2007.

3 The GATE/GALILEO RECEIVERS

The GATE user terminal consists of the receiver itself and the user interface that is in fact a Panasonic Toughbook with touch screen TFT display. The user interface and the receiver communicate via Ethernet cable over UDP protocol. The navigation processing and visualization is done on the user interface, shown in Fig. 5.

The GATE user terminal is a three-frequency GPS / Galileo receiver that covers GPS L1, Galileo L1, Galileo E5a and E5b and Galileo E6 positioning. Since there is still no definition of the Galileo E6 CNAV navigation message content, positioning with E6 is currently not possible. For Galileo/GATE L1 and or E5b positioning the Galileo/GATE INAV message is used. For Galileo/GATE E5a positioning the FNAV message is used. In the actual development stage the navigation software processes each frequency on its own, except of reasonable ionosphere free linear combinations like Galileo/GATE L1 and E5a or L1 and E5b. The latter frequency combination benefits from the fast I/NAV message transmission via both frequencies and leads to a position fix after minimal 15 seconds and maximal 29 seconds, after acquisition of signals from at least three transmitters/satellites was achieved. The navigation software also provides various logging capabilities for data post processing. Additional the GATE User Terminal provides NMEA position message output via serial COM port.

The algorithm used for position estimation is an epoch-by-epoch standard least-square adjustment, because this yields to unfiltered position estimates and therefore unpolished performance results. The GATE User Terminal Software (GUT-SW) differs to other GNSS positioning software packages in that way, that different navigation message data streams have to be handled. For GPS positioning we have the normal GPS navigation message bitstream, also in the GATE Virtual Satellite Mode (VSM), where the navigation message is based on the Galileo navigation message. In GATE Base Mode (BM) and Extended Base Mode (EBM) is content of the navigation message is different, because there we have satellites/transmitters located on the earth. These locations cannot be described adequately by the elements of Kepler and therefore the navigation message content had to be changed. The mode of operation of the GATE system is detected by a synchronization word in the navigation message, so that the GUT-SW can switch to the adequate navigation message-decoding module.

While in standard GPS positioning scenarios the centre of the earth as best guess for the users a-priori position, is sufficient to make the position solution converge to the correct solution, this will not work in GATE BM and EBM modes. The reason for this is the small-sized area of GATE. To make the position solution converge in GATE BM and EBM the approximate user position has to be known better than 50m in horizontal position and 10-5m in vertical position. The closer the user comes to the height of the lowest transmitter the worse is the height accuracy and the better the users approximate height has to be known. Therefore the GATE user equipment contains an external GPS Bluetooth receiver, which is typically a SIRF III GPS mouse, to feed the GUT-SW's positioning algorithm with a-priori coordinates. This external GPS receiver also enables the user on the flight comparison between the GPS estimated position and the position estimated with GATE/Galileo signals.

Fig. 5 GATE User Terminal

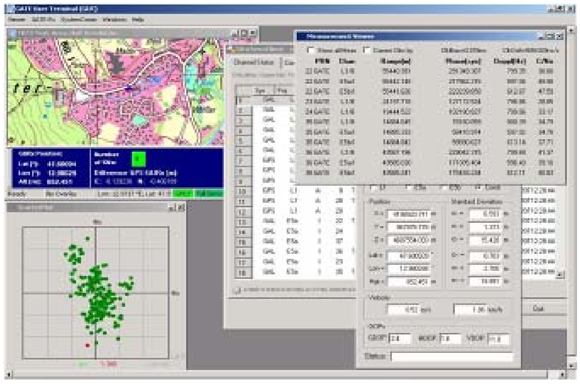


Fig. 6 GATE User Interface

Due to the very low elevation angles, usually not exceeding 15°, of the transmitters seen by the user in the GATE service area and the corresponding degradation of height accuracy, the GUT-SW additionally provides a 2-D positioning mode. In 2-D positioning mode the users height is fixed, which in fact means that the users height is set to the height estimated by the external GPS mouse. This 2-D positioning mode is automatically switched on, when only three transmit stations are visible and therefore improves the position availability for the GATE user.

Furthermore a special correction algorithm for the tropospheric delay in GATE BM and EBM is implemented. This tropospheric model is quite similar to a classical model for atmospheric correction of geodetic microwave distance measurements. This model is based on means values for monthly data of temperature, humidity and pressure over several years from a local weather station. Of course the user can enter actual weather data via the graphical user interface of the GATE user terminal software.

