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BBD-V: A National, Transport-focused Ground Motion Monitoring Service in Germany

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Abstract

Transport infrastructure is vulnerable to ground motion caused by natural or anthropogenic processes. Monitoring ground motion from space through multi-temporal interferometric synthetic aperture radar (MT-InSAR) is less resource-intensive than traditional methods. It allows for an increased data comparability on large spatial extent, the transferability of approaches between different linear transportation infrastructure - roads, rail-, and waterways - and processing consistency across Germany. The BBD-V (*germ.* Bodenbewegungsdienst für den Verkehrssektor) is a currently developed transport-focused and Sentinel-1 MT-InSAR-based ground motion service for Germany. By tailoring monitoring to the transport sector, it aims at increasing the applicability of the approach to linear infrastructure in terms of usage, process adaptation, and user-targeted communication of results.

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1. Ground Motion in Germany and Its Impact on Linear, Ground-Based Transport Infrastructure

With a dense network of approximately 830'000 km of roads including 13'210 km highway; 40'000 km of railway and 7'300 km of waterway, Germany's ground-based transport infrastructure is subject to a wide range of ground motion inducing processes which present a hazard to the usability of the above-outlined infrastructure, imposing a risk to transported goods and its users. Given the vast transport network, traditional monitoring methods lack scalability to respond adequately on a country-wide scale. Earth observation methods for infrastructure monitoring, in this case multi-temporal interferometric synthetic aperture radar (MT-InSAR) based monitoring of ground motion, provide powerful tools to cope with the analysis on large spatial scale. To proactively manage ground motion in Germany, a nationwide, accessible, and user-oriented ground motion monitoring service such as the BBD-V is essential.

1.1. Ground Motion in Germany: Process, Impact and Hazard Potential

Ground motion results from the ground's susceptibility and from one or multiple drivers, including cascading effects, that lead to changes in the earth's surface (e.g. Braun 1908). Geogenic drivers of ground motion span soil compaction, slope instability leading to landslides, sinkholes and tectonic processes. Anthropogenic processes are, e.g., any sort of extraction (groundwater, natural gas, mining), underground storage operations or (underground) construction. Not only subsidence but also ground motion induced slope instability in road or track surrounding areas has large effects on the functionality of the transport infrastructure – with changing weather patterns such as heavy rain occurrence contributing to an increase in risk probability (Szymczak et al. 2023). MT-InSAR detected ground motion corresponds to a superposition of geogenic and anthropogenic driving processes that contribute to the quantified topographic change of the earth's surface. Therefore, a comprehensive interpretation of the MT-InSAR measurements often requires in-depth knowledge of the involved process dynamics. On the other side, the ability to conduct MT-InSAR covering entire continents can support infrastructure maintenance by mapping areas with high motion dynamics. Subsequent investigation by responsible authorities can then, e.g., use conventional ground-based measurement techniques and perform comprehensive interpretation of all available observations to assess the risk.

Risk is a product of hazard, exposure and vulnerability (ADRC 2005), Fig. 1. Both for risk assessment and management, monitoring ground motion is essential. Ground motion acts as the hazard, impacting infrastructure and its environment in the form of cracks in the road's surfaces, destabilized foundations and deformation, changes to the position and level of the tracks in the worst cases leading to derailling, and by impacting the stability of dam infrastructure. Particularly road and rail have in common that their usage involves high speeds and, thus, a strong reliability on an intact transport infrastructure. All types of ground-based, linear infrastructure have in common that goods and humans are exposed – with a risk potential for damage to both. While risk management spans the three components of risk as visualized in Fig. 1, a nationwide monitoring of ground motion targets a spatial understanding of the hazard potential and a data-driven approach to prevent damage to the transport infrastructure.

