# Opening the GATE

## Germany's Galileo Test and Development Environment

**GÜNTER HEINRICHS, ERWIN LÖHNERT, AND ELMAR WITTMANN**
IFEN GMBH, GERMANY
**ROLAND KANIUTH**
INSTITUTE OF GEODESY AND NAVIGATION, UNIVERSITY FAF MUNICH, GERMANY

**How can receiver designers and manufacturers develop and test products for new signals or GNSS systems before satellites are on orbit and transmitting? Of course, they can use signal generators and other laboratory test equipment. But those tools cannot fully replicate the experience of receivers operating in a real-world geography. To bridge this gap, Europe's Galileo program is establishing outdoor test facilities in Germany and Italy. This article by project managers and system designers at Germany's Galileo Test and Development Environment (GATE) describes architecture, operations, and initial results from field trials there.**

*FM-radio and mobile network transmitter pylon on which the GATE Monitor Station antennas are mounted*

Nestled amid the slopes and valleys of southeastern Germany's precipitous Alps, a novel installation has taken form over the past three years that will allow receiver designers and application developers to have real-world experience with Galileo signals years before Europe's GNSS becomes operational.

Beginning this spring, the Galileo Test and Development Environment, or GATE, has been transmitting Galileo signals from six ground-based transmitters erected on hills and mountains surrounding the picturesque Bavarian town of Berchtesgaden. To obtain a reasonably realistic emulation of the Galileo satellites, the GATE transmitters must be located high overhead to ensure good visibility (low risk of signal obstruction due to vegetation, buildings, topography, and so forth) and angle of arrival for the signals, while also surrounding the test area with simulated satellite transmissions.

This realistic test environment, which will open later this year for commercial activities, provides an opportunity for receiver, application, and service developers to perform field trials of Galileo hardware and software at an early stage. By conducting trials within the GATE facility, researchers and product designers can also incorporate signals from operational GNSS satellites, such as GPS or GLONASS, along with the Galileo test signals. In this way GATE will also support German and European products for Galileo entering the market.

This article presents the current project status and reports on the first experiences and results of the GATE segment acceptance tests as well as results from static and dynamic positioning trials at the facility.

## Purpose and Design

Before implementation of GPS, the first full-fledged GNSS, the U.S. Air Force established a ground-based ranging test-bed at the Yuma Proving Grounds in Arizona during the 1970s to prove the concept of satellite navigation. Nearly 40 years later, no one doubts that Galileo will work from a conceptual point

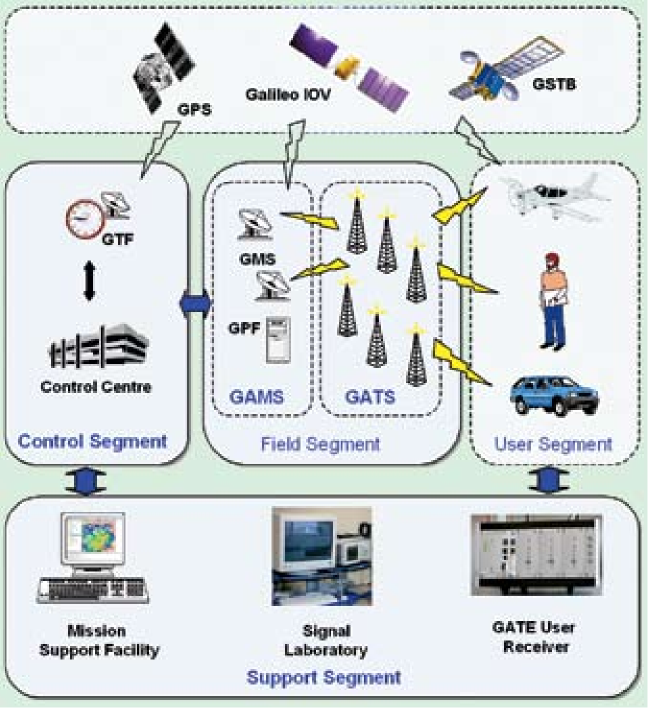



FIGURE 1 GATE Infrastructure Overview


FIGURE 2 GATE Transmitter Locations and Transmitter Rack

*Transmit station at Gruenstein mountain and helicopter transport of GTS transmitter rack*

of view. However, developing the new GNSS remains an ambitious technological project, introducing a signal structure far more sophisticated than the GPS C/A code. In fact, GATE must fulfill three major mission objectives: signal experiments, receiver testing, and user applications.