Positioning Performance in the GATE test area

The positioning performance tests presented in this article consists of static positioning tests at the GATE monitoring station on all available frequencies and combinations as well as static and dynamic positioning tests in the GATE area near the GATE central point in the middle of the service area. The positioning tests at the GATE monitoring station were performed with the GATE monitor receiver that contains a rubidium clock. The positioning tests in the GATE area were carried out with the GATE user receiver light. This light version of the user receiver only holds base-band processing boards for L1 and E5 frequency.

Fig. 7 Tropospheric path delay from GATE central point to the GATE transmitters

The GNSS antennas at the GATE monitoring station are mounted on a quite big transmitter pylon, operated by the "Bayerischen Rundfunk", which is shown in Fig. 7. The radio pylon is covered with transmitting antennas from various radio stations and mobile communication networks, which of course, provides no ideal "radio" environment. The impact can be seen by comparing a GPS only positioning solution from an antenna situated on the roof of the IFEN company building in Poing/Munich and a GPS only positioning solution from the GATE monitoring antenna mounted on the pylon. This comparison is illustrated in Fig. 8. However, tests performed up to now have shown that the GATE monitor antennas, especially designed for this harsh environment, work very well and that the "radio" environment at the pylon does not affect GATE operations. Furthermore it has to be noted, that the GATE monitor stations have to track GPS only for synchronization purposes, thus one single GPS satellite would suffice.

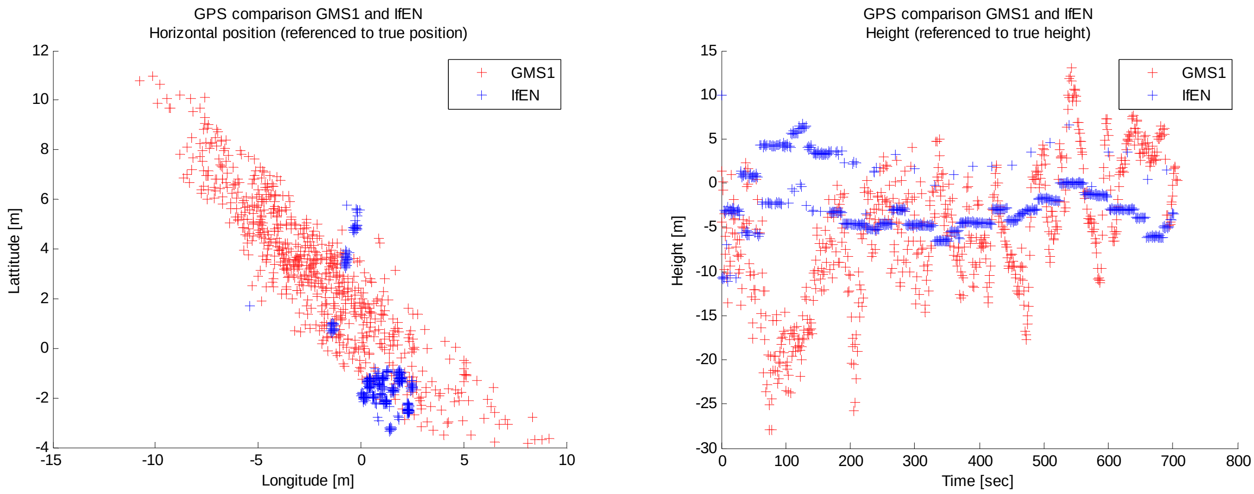


Fig. 8 Comparison of scattering of GPS position estimates at the GATE monitoring station (red crosses) and IFEN's roof antenna in Poing (blue crosses)