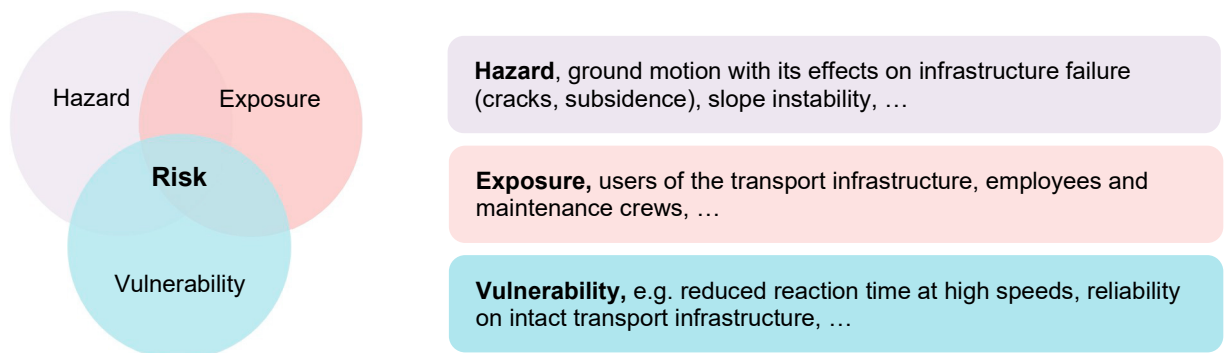


Fig. 1: Risk is a composite of a hazard, exposure and vulnerability (ADRC 2005), here applied to understanding risk evolving from ground motion for ground-based transport infrastructure.

2. A Nationwide Ground Motion Service for the Transport Sector in Germany

Traditional monitoring methods provide site-specific monitoring at very high spatial resolution. Required during maintenance, they reliably monitor the effects of each measure and serve as systematic, well-regulated and often compulsory means of documentation. All these monitoring methods lack, however, the spatial scalability to the entire Federal Republic of Germany (approx. 360'000 km²), a possibility for site-independent investigation, and a common time interval enabling high data comparability. MT-InSAR offers the possibility to monitor ground motion at regional to continental scale with a sufficient point density for the observation of single objects as well as, particularly, wide-area surveying (Even et al., 2024). Generated interferograms hold displacement information of the earth's surface between the acquisition times and in line-of-sight (LOS) of the satellite-mounted sensor. The use of multiple interferograms for persistent scatterers (PS), objects in space that persistently scatter the radar signal during an observation time series, reduces technical ambiguities allowing for a robust detection of ground motion (Even et al., 2024). While MT-InSAR is feasible on a multitude of radar imagery, Sentinel-1 data stands out by its free availability, its wide area coverage, high revisit time, and archive. Designed as a two-satellite constellation, the Copernicus Sentinel-1 mission provides weather- and daylight independent imagery, with its continuity ensured by the Sentinel-1 Next Generation (Torres et al. 2024). Challenges arise with the orientation of infrastructure in space as due to the satellites' polar orbits and side-looking geometry, MT-InSAR has very limited sensitivity to ground motion in the N-S direction. PS interferometry (PSI) enables precise measurements of ground motion in the range of millimeters. A potential inclusion of temporary persistent scatterers (TPS) broadens the methods' applicability.

2.1. The BBD-V: a Sentinel-1 MT-InSAR based Ground Motion Service for the German Transport Sector

The ground motion service for the transport sector (*germ.* Bodenbewegungsdienst für den Verkehrssektor, BBD-V) targets the development of an operational, transport sector focused and Sentinel-1 MT-InSAR based ground motion monitoring service for Germany implemented as Web-Application, Fig. 2. The project is motivated by the gap existing between the existence of operative MT-InSAR PSI based ground motion monitoring services available in Germany and their lack of application in the transport sector. Currently in development, it is advanced as consortium of all co-authors and funded within the framework of the national Copernicus integration measure by the German Space Agency at the German Aerospace Center with funds from the Federal Ministry of Transport. Here, we present our review of end user needs and provide first results of the currently ongoing activities. These include an optimization of the BBD for the transport sector aimed at improving the usability and interpretability of these products for transport-related applications next to method development for the detection of ground motion patterns, the use of TPS as well as an increase of the actualization rate for MT-InSAR. The chapter closes with an outlook on the future of the BBD-V.