**Gate System Architecture.** Differing as it does from real navigation satellite missions, GATE cannot be simply divided into the typical segments — space, ground, and user — associated with operational GNSSes. Instead, GATE's developers subdivided the system into the following four segments considered to be more appropriate (see also Figure 1):

**Installation of the GATE transmitters on well-exposed sites allows for the emission of Galileo-like signals with average elevation angles between 10 and 15 degrees from the point of view of a user operating within the GATE test area.**

- The *Transmit Segment* (GATS), consisting of six earth-fixed GATE transmit Stations enclosing the service area. The ground-based transmitters, which are part of the GATS, will emit all frequencies foreseen for Galileo. Therefore, the equipment had to be flexible in signal generation and readily adaptable to accommodate changes in signal structure. As GATE is a real-time system, it needs to feed the navigation message in real-time to the transmitters, which are also equipped with stable atomic clocks. Figure 2 shows the six transmitter locations, as well as the transmitter rack and the corresponding transmit antenna.
- 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 GAMS monitors the navigation signals by using two GMSs, performs the time synchronization of all system clocks, and generates navigation messages and steering commands to be sent to the six transmitters. The tasks are mainly performed by the two GAMS core elements, the GATE Processing Facility and the GATE monitor receiver (GMRx).
- The *Control Segment* (GCS) includes the GATE Monitoring & Control Facility (GMCF), the GATE Archiving & Data Server (GADS), and the GATE Time Facility (GTF). The GCS includes all the functionality and facilities that are required for the mission control and operation. Its main tasks include the following: monitor and control the entire GATE system; host and operate the control center, which serves as the operational node of GATE for such activities as mission planning; host and provide GATE system time; and archive the GATE mission data.
- The *Support Segment* (GSS) consists of the facilities and functionalities for preparing and supporting the GATE missions. Specifically, these are the mobile GATE User Terminal (GUT) with the user receiver, the GATE Mission Support Facility, and the GATE Signal Laboratory. The GSS mainly supports the appropriate preparation — for example, through simulation and planning — of the GATE experiments with dedicated software tools, as well use of the GATE user terminals equipped with a combined Galileo/GPS receiver.

The GATE signal generators are designed to generate simultaneously the Galileo navigation signals in the E5, E6, and L1 bands. As seen in the left-hand photo in Figure 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. This provides a high degree of freedom for configuring by software according to the various channel setup requirements.

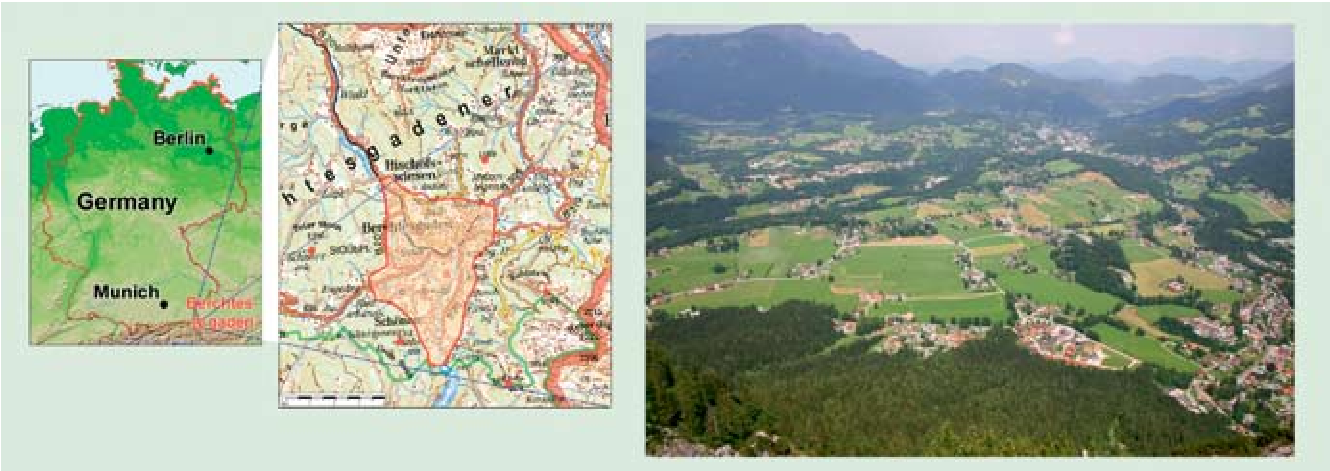



FIGURE 3 GATE Service Area Berchtesgaden / Germany (core test area marked in red) and view into the GATE test area (red dots in center map represent the locations of the transmitters)

## GATE Test Area Berchtesgaden

The maps in **Figure 3** show the location of the GATE test area. Roughly delimited by imaginary lines connecting the signal transmitters (the six red dots on the center map), GATE contains about 65 square kilometers. The core test area (red shaded area on the map) is about 25 square kilometres in size. The two monitoring stations are situated at a highly visible location near the center of the test area.