The red crosses on the left viewgraph denote the GPS position estimates at the GATE monitoring antenna, while the blue crosses denote the GPS position estimates at the IFEN roof antenna in Poing. Both position estimates are referenced to their true positions. For both experiments the Gut Software was used for positioning, ionospheric and tropospheric correction were switched off and no carrier smoothing was applied. While the position estimates from the IFEN roof antenna show a little scattering around the true position the scattering at the GMS1 antenna is bigger. The standard deviation of the position estimates is about 2.07m for the IFEN position and 4.51m for the GMS1 position. The right viewgraph shows the height estimates at both stations. Here also the estimates at the GMS1 station are more noisy than the ones at the IFEN antenna. It has to be noted that the number of tracked satellites differed between the GMS1 location and the IFEN antenna location. Since no obstructions at the IFEN roof antenna exist, the GATE receiver tracked here eight GPS satellites on average, compared to six and less for the GATE receiver at the GMS1 antenna at Sulzberg due to GPS shadowing by the radio mast. The "radio" environment at the communication pylon at Sulzberg is under further investigation. The following tests cover static positioning at the GATE monitoring station (GMS1) on GATE/Galileo frequencies L1 and E5a. For this test the GATE monitoring receiver, which is connected to the GATE monitoring antenna was used. An external rubidium clock clocks the monitor receiver. The left plot in Fig. 9 shows the horizontal position scattering around the true GMS1 position, which is around +-10m lateral and longitudinal which is at the accuracy level of the GPS position estimates shown in FIG. 8. As described before, the height accuracy in GATE BM and EBM is worse than for GPS or GATE VSM mode. This underlines a VDOP value of about 14.7 at the GMS1 location. The right viewgraph of Fig. 9 shows the difference of the height estimates on L1 and E5a referenced to the true height of GMS1. It can be noticed, that the variation of the height estimates from L1 observations are slightly smaller than the ones from E5a observations. This effect has to be further investigated because from the performance point of view, the E5a signal should be better than the L1 signal.

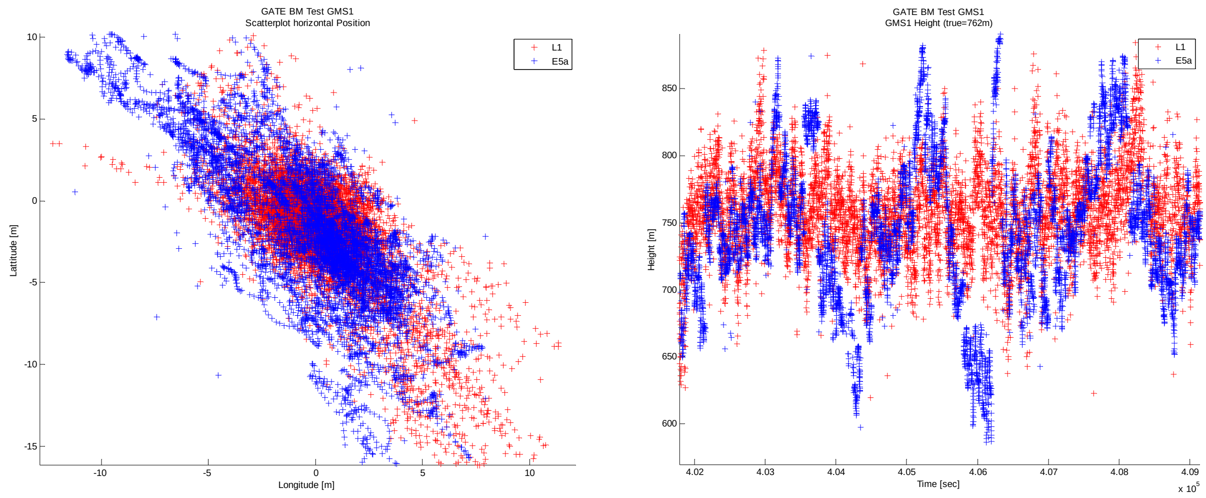


Fig.9 Comparison of position estimates with L1 (red crosses) and E5a (blue crosses) at the GATE monitoring station GMS1

Static field tests

At the GATE central point all transmit stations (GTS) are visible and HDOP and VDOP values are very good for the GATE service area. Therefore the positioning accuracy obtained is very favourable in the vicinity around the GATE central point. The Figs. 10a, 10b and 11 show the positioning performance at the GATE central point for a static receiver in the three different GATE modes. For this experiment the light version of the GATE user receiver was used. This light version of the GATE receiver was configured to perform only L1 and E5 base-band processing and has an internal TcXo clock. It was installed in a van with the GATE user antenna on the top of the van. The van was parked beside the road at a reference mark, which had been surveyed with a precision of 10 cm.

