Unique GNSS based Structural Health Monitoring

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1. SUMMARY

The continuous development of geodetic measurement methods and sensor systems for the automated recording of structural deformations has significantly optimised the versatile capabilities of automated monitoring solutions in geodesy, construction, and geosciences [Stempfhuber, 2010], [Engel, 2015] [Schiefelbein, et. al 2020]. In addition to commercial complete systems, individual platforms are increasingly available. Depending on the task at hand, terrestrial or GNSS-based methods are used to determine changes in elevation and position relative to a reference epoch. In addition, inclination, acceleration, and meteorological sensors are often integrated. The monitoring systems are typically based on comprehensive software solutions for control, data processing, and storage of measurement results in database systems. This means that many existing solutions are resource-intensive in terms of hardware, licensing, and operating costs. While many systems run on Windows computers, low-cost single-board computers or optimised microcontrollers are only in limited application to date.

A frequently used approach is the distributed organisation of sensor technology and control in open geosensor networks [Pink, 2008]. This architecture enables high flexibility, system openness, and adaptability to different monitoring requirements. Before planning and implementing automated monitoring tasks – such as on dams, bridges, towers, tunnels, high-rise buildings, sheet piling, wind turbines, landslides, or glaciers – the concepts are evaluated based on various criteria, including:

- Costs for acquisition, licenses, and operation
- Functional scope and adaptability
- Required computing performance
- Number, type, and capabilities of the sensors

- Modularity and interchangeability
- Requirements for installation, connectivity, and power supply
- Security and access conditions
- Requirements for data analysis and evaluation methods
- Degree of automation
- Configuration and formatting of results
- Expandability through open interfaces and software modules
- Integration into higher-level geosensor networks
- Communication and remote maintenance options
- Potential for using low-cost components
- Redundancy, system security, and backup strategies

Experience from previous projects shows that demanding monitoring tasks often give rise to specific additional requirements. Open systems offer decisive advantages in this regard, as they are flexibly adaptable and programmable. Findings from many years of application and optimisation are currently being incorporated into various research and practical projects where they are being validated. The paper aims to empirically investigate the performance of these systems as well as their technical limitations, accuracy parameters, and reliability.

ZUSAMMENFASSUNG

Die stetigen Entwicklungen geodätischer Messverfahren und Sensorsysteme zur automatisierten Erfassung von Bauwerksdeformationen haben die vielseitigen Möglichkeiten vom automatisierten Monitoringlösungen in Geodäsie, Bauwesen und Geowissenschaften signifikant optimiert [Stempfhuber, 2010], [Engel, 2015], [Schiefelbein, et. al 2020]. Neben kommerziellen Komplettsystemen existieren zunehmend individuelle Plattformen. Je nach Aufgabenstellung kommen terrestrische oder GNSS-basierte Verfahren zur Bestimmung von Höhen- und Lageänderungen gegenüber einer Referenzepoche zum Einsatz. Ergänzend werden häufig Neigungs-, Beschleunigungs- und meteorologische Sensoren integriert. Die Monitoringsysteme basieren in der Regel auf umfangreichen Softwarelösungen zur Steuerung, Datenverarbeitung und Speicherung der Messergebnisse in Datenbanksystemen. Hinzu kommt, dass viele bestehende Lösungen sowohl hardwareseitig als auch hinsichtlich Lizenz- und Betriebskosten ressourcenintensiv sind. Während viele System auf Windows-Rechner laufen, finden kostengünstige Einplatinencomputer oder optimierte Mikrocontroller bislang nur begrenzt Anwendung.

Ein häufig genutzter Ansatz ist die verteilte Organisation von Sensorik und Steuerung in offenen Geosensornetzwerken [Pink, 2008]. Diese Architektur ermöglicht hohe Flexibilität, Systemoffenheit und Anpassungsfähigkeit an unterschiedliche Monitoringanforderungen. Vor der Planung und Umsetzung automatisierter Überwachungsaufgaben – etwa an Staumauern, Brücken, Türmen, Tunneln, Hochhäusern, Spundwänden, Windkraftanlagen, Rutschhängen oder Gletschern – werden die Konzepte anhand verschiedener Kriterien bewertet, darunter:

- Kosten für Anschaffung, Lizenzen und Betrieb
- Funktionsumfang und Anpassbarkeit
- Erforderliche Rechenleistung
- Anzahl, Typ und Leistungsfähigkeit der Sensoren
- Modularität und Austauschbarkeit
- Anforderungen an Installation, Konnektivität und Energieversorgung
- Sicherheits- und Zugangsbedingungen
- Anforderungen an Datenanalyse und Auswerteverfahren
- Automatisierungsgrad
- Konfiguration und Formatierung der Ergebnisse
- Erweiterbarkeit durch offene Schnittstellen und Softwaremodule
- Integration in übergeordnete Geosensornetzwerke
- Kommunikations- und Fernwartungsoptionen
- Einsatzpotenzial von Low-Cost-Komponenten
- Redundanz, Systemsicherheit und Backupstrategien

