Advancing Bridge Safety Through Affordable GNSS-Based Continuous Monitoring

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1. SUMMARY

The ageing of bridge infrastructure and increasing traffic demands require monitoring solutions that are both reliable and economically feasible. Conventional structural monitoring methods, such as periodic geodetic surveys or complex sensor installations, involve high costs and operational effort and are therefore usually limited to selected critical structures. Consequently, many bridges are operated without continuous information on their actual structural behaviour under real traffic and environmental loads.

This paper presents a low-cost, GNSS-based continuous monitoring system for bridges and other civil engineering structures. The system combines affordable multi-frequency GNSS receivers with individually calibrated antennas and modular sensor units, enabling precise three-dimensional displacement monitoring at significantly reduced cost. Continuous GNSS observations provide time series data that allow structural movements and deformations to be analysed over long periods, with detectable displacement magnitudes in the millimetre range. A key benefit of continuous monitoring is the ability to distinguish reversible, environmentally induced effects—such as thermal expansion—from irreversible, structurally relevant changes. By correlating GNSS displacement data with environmental measurements, cyclic influences can be identified, modelled, and filtered, resulting in a higher informational value than conventional periodic measurements.

The monitoring concept has been validated on reinforced concrete, and prestressed concrete bridges. The results demonstrate that GNSS-based monitoring is suitable for detecting fatigue-related stiffness changes, creep and shrinkage effects, bearing malfunctions, and long-term prestress losses. In addition, a hybrid evaluation approach combining AI-supported time-series analysis with finite element modelling is introduced to support scalable anomaly detection while maintaining engineering interpretability.

Overall, the presented approach provides a structure-independent, cost-efficient tool for condition-oriented bridge assessment and supports predictive maintenance strategies, improved safety, and sustainable infrastructure management.

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2. Introduction

The research project investigates the potential of low-cost, continuous monitoring of bridges and other civil engineering structures using GPS (GNSS) technology. The objective is to develop a method that enables precise and reliable statements about structural movements and deformations despite reduced costs, thereby contributing to early damage detection and increased operational safety.
Traditional monitoring methods, such as manual leveling or complex sensor systems, involve considerable financial costs and personnel effort and are therefore usually applied only to particularly exposed or already damaged structures. Continuous monitoring - i.e., the permanent acquisition of movements and changes in structural condition - therefore generally fails due to economic constraints. However, such continuous observation would be crucial for detecting damage development at an early stage and initiating appropriate measures before structural capacity is compromised or closures become necessary.
Based on many years of research at the Berlin University of Applied Sciences and Technology, a novel modular monitoring system has been developed that is based on freely programmable Raspberry Pi units. The combination of GPS receivers with additional sensors (e.g., temperature, humidity, inclination, or acceleration sensors) allows flexible adaptation to different types of structures and measurement requirements. The cost per measurement point amounts to only approximately 30–40% of that of conventional systems.
Through the continuous acquisition of position data, displacements on the order of approximately 5 mm can be detected and evaluated over long time periods. In conjunction with simultaneously recorded meteorological data, temperature- and humidity-induced deformations can be distinguished from structurally relevant changes. This enables a more precise assessment of structural behavior than is possible with point-based measurements conducted at weekly or monthly intervals.
The results show that the informational value of continuous measurement series—despite lower single-point accuracy compared to classical terrestrial surveying methods—is overall higher, as cyclical influences can be identified and mathematically separated. The presented low-budget system thus opens up new perspectives for large-scale, preventive monitoring of civil engineering structures.
Using this method, structures that have previously been excluded from monitoring due to high costs can also be observed in the future. This enables predictive maintenance planning and contributes to extending service life, increasing safety, and avoiding costly closures within

transportation networks. The research project therefore makes an important contribution to the digitalization and economic efficiency of structural health monitoring.