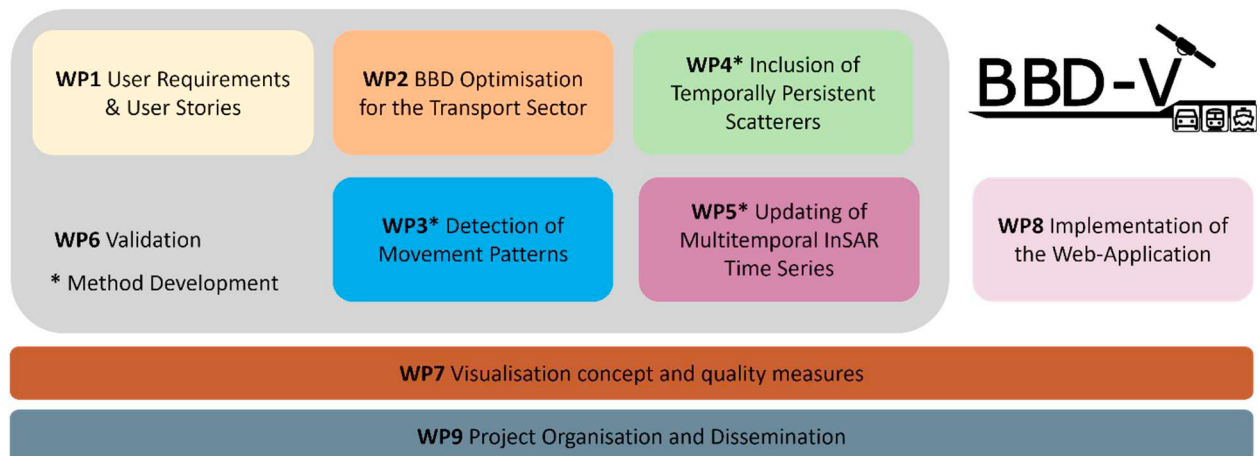


Fig. 2: Framework of the ground motion service for the German transport sector (*germ.* Bodenbewegungsdienst für den Verkehrssektor, BBD-V) which is currently being developed in a consortium effort. The figure visualizes the project's work packages (WPs).

2.2. Completed: User Requirements and User Stories

To identify potential users and use cases, three user workshops of each transport sector (road, rail- and waterway) and an online survey were conducted. The participants included mainly personnel from organizations responsible for the monitoring and maintenance of transportation route sections and structures. In an interactive format, detailed needs for ground motion monitoring were addressed and typical monitoring workflows discussed. Such workshops will continue to accompany the development and implementation of the BBD-V to build a user-targeted product.

During the workshops, the participants described their use cases regarding several technical parameters, e.g. movement pattern or movement direction, Tab. 1. The most frequently mentioned use cases in all workshops were

- Long-term monitoring of route sections and infrastructure objects in areas with ground-movement occurring
- Long-term monitoring of buildings and infrastructure surrounding the transport infrastructure
- Monitoring of adjacent slopes and embankments
- Quality assurance following construction work
- Monitoring of post-mining areas and their impact on the transport infrastructure and its vicinity
- Monitoring of sections with continuous subsidence occurring
- Monitoring of areas with continuous subsidence occurring in the wider area around transport infrastructure
- Early detection of ground movements in transport network
- Early detection of potentially problematic subsidence areas
- Forecast of future hazard zones resulting from planned mining/flooding

In the eyes of the participants, long-term monitoring with regular MT-InSAR is expected to reduce damage to the direct route infrastructure and its vicinity as gradually occurring movements can be detected allowing for early measures and the avoidance of substantial damage. We contextualized the communicated user requirements of technical parameters for feasibility, Tab. 1. All (long-term) monitoring use cases are feasible, partially with restrictions. These arise due to the size and orientation of the monitored object, e.g. singular buildings and N-S orientation, or the PS availability which can be challenged by vegetation cover or during phases of construction. Given the resolution of Sentinel-1 based MT-InSAR, the location accuracy may fall below the communicated requirements. The update rate and latency of the BBD-V will be quarterly at highest, balancing processing capacity and the focus on providing a service for the entire Federal Republic of Germany. The user requirements are not feasible for the category early detection and forecasting. Therefore, these cases are not within the scope of the BBD-V.

2.3. Ongoing: The Optimization of BBD Ground Motion Monitoring for the Transport Sector

Operational national and continental ground motion services provide Sentinel-1 based MT-InSAR PSI products with a millimeter per year precision and an open data policy, e.g., for Europe (Costantini et al. 2021) and Germany (Ground Motion Service Germany, *germ.* Bodenbewegungsdienst Deutschland, BBD; Kalia et al. 2017, 2021). They are, however, not specifically adapted for the monitoring of linear transportation infrastructure. Current filtering approaches in EGMS and BBD rely on an RMSE threshold to remove unreliable PS observations. To enhance this filtering step, time-series modelling, robust outlier detection, and spatial consistency analyses are proposed in addition to thresholding on a single variable (Hooper, 2008; Bakon et al., 2017). Therefore, we currently develop a model-based and robust-statistical framework that focuses on the spatiotemporal consistency of displacement signals to increase the number of reliable PS. For each PS, an idealized displacement model consisting of linear and seasonal motion components is fitted to the time series. Deviations from this model are then analyzed to evaluate residual variability, temporal stability, and signal consistency. Additional quality measures include robust outlier statistics and neighborhood-based spatial consistency analyses to identify artefacts and unstable deformation signals while preserving a larger number of physically plausible PSs. Conventional coherence-based filtering can substantially reduce the spatial density of PS observations. Bakon et al. (2017), for example, reported a reduction from 9,247 to 5,514 PS when applying a standard coherence threshold of 0.7, corresponding to a loss of approximately 40% of the observations. In contrast, first results of our proposed workflow based on BBD PS data indicate that only around 17-19% of the PS are discarded, while maintaining the spatial and statistical consistency of the deformation signal.