Erfahrungen aus bisherigen Projekten zeigen, dass bei anspruchsvollen Monitoringaufgaben häufig spezifische Zusatzanforderungen entstehen. Offene Systeme bieten hierfür entscheidende Vorteile, da sie flexibel anpassbar und programmierbar sind. Erkenntnisse aus langjährigen Anwendungen und Optimierungen fließen derzeit in verschiedene Forschungs- und Praxisprojekte ein und werden dort validiert. Das Paper soll die Leistungsfähigkeit dieser Systeme sowie deren technische Grenzen, Genauigkeitsparameter und Zuverlässigkeit empirisch untersuchen.

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2 MONITORING APPLICATION IN THE OPENLAB RESEARCH PROJECT

Economical, reliable monitoring of infrastructure objects that meets accuracy requirements is of central importance for every economy. In connection with civil engineering, it enables the early detection of potential risks and the timely initiation of appropriate measures. Alongside regular inspection reports, traditional geodetic monitoring methods, including tachymetric measurements, hydrostatic level measurements, and inclination sensor technology, are used and often supplemented by GNSS-based methods [Resnik, 2016]. A fundamental distinction must be made here between real-time kinematic (RTK) measurements and the analysis of baselines from recorded raw data in post-processing. When the receiver board, antenna, and analysis algorithm are optimally combined, both approaches enable deformation measurements in the millimetre range in terms of position and elevation [Glabsch, 2017]. In the *OpenLab* (http://82.165.222.27/OpenLab/) research project in Bautzen/Dresden, the behaviour of a model bridge approximately 45 m long was investigated using various measurement technologies.

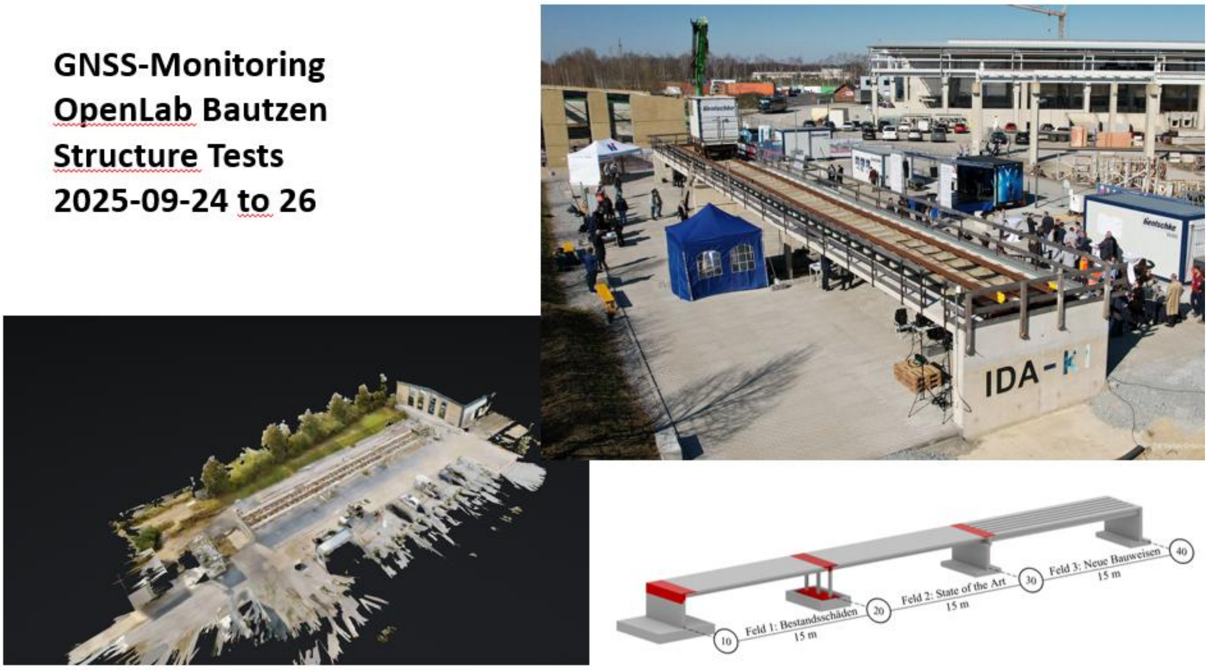

Fig. 1: Bridge Details OpenLab Bautzen
(Ref: https://tu-dresden.de/bu/bauingenieurwesen/imb/forschung/openLAB)

Additional investigations with the extended project team were conducted in November 2025 on a bridge in Worms together with the project partners. The same measurement technology was used there as well and was validated by independent reference measurements.
The results of both investigations confirm that the approach is ideally suited for the highly accurate measurement of structural deformations. The measurement accuracies achieved are comparable to those of geodetic GNSS receivers, while the hardware costs are only about 5% of a traditional geodetic GNSS system.