3. General Methodological Approach

The assessment of the condition and load-bearing capacity of bridges has traditionally been based on analytical calculations that determine the theoretically permissible structural behavior under normative assumptions. However, these calculations inevitably represent an idealized approximation of reality and are particularly affected by uncertainties in the case of existing bridges, such as unknown material properties, boundary conditions, prior damage, and time-dependent effects. Against this background, continuous monitoring of real structural deformations is gaining increasing importance.

GNSS-based monitoring enables highly precise, three-dimensional recording of absolute displacements at selected structural points over long periods of time. The systems presented by Stempfhuber et al. combine RTK processing with high-precision post-processing of GNSS raw data and achieve accuracies in the millimeter to sub-millimeter range. These continuous time series make the real structural behavior under traffic loads, temperature variations, and other environmental influences directly observable.

Methodologically, the integration of GNSS monitoring into structural condition assessment follows a uniform workflow consisting of measurement, filtering, interpretation, and model comparison. While the measurement methodology is identical across different structures, the dominant influencing factors and interpretative focus vary depending on structural type. These material- and system-dependent differences shape the analysis of the time series and their integration into structural analysis models.

4. GNSS-Based Measurement Method and Technical Implementation

4.1 Sensor Technology and Antenna Systems

The metrological basis of the presented monitoring system is the use of multi-frequency GNSS receivers in the low-cost segment. GNSS boards of the type u-blox ZED-F9P are used, capable of processing signals from GPS, GLONASS, Galileo, and BeiDou satellite systems. The receivers support both Real-Time Kinematic (RTK) positioning and full recording of GNSS raw data for subsequent post-processing analysis. Measurement frequencies of up to 10 Hz allow the detection of quasi-static as well as dynamic structural movements.

A key factor influencing achievable measurement accuracy is the antenna technology employed. The system uses calibrated GNSS antennas with stable phase centers. Phase center variations are accounted for during post-processing using standardized ANTEX antenna models. The antennas are strategically distributed across the structure and supplemented by a permanently installed reference station with known coordinates. This configuration enables robust relative determination of horizontal and vertical changes at individual measurement points.

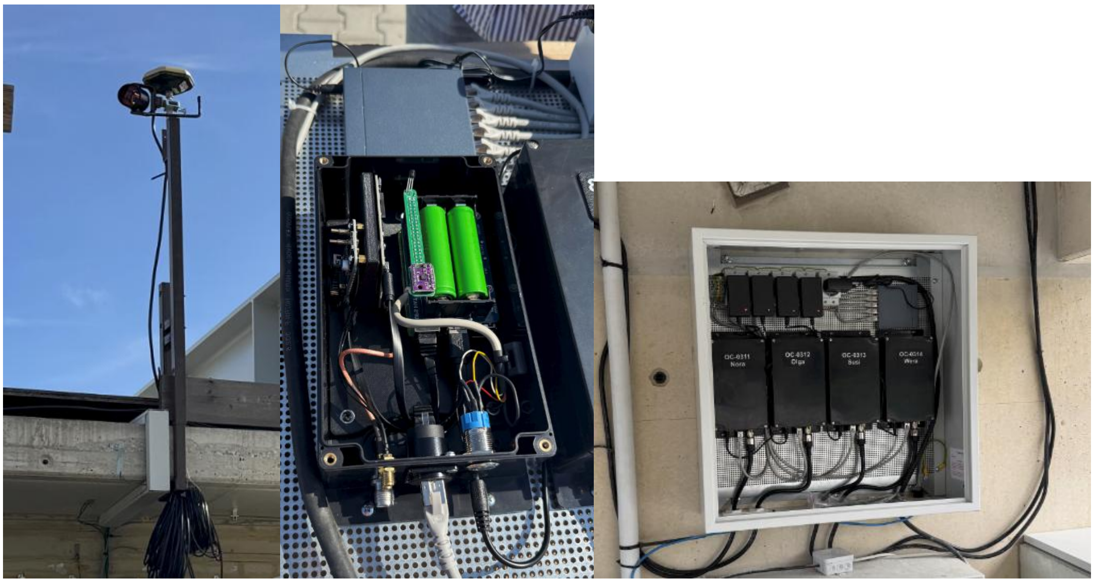
Due to the low power consumption of the GNSS sensors, both grid-connected and energy-autonomous applications are possible. Depending on the application scenario, the sensor system can be expanded with additional components such as temperature, humidity, inclination, or acceleration sensors to jointly capture structural and environmental influences.

