Impact of GNSS Antenna Calibration on High-Precision Bridge Deformation Monitoring

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1. SUMMARY

This paper investigates the impact of GNSS antenna quality and calibration on the achievable accuracy of high-precision monitoring applications. The focus is placed on the antenna as a key accuracy-determining component within the GNSS measurement chain rather than on structural deformation results. Individually calibrated antennas from a uniform antenna series are analyzed with respect to their frequency- and elevation-dependent characteristics for GPS and Galileo signals.
The results of the absolute robotic antenna calibration reveal pronounced, frequency-dependent phase center variations that propagate systematically into the positioning solution. At the same time, a very high level of consistency is observed among the calibrated antennas. The spread of PCV values remains at the sub-millimeter level, confirming both the high manufacturing quality of the antennas and the robustness of the calibration methodology. The study demonstrates that neglecting or simplifying antenna calibration leads to systematic errors that significantly limit high-precision GNSS applications. For monitoring tasks with the highest accuracy requirements, individual antenna calibration is therefore essential.

Zusammenfassung

Dieser Beitrag untersucht den Einfluss der GNSS-Antenne und ihrer Kalibrierung auf die erreichbare Messgenauigkeit in hochpräzisen Monitoring-Anwendungen. Der Fokus liegt auf der Antenne als zentralem Genauigkeitstreiber innerhalb der GNSS-Messkette und nicht auf der strukturellen Bewertung von Bauwerken. Individuell kalibrierte GNSS-Antennen einer einheitlichen Antennenserie wurden hinsichtlich ihrer frequenz- und elevationsabhängigen Eigenschaften für GPS- und Galileo-Signale analysiert.
Die Ergebnisse der absoluten, robotergestützten Antennenkalibrierung zeigen ausgeprägte, frequenzabhängige Phasenzentrumvariationen, die systematisch in die Positionslösung eingehen. Gleichzeitig weisen die Kalibrierungsdaten eine sehr hohe Konsistenz zwischen den einzelnen Antennen auf. Die Streuung der PCV-Werte liegt im Submillimeterbereich und belegt sowohl die hohe Fertigungsqualität der Antennen als auch die Reproduzierbarkeit des Kalibrierverfahrens. Die Untersuchung zeigt, dass eine fehlende oder unzureichende Antennenkalibrierung zu systematischen Fehlern führt, die hochpräzise GNSS-Anwendungen

erheblich einschränken. Für Anwendungen mit höchsten Genauigkeitsanforderungen ist daher eine individuelle Antennenkalibrierung unerlässlich.

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1. Introduction

Global Navigation Satellite Systems (GNSS) have become an established tool for high-precision deformation monitoring in engineering applications. In particular, the monitoring of bridges and other large-scale structures benefits from GNSS due to its ability to provide absolute positioning, continuous observations, and independence from line-of-sight constraints between measurement points.

Despite significant advances in GNSS receiver technology and data processing strategies, the achievable measurement accuracy in many applications is still limited by systematic error sources. In addition to atmospheric effects and multipath, antenna-related errors represent a critical factor. Phase center offsets, phase center variations, and elevation- and azimuth-dependent antenna characteristics directly influence the positioning solution and may significantly bias deformation estimates, especially when deformations at the millimeter level are to be detected.

In practical GNSS-based Structural Health Monitoring (SHM) applications, the influence of antenna calibration is often underestimated or addressed only by using generic antenna models. This approach is increasingly insufficient in view of the growing demand for reliable, reproducible, and highly accurate deformation measurements under both static and dynamic loading conditions.

Against this background, this paper investigates the impact of individually calibrated GNSS antennas on the accuracy of bridge deformation monitoring. Within a dedicated research project, a test bridge was deliberately destabilized under controlled loading scenarios and monitored using a high-precision GNSS measurement system. The objective is to quantify the contribution of antenna calibration to the reduction of systematic errors and to demonstrate its effect on the detectability of very small structural deformations.

2. Background and Motivation

GNSS-based measurement techniques have become an established tool for deformation monitoring in engineering applications. In the field of Structural Health Monitoring (SHM), GNSS enables continuous, absolute positioning with high temporal resolution and is increasingly used to detect structural displacements at the millimeter level.

However, the achievable accuracy of GNSS-based deformation measurements is largely governed by systematic error sources. While atmospheric effects, satellite geometry, and multipath mitigation are nowadays well addressed by advanced processing strategies, the antenna remains one of the most critical components of the measurement chain. Antenna-related effects directly influence the carrier-phase observations and therefore have a decisive impact on high-precision positioning results.