As can be seen from the photo (at right in Figure 3), Berchtesgaden is surrounded by high mountains rising up to more than 2,000 meters. Installation of the GATE transmitters on well-exposed sites allows for the emission of Galileo-like signals with average elevation angles between 10 and 15 degrees from the point of view of a user operating within the GATE test area.

Five transmitters use existing infrastructure, e.g. TV or mobile phone

FIGURE 4 GATE User Terminal and its User Interface

masts. So, only one additional, completely autonomous GTS had to be established. Within this context, the German Regulatory Authority for Telecommunications and Posts (RegTP) has approved the usage of the requested frequency bands E5a/b (centered at 1192 MHz), E6 (1278 MHz), and L1 (1575 MHz) for the transmission of the GATE signals in the Berchtesgaden area.

The first two transmit stations were installed at the Gruenstein and Stoehrhaus sites. As shown in the accompanying photos, the container for accommodating the transmit equipment at Gruentein was conveyed by helicopter to a location near the mountain top. In the final step, solar panels providing the autonomous power supply were mounted on the roof of the container.

Initial tests of remotely accessing and controlling the transmit station were performed successfully at the end of 2006.

## GATE/Galileo Receivers

The GATE user terminal consists of the receiver itself and the user interface that that runs on a laptop computer with touch screen TFT display. The user interface and the receiver communicate via Ethernet cable over UDP protocol. The navigation processing and visualization takes place on the user interface, shown in **Figure 4**.

The GATE user terminal is a three-frequency GPS/Galileo receiver that covers GPS L1/Galileo L1, Galileo E5a/E5b, and Galileo E6 positioning. For Galileo/GATE L1 and/or E5b positioning the Galileo/GATE integrity navigation (I/NAV) message is used. (The I/NAV message type provided by E5b and E1-B signals will support Galileo Safety of Life Service with extended system integrity information.)

At E5a, the freely accessible navigation message (F/NAV) provides Galileo/GATE positioning. Because the Galileo commercial navigation (C/NAV) message content still must be defined, positioning with E6 is currently not possible. (For more information on these message types, see the *Galileo Open Service Signal In Space Interface Control Document* referenced in the Additional Resources section near the end of this article.)

At present, the navigation software processes each frequency on its own except for reasonably ionosphere-free linear combinations of code measurements, such as Galileo/GATE L1 and E5a, or L1 and E5b. The latter combination benefits from the fast I/NAV message transmitted on both frequencies, which leads to a position fix within 15 to 29 seconds after acquiring signals from at least three transmitters/satellites. The navigation software also provides various logging capabilities for data post-processing, and the GATE user terminal provides NMEA position message outputs via a serial COM port.

The algorithm used for position estimation is an epoch-by-epoch, standard least-squares adjustment, because this yields unfiltered position estimates and, therefore, unpolished performance results.

## GATE Operational Modes

The user terminal software (GUT-SW) differs from other GNSS positioning software packages in that a variety of navigation message data streams have to be handled simultaneously. For GPS positioning we have the normal GPS navigation message bit-stream, also in the *GATE virtual satellite mode* (VSM), where the navigation message is based on the Galileo navigation message.

VSM realistically simulates signal propagation delays through the ionosphere and the troposphere as well as Doppler shifts. The GATE signal generator accomplishes this by creating an artificial clock offset using its rubidium clock and an adjustable 10 to 122.76 MHz synthesizer. This more sophisticated mode of operation requires careful mission planning, creation of a user scenario, and use of the test facility by only one customer at a time.

In the GATE *base mode* (BM) the GTSs transmit a constant power level that is not steered with regard to phase or Doppler, in effect acting as pseudolites, although in BM no pulsed signals are emitted; they are all continuous Galileo signals. The position transmitted in the navigation message is the actual position of the transmitter antenna's phase center. Any number of users can perform tests within the GATE area, but these require use of GUT equipment.

The *extended base mode* (EBM) compensates for the near/far effect by dynamic adjustment (steering) of signal power levels based on user positions that are fed back into the system via data link.

