

GATE - The German Galileo Test Environment

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BIOGRAPHY

Dr. Robert Wolf holds a degree in Aerospace Engineering from the Technical University of Munich and a Ph.D. from University FAF Munich. Since 1995 he worked in the field of hybrid GPS / INS navigation and later on precise orbit estimation and integrity determination. He joined IfEN GmbH in 1999 as a systems engineer. Between 1999 and 2002 he was working on the development and optimisation of the EGNOS CPF Check Set algorithms, since 2001 as the technical responsible. He is currently the project manager of GATE.

Dr. Markus Thalhammer holds a diploma in geodesy from the Technische Universität München and a PhD in satellite geodesy and celestial mechanics. He has several years experience in system engineering and satellite missions. He joined IfEN in 2002 as a head of quality assurance.

Dr. Guenter W. Hein is Full Professor and Director of the Institute of Geodesy and Navigation of the University of the Federal Armed Forces, Munich, Germany. He is responsible for research and teaching in the field of satellite positioning and navigation as well as physical geodesy. He is working in the field of GPS since 1984 and is author of more than 200 papers. In 2002 he received the Johannes Kepler Award.

ABSTRACT

Complimentary to the development of the ESA Galileo System Test Bed (GSTB), a German industry consortium is building up in southern Germany a local ground-based, flexible Galileo Test Environment (GATE) using signal generators at dedicated stations. The mission objectives are: (1) Contribution to the design and validation of the Galileo signal structure, (2) Establishment of an early test facility for the development of Galileo receivers and its interoperability with GPS and (3) Built-up of a test site for various Galileo/GPS applications on land, for marine and airborne environment.

For the built-up a phased development was chosen: After the definition phase (ending in June 2003) a development and testing phase, in particular for the signal generators and the Galileo/GPS receivers, is taking place. The initial operational capability (IOC) is planned for beginning 2005. GATE is designed in such a way that also observations to the ESA GSTB V2 Galileo test satellite – it is in orbit - can be processed jointly with the observations from the local transmitters as well with GPS observations. The last are also used for the verification of the derived positioning. This means that a careful selection of the test area has to be carried out as well as the so-called near/far effects have to be solved in the terrestrial transmission of the GALILEO signals.

INTRODUCTION

What is GATE? GATE is a ranging system using Galileo signals. It is based on stationary ground based signal transmitters with the GATE service area located near Munich, in the southwest, around Weilheim. It is funded by the German DLR and developed by a consortium of 7 companies with IfEN GmbH being prime contractor.

The definition phase (phase I) has ended with a successful PDR in 06/03. The procurement and development phase (phase II) will start beginning of 2004. While GATE is a national project, it is not in competition with test bed activities launched by ESA. It is perfectly complementary and fills the gap between laboratory and orbit.

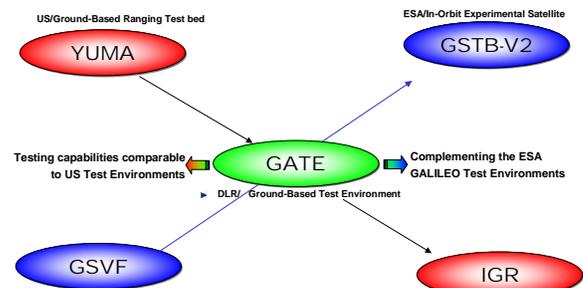


Figure 1: Relation of GATE to other Test Beds

The idea of building a ground based ranging system is not new: prior to launch of the first GPS Block I satellites, the Yuma test range was built, and recently the Inverted GPS Range in White Sands Missile Range has been developed by the US. Besides some commonalities with Yuma / IGR and complementary properties to ESA test facilities, there is one fundamental difference: GATE will be open to *any* user.