Phase center offsets (PCO) and phase center variations (PCV) introduce elevation- and azimuth-dependent distortions that propagate into coordinate time series as systematic biases rather than random noise. When very small deformations are to be detected, these effects may dominate the error budget and significantly limit the reliability and interpretability of the results.
In practical GNSS applications, antennas are often used without individual calibration or by relying solely on generic antenna models. This implicitly assumes that antenna-specific characteristics are negligible or sufficiently represented by average models. While such assumptions may be acceptable for applications with moderate accuracy requirements, they are inadequate for deformation monitoring tasks targeting millimeter-level precision.
Against this background, antenna calibration must be regarded as a key element of any high-precision GNSS measurement system. A rigorous, antenna-specific calibration is essential to reduce systematic errors and to enable the reliable detection of minimal structural deformations.
The motivation of this study is therefore to investigate the influence of antenna calibration on the accuracy of GNSS-based bridge deformation monitoring. The objective is to demonstrate that antenna calibration is not a secondary refinement but a decisive factor in achieving a level of precision that would otherwise not be attainable.

3. Antenna Calibration Methodology

The foundation of the high-precision GNSS measurements presented in this study is the quality of the employed GNSS antennas and their rigorous individual calibration. For deformation monitoring at the millimeter level, an accurate modelling of antenna characteristics is essential, as antenna-related effects directly affect carrier-phase observations and therefore the achievable positioning accuracy.

All GNSS antennas used in this project were individually calibrated prior to their deployment. The calibration was performed using a robotic calibration system based on the well-established procedure developed by Geo++, which is widely regarded as a reference standard for absolute GNSS antenna calibration.

The robotic calibration facility is operated by the Senatsverwaltung für Stadtentwicklung und Wohnen and provides a controlled and highly repeatable environment for antenna calibration. The robotic system allows precise and automated positioning of the antenna under test, ensuring a dense and uniform sampling of azimuth and elevation angles across the entire upper hemisphere.

During the calibration process, the antenna is systematically rotated and tilted while continuously tracking GNSS signals. This procedure enables the determination of antenna-specific phase center offsets (PCO) and phase center variations (PCV) as functions of azimuth and elevation. In contrast to generic or type-averaged antenna models, the resulting calibration data represent the true electromagnetic behavior of each individual antenna.

The use of a robotic calibration approach offers several advantages. It minimizes setup-related uncertainties, reduces human-induced errors, and ensures a high degree of repeatability. This level of precision is particularly critical for GNSS-based deformation monitoring, where even small unmodelled antenna effects may dominate the overall error budget.

The antenna-specific calibration models derived from the robotic procedure were subsequently integrated into the GNSS data processing workflow. By applying these models consistently, antenna-related systematic errors could be significantly reduced at the observation level, forming the basis for the high-precision deformation measurements presented in the following sections.

4. Calibration Results for GPS and Galileo Frequencies

The antenna calibration results were analyzed for multiple GNSS frequencies. In this paper, the focus is deliberately placed on the GPS and Galileo satellite systems, as these provide highly stable signals, multi-frequency capability, and are particularly well suited for high-precision GNSS applications in engineering geodesy.

The calibration results clearly demonstrate that GNSS antenna characteristics are frequency-dependent and must be modelled accordingly. Phase center variations (PCV) differ significantly between frequencies and satellite systems, and these effects directly propagate into carrier-phase-based positioning results. Consequently, accurate antenna calibration is a prerequisite for reliable deformation measurements at the millimeter level.

4.1 GPS Frequencies

Figure 1 shows the PCV (NOAZI) as a function of elevation angle for GPS L1 (G01) for all five calibrated antennas. The nearly identical curves indicate a very high level of consistency between the antennas and confirm the reproducibility of the robotic absolute calibration procedure. At the same time, the pronounced elevation-dependent PCV structure illustrates that unmodelled antenna effects would introduce systematic errors into the positioning solution.

The calibration results for GPS L5 (G05) are presented in Figure 2. Compared to L1, a distinctly different PCV pattern can be observed, underlining the fact that antenna behavior is not frequency-neutral. For multi-frequency GNSS processing, the correct modelling of these frequency-specific characteristics is therefore essential. The small spread between the five antennas further confirms the high quality of both the antennas and the calibration process.