All modes permits static and dynamic user positioning. In the latter two modes, the content of the navigation message is different that of actual Galileo signals and VSM (which include satellite orbital positions in their nav messages), because for BM and EBM we use have satellites/transmitters located on the earth. These latter locations cannot be described by Keplerian elements as is done with orbiting satellites. As a result, 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 appropriate navigation message-decoding module.

In standard GPS positioning scenarios the center of the earth serves to provide a best guess for the user's a priori position and suffices to make the position solution converge to the correct solution. However, this will not work in GATE BM and EBM modes due to the small size of the GATE test area. Consequently, in order to make the position solution converge in GATE BM and EBM modes, the approximate user position has to be known to better than 50 meters in horizontal dimensions and 5 to 10 meters in the vertical.

As a GATE user comes closer to the elevation of the lowest transmitter, the height accuracy worsens and the better the user's approximate height needs to be known. Therefore, the GATE user equipment contains an external GPS Bluetooth receiver, to feed the GUT-SW's positioning algorithm with a priori coordinates. This external GPS receiver also enables the user to obtain an on-the-flight comparison between the GPS-calculated position and that estimated using GATE/Galileo signals.

Due to the very low elevation angles — not exceeding 15 degrees — 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 two-dimensional positioning mode. In 2-D positioning the height of a user's receiver is fixed, which in fact means that its height is set to that estimated by the external GPS mouse. This 2-D positioning mode is automatically switched on whenever only three transmit stations are visible and improves the position availability for the GATE user.

Furthermore, the GUT-SW implements a special correction algorithm for the tropospheric delay in GATE BM and EBM.

**Figure 5** shows tropospheric path delay to the six GATE transmit stations seen from the GATE central point over 12 month. The base data for temperature, humidity, and pressure for this simulation are derived from mean values over several years. The green line denotes the tropospheric path delay to GTS-2, which is more than four times farther away from the central point than GTS-3 (red line).

The delay variations among the various transmit stations during a year are about 10 percent with a maximum of about 0.3 meter. From this data, we conclude using a that tropospheric delay correction with averaged weather data should be sufficient.

## GATE Positioning Performance

The data 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 near the central point in the GATE service area. At the GATE monitoring station, the tests were performed using the GMRx, which contains a rubidium clock that provides a stable GATE system time. Furthermore the GATE monitoring receiver works a link between the GATE time facility, situated at the DLR in Operpfaffenhofen, and the GATE system.

The positioning tests in the GATE area were carried out with the GATE user receiver "light," which only contains baseband processing boards for L1 and E5 frequency and no rubidium clock. The GNSS antennas at the GATE monitoring station are mounted on quite a large transmitter pylon operated by the "Bayerischen Rundfunk," which is shown in the photo on page 44.

In the photo, one can readily see that the pylon is filled with transmitting antennas from various radio stations and mobile communication networks.

The effect of these nearby transmit antennas 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. **Figure 6** illustrates the effects in the results from static positioning tests at the two sites.

The red crosses in the left graph denote the GPS position estimates at the GATE monitoring antenna (GMS1), while the blue crosses denote the GPS positions obtained at the IfEN roof antenna in Poing. Both position estimates are referenced to their true positions. For both experiments, we used the GUT software for positioning, with ionospheric and tropospheric correction switched off, and without applying carrier smoothing.

While the position estimates from the IfEN roof antenna show a little scattering around the true position the scattering at the GMS1 antenna is much bigger. The standard deviation of the position estimates is about 2.07 meters for the IfEN position and 4.51 meters for the GMS1 position.

The right viewgraph in **Figure 7** shows the height calculations at both stations. Here also the data from the GMS1 sta-

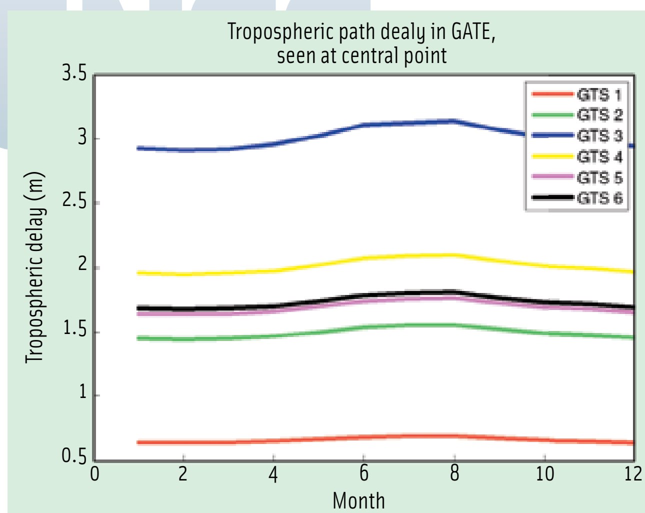



FIGURE 5 **Tropospheric path delay from GATE central point to the GATE transmitters (GTS)**