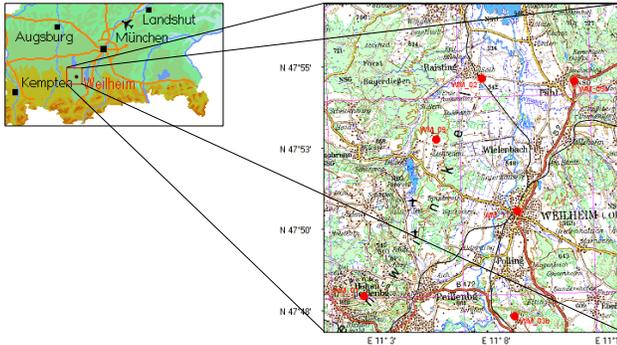


Figure 2: GATE Service Area, approximately 20 x 12 km in size

OBJECTIVES AND MOTIVATION

While the motivation of the Yuma Test Range 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



Figure 3: GATE Top Level Mission Requirements

Signal Experiments:

By building GATE, we will gain experience in building a GALILEO ranging system, in particular gain experience with new the Galileo signal structure. This implies to keep signal generation

- flexible, for upcoming signal refinements (AltBOC(15,10), PRS)
- extendible, for optional provision of (GPS-L2, L5)
- adaptable, to study effects interference and jamming

Receiver Testing:

GATE is intended as a test facility for GALILEO receivers, enabling test of new BOC receiver algorithms. To allow full end-to-end testing of *unmodified* Galileo receivers GATE has to emulate reality with respect to

- signal behaviour, i.e. Doppler shift and signal strength
- atmospheric effects simulation
- ICD conformity of navigation message

User Application:

GATE shall not only provide an *environment* for testing of user applications, but shall also *provide the test receiver to users*. This includes in particular a receiver capable of hybrid GPS/GALILEO navigation. Furthermore, it shall be extendible for local applications (i.e. CAT I-III, ...) even beyond GALILEO FOC.

CAPABILITIES & LIMITS

GATE vs. „the Real Thing“

A ground based system like GATE will differ from the real Galileo system to some extent. The most obvious constraint is with respect to geometry, i.e. achievable DOPs and transmitter visibility. This has been mitigated by careful choice of the service area. The GATE service area provides at minimum 4 visible GATE transmitters in view while preserving a HDOP < 4. The VDOP has not been a design criterion, except the requirement that the DOP matrix must not become singular when computing a full 3D position solution.

Furthermore there are constraints in local signal propagation effects, like multipath, ionosphere and troposphere. The latter two are driven by the user geometry and can be predicted and emulated.

Multipath is not so easy to predict, because it depends strongly on the interaction between antenna and reflecting surfaces, but also here GATE provides realism with respect to the Galileo signal characteristics. There are two components in the multipath, due to satellite motion and due to user motion. GATE transmitter - user geometry always corresponds to a satellite - user receiver worst case geometry due to the flat elevations. This effect is inevitable, but fortunately has normally low amplitude. Multipath due to user motion yields large ranging errors at higher oscillation frequencies. This results from the very fast changing geometry between user antenna and reflecting surfaces of the surrounding environment. This is *absolutely comparable* for a satellite-user and GATE transmitter - user geometries. Moreover, *this is usually the dominating part of the multipath error*.

To summarise this section: In virtual satellite mode (description see below), GATE will act just like the real thing with respect to signal variations induced by

- orbit dynamics
- satellite clock dynamics

- tropospheric delays
- ionospheric delays
- noise

With the limitation of always being the worst case, GATE provides also realistic multipath.

GATE vs. Laboratory / Simulator

Some operations like end-to-end testing of a receiver could be done in the laboratory too. Besides that fact that there are commercial solutions for GPS, but not for Galileo, the question arises *how* “end-to-end” this would really be!

Laboratory simulators usually bypass the receiver antenna, and therefore have to model noise and multipath effects by taking more or less realistic assumptions. The receiver is fix mounted in the laboratory; therefore virtual predefined trajectories are used to compute the observation geometry.

GATE on the other hand allows real time dynamics, includes the antenna and moreover allows free selection of the users hosting vehicle, which is normally driven by the application.

Galileo utilises new signals. Dynamics combined with BOC modulation may cause new problems:

- Increased complexity to achieve and maintain lock on BOC signals.
- Phase lock loop jitter with vibration may result in loss of lock

Modelling these effects in a simulator (if possible at all!) means taking assumptions without the possibility to verify them. In GATE, these effects are not modelled they are there as a result of the dynamic field environment.

GATE OPERATIONS

System Use Cases

The following section shows some examples of performing test within GATE, and already tries to address the appropriate user community.