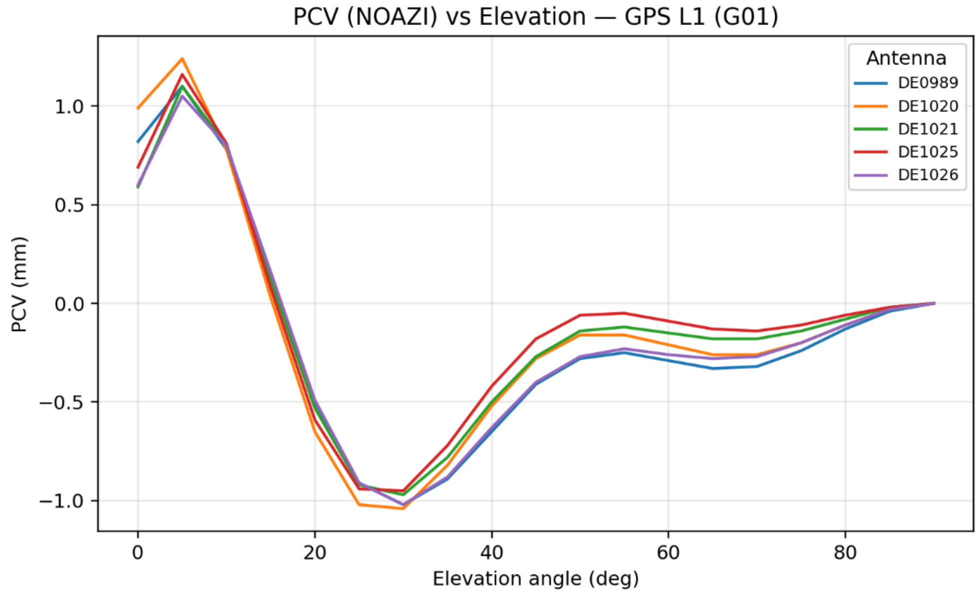

Figure 1

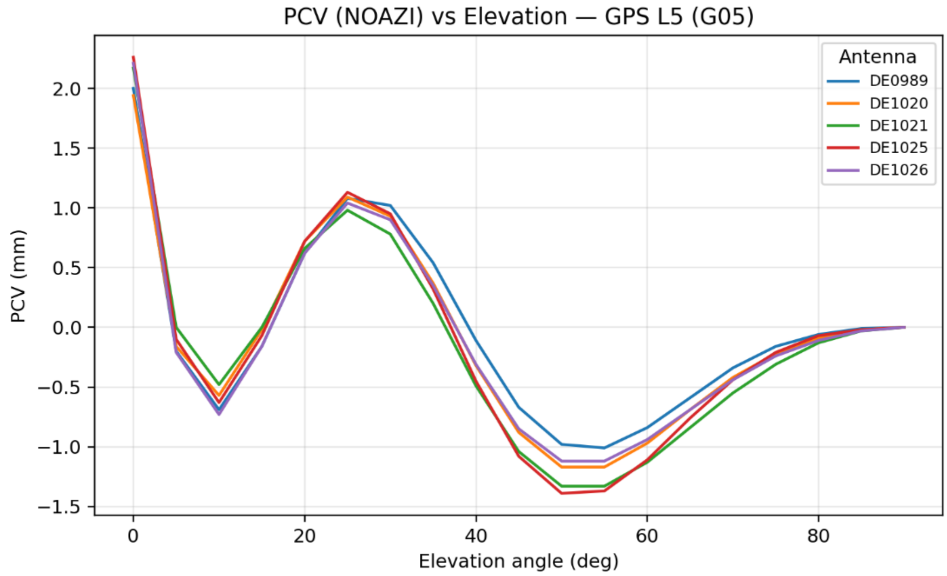

Figure 2

4.2 Galileo Frequencies

Figure 3 presents the PCV results for **Galileo E1**. While the overall shape of the PCV curve differs from that of GPS L1, the antenna responses remain highly consistent across all five units. This demonstrates that even for comparable carrier frequencies, system-specific antenna effects exist and must be considered through system- and frequency-dependent calibration models. The calibration results for **Galileo E5** are shown in Figure 4. Due to the AltBOC signal structure and the excellent phase quality of this frequency, accurate antenna modelling is of particular importance. The results reveal a stable and homogeneous antenna behavior, confirming the suitability of Galileo E5 for high-precision GNSS applications when proper antenna calibration is applied.