3 GNSS BASED GEODATIC MONITORING

The hardware and software components, technologies, and algorithms required for GNSS processing in automated monitoring operations, both in real time and in post-processing, are presented below. The realisation is carried out and implemented on the OpenLab bridge.

3.1 Boards

In addition to GNSS sensors from manufacturers of geodetic surveying instruments, there are now many low-cost, high-performance multi-frequency GNSS boards available with cm and mm accuracy for RTK and post-processing. The following list provides examples of some manufacturers of OEM solutions, including a specific receiver type (some of these OEM manufacturers offer different receiver modules for similar tasks):

GNSS OEM Manufacture	Typ
Fa. uBlox (https://www.u-blox.com/)	F9P/x20
Fa. NVS (http://nvs-gnss.ru/)	NV216C-RTK
Fa. Septentrio (https://www.septentrio.com/)	Mosaic x5
Fa. Trimble https://www.trimble.com)	BD990 or 2
Fa. Javad (https://www.javad.com/)	TR-XXX
Fa. Novatel (https://novatel.com)	OEM7xx
Fa. Hemisphere (https://www.hemispheregnss.com/)	Vega/Phantom
Fa. https://en.unicore.com/	UC98xx UM98xx

Tab. 1: OEM GNSS Boards [Alberding, et. al. 2017]

The research project uses uBlox ZED-F9P boards (with the F9K variant, IMU data can also be used). It is a cost-effecient, dual-frequency GNSS receiver [GPS (L1C/A, L2C); GLONASS (L1OF, L2O); Galileo (E1, E5b); BeiDou (B1I, B2I)] that is generally well suited for 3D monitoring applications. The module supports all GNSS signals, enabling high satellite availability as well as robust ambiguity resolution in RTK applications. The integrated RTK engine allows real-time positioning with high accuracy requirements without the need for external add-on modules. Alongside real-time processing, the GNSS chip provides all raw data, thereby enabling subsequent analysis using post-processing in static or kinematic analysis methods. The power consumption of the module must be taken into account when using applications with solar modules that record raw data using data loggers and then send it to the analysis server. At around 0.5 – 1.0 watts with a supply voltage of 3.0 – 5.5 volts, this is very low. Microcontrollers such as the ESP32, the Raspberry Pico, and single-board computers based on the Raspberry Pi or Zero perform these tasks very well. The interfaces available are UART, USB, I²C, and SPI. Measurement frequencies up to 10 Hz are possible. The SMA standard is used for external GNSS antennas. The extremely compact size of the chip, measuring approx. 17 × 22 mm, its high robustness and temperature stability, as well as the option to integrate into embedded systems led to the selection of this sensor.

The receiver achieves extremely high accuracies when combined with high-quality GNSS antennas and suitable correction services (ideally through a dedicated reference station with an identical structure). The use of all-band frequencies (such as those provided by the uBlox x20) does not result in any significant improvement in accuracy. The configuration for real-time operation and the respective recording of raw data in ubx format results in a large number of variations. Optimal raw data is recorded through the appropriate use of parameters, filter adjustment, and configuration.

3.2 GNSS-Antennas

Alongside the receiver board and the analysis software, the GNSS antenna forms the central interface between the space segment of satellite navigation systems and the GNSS receiver. It receives the signals transmitted by the satellites in the L band, converts them into electrical signals, and makes them available to the receiver as raw data for further processing [Rost, 2011]. From the user's perspective, the antenna has a significant impact on the quality of 3D positioning, as it determines signal strength, phase stability, and interference resistance. Key requirements include a stable phase centre variation (PCV), high multipath suppression, and robust filtration and amplification of the received signals. The stability of the *electrical phase centre (EPC)*, i.e., the nearly point-like reception centre that is dependent on frequency, direction, and elevation, is particularly relevant. The phase centre variations can be modelled using the appropriate calibrations. Calibrations for the various types in ANTEX format are provided by IGS, for example, and can be taken into account in post-processing. In terms of design, a distinction is made here between patch and helix antennas, each of which has different characteristics in size, efficiency, reception quality, and cost. The board manufacturers recommend using their own antennas (e.g., the ANN antenna for uBlox). Our application used antennas from *NavXperience*, which had previously been calibrated at the Berlin calibration facility.