The experiment was performed in the GATE Base Mode and Extended Base Mode (Figs. 10a and 10b) as well as in Virtual Satellite Mode (Fig. 11), where the GATE/Galileo signals are simulated as they were transmitted from orbiting satellites. In fact of course the signals are transmitted by the earth fixed transmitters, so that signal fading and multipath effects, due to building and the landscape, are still present. The left viewgraphs in Figs. 10/11 show the position solutions on L1 frequency. The right-hand figures depict the corresponding E5a position solutions. The observation time for the static measurements was about 5 to 10 minutes for each GATE mode. The GATE position accuracies (2 σ) for these measurements are below 10 m for all three modes and both frequencies, L1 and E5.

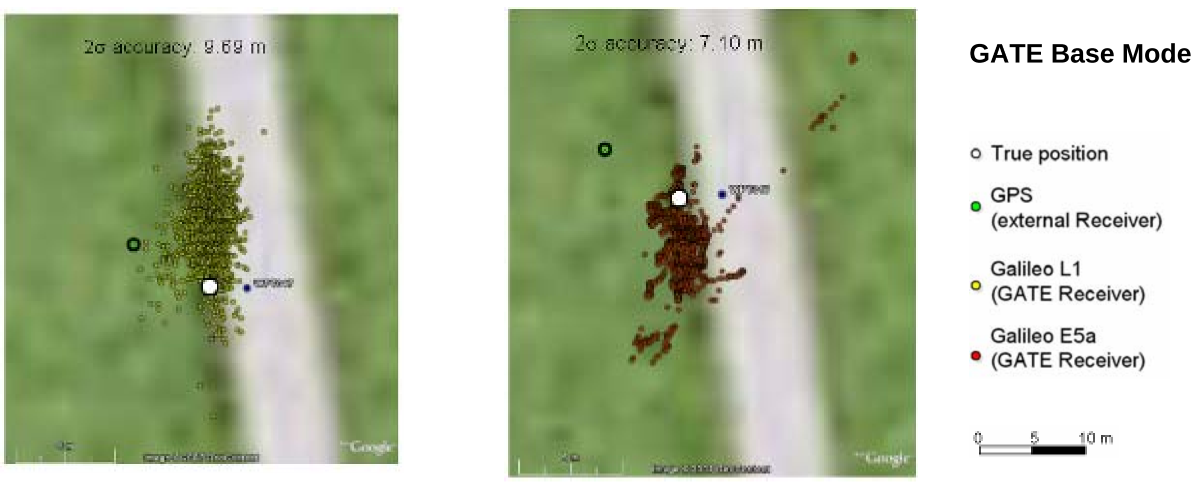


Fig. 10a Position estimates with L1 and E5a in BM at the GATE central point, Map © Google

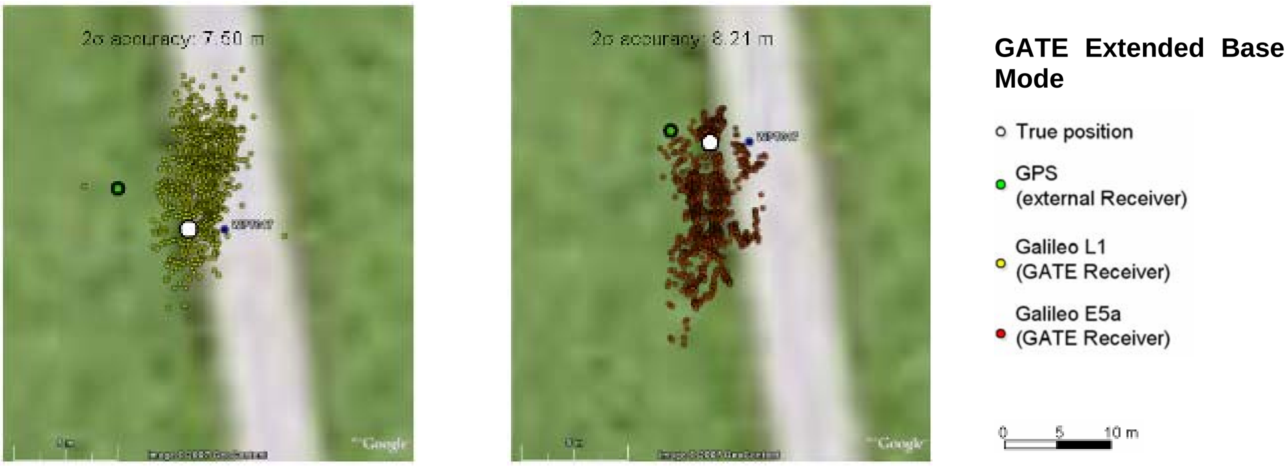


Fig. 10b Position estimates with L1 and E5a in EBM at the GATE central point, Map © Google