4.2 GNSS Processing (RTK and Post-Processing)

Position determination is carried out either in real time using RTK or via post-processing of recorded GNSS raw data. In RTK mode, correction data in RTCM format are transmitted from a local reference station or via NTRIP services to the rover stations. By differencing reference and rover observations, major systematic error sources such as satellite orbit and clock errors as well as atmospheric effects can be largely eliminated. The resulting position solutions exhibit short-term noise in the centimeter to millimeter range and are particularly suitable for the timely detection of short-term deformations and load conditions.
For applications requiring the highest accuracy, GNSS raw data are processed in post-processing mode. The raw data are converted into RINEX format and processed using geodetic analysis software that applies established models for correcting ionospheric and tropospheric delays, satellite orbit and clock errors, and antenna effects. Adjustment is performed using the least-squares method with simultaneous estimation of coordinates, ambiguities, and atmospheric parameters. With longer observation intervals, accuracies in the millimeter to sub-millimeter range can be achieved.
By analyzing continuous time series, daily periodic effects, temperature-dependent length changes, and other cyclical influences can be identified and statistically separated from structurally induced deformations. The combination of RTK and post-processing thus enables both near-real-time.

4.3 System Architecture and Data Management

The technical implementation of the monitoring system is based on a modular, decentralized system architecture. Central components are GNSS data loggers based on single-board computers with Linux operating systems (Raspberry Pi architecture), which handle sensor control, local data storage, and communication. Data transmission is primarily carried out via mobile networks (LTE/4G), with optional support for alternative wireless technologies, enabling location-independent operation and remote access.
The open software architecture allows automated processing of GNSS raw data at freely definable intervals, such as hourly or daily. Results are stored in database systems, continuously monitored, and visualized via web-based dashboards. Additional features include quality control, alarm functions, and system diagnostics.
By separating sensor technology, data processing, and data storage, and by using freely available hardware and software components, a scalable and vendor-independent monitoring system is created. This system can be flexibly adapted to different structural and site conditions and represents an economical alternative to proprietary GNSS monitoring solutions.



Antenna, data logger (individual units) Equipment cabinet housing the data logger units

4.4 Antenna Technology as a Key Factor in High-Precision GNSS Bridge Monitoring

The GNSS antenna, as the primary accuracy driver within the measurement chain, represents a decisive factor for high-precision monitoring applications. Especially when detecting deformations in the millimeter range, antenna-related effects account for a dominant share of the systematic error budget.

A homogeneous series of high-quality multi-GNSS antennas is employed, each of which was individually and absolutely calibrated prior to deployment. Calibration was performed using a robot-assisted procedure following the established Geo++ approach, which enables dense and reproducible sampling of the entire upper hemisphere. In this process, antenna-specific phase center offsets (PCO) as well as frequency-, elevation-, and azimuth-dependent phase center variations (PCV) are precisely determined. In contrast to type- or manufacturer-based antenna models, these individual calibrations reflect the true electromagnetic behavior of each antenna.

The calibration results reveal pronounced frequency-dependent PCV structures for GPS and Galileo signals, particularly between L1/E1 and L5/E5. These effects are systematic in nature and propagate directly into carrier-phase-based position solutions. Without explicit modeling, they would lead to apparent movements in coordinate time series and significantly impair the reliable detection of very small deformations. At the same time, the investigated antennas show exceptionally high consistency: the dispersion of PCV values among individual antennas remains within the sub-millimeter range across all frequencies and elevations. This demonstrates both the high manufacturing quality of the antennas and the reproducibility and stability of the applied calibration procedure.