Abb. 2: Mounting of the five antennas in the research project, along with their assigned names

3.3 GNSS-Dataprocessing

3.3.1 RTK

The real-time kinematic GNSS (RTK) method is an efficient procedure for carrier phase ambiguity resolution between a reference station or reference network and a rover. By eliminating sources of error, particularly satellite clock errors, orbit errors, and atmospheric delays, RTK typically achieves accuracies in the centimetre range and with optimisation and very short base lengths, even in the millimetre range. This is based on the formation of differences between the observations of both receivers, which largely compensates for systematic errors. The RTCM format has become established as an international standard for the transmission of correction data. These RTCM messages are transmitted either via a GSM module using the NTRIP protocol (Networked Transport of RTCM via Internet Protocol), via LAN connections, or via radio data transmission. The www.rtk2go.com process is an excellent means of achieving a distributed provision of RTCM. Another option is to directly process the RTCM messages. To do this, RTCM Messages 3.3 (1005-4072) must be activated in the uBlox reference configuration. (Both variants are implemented in the overall system.) In addition to RTCM, there are proprietary protocols such as SPANTAN. The positions are output in NMEA format and processed further. Redundancy is generally not realistic, as the rover only ever receives the correction data from the reference.

3.3.2 Postprocessing

Fundamentally, a variety of options are available for GNSS processing of raw data. Ideally, these should be in RINEX format with the correct naming convention. A distinction must be made here between scientific analysis packages such as *Bernese Software*, open-source solutions such as *RTKLib*, and commercial programs. Wanninger software is exclusively used in this project. The *waPNet* module is only suitable for longer baselines, so the baseline calculation is conducted with the *Wa2* module including compensation using the corresponding antenna correction files. The *Wa2* module is used for the geodetic analysis of raw GNSS data. It processes observations from RINEX files or converted receiver data and uses them to generate precise position solutions. The basic process begins with the pre-processing of the data: *Wa2* checks the observation files for completeness, detects cycle interruptions and outliers, and converts the measurement values into an internal format. This is followed by modelling of the most significant sources of error that occur in GNSS measurements. These include ionospheric and tropospheric delays, satellite clock errors, orbit errors, multipath effects, and antenna variations. *Wa2* uses established geodetic models such as ionospheric linear combinations, standard tropospheric models, and antenna models in ANTEX format. The observation equations are constructed on this basis. Both code measurements (pseudorange) and carrier phase measurements are processed. The latter are particularly precise, but contain unknown integer ambiguities, which *Wa2* estimates during the compensation process. The compensation is conducted using the least squares method, whereby position, ambiguities, and atmospheric parameters are simultaneously determined. The result is a statistically optimal solution, supplemented by a covariance matrix that provides information regarding accuracy. After the compensation, *Wa2* conducts a comprehensive quality control check. Among other things, residual gaps, variance factors, DOP values, and ambiguity status are evaluated. This allows assessment of whether the solution is stable, whether there are measurement errors, or whether certain satellites should be excluded. The results can then be exported and further processed. *Wa2* is capable of analysing both static and kinematic measurements. In static measurements, maximum accuracy is a priority, while filtering techniques in kinematic measurements are used to continuously track the receiver's movements. The typical workflow includes importing raw data, defining station parameters (antenna type, antenna height), loading ephemerides and, if necessary, precise orbital data, selecting the analysis mode, and setting the filter and model parameters. After the compensation, the quality parameters are analysed and the calculated coordinates and statistical values are exported. PPP analyses are also possible, but are not used in the project.

4 DATENLOGGER

The GNSS data logger is a central component. It must reliably store and forward the recorded raw measurement data in all configurations. With RTK, it must also distribute or record the correction data in real time. The data loggers used are based on the Raspberry Pi single-board computer as the central recording platform. Due to its Linux architecture, high computing power, and numerous integrated interfaces, the Raspberry Pi is ideal for use in GNSS-based monitoring applications. Industrial variants of the Raspberry Pi, such as CM4 or CM5, represent even better options. Communication with the logger takes place via a mobile phone modem, among other things. The integrated SIM card enables independent data transmission via LTE or 4G networks, ensuring connectivity in the areas of operation. LoraWan technologies can be optionally used. The connections are used for the transmission of measurement data to an external server as well as for remote access to the system, thereby enabling software updates, status queries, and configuration changes without physical access. The data logger has several standardised interfaces that allow flexible integration of different sensors. Due to its combination of modular hardware, open software architecture, and mobile data transmission, the Raspberry Pi data logger is an economical yet powerful solution for GNSS monitoring tasks. The platform allows precise adaptation to specific requirements and thus offers a flexible alternative to proprietary monitoring systems. This solution is ideal for applications with power supply. In solar-powered solutions, data storage and distribution resources must be used in an optimised manner. Systems based on microcontrollers with buffer batteries are available for this. These also provide sufficient power for small solar panels (e.g., 25x35cm) during the winter months.