Tab. 1. Use cases most frequently mentioned by workshop participants, including respective user requirements. Restrictions in technical feasibility are visualized with underlined (feasible with restrictions) and *italics* (not feasible). RML = Relevant Measurement Locations, MP = Movement Pattern (1: continuous, 2: periodical, 3: abrupt), MD = Movement Direction (all = horizontal in all directions and vertical), MVA = Mean Velocity Accuracy, LA = Location Accuracy, MI = Measurement Interval, UR = Update Rate.

Category	Use Case	RML	MP	MD	MVA	LA	MI	UR	Latency
Long-term monitoring of route sections & their direct environment	Infrastructure monitoring	Superstructure, <u>pillars of bridges</u> , ...	1	<u>All</u>	mm/a	< <i>m</i>	< 1 Week	<u>Monthly</u> to quarterly	Quarterly
	Section monitoring	Selected sections	1	<u>All</u>	mm/a	<u>m</u>	Monthly to quarterly	Quarterly to yearly	Quarterly
Long-term monitoring of the surrounding environment	Monitoring of surrounding infrastructure	Infrastructure and buildings	1	<u>All</u>	mm/a	<u>m</u>	Monthly to quarterly	Quarterly to yearly	Quarterly
	Monitoring of slopes & embankments	<u>Crest, base</u>	1, 2	<u>All</u>	mm/a	< <i>m</i>	< 1 Month	Quarterly	Quarterly
	Quality assurance after construction	Selected sections, <u>single buildings</u>	1	<u>All</u>	mm/a	<u>m</u>	15 days	<i>Monthly</i> to quarterly	<u>Monthly</u>
Monitoring of land subsidence	Monitoring of subsiding areas	Selected sections	1, 2	Vertical	mm/a	<u>m</u>	(Weekly) to Monthly	<u>Monthly</u> to quarterly	<u>Maximum</u>
	Continuous subsidence monitoring	Selected sections, single buildings	1	Vertical	mm/y	<u>m</u>	Yearly	Yearly	Quarterly
	Post-mining monitoring	Selected sections	1	Vertical	mm/a	<u>m</u>	Yearly	Yearly	Quarterly
Early detection and forecasting	Early detection of ground motion	Selected sections	3	<u>All</u>	mm/a	<u>m</u>	Monthly	<u>Monthly</u>	<u>Maximum</u>
	Early detection of subsidence	Selected sections	3	<u>All</u>	mm/a	<u>m</u>	Monthly	<u>Monthly</u>	<u>Maximum</u>
	Forecast of hazard zones	Selected sections	1	<u>All</u>	mm/a	<u>m</u>	Monthly	<u>Maximum</u>	<u>Maximum</u>

2.4. Ongoing: The Detection of Movement Patterns

Based on the filtered PS dataset, we currently develop a systematic framework for detecting and characterizing deformation processes relevant to transportation networks on a nationwide scale. Methodologically, the connection between damaging events and spatiotemporal deformation patterns is to be established. The approach is based on the detection of active deformation areas (ADAs) (Barra et al., 2017, Navarro et al., 2020) to distinguish active, i.e., points where we measure movements, from stable PS (Barra et al., 2017). Therefore, road, rail-, and waterway infrastructure are characterized based on parameters such as deformation patterns and thematic data (e.g., geological, and soil maps). These datasets can serve as input for investigating correlations between damaging events and adapted BBD data. The approach has already been applied to various case studies, including landslides (Solari et al., 2020), urban subsidence (Cuervas-Mons et al., 2022), and mining areas (Hu et al., 2023). Extrapolating to national or continental scales, as proposed by Navarro et al. (2022), highlights the challenges involved in handling large volumes and variability of data. The resulting national deformation map for transportation infrastructure is being validated through case studies in Hamburg and North Rhine-Westphalia.