A key outcome of the study is that even the use of type-averaged antenna models is insufficient for high-precision monitoring applications. Although such models represent an improvement over uncalibrated antennas, residual systematic effects remain and negatively

affect the long-term stability of coordinate time series. For applications with the highest accuracy requirements, individual antenna calibration is therefore indispensable.
The successful integration of individually calibrated antennas into a real bridge monitoring system confirms their suitability for demanding structural health monitoring applications. The study thus demonstrates that the GNSS antenna must not be regarded as an interchangeable standard component, but rather as a critical system element whose quality and precise modeling decisively determine the performance of high-precision GNSS-based monitoring techniques.

5. GNSS-Based Monitoring as an Integral Component of Bridge Condition and Load-Bearing Assessment

In classical displacement measurements, total stations are generally used. For continuous measurements with high sampling rates, each measurement point would require its own total station and prism. Even if measurements are automated, the equipment requires frequent inspection and protection, resulting in high costs per measurement point for continuous monitoring.
To verify the accuracy of GNSS measurements, control measurements using classical total stations were carried out during the experimental campaign. In this context, personnel were continuously engaged in performing the control measurements, clearly illustrating the high material and labor effort associated with classical surveying methods. Typically, total station measurements are conducted as single-epoch observations; for continuous measurements, special total stations and dedicated data management are required. In the present case, measurement results from total stations were transferred via physical data carriers (USB storage) for further processing.
This approach can only be applied in exceptional cases, as the effort required for continuous data acquisition—particularly for remote structures—is generally impractical.
High-precision GNSS measurements, by contrast, open up entirely new analytical possibilities for bridge structures that were previously unavailable. These possibilities are briefly demonstrated

Control measurements using a total station (Bautzen)

Control measurements: classical displacement monitoring – four measurement points requiring four total stations (Bautzen)

Layout of measurement points at the Bautzen test bridge

Arrangement of the loading portal and total stations for control measurements (right)

GNSS antenna with integrated prism (center); total station used for control measurements (right)

5.1 Application to Steel Bridges

In steel bridges, deformation behavior is primarily governed by thermally induced length changes, dynamic effects, and fatigue-related stiffness degradation. Due to the high coefficient of thermal expansion of steel, GNSS time series exhibit pronounced daily and seasonal movements, which often mask traffic-induced deformation components.
GNSS monitoring enables continuous recording of these movements in both horizontal and vertical directions. A key analytical step consists of modeling and filtering thermal effects, for example by correlating measured displacements with temperature data. After removing reversible, temperature-induced components, residual deformations can be analyzed as indicators of structural changes.
GNSS monitoring is particularly relevant for the assessment of bearings and restraint conditions. Unexpected displacement constraints or asymmetric deformation patterns may indicate blocked bearings, damage, or insufficiently accounted restraint forces. Furthermore, changes in deformation amplitudes under comparable traffic loads can be interpreted as indicators of fatigue processes or stiffness loss.
Comparison with finite element (FE) models allows boundary conditions, temperature assumptions, and load distributions to be calibrated in a realistic manner.

5.2 Application to Reinforced Concrete Bridges

In non-prestressed reinforced concrete bridges, long-term effects such as creep, shrinkage, and crack formation become dominant in addition to thermal influences. These processes lead to time-dependent, partially irreversible deformations that can only be captured to a limited extent using classical periodic measurements.
GNSS-based monitoring enables observation of long-term trends in deflection and settlement, providing insights into the actual stiffness level of the structure. In particular, the evolution of deformation responses under traffic loads is relevant for condition assessment: increasing

deflections under comparable loading conditions may indicate progressive cracking, reinforcement fatigue, or changes in bearing behavior.
By combining GNSS time series with environmental measurement data, reversible temperature- and humidity-related effects can be separated from irreversible structural changes. The corrected residual time series provide a robust basis for comparison with FE models that account for cracked concrete states and reduced bending stiffness. In this way, GNSS monitoring contributes to the plausibility assessment of analytical assumptions and reduces uncertainties in load-bearing capacity evaluation.