5 OVERALL SYSTEM

The GNSS monitoring system is based on the following basic components

- Data logger with GNSS receiver and antenna
- Analysis module for baseline analysis and compensation with network protocols
- Database for storage, alerting, and function testing

While RTK-GNSS measurements typically exhibit fluctuations in the cm range in terms of position and elevation, accuracies of less than 1 cm can be achieved by analysing raw GNSS data over observation intervals of several hours. The highest levels of precision are achieved with 24-hour observation periods, as all influences run through an entire cycle. In such long-term solutions, the measurement noise is approximately 1 – 2 mm (2σ) depending on the external environmental parameters, so even very small deformations and long-term movement trends in the submillimetre range can be detected here.

Fig. 3: Dataprocessing GNSS Postprocessing

The GNSS post-processing module automatically processes the raw measurement data at defined intervals, e.g., hourly or once daily. Our own 3D network compensation. Fig. Xx shows the flowchart schematically. The results are presented and discussed below using the two projects mentioned above as examples.

5 GNSS RESULTS

The GNSS system described above is installed on the bridge in Bautzen, among other locations. A stable reference station with fixed coordinates provides correction data for the four rover stations in real time and in post-processing mode. All processed measurement results are updated and displayed on the dashboard in hourly solutions. In addition, the last 3 hours of RTK measurement at 1 Hz are always stored in the database. The Matterport model and meteorological data are also available, as is the detailed analysis report. The relative movements at the Nora station are graphically represented in the following figure as an example. RTK and post-processing result in virtually no differences.