2.5. Ongoing: The Inclusion of Temporary Persistent Scatterers

Standard PSI algorithms are only capable of analyzing PS, which are mostly found on man-made infrastructure, and per definition maintain their backscatter characteristics over the whole time series of interest. However, good-quality point scatterers can appear or disappear in periods of the time series, due to different drivers such as construction activities, floods, or other natural decorrelation (Ferretti et al., 2003). Doerr et al. (2022a) present an approach to fully integrate such TPS into the PSI, while Doerr et al. (2022b) showed that the integration can significantly increase the number of measurement points, with an increasing gain as the time series length increases. Further, Doerr et al. (2022b) demonstrated that the number of TPS can compensate for decreasing numbers of PS over time, while at the same time enhancing the geodetic observation network. Within the framework of the BBD-V project, the mentioned approach is currently being optimized for transport infrastructure monitoring and generalized for different application cases and infrastructure. The goal is to improve the PSI monitoring capabilities in areas characterized by construction activities and surface changes over time. Finally, the information gain by the TPS integration over the standard BBD PSI processing will be evaluated. In addition to the increase in measurement points and general information gain in specific applications, this evaluation will contain discussions on the reliability of the TPS measurements, the processing runtime, and the complexity of the visualization of the results.

2.6. Ongoing: The Updating of MT-InSAR Time Series

MT-InSAR techniques such as PSI are typically executed in batches, where a sufficiently large number of SAR acquisitions are aligned and combined to produce interferograms, following either a single-reference scheme or a different pairing strategy. These are compensated for nuisance terms, and the relevant signal related to deformation is isolated and analysed. Batch processing schemes are widely recognized as a robust and accurate approach for ground-motion analysis, provided that a sufficiently large data archive is available and timeliness is not a primary requirement. However, they are generally not suited for fast or near-real-time (NRT) monitoring applications. While fast updating of MT-InSAR deformation time series has become a highly active research area, most existing techniques remain largely experimental. Relevant contributions from European research groups in this domain include: Marinkovic & Hanssen (2007), Dalaison & Jolivet (2020), and Wang et al. (2024). Within the BBD-V framework, alternative methods for fast and efficient time series processing are currently being developed to evolve the technique from retrospective analytics to proactive, NRT monitoring.

2.7. Outlook on (Near-)Future Work Packages of the BBD-V

The validation of the BBD-V will consider both individual aspects of method development and the BBD-V as a whole. Independent reference and comparison data form the basis for evaluating the newly developed methodological approaches and optimized data processing. Here, both the consistency with known movement patterns and events is analyzed and the quality of the results evaluated. Given its user-oriented nature, the degree of consistency between the user requirements and the implemented functionalities of the BBD-V is a decisive evaluation criterion for the added value that has been created. Interviews, workshops, and dedicated software tests by users will provide information on how high the added value can be rated and will reveal potential for immediate optimization.

Our visualization concept will balance the users' needs with the technical needs established by the optimized filtering approaches and methods developed for the detection of movement patterns, TPS inclusion, and time series updating. It is closely intertwined with the implementation of our Web-Application that aims at an interactive, user-specific experience for investigating ground motion for the German ground-based transport infrastructure.

3. Conclusion

Ground motion represents a spatio-temporally heterogeneous hazard for Germany's extensive transport network. Gradual subsidence, slope instability, post-mining deformation, and construction-related processes can compromise the safety, reliability, and economic performance of roads, rail-, and waterways. Given the scale of the German network and the increasing pressures arising from climate change and land-use dynamics, conventional monitoring alone is insufficient to provide a comprehensive, comparable, and regularly updated assessment of hazard potential. Sentinel-1 focused MT-InSAR offers a scalable, consistent solution for nationwide ground motion monitoring.

While existing services such as the EGMS and BBD provide high-quality products, their direct integration into transport-sector workflows remains limited. By systematically aligning MT-InSAR based ground motion monitoring with the operational requirements of infrastructure managers and authorities, the BBD-V addresses this gap. Through a structured framework encompassing user engagement, methodological optimization, pattern detection, inclusion of TPS, accelerated time-series updating, validation, and web-based visualization, the BBD-V advances from a generic deformation service toward a sector-specific decision-support system. By integrating clearly formulated user stories into the technical development process, the service is tailored to practical monitoring scenarios. At the same time, the integration of TPS and the development of efficient update strategies for MT-InSAR represent methodological enhancements and improve spatial coverage and temporal responsiveness. Validation against independent reference data and systematic user feedback ensures both scientific robustness and operational relevance.

The BBD-V demonstrates how earth observation enables retrospective large-scale analysis supporting, e.g., a prioritization in infrastructure risk management. By enabling the identification of anomalous deformation patterns along and adjacent to transport corridors, the service contributes to a data-driven prioritization of in-situ inspections and maintenance resources. In doing so, it supports a shift from reactive damage mitigation to preventive risk management, strengthening the resilience of Germany's transport infrastructure. The BBD-V, thus, represents not only technological advancement, but also an institutional and procedural step toward embedding satellite-based ground motion monitoring into routine infrastructure management practice to enhance transport infrastructure resilience.

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