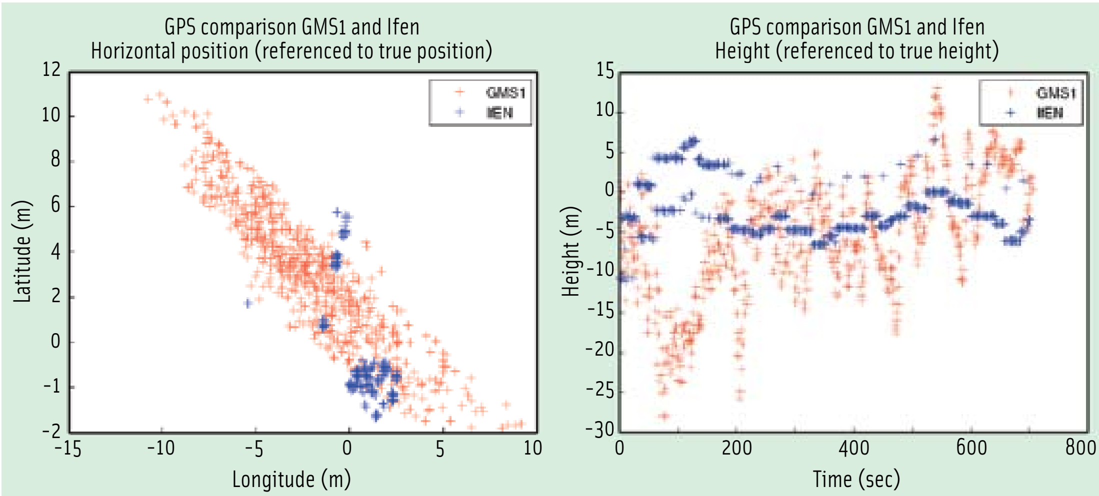



FIGURE 6 Left panel: comparison of GPS position estimates (red crosses) at the GATE monitoring station (GMS1) and IfEN's roof antenna in Poing (red crosses); right panel, height calculations at the same locations

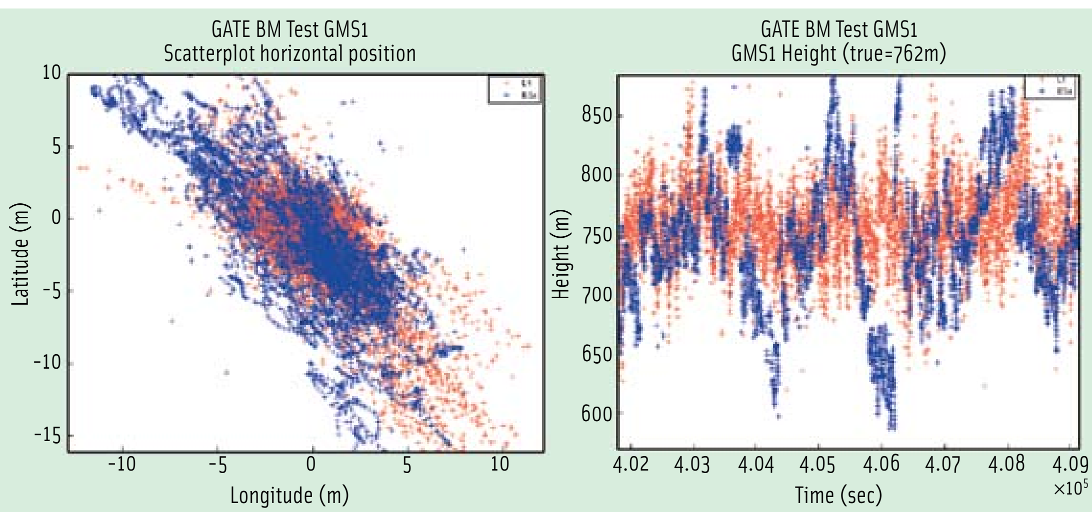



FIGURE 7 Comparison of horizontal (left panel) and vertical (right panel) position estimates with L1 and E5a at the GATE monitoring station GMS1

tion are much noisier than the data at the IfEN antenna. Also the number of tracked satellites differed between the GMS1 location and the IfEN antenna location. While at the IfEN roof antenna the GATE receiver tracked eight GPS satellites on average, the GATE receiver at the GMS1 antenna only tracked four GPS satellites. This leads to the conclusion that the transmitting antennas on the pylon, seen in the photo, have much more influence on the GNSS signal quality than previously assumed.