5.3 Application to Prestressed Concrete Bridges

Prestressed concrete bridges represent the most complex structural class due to prestressing and pronounced time-dependent material effects. Structural behavior is strongly influenced by prestress losses resulting from relaxation, creep, and shrinkage, as well as by temperature-dependent length changes. These effects can only be approximated analytically and are associated with significant uncertainties, particularly in older structures with incomplete documentation.

GNSS monitoring provides decisive added value in this context, as it captures integrated structural responses in which all influencing factors are superimposed. Vertical deformations, in particular, serve as sensitive indicators of changes in effective prestressing force. Progressive prestress loss would manifest itself in increasing long-term deflections or altered deformation amplitudes under traffic loads.

The results presented by Stempfhuber et al. demonstrate that even very small long-term trends can be detected through high-precision post-processing analyses. Correlation analyses with

temperature data allow thermally induced, reversible deformations to be modeled and filtered out. The remaining residual time series enable targeted analysis of irreversible processes such as creep, shrinkage, or settlements.

6. Classification of the Approach

Regardless of structural type, the overarching question remains the same: does the observed structural behavior correspond to the analytically expected behavior under real actions?

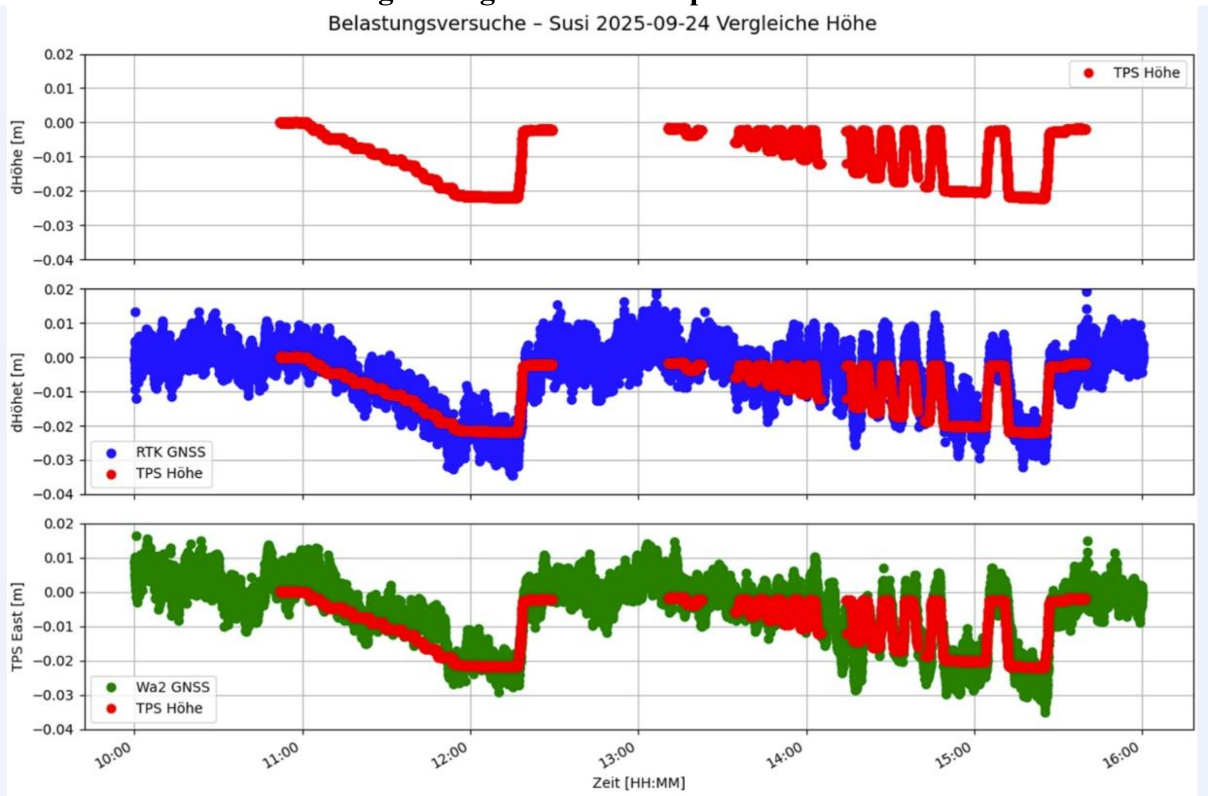
GNSS-based monitoring provides a structure-independent tool whose strength lies not in direct load-bearing capacity calculation, but in the objective observation of actual structural performance.