Galileo Development Support

The Galileo signal isn't fixed today, although the choice of frequencies seems to converge. Some issues are still to be clarified, like exact signal structure and data rate and structure. GATE provides the opportunity to clarify open issues by performing several dedicated test cases:

- **Interference with / Jamming of GPS:** Switch on Transmitters using Galileo signal, and see if GPS can still be tracked by a low cost or a high end GPS receiver.

- **Tracking & Acquisition:** Transmit Galileo Signal (from GATE Transmitters), and see if Galileo receiver is capable to track GATE signal, under presence of GPS and other interfering environment like radar, Cellular Mobile Phone Infrastructure etc. It is not even necessary to put a real navigation message on the SIS, because no positioning will take place.
- **Data Rates Testing:** Same as above, but put data on the signal and vary the data rate. It is still not necessary to have a real navigation message with meaningful content in the data stream. Some predefined bit patterns to verify if decoding was correct (“Hello World” or similar) should be sufficient.
- **Bandwidth Testing:** Define navigation message structure (frame / sub frame assignment) and put data on the signal. Decode signal.

Of course these tests would be performed in the signal lab first, then in the field test bed.

These tests will most probably be performed by the GATE operator or even the GATE development team, without order of a “customer”. The results will be used to support the Galileo development actively. It is a primary mission objective that results obtained during development, validation and operation of GATE will be made available to ESA on request.

Receiver Manufacturer Support

As soon as the Galileo signal structure is fixed, receiver manufacturers will become interested in GATE. Why?

- There is an upcoming new satellite navigation system, namely Galileo.
- At this time there is still no test equipment commercially available. ESA is developing the Galileo Signal Validation Facility (GSVF), but this facility will not be available to the public.
- Receiver manufactures will face the problem either to develop test facilities on their own costs, or
- Wait until such test equipment becomes available, jeopardizing ‘time to market’ requirements.

GATE offers a dynamic field environment, as well as a signal laboratory for first functional test. The test foreseen here will also be conducted in a very early stage for the GATE reference receiver themselves.

- **GPS Positioning Testing:** Test positioning of user receiver (Hybrid GPS/Galileo receiver) with GPS signal. Compare to results obtained by GATE reference receiver.

- **Galileo Positioning Testing:** Test positioning of user receiver (Hybrid GPS/Galileo receiver) with Galileo signal provided by GATE. Compare to results obtained by GATE reference receiver.
- **GPS / Galileo Positioning Testing:** Test positioning of user receiver (Hybrid GPS/Galileo receiver) with GPS signal and Galileo Signal provided by GATE. Compare to results obtained by GATE reference receiver.

End User Support

Not everyone who requires early Galileo test capability to be ready for the upcoming market is a receiver manufacturer. In fact, the vast majority of users are expected to come from industries where GNSS receivers are not the prime item of interest, but are to be integrated into systems. This important user group is normally condemned to wait until Galileo receivers become commercially available. GATE is supporting market predevelopments of those users by providing a hybrid Galileo / GPS receiver (to be developed in parallel with the monitoring receiver).

Modes

Pseudolite Mode (PM)

In this mode, the transmit platforms will act like what is called a pseudolite in GPS terminology, i.e. they transmit at constant power levels a signal which is not steered (wrt. phase and Doppler). The position transmitted in the navigation message is the actual position of the transmitters phase centre. In this mode, GATE is capable of serving an arbitrary number of users, as long as they are located in the service area. The transmitter do not try to mimic a real satellite, therefore the receiver has to accept for example measurements with an elevation below the normal rejection threshold.

Extended Pseudolite Mode (EPM)

In this mode, the pseudolite mode above is extended by compensation of the near / far effect by dynamic adjustment (steering) of signal power levels according to user position which is fed back into the system via data link. In EPM, GATE becomes a single user system.

Virtual Satellite Mode (VSM)

Assuming a generic GNSS receiver (similar to those available for GPS) a system based on ground transmitters will face some problems

- The receiver would reject the measurements as being to flat (below elevation mask)
- There is no way to express earth fixed positions by orbit parameters

Fortunately the GATE transmitters can mimic satellites, by shifting code phase, Doppler shift and signal power level of carrier and code forth and back in a way that the signal is perceived as coming from orbit.