**GATE Field Tests.** The following tests cover static positioning at the GATE monitoring station (GMS1) on GATE/Galileo frequencies L1 and E5a. For this test we used the GATE monitoring receiver, which is connected to the GATE monitoring antenna. An external rubidium clock provides precise time to the monitor receiver.

The left plot in Figure 7 shows the horizontal position scattering of GPS (red crosses) and E5a (blue crosses) around the true GMS1 position — an error averaging around ±10 meters lateral and longitudinal, which is at the accuracy level of the GPS position estimates shown in Figure 6. As mentioned earlier, the height accuracy in GATE BM and EBM is worse than for GPS or GATE VSM mode. This underlines a vertical dilution of precision (VDOP) value of about 14.7 at the GMS1 location.

The right viewgraph of Figure 7 reveals the difference of the height estimates on L1 (red crosses) and E5a (blue crosses) referenced to the true height of GMS1. Note that the variation of the height estimates from L1 observations is slightly smaller than the ones from E5a observations. These results need to be investigated further because, from the performance point of view, the E5a signal should be better than the L1 signal.

We conducted a comparative series of positioning tests along roads at the same locations near the center of the GATE site. The results are shown in the following three figures, where the positions calculations appear on the aerial photos as red dots.

The experiment illustrated in **Figure 8** using the base mode begins with static positioning (the cloud of dots) followed by low-velocity dynamic positioning (in a slow drive from parking position to south direction towards the crossing),

Static positioning was repeated in the GATE VSM mode (**Figure 9**), where the GATE/Galileo signals are simulated as though they were coming from orbiting satellites. Of course, the GATE signals are emitted by terrestrial transmitters; so, signal fading and multipath effects are still present. The positioning accuracy is comparable with that from Figure 8.

Finally, we performed a preliminary dynamic positioning test using the E5a signal in EBM operation mode, where the signal strength is steered depending on the user's location to ensure a good carrier-to-noise ratio. This test started at the GATE central point, marked as (1) in **Figure 10**. The red dots denote the positions calculations.

After stopping several minutes at the central point the test vehicle turned right in a westerly direction at the crossing close to the central point. Shortly after turning west, a large bus passed our vehicle, and three of five signals were lost. Intensive analysis of the data from this test showed that signal fading and multipath cause most of these signal losses.

These negative effects on the signals result from the low elevation of the transmit stations and the subsequent signal reflections from the ground and objects surrounding the users. At the point marked as (2) in Figure 10 the receiver reacquired the signals to 4 GTS and positioning went on until a new signal loss. Especially at section (3) and (5), the high accuracy of the position estimation can be seen, where no objects block the signals.

From a potential GATE user point of view the availability of a position fix is insufficient during the dynamic test shown in Figure 10. We will perform further investigation into how to improve the receiver's robustness against signal degradation due to multipath and fading. In addition to this, we may be able to modify the positioning software to aid the receiver's signal processing.

## Conclusion

GATE is a terrestrial test environment for developers of Galileo (or Galileo/GPS) receivers, applications, and services currently being built up in the region of Berchtesgaden, Germany. The facility will be operational from autumn 2007.

GATE is considered to be a necessary intermediate step for Galileo in terms of realistic RF signal transmission, part way between laboratory experimentation and field trials once sufficient Galileo satellites are in orbit. The facility will not only support signal validation by providing valuable test data but will, by the very act of GATE's construction, also provide insight into building a ranging system. This helps to mitigate risks in the development of Galileo.

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, — several years before the full operation of the Galileo system. And, last but not least, GATE will allow full end-to-end testing of unmodified commercial Galileo receivers.

GATE is designed as a flexible test bed for satellite navigation users before GALILEO itself becomes available. But with its capability for evolutionary extension, GATE can continue to be used for special tasks, even after the Galileo system has already become fully operational.