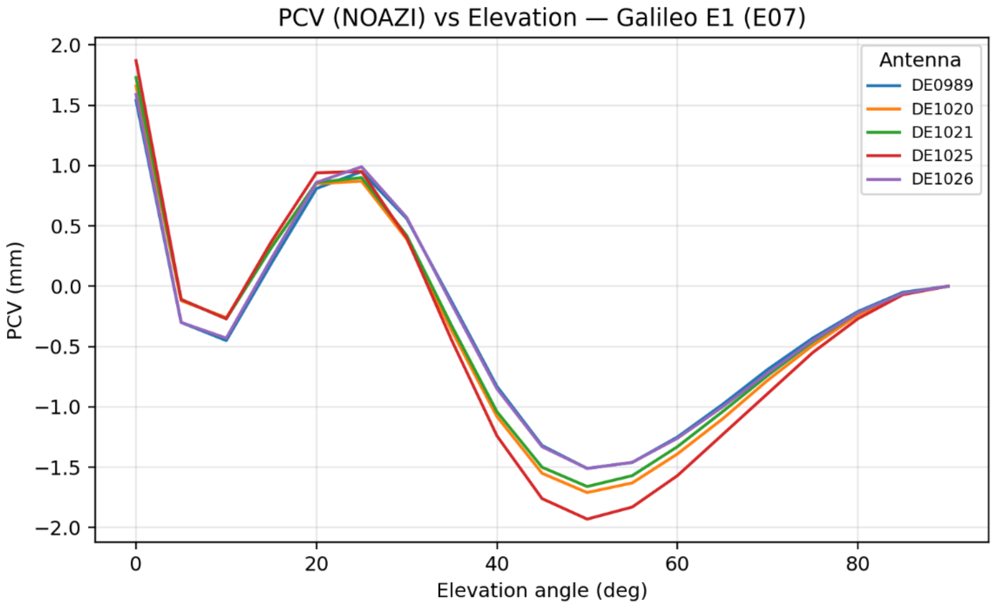

Figure 3

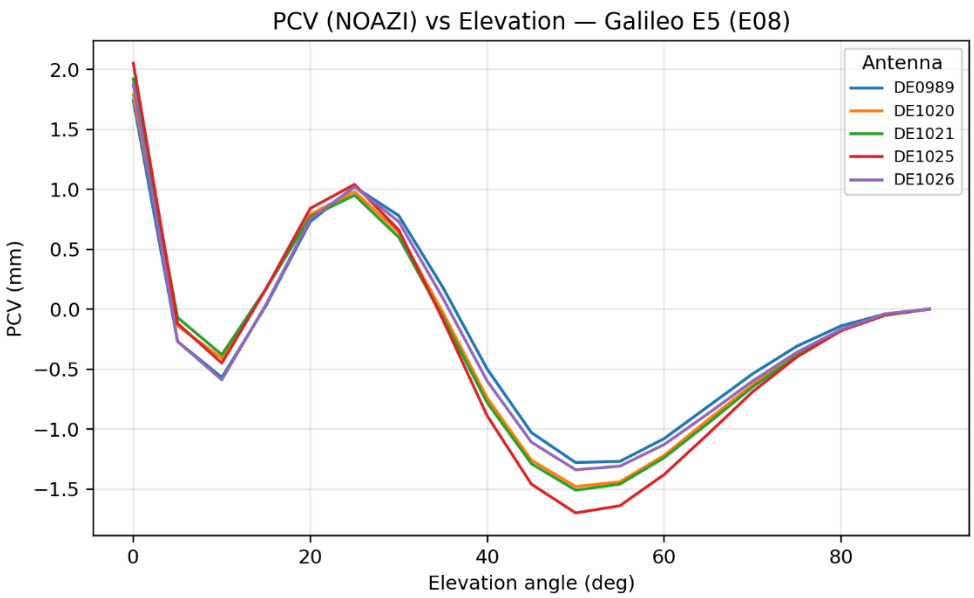

Figure 4

4.3 Consistency of Calibration Results

The overall calibration quality is further illustrated by the standard deviation of the PCV values across all five antennas, shown in Figure 5 as a function of elevation angle. The standard deviation remains well below the millimeter level over the entire elevation range, demonstrating both the homogeneity of the antennas and the robustness of the calibration methodology.

This high level of consistency is a key requirement for applications where small structural deformations must be distinguished from systematic measurement effects.