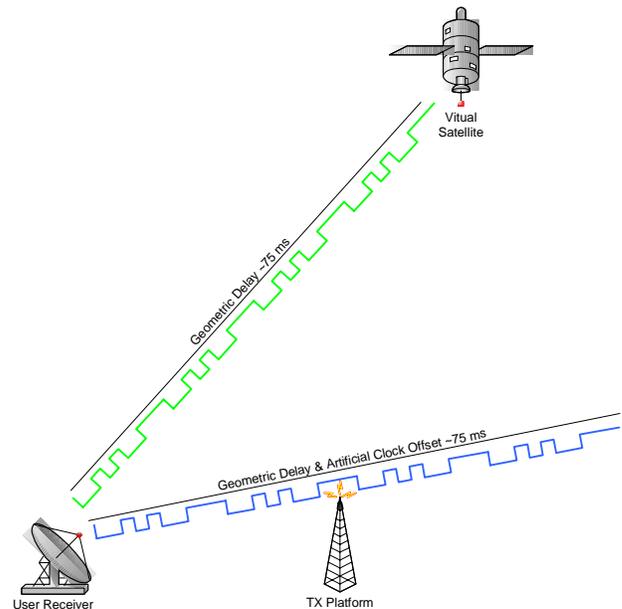


Figure 4: GATE Virtual Satellite Concept

Similar to a laboratory simulator, the signal delay experienced by the user due to orbit-user-geometry is emulated by an artificial clock offset of same size, as indicated in the figure above. This requires high fidelity simulation of the satellite movement, signal path delays etc. The navigation message broadcast then actually contains orbit parameters exactly matching the signal steering. The GATE transmitters indeed become virtual satellites. Like in EPM, GATE becomes a single user system.

Hybrid GATE / GSTB-V2 Operation

As soon as the GSTB-V2 satellite will be available, it will be monitored by GATE mission control. To allow hybrid navigation, the broadcast clock parameters of the GATE transmitter can be synchronized to the GSTB-V2 time instead of GATE system time. GATE will establish a close cooperation with ESA, allowing access to the experimental satellites navigation data even if not contained in the signal in space. In this case the navigation message will be transmitted to the GATE user via the existing data link to GATE control (in virtual satellite mode). It has to be emphasized that without a system like GATE no one will be able to use the experimental satellite for positioning.

Hybrid GATE / GPS Operation

Similar to the GSTB-V2 operation it will be possible to synchronize GATE transmitter clocks to GPS time,

eliminating synchronisation errors. This hybrid navigation mode will be the most interesting one for the vast majority of the user community (dual constellation testing).

Hybrid operations of GATE with GPS and / or GSTB-V2 are in fact “add-on modes”. They can be combined with the first three modes, but the best realism is reached when combined with virtual satellite mode.

SYSTEM INFRASTRUCTURE

The following figure gives an overview on the system architecture. Within the service area, a user receives the signals from at least 4 GATE transmitters simultaneously (GATE SIS), enabling a full 3D position solution.

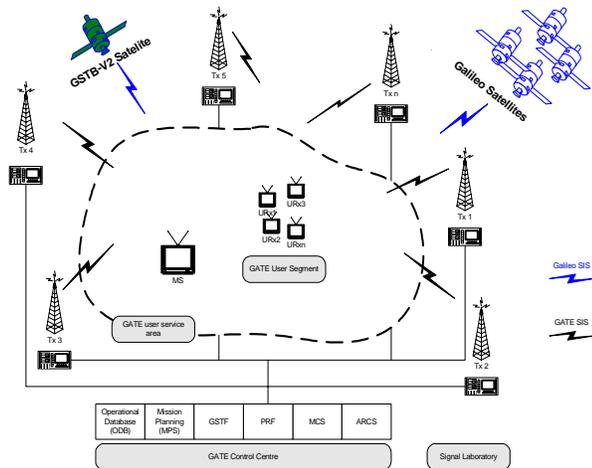


Figure 5: GATE Infrastructure Overview

Additional to the ranging code, the user receivers need some data indicating transmitter positions, clock states, relation to the worldwide time scale UTC etc. The so-called navigation message is fed in real time to the transmitters, like in a real GNSS. Instead of performing “uplink” operations restricted by satellite / uplink station geometry and therefore available only a few hours per day, conventional ISDN communication lines are used. These are available at any time for continuous data uplink, allowing fast interaction between ground mission & control segment and “space segment”.