Prospective examples for such application scenarios include adding PRS and/or GPS L2C signals, transmitting differential GNSS correction data, generating interference to the transmitted signals for "signal quality monitoring" experimentation, incorporating local components

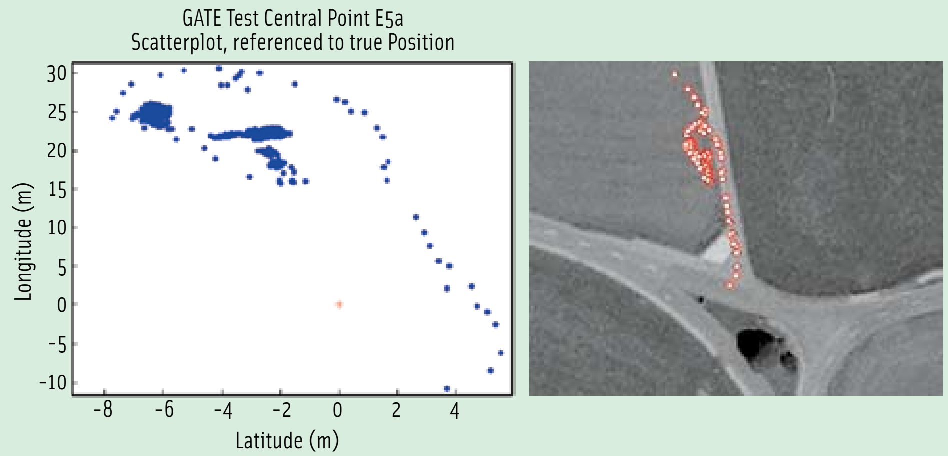



FIGURE 8 Position estimates with E5a in base mode (BM) in relation to the red star representing the GATE central point

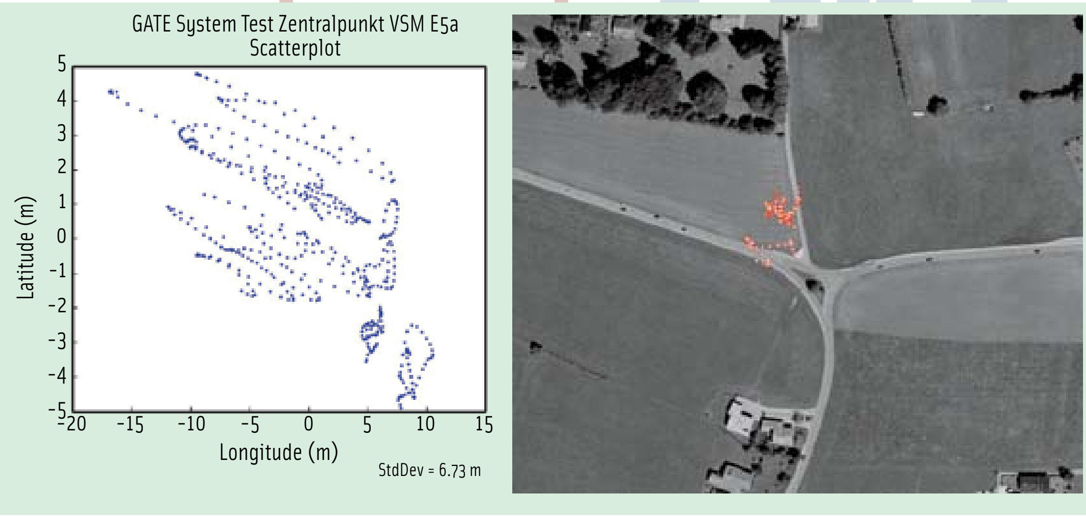



FIGURE 9 Position estimates with E5a in virtual satellite mode at the GATE central point