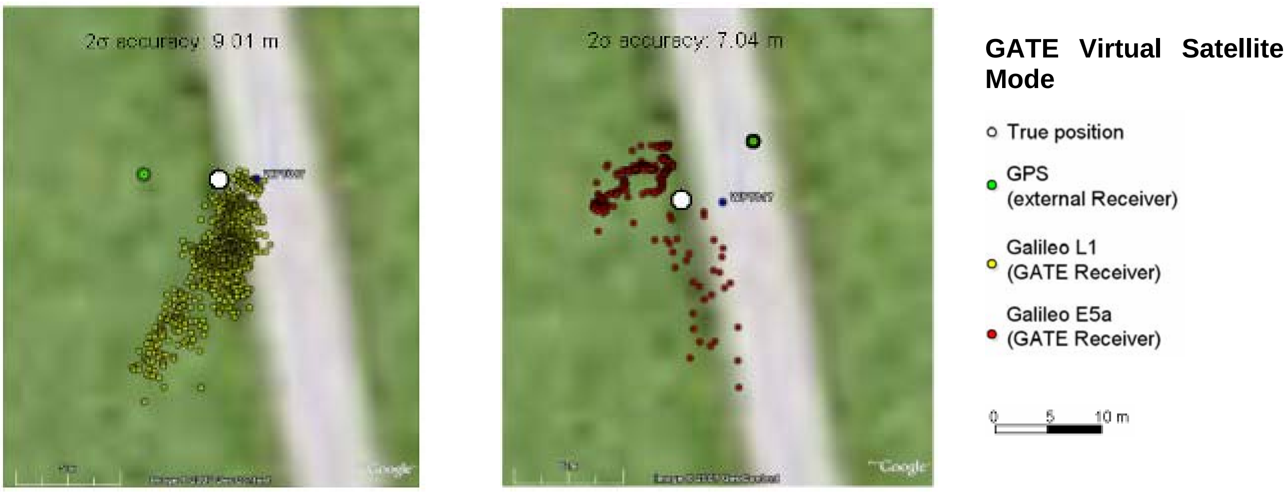


Fig. 11 Position estimates with L1 and E5a in VSM at the GATE central point, Map © Google

Dynamic field tests

Several tracking / positioning tests with the GATE system under dynamic conditions with a speed of up to 100 km/h were performed. The dynamic tests cover low dynamic tests with an averaged speed of about 30 kilometers per hour.

Fig. 12 shows the position solution from a dynamic positioning test in the GATE area in the GATE EBM mode. Due to shadowing of the direct line of sights, by trees and buildings, to some transmitters, especially in the south of the GATE area, a position fix can not always be reached (marked in yellow).

High dynamic tests on can only be performed at a section of the road B20 which passes the eastern part of the GATE area in north/south direction, where a good visibility of the GATE transmitters is available. The road B20 is the only one in the GATE area where it is allowed to drive at 100 km/h. As starting point a dedicated position at the roadside was selected where all 6 GATE transmitters could be tracked well. After a short time of static positioning with all 6 signal sources – to make sure that the GATE receiver is in a well-defined starting position with stable tracking – the test car was accelerated rapidly up to a velocity of more than 90 km/h.

The same test scenario was repeated for all three GATE modes (BM, EBM and VSM). The results of the test drives are presented in the following section. The GATE position data logged with the GATE User Terminal Software is displayed together with the corresponding GPS position data from the external COTS GPS receiver in the satellite image maps. Furthermore the speed of the test car for every measurement epoch is shown and plotted in the diagrams below the map images.