Applying the same segmentation to the system as usual for GNSS, the systems infrastructure can be subdivided into

- Space Segment
- Ground Control & Mission Segment
- User Segment

GATE Space Segment

Of course there is no equipment in space in GATE. The transmitters are ground based but play the role of satellites in a real satellite based navigation system, i.e. they will emit all frequencies foreseen for Galileo. The Galileo signal is not fixed yet, therefore they have to be flexible in signal generation and adaptive to possible changes in signal structure definition. They are also equipped with stable atomic clocks. The following figure shows one of the envisaged transmitter locations, as well as schematic transmitter assembly.

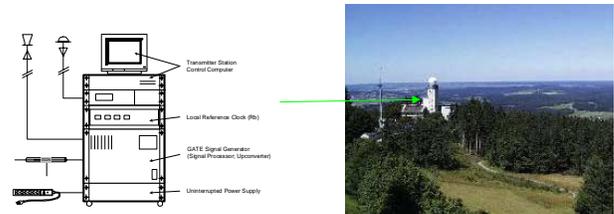


Figure 6: GATE Transmitter Location Hohenpeissenberg

GATE Ground Control & Mission Segment

The GATE ground segment has to perform several tasks related to system operation as well as mission control. Besides the more functional aspects of system monitoring & control, there are several system parameters which have to be observed and estimated in real time to ensure system performance. In particular the atomic clocks at the transmit stations have to be observed and a prediction of their future behaviour (required by the GATE user) has to be included within the navigation message.

If GATE is operated in one of the more sophisticated modes like the virtual satellite mode, the signal generators will have to be steered according to the user position fed back into the system, to provide range measurements, Doppler offsets and power levels like perceived from orbiting satellites. This is one of the major tasks of the processing center.

The user as the customer will most probably be interested in analysing the results obtained with his application within GATE, therefore the ground segment provides a data archiving service as well.

User Segment

GATE will obviously be a highly attractive field test environment for receiver manufactures, but also the general user is seen as customer. There are many applications requiring integration of GNSS receivers and these require testing prior to offering them to the market. To satisfy both communities, GATE will provide a few Galileo prototype receivers to be used by system integrators as primary receiver, but also for receiver manufactures as a reference!

PERFORMANCE ANALYSIS RESULTS

The decision for the service area Weilheim was driven mainly by performance requirements as well as infrastructure criteria (communication). To enable full 3D positioning capability, at minimum 4 visible GSTx are required. A HDOP < 4 and an at least existing VDOP required a mountainous area to provide some GSTx elevation. Moreover, typical user environment should be available, like streets and railways. To reduce costs, it is desirable to reuse existing sites as much as possible. The chosen area around Weilheim matches all criteria.

As the visibility is mainly limited by blockage due to the terrain, digital terrain models have been used in a the GATE Service Volume Simulation Tool to assess suitability of the area. In the following the results obtained for GATE service area Weilheim are shown.

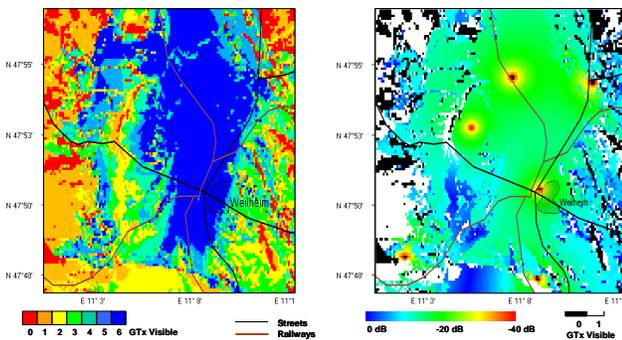


Figure 7: Visibility and Power Levels in Service Area

The left figure shows the visibility of GATE transmitters in the service area. The right figure shows the “forbidden zones” due to near far effect in red. Note that the near far effect is applicable only for the pseudolite mode (PM).