While the focus for steel bridges lies on thermal effects and fatigue, for reinforced concrete bridges on creep, shrinkage, and cracking, and for prestressed concrete bridges on prestressing and time-dependent effects, the measurement methodology remains identical. Differences arise in the interpretation of time series and their integration into analytical models. GNSS monitoring thus forms a key link between observation and calculation and enables a consistent, condition-oriented assessment of different types of existing bridges.

6.1 Data Evaluation – Methodology and Perspectives

The evaluation of load tests on the prestressed concrete bridge in Bautzen illustrates the comparison between control measurements (red) and GNSS measurements (blue/green). Continuous GNSS monitoring allows deformation behavior to be analyzed with high temporal resolution, providing insights that cannot be obtained through classical single-epoch measurements.

6.2 Datenauswertung – Vorgehen und Perspektiven



Evaluation of load tests on the prestressed concrete bridge in Bautzen (red: control measurements; blue/green: GNSS measurements)

6.3 Hybrid Approach: AI-Supported Data Analysis and FE Modeling

The evaluation of continuous GNSS monitoring data over periods of months or years requires methods that can efficiently process large datasets while ensuring engineering-based interpretability. Against this background, a hybrid approach combining AI-supported data analysis with physics-based FE modeling has proven particularly effective. AI is not understood as a replacement for classical structural analysis, but as a supporting tool for structuring, condensing, and prioritizing relevant information.

In a first step, AI continuously analyzes GNSS time series. Based on statistical indicators, trend information, and relative comparisons between measurement points, deviations from previous structural behavior are identified. These may manifest as changes in deformation amplitudes, newly emerging trends, or asymmetric movement patterns. The goal of this analysis is not immediate load-bearing assessment, but early detection of potentially relevant anomalies within extensive datasets.

The deviations identified by AI are subsequently subjected to engineering evaluation. This includes systematic classification with respect to spatial location, temporal evolution, and movement direction. In particular, it is analyzed which measurement points are affected, whether multiple points exhibit consistent patterns, and whether observed changes can be explained by known environmental or operational conditions. This ensures that data-driven anomalies are always interpreted within the structural context.

Based on this evaluation, the analytical structural or FE model is applied in a targeted manner. Instead of simulating a wide range of hypothetical scenarios, only those load and boundary conditions that plausibly explain the observed deformations are modeled. These may include altered bearing conditions, temperature gradients, reduced stiffness, or— in the case of prestressed concrete bridges—different prestress states. Comparison between simulated and measured deformations allows physically sound validation of AI-based indications.

In the final step, the engineering relevance of the identified deviations is assessed. If measured and simulated deformation patterns correspond, the anomalies can be classified as explainable and non-critical. Deviations from model-based expectations, however, provide targeted indications of structural changes and may trigger further measures such as detailed recalculations, monitoring adjustments, or on-site inspections.

This hybrid approach combines the scalability of AI-supported analysis with the interpretability of physical models and provides a robust basis for condition-oriented assessment of bridge structures.