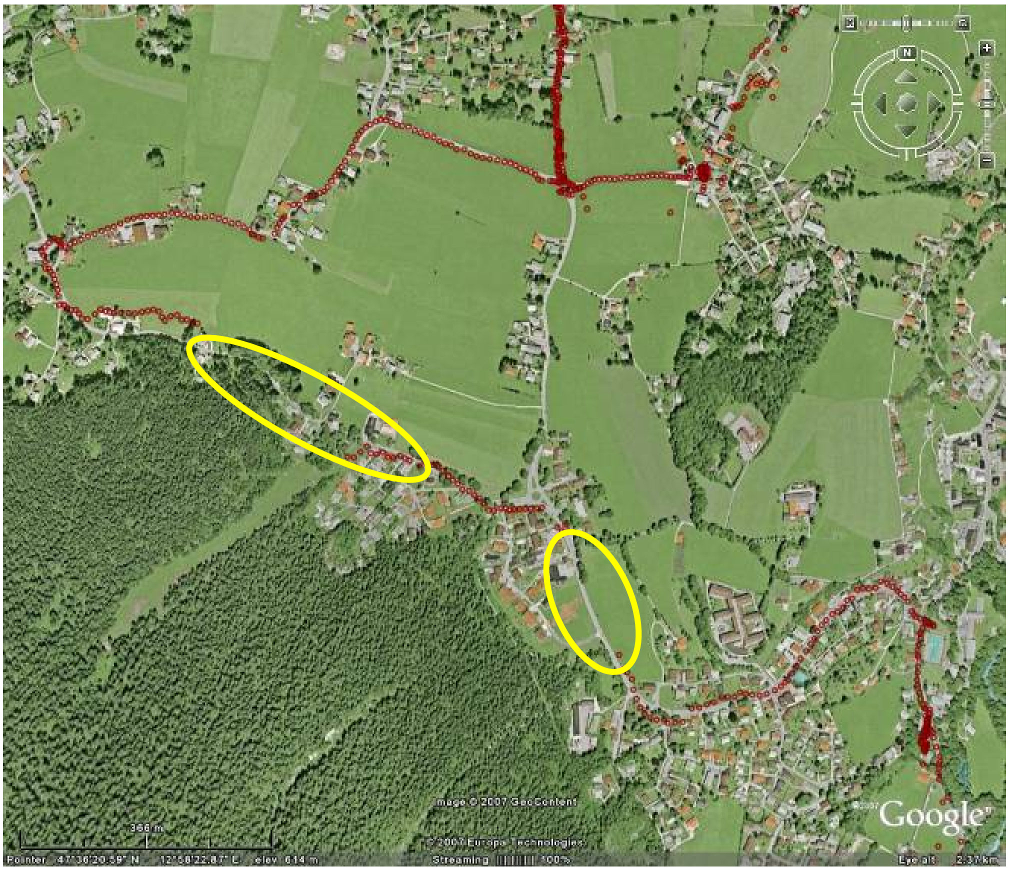


Fig. 12 Dynamic positioning test in EBM, Map © Google

The dynamic positioning tests of the GATE receiver with Galileo signals in the GATE test area gave proof of the operational capability as well as the performance of the receiver and the whole system also under dynamic conditions in all three GATE modes. This was evaluated not only for the receiver in uniform motion but also particularly with regard to significant accelerations of the receiver. As it can be seen from the velocity plots above the acceleration values during the relevant parts of the test runs were in the range from about 15 to 20 seconds for speeding up from 0 to about 100 km/h. Also under these conditions regular Galileo position updates were obtained. Slight outages in the position solution, as seen in Figs. 12, 13 and 14 are the result of a conventional epoch by epoch data processing of the GATE User Terminal Software. For estimation of the position solution a standard least-squares approach is used to get unfiltered solutions for each single epoch. A Kalman-Filter or dead-reckoning algorithm as it is implemented in common low cost GPS receivers would smooth such outliers in the position solution. For the position estimates illustrated in this paper even no carrier smoothing was applied to smooth the pseudo-ranges obtained from the code measurements from only data channels.