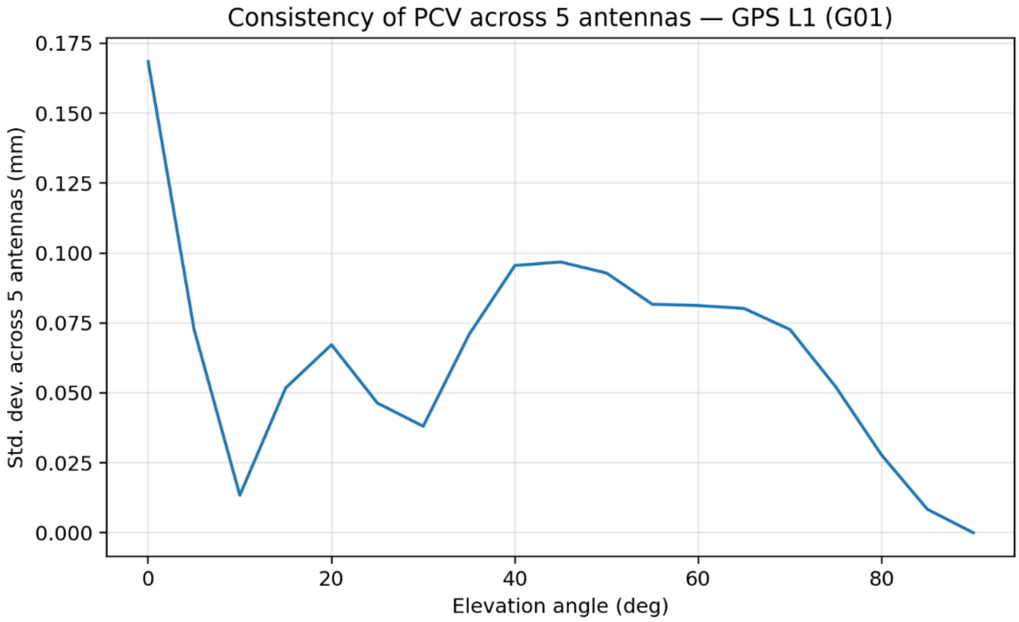

Figure 5

5. Implications of Antenna Calibration for High-Precision Bridge Monitoring

The calibration results presented in the previous chapters demonstrate that the quality of the GNSS antenna and its precise modelling have a decisive impact on achievable measurement accuracy. For high-precision bridge monitoring applications targeting millimetre-level deformations, the antenna represents one of the dominant contributors to the overall error budget.

The analysis of phase centre variations for GPS and Galileo frequencies shows that antenna-related effects are strongly frequency- and elevation-dependent. These effects are systematic in nature and propagate directly into GNSS-derived coordinate time series. Without proper modelling, even advanced GNSS processing strategies are unable to reliably achieve the accuracy required for Structural Health Monitoring applications.

A key outcome of the calibration analysis is the high level of consistency observed within the investigated antenna series. The very small spread of PCV values at the sub-millimetre level confirms both the high manufacturing quality of the antennas and the robustness of the applied calibration methodology. For practical bridge monitoring applications, this consistency is essential, as it enables reliable and comparable measurements across multiple observation points.

The results further indicate that while the use of a type-averaged antenna model represents a clear improvement over uncalibrated antennas, it is not sufficient to fully eliminate residual systematic effects. For applications demanding the highest possible accuracy, individual antenna calibration remains necessary in order to minimise residual biases and to ensure long-term stability of coordinate time series.

Overall, the presented findings highlight that the selection of suitable GNSS antennas and their rigorous calibration are fundamental prerequisites for high-precision bridge monitoring. The investigated antenna series exhibits homogeneous and stable calibration characteristics, making it well suited for demanding Structural Health Monitoring applications in which the antenna must not act as a limiting factor of measurement accuracy.

6. Demonstration in a Real-World Monitoring Setup

The calibration results and their implications for high-precision bridge monitoring presented in the preceding chapters were demonstrated within a real-world monitoring setup. The purpose of this application was to verify the practical applicability of the calibrated antennas under realistic operating conditions, without addressing the structural deformation results themselves.

The individually calibrated GNSS antennas were deployed in a bridge monitoring project involving controlled loading and destabilization scenarios. In this context, the monitoring setup served solely as a demonstrator to confirm that the investigated antenna series can be operated in a stable and reliable manner under real environmental and operational conditions.