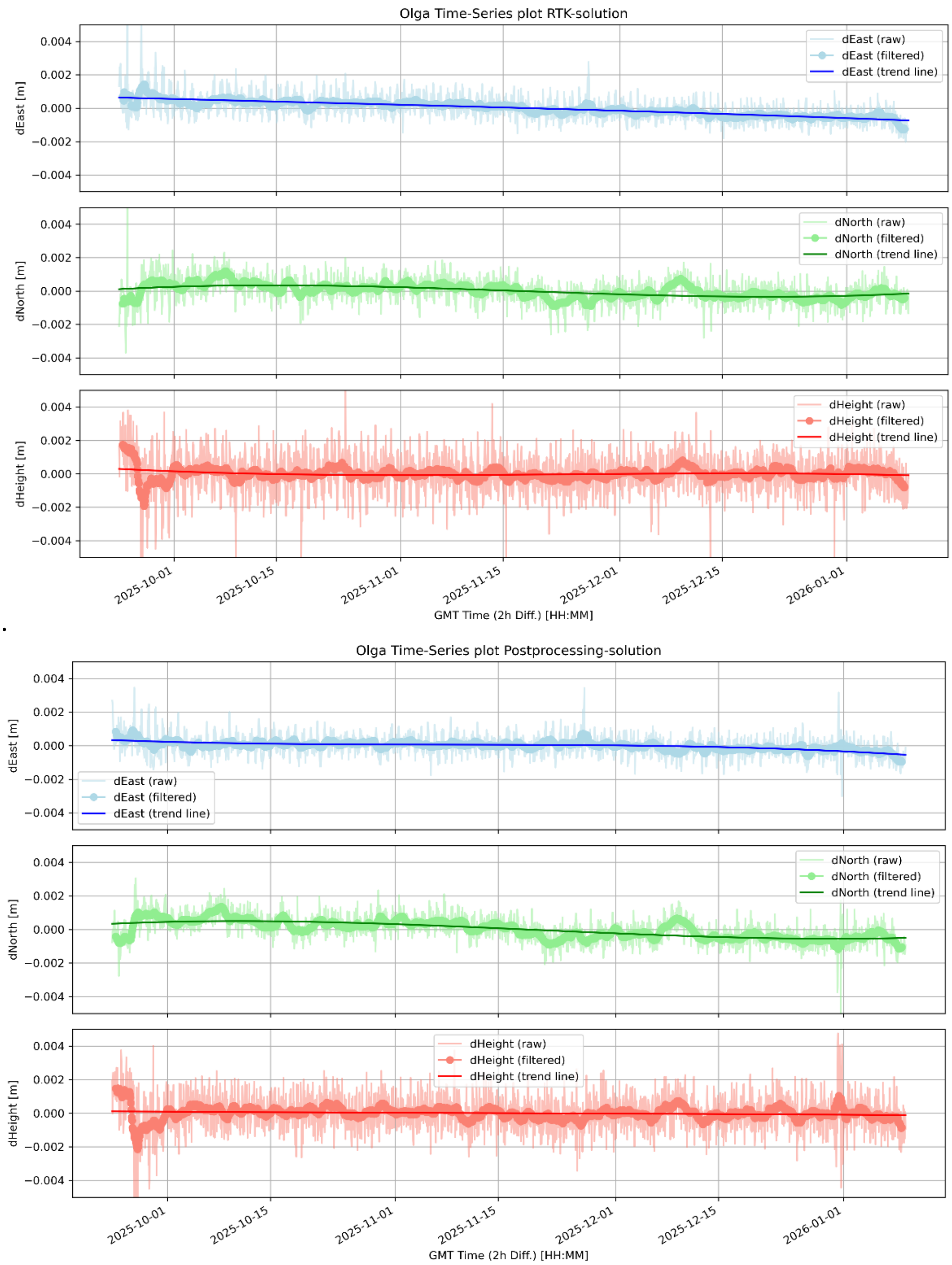

Fig. 4: 3D-Position accuracies at Nora in Bautzen: RTK vs post-processing

A daily variation of approximately 2 mm as a sine wave is still the result of residual errors in antenna calibration and the atmosphere in the transverse direction and elevation. This is the case with both analysis variants. The material expansion of the bridge is also superimposed in the longitudinal direction of the bridge. The correlation in Figure xx clearly shows this and confirms the high accuracy and reliability of the system. These effects can also be calculated. However, the progression of the elevation change is decisive.

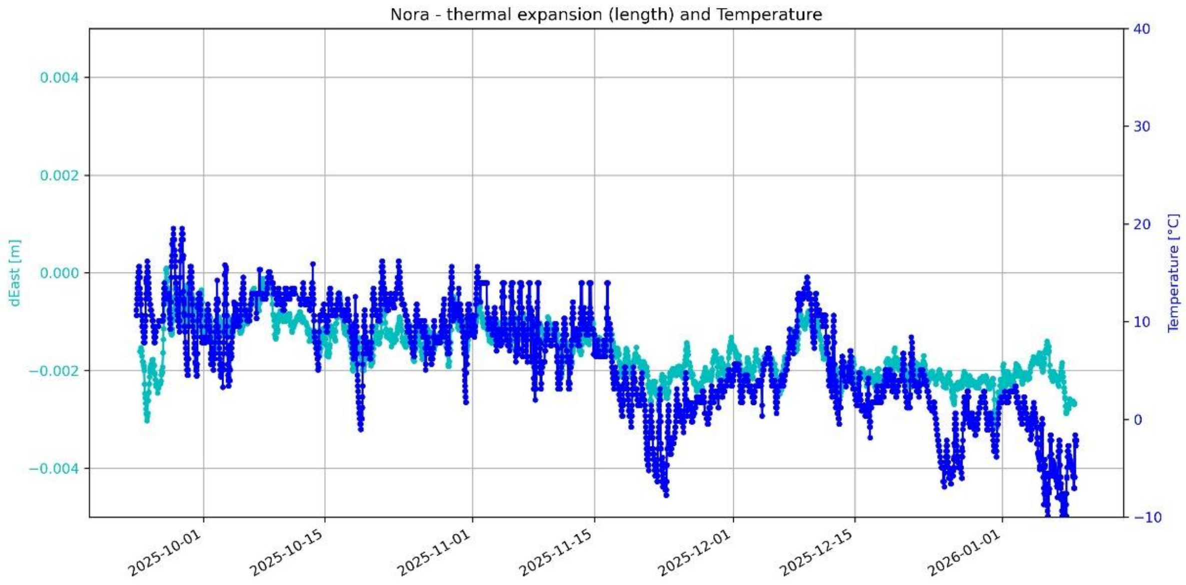

Fig. 5: Temperature behavior in comparison to the longitudinal expansion of the bridge

In September 2025, stress tests were conducted over a period of three days. Tachymetric observations served as a reference. The results precisely confirm the movements of the reference system.