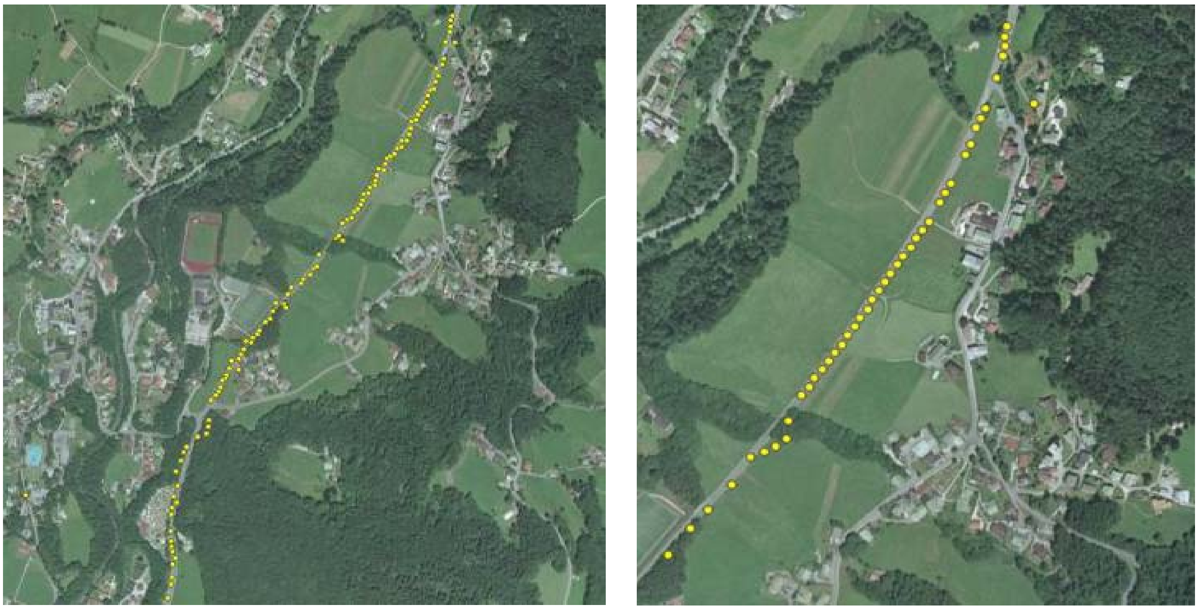
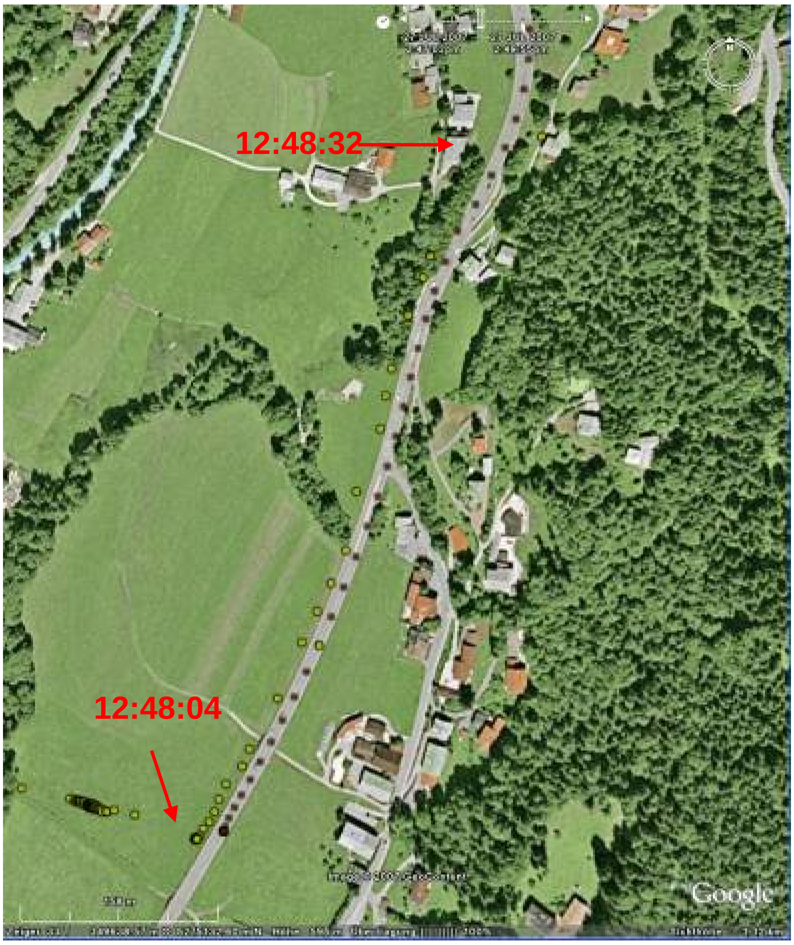