GNSS data were recorded continuously using the antenna models described in the previous chapters. Particular emphasis was placed on the consistent integration of the individual antenna calibration into the entire data processing workflow. This ensured that antenna-related systematic effects were minimized already at the observation level.

The analysis and interpretation of structural deformations are outside the scope of this paper and are presented in a complementary study. The focus of the present contribution is exclusively on the role of the GNSS antenna and its calibration in high-precision monitoring applications.

The successful deployment of the calibrated antennas in a real-world monitoring setup confirms the suitability of the investigated antenna series for demanding Structural Health Monitoring applications. The demonstration highlights that high and reproducible antenna quality, combined with rigorous calibration, represents a fundamental prerequisite for reliable GNSS-based monitoring at the millimeter level.

7. Discussion

The presented antenna calibration results and their analysis demonstrate that the GNSS antenna has a decisive influence on the achievable accuracy of GNSS-based monitoring applications. In particular for high-precision bridge monitoring tasks targeting millimetre-level deformations, antenna-related systematic effects may dominate the overall error budget if not properly addressed.

The calibration results for GPS and Galileo frequencies reveal pronounced frequency- and elevation-dependent phase centre variations. These effects are physically inherent to the antenna and must not be interpreted as random measurement noise. If they are neglected or insufficiently modelled, they propagate directly into GNSS-derived coordinate time series and may lead to systematic distortions. This is especially critical in long-term monitoring applications, where such effects may accumulate or vary with changing satellite geometry.

A key finding of this study is the high level of consistency observed within the investigated antenna series. The very small spread of PCV values at the sub-millimetre level confirms both the high manufacturing quality of the antennas and the reproducibility of the applied robotic calibration methodology. This homogeneity is of central importance for monitoring applications, as it enables reliable comparisons between multiple observation points and minimises antenna-induced systematic differences.

The results further allow a clear assessment of different calibration strategies. While the use of a type-averaged antenna model represents a significant improvement compared to uncalibrated antennas, residual systematic effects remain that are relevant for high-precision applications. For monitoring tasks with the highest accuracy requirements, individual antenna calibration is therefore preferable in order to further reduce residual biases and to improve the long-term stability of coordinate time series.

Overall, the findings of this contribution emphasise that the GNSS antenna must not be regarded as a secondary component within the measurement chain. Instead, antenna quality and calibration constitute key elements that largely determine the suitability of GNSS for high-precision Structural Health Monitoring applications.

8. Conclusions and Outlook

This paper investigated the impact of GNSS antenna quality and calibration on the achievable accuracy of high-precision monitoring applications. The results clearly demonstrate that the antenna and its correct modelling represent a decisive factor for GNSS-based measurements at the millimetre level.

The analysis of individually calibrated antennas for GPS and Galileo frequencies shows that antenna-related effects are strongly frequency- and elevation-dependent. These effects are systematic in nature and propagate directly into the positioning solution. Insufficient or missing antenna calibration therefore inevitably leads to residual systematic errors that can significantly limit the reliability of high-precision monitoring applications.

A key outcome of this study is the high level of consistency observed within the investigated antenna series. The very small spread of phase center variations at the sub-millimeter level confirms both the high manufacturing quality of the antennas and the stability and reproducibility of the applied robotic calibration methodology. As a result, the investigated antennas fulfil essential requirements for use in demanding Structural Health Monitoring applications.

The results further underline that while type-averaged antenna models represent a substantial improvement over uncalibrated antennas, they are not sufficient for applications with the highest accuracy demands. For precise bridge monitoring, individual antenna calibration is required to minimize residual effects and to ensure long-term stability of GNSS-derived coordinate time series.

In conclusion, this contribution shows that high-quality GNSS antennas combined with rigorous, individual calibration form a fundamental prerequisite for the successful use of GNSS in high-precision monitoring applications. Future work will focus on the integration of such antenna concepts into long-term monitoring systems and on further refinement of antenna models for multi-GNSS and multi-frequency applications.

The findings presented in this paper complement recent GNSS-based Structural Health Monitoring studies in which the monitoring concept, deformation analysis, and structural interpretation of bridge behavior are addressed in detail. While those contributions focus on continuous monitoring strategies and the assessment of structural responses, the present paper deliberately concentrates on antenna-related accuracy aspects as a fundamental prerequisite for such applications. By separating antenna performance and calibration from the structural analysis, this work provides a methodological basis that supports and strengthens GNSS-based monitoring approaches presented in complementary publications.

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BIOGRAPHICAL NOTES

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 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.

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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