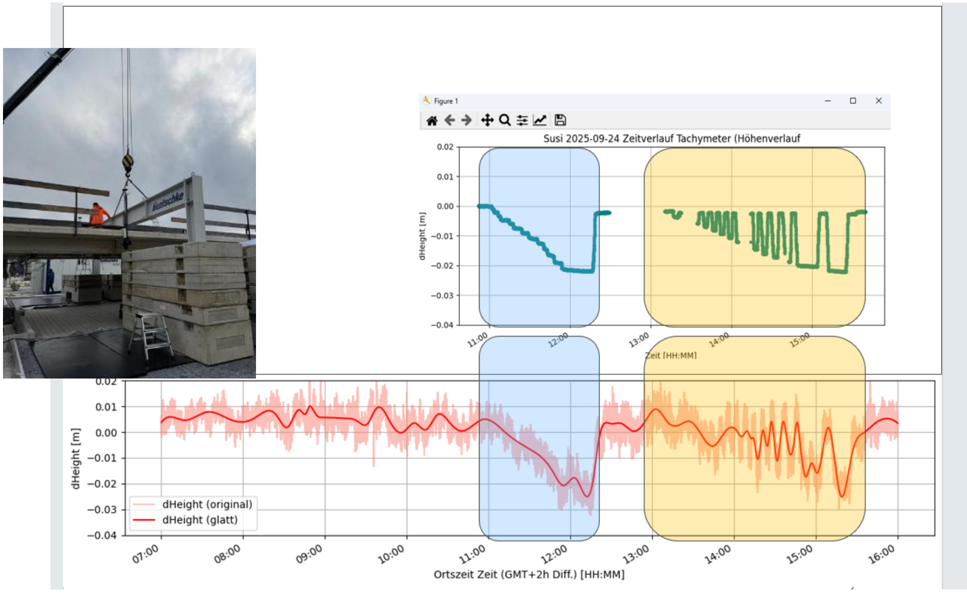

Fig. 6a: Results of the load tests / OpenLab Bautzen

The progressions are identical. The only difference is that the measurement noise is slightly higher. This is also clearly recognisable in the following figure.

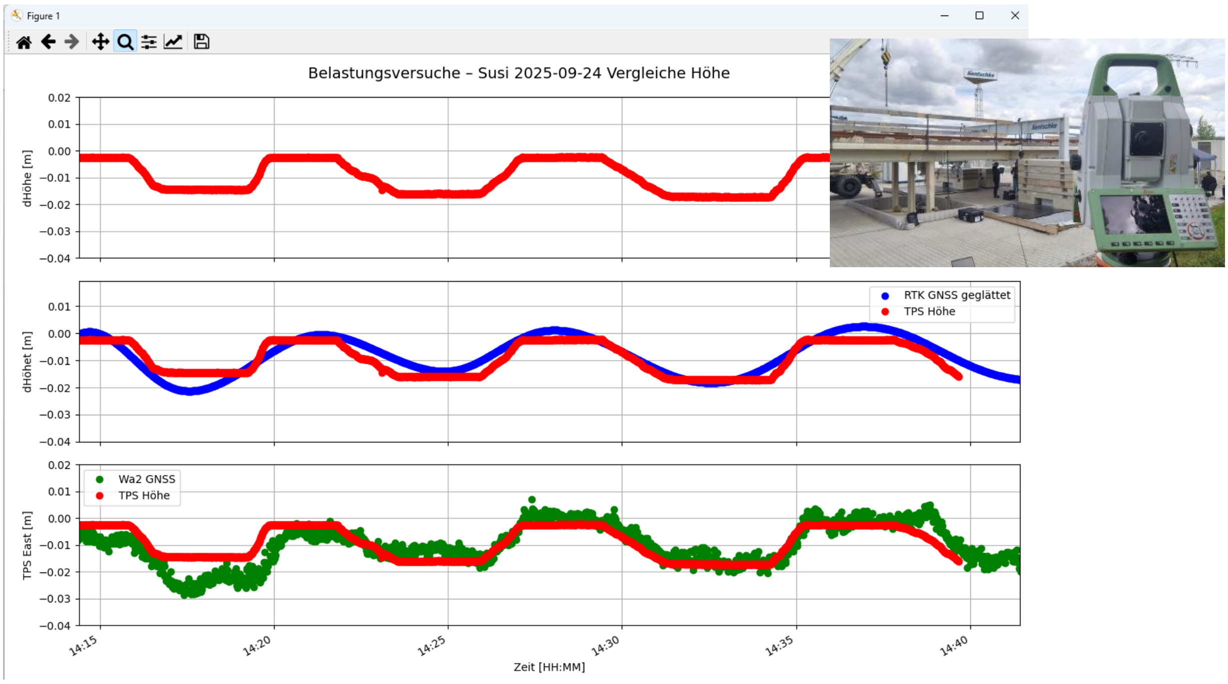

Fig. 6b: Results of the load tests / OpenLab Bautzen

Results Test in Worms

Load measurements are also carried out on a second bridge (the Nibelungen Bridge in Worms). In addition to static tachymeter measurements, a water level was available here as a reference system. The same deformation behaviour was also evident with the GNSS monitoring system.