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BIOGRAPHICAL NOTES

Jens Kickler

Professor Jens Kickler studied civil engineering at the Technical University of Berlin from 1986 to 1992. He worked besides his studies on different construction sides. His Diploma Thesis he wrote on earthquake problems. For this he spends two months in Peru to study the real problems on the construction side in that country.

From 1995 to 1999, he worked as a research assistant at the Chair of Wood Construction at the Technical University of Berlin. In 1999, he completed his doctoral degree with a dissertation entitled *“Fracture Mechanic at Layered Materials – Theory and Practice”.*

From 2000 to 2001, he founded an engineering office at Berlin, which he still runs today. This office is running all kind of civil engineering projects in Germany.

In October 2001, he was appointed as a Full Professor at the Hildesheim University of Applied Sciences (HAWK former Fachhochschule), in 2010 he changed to Berlin, he was appointed as a Full Professor at the Berlin University of Applied Sciences and Technology in April 2010. During the summer semester of 2018, he completed a research sabbatical at the University in St. Peterburg. This research work was continued in winter semester 2022/23.

Dirk Kowalewski

I received my Dipl.-Ing. in Geodesy from TFH Berlin in April 1991. My career began with a strong focus on CAD software, total stations from Zeiss and Topcon, and GNSS technology, working with industry leaders such as Trimble, Ashtech, and Topcon. For the first ten years, I worked for various companies as a specialist in these fields, gaining extensive experience in geospatial technology, surveying instruments, and high-precision positioning systems.

n March 2001, I decided to start my own business and founded Geo.IT Systeme GmbH. This step allowed me to apply my expertise in GNSS technology to develop innovative solutions. A major milestone in my career was the foundation of navXperience together with Franz-Hubert Schmitz. In early 2010, we began developing the 3G+C GNSS antenna technology, a significant advancement in high-precision GNSS applications. By the end of 2010, we successfully launched the product, establishing navXperience as a key player in the GNSS industry.

Between 2009 and 2011, I worked together with Frank Heinen on the MoDeSh research project, where we developed a six degrees of freedom (6DoF) software to measure movements and deformations on vessels. This project helped advance geodetic monitoring applications and contributed to new measurement techniques. In 2013, the concept of the OSR receiver was born, aiming to enhance GNSS correction services. Since 2015, I have been working with navXperience, Gutec, and Datagrid on this project, pushing the boundaries of high-accuracy GNSS technology.

Since 2012, I have been an active member of the working group AK 3 "Measurement Methods and Systems" within DVW Germany, where I contribute to discussions on geodetic measurement technologies, industry standards, and innovation in positioning systems. Throughout my career, I have been passionate about developing high-precision GNSS solutions that support applications in surveying, precision agriculture, autonomous navigation, infrastructure monitoring, and other demanding positioning tasks. My focus has always been on bridging the gap between research and practical applications, ensuring that new technologies meet real-world needs.

Werner Stempfhuber

Professor Werner Stempfhuber studied geodesy at the Technical University of Munich from 1993 to 1998. He spent part of his studies at the University of Greenwich in England at the School of Earth Science, as well as at the University of New Brunswick in Canada.

From 1999 to 2005, he worked as a research assistant at the Chair of Geodesy at the Technical University of Munich. In 2004, he completed his doctoral degree with a dissertation entitled *"An integrity-preserving measurement system for kinematic applications."*

From 2005 to 2007, he was employed as a Senior Engineer at Leica Geosystems in Heerbrugg. Between 2007 and 2010, he served as a senior research associate at ETH Zurich, working at the Institute of Geodesy and Photogrammetry in the field of geodetic measurement techniques and engineering geodesy.

In April 2010, he was appointed as a Full Professor at the Berlin University of Applied Sciences and Technology. During the winter semester of 2016/17, he completed a research sabbatical at the University of Cape Town. His research activities and projects span the full spectrum of engineering geodesy.

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