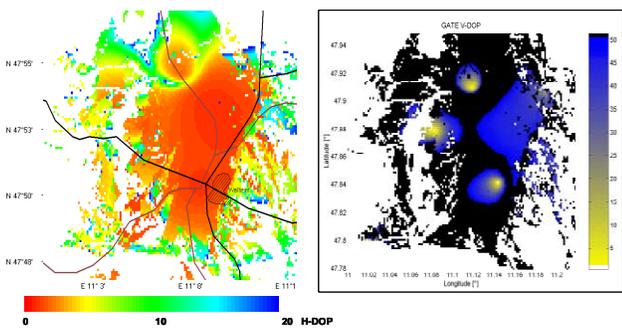


Figure 8: HDOP (left) / VDOP (right) at Terrain Level

The figure above shows HDOP (left) and VDOP (right) at terrain level. Note that there are large areas with HDOP ~ 2. VDOP is bad due to the flat geometry, but vertical accuracy has not been a design driver for GATE. This however is true only for the user at terrain level. The figure below shows the VDOP for an airborne user at 2700m altitude.

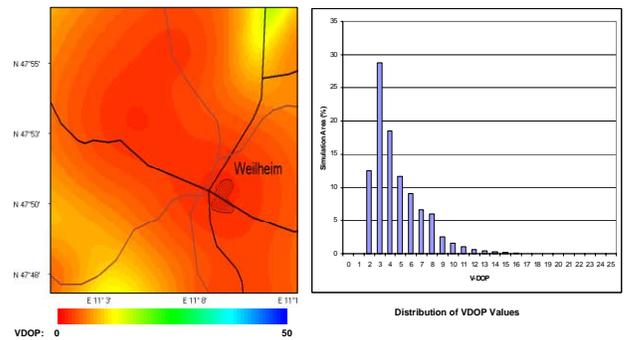


Figure 9: VDOP at an Altitude of 2700 m (Airborne User)

Another way to improve VDOP is the inclusion of a real satellite, i.e. the GSTB-V2. The following figures show VDOP at terrain level for different elevations. Even at 5 degrees, the GSTB satellite improves the VDOP significantly.

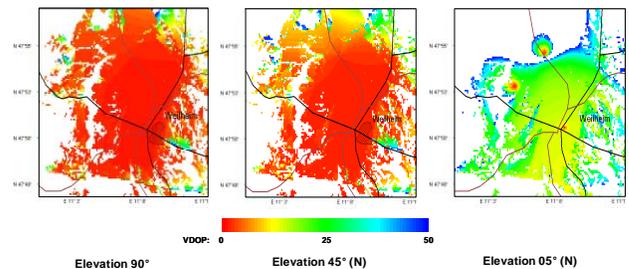


Figure 10: VDOP at Terrain Level (GATE & GSTB-V2 Satellite)

Note that this improvement requires only one satellite! A hybrid navigation solution including GPS would improve VDOP to < 2 at any time of the day, as there is always at least one GPS satellite visible above 45 °.

CONCLUSION

GATE is a necessary intermediate step for the development of Galileo from laboratory into orbit in terms of realistic (RF) signal transmission. It will support Galileo signal validation even during its own development by providing valuable results and provide insight in building a ranging system. This contributes to mitigate risks in the development of Galileo.

GATE provides capabilities similar to the Yuma Test Range (build in the 70's to prove the concept of satellite navigation), but far more sophisticated as it provides a mode of operation to emulate the Galileo constellation (Virtual Satellite Mode). This is normally the domain of laboratory simulators, but as a field test environment GATE provides “naturally” more realism, also with

respect to the unknown properties of tracking the new BOC signals in a dynamic environment.

One of the greatest benefits of GATE is the moment it becomes operational: Galileo is well on course, but is still far enough in the future. Receiver manufacturers as well as system integrators starting then with a highly capable, public available field test environment will be ready for the Galileo market, right in time when the Galileo system reaches full constellation.

ACKNOWLEDGMENT

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As mentioned in the introduction the project is carried out by a consortium of companies and institutes, reflected in the following summary:

Customer:

DLR Bonn-Oberkassel

Prime contractor:

IfEN GmbH, Poing

Sub contractors:

Astrium GmbH, Ottobrunn

DLR Oberpfaffenhofen

Kayser-Threde GmbH, Munich

Telematica, Linden

University FAF Munich, Institute of Geodesy and Navigation (Neubiberg)

VEGA GmbH, Darmstadt