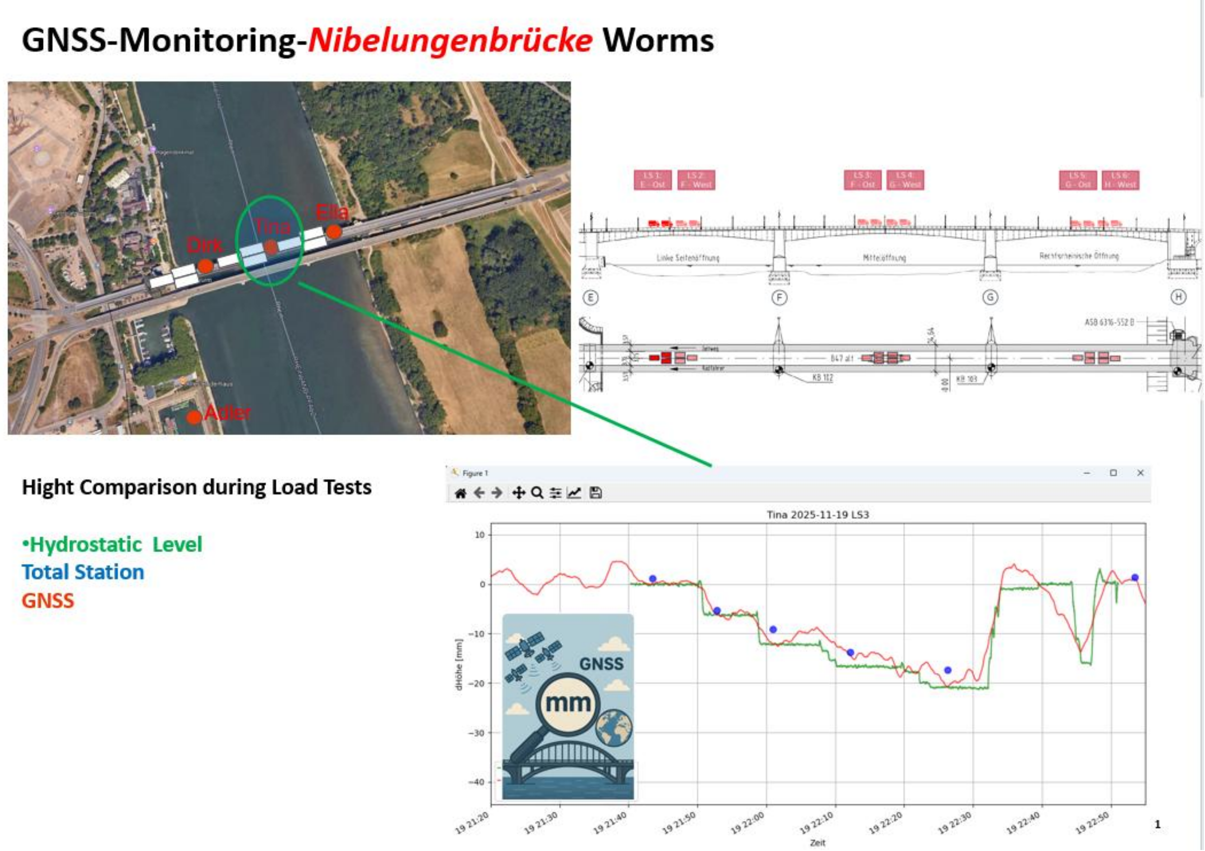

Fig. 7: Load Testing Results Worms

The two results from the installations shown clearly demonstrate that the system fulfils the requirements for high-accuracy deformation measurements in a monitoring system, thereby enabling fully automated monitoring at low cost.

6 SUMMARY

The goal of this article is to present the technical possibilities of GNSS-based monitoring systems and demonstrate their performance capabilities. The overall system, which combines cost-effective GNSS receivers with modular computing units, creates an efficient system that is suitable for a wide range of geodetic monitoring tasks. In conjunction with optimised server and database solutions, this approach offers a powerful yet economical alternative. The advantages of this approach particularly lie in the capability of individual system configurations, the easy integration of different GNSS sensors, the use of inexpensive and freely available hardware and software components, the flexible expandability of data storage, and the customisable analysis and visualisation of GNSS measurement data. The independence from manufacturer-specific solutions and the high variability of the sensor network also enable easy integration into existing geodetic workflows. The modular structure allows precise adaptation to the respective task and thus opens up new possibilities for flexible, cost-efficient, and scientifically based monitoring solutions. At the same time, the approach shows that RTK solutions are absolutely comparable to post-processing solutions. The system is ready for practical use and can be installed without problems or restrictions.

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BIOGRAPHICAL NOTES

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.

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.

In 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.

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.

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