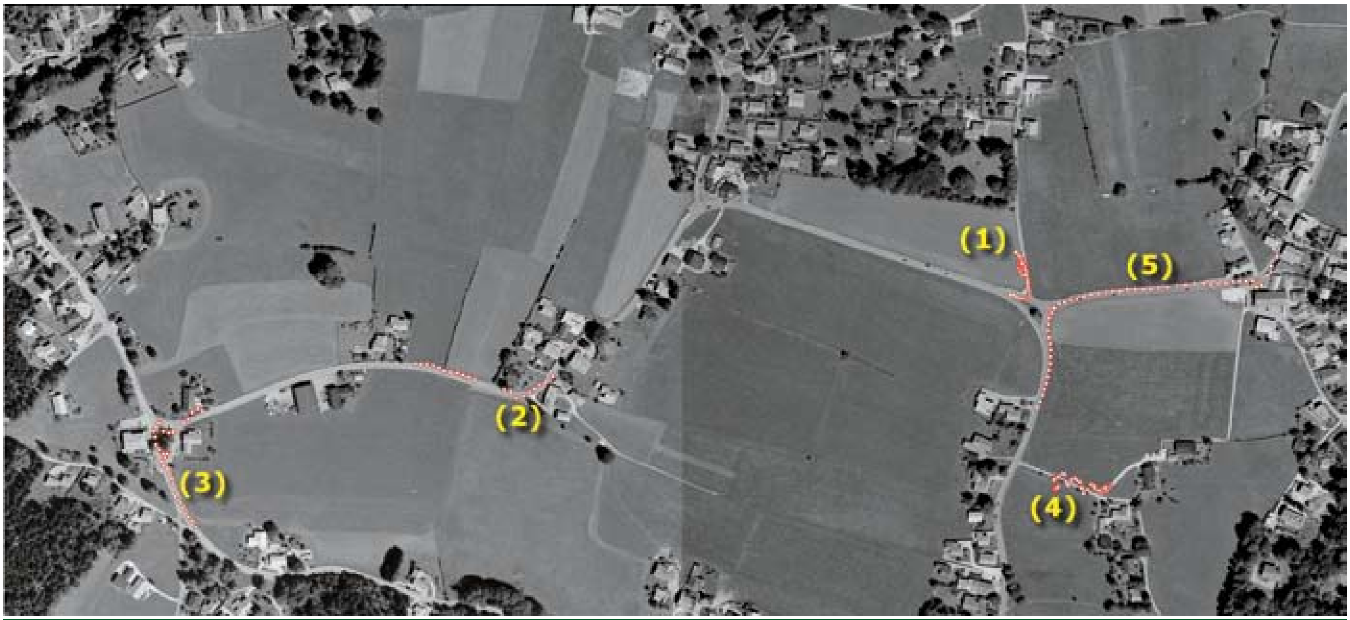



FIGURE 10 Position estimates with E5a in EBM at the GATE central point

as soon as GALILEO is available (for example, a test bed for high-precision landing approaches), adjusting signal power levels according to special user needs, beyond the GATE Virtual Satellite Mode.

For further information on GATE please refer to the official project homepage <http://www.gate-testbed.com>.

## Acknowledgments

GATE is being 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 appreciated.

## Manufacturers

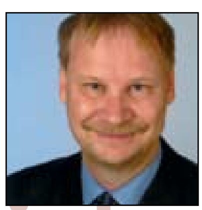
The Galileo signal generators were developed by **EADS Astrium GmbH**, Munich, Germany. The GATE Processing Facility (GPF) and the GATE Monitor Receiver (GMRx), were both developed by **IfEN GmbH**, Poing, Germany. The GATE User Terminal interface runs on a Panasonic Toughbook laptop computer from **Matsushita Electric Industrial Co., Ltd.**, Osaka, Japan. The GATE user terminal typically operates in combination with a a GPS mouse the incorporates a SiRFstarIII GPS receiver from **SiRF Technology**, San Jose, California.

## Additional Resources

*Galileo Open Service Signal In Space Interface Control Document* (OS SIS ICD), European Space Agency/Galileo Joint Undertaking

GATE Information Flyer, 2006, available on-line at < http://www.gate-testbed.com/publications/GATE_Flyer_2006_uk.pdf >. A list of related articles can also be found at the website.

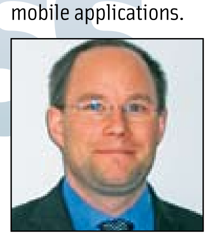
## Authors

**Günter Heinrichs** received a Dipl.-Ing. degree in communications engineering from the University of Applied Science Aachen and a Dipl.-Ing. degree in data processing engineering and a Dr.-Ing. degree in Electrical Engineering from the University Paderborn. 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 business development and R&D management.

**Erwin Löhnert** received a diploma in aerospace engineering from the Munich University of Technology. In 1994 he joined the Institute of Navigation and Geodesy at the Universität Bundeswehr Munich (Federal Armed Forces University, Munich) as a research associate, working mainly on aerogravimetry and GPS/INS integration. In 2000 he joined IfEN GmbH as a project manager for integrity determination. Since 2001 he been head of IfEN's mobile applications & services department, managing several projects and currently serving as technical manager of the GATE project.

**Elmar Wittmann** received a Dipl.-Ing. degree in geodesy from the Munich University of Technology and then joined IfEN GmbH, where he is now working as a systems engineer in the field of GPS/Galileo satellite navigation and software development for mobile applications.



**Roland Kaniuth** received his Dipl.- Ing. Degree in geodesy from the Munich University of Technology. From 2000 to 2001 he worked as research associate at the German Geodetic Research Institute. Since then he has been a research associate and Ph.D. candidate at the Institute of Geodesy and Navigation at the University of the Federal Armed Forces Munich. He is involved in several projects dealing with GNSS system simulation and navigation processing software. IG