Fig. 13 Sample track of dynamic GATE positioning in EBM (left) and VSM (right), Map © Google



Time (UTC)	GPSVelocity (km/h)
124803	0
124804	0
124805	9.77856
124806	20.63128
124807	30.35428
124808	36.37328
124809	44.76284
124810	53.48576
124811	61.3938
124812	65.20892
124813	70.61676
124814	76.19128
124815	80.63608
124816	83.50668
124817	87.74776
124818	90.72948
124819	91.3036
124820	90.04424
124821	88.30336
124822	87.11808
124823	85.96984
124824	85.0068
124825	84.11784
124826	83.21036
124827	84.95124
124828	83.0622
124829	88.5256

Fig. 14 (a) “High-dynamic” test GATE VSM: Positions, Map © Google

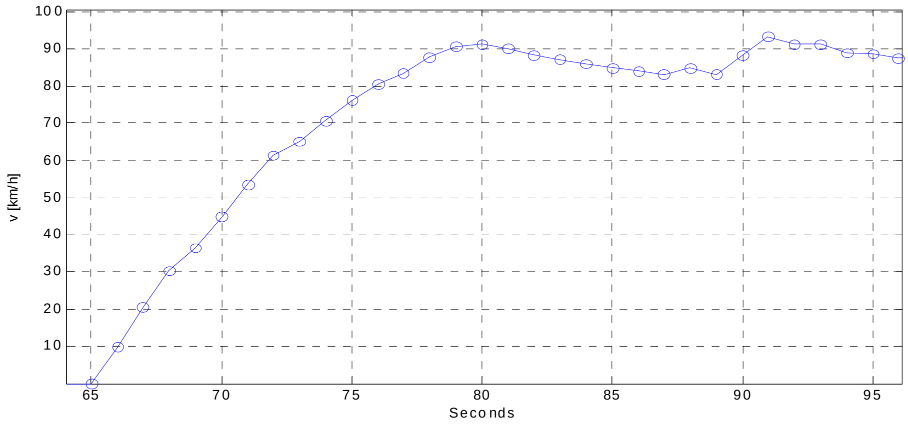


Fig. 14 (b) High-dynamic" test GATE VSM: Velocity

Regarding the illustrated tests in this paper it should be pointed out, that in all operational modes of the GATE system the receiver sees at maximum six GATE transmit stations. Due to fouling and housing in the GATE test area and the low elevation angles of the transmitters seen at the user receiver position, shading of lines of sight to the transmitters occurs very often, while moving through the test area. Most of the position outliers are caused due to heavily degraded HDOP values, especially in the VSM mode, when the remaining (not shaded) lines of sight represent a satellite constellation where the satellites and the user form a polyhedron with a very small volume (e.g. the satellites are situated nearly in one line from the users point of view). It nearly impossible to avoid such cases, because this could yield in to frequent PRN switches of the transmitters. A PRN switch will decrease the number of potential available measurements at least for the time which is needed to receive the whole navigation message of the "new" satellite (at least 50 seconds for F/Nav and 15 seconds for I/Nav messages)

4 CONCLUSIONS

GATE is a terrestrial test environment for developers of Galileo (Galileo/GPS) receivers, applications and services. It is currently being built-up in the region of Berchtesgaden/Germany and will be operational soon. GATE is considered to be a necessary intermediate step for Galileo from laboratory into orbit in terms of realistic RF signal transmission. It will not only support signal validation by providing valuable data but provide insight in building a ranging system, simply by building it. This contributes to mitigate risks in the development of Galileo. The presented test results show that GATE will meet its requirements and the expected performance.

GATE will provide the opportunity for receiver, application and service developers to perform realistic field-tests of hardware and software for Galileo at an early stage, i.e. several years before the full operability of Galileo. And last but not least, GATE will allow full end-to-end testing of unmodified / commercial Galileo receivers. For further information on GATE please refer to the official project homepage http://www.gate-testbed.com.

ACKNOWLEDGMENTS

GATE is developed on behalf of the DLR (German Aerospace Center, Bonn-Oberkassel) under contract number FKZ 50 NA 0604 with funding by the BMWi (German Federal Ministry of Economics and Technology). This support is greatly acknowledged.