Bridging the scales

Earth observation infrastructure and geodetic deformation monitoring

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Abstract

Geodetic deformation monitoring has been a topic of high geodetic interest and productivity since decades. Main fields of application are structural monitoring and geodynamic monitoring. Over the years, outstanding progress has been achieved on the one hand in terms of geodetic instrumentation including and exploiting new sensor technologies and on the other hand in terms of geodetic modelling and analysis. During the last two decades, Earth observation infrastructure (such as, e.g., Global Navigation Satellite Systems (GNSS) or the European Remote Sensing System Copernicus) have become increasingly available. Such infrastructures are operated on a long-term sustainable basis, and their data and products are provided based on an open data policy. This allows to merge previously independent approaches for structural and geodynamic monitoring, geodetic networks and point clouds as well as local and regional scales and short-term and long-term temporal resolution. In this presentation, these developments are addressed emphasizing the opportunities, needs and challenges with respect to a fully integrated geodetic monitoring that bridges scales and disciplines. Examples of geodetic monitoring are presented which are derived from recent projects of the Geodetic Earth Systems Science group of the Geodetic Institute of the Karlsruhe Institute of Technology with a focus on the integration on GNSS and Radar Interferometry.

Keywords: Earth observation, GNSS, PSInSAR, integrated approaches

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1 Introduction

During the last two or three decades, several key innovations of general interest in technology and infrastructure have become available. As a consequence, they have advanced, enhanced and modified geodetic work significantly.

On the one hand, this refers to global navigation satellite systems (GNSS) which can be used at any time and at (nearly) any place on and close to Earth for positioning, navigation and timing purposes as well as to remote sensing satellite systems such as the European Copernicus system[1], which provides regularly repeated representations of (parts of the) physical surface of the Earth. In both cases, respective time series of observations and derived products with high temporal and spatial resolution as well as open access could be initiated and continuously extended.

On the other hand, a comprehensive digitalization of objects, processes and workflows has become capable which is based on progress in information and communication technologies and which enabled comprehensive automation. This allowed to complement these new observation infrastructures by efficient data infrastructures.

Moreover, geodetic expertise has contributed to and benefitted from this progress in both cases. This can be seen, e.g., in the long-term availability of global and regional GNSS networks for geodetic purposes. Thus, high-quality products such as satellite clock and orbit parameters are provided which are available on a free-and-open data policy in real-time

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[1] https://www.copernicus.eu/en

provided by, e.g., the International GNSS Service (IGS). This is also illustrated by the disruptive re-design of classical surveying instruments like total stations or levelling devices which are fully digitalized and automated today. In addition, the availability of terrestrial laser scanning (TLS) devices has introduced areal, i.e. surface-based approaches which are complementary to the classical approaches with marked survey points.

The mentioned observation and data infrastructures are key components of present-day Earth observation. Generally, they are defined and provided on a global basis. In this regard, GNSS are capable to provide highly resolved time series for the coordinates of discrete but precisely defined control points. This enables applications on mostly all Earth-related spatial scales. The Copernicus system provides remote sensing data in terms of time series of optical and radar images covering the whole Earth with a repetition rate of six to twelve days. For geodetic purposes, the availability of interferometric synthetic aperture radar (InSAR) is of main interest as it enables the composition of time series of the motion of natural and artificial backscatterers which are either point-wise (persistent = PS) or areal (distributed = DS); see Crosetto et al. (2020) for an assessment of the recent developments.

In contrast, the mentioned surveying instruments refer to more or less local applications. The respective observation techniques can be considered as well-understood with an elaborated methodology in terms of measurement and analysis issues. This refers, e.g., to the dedicated design of geodetic networks, the estimation of parameters such as point coordinates and the statistical analysis of the results. This does not hold for TLS which is an ongoing research subject in terms of methodology and applications.

In this context, the use of GNSS equipment can be seen as the (at present) only established link between the global and regional scales and the local scale. This is not yet the case for areal data where InSAR is capable to cover the larger scales and TLS acts on the small scales. Challenges, opportunities and explicit tasks with respect to bridging these scales are subject of this contribution. In addition, it will be motivated that this aim is directly connected with interdisciplinary collaboration. Here, due to the limited space in this contribution, the respective discussion can neither be treated exhaustively nor comprehensively. Instead, some key ideas are presented and illustrated based on project examples.

It is assumed that the reader is familiar with the topical background. Thus, this paper is organized as follows. In the first two sections, geodetic deformation monitoring and Earth observation infrastructure are presented and discussed independently regarding their respective traditions and roles. Then, they are compared and discussed and the mutual contributions are assessed. Finally, three examples are briefly presented which are based on recent projects of the Geodetic Earth Systems Science (GESS) group of the Geodetic Institute (GIK) of the Karlsruhe Institute of Technology (KIT).

2 Geodetic deformation monitoring

Geodetic deformation monitoring (GDM) has a long and outstanding tradition in engineering geodesy. Since decades, a multitude of dedicated contributions to theory and applications has been published in scientific journals and textbooks; see, e.g., Heunecke et al. (2013) and the references therein. The topical focus of GDM is mainly twofold addressing either structural monitoring (with a strong link to engineering geodesy) or geodynamic monitoring (also as part of physical geodesy and embedded in geosciences) – or a combination of both. Thus, interdisciplinarity is obvious both inside the broad area of geodesy and surveying and with the neighbouring sciences.

Today, typical instruments in use are total stations, GNSS devices, levelling devices and increasingly TLS. In addition, there is a multitude of other sensors like inclinometers or strainmeters which can be used for specific monitoring purposes. Due to the established methodology, geodetic networks consisting of control points and object points are the basis for GDM as they provide both a stable spatial reference and enable the repeated observability of the object points.

The availability of TLS since about two decades paved the way for areal (instead of point-wise) monitoring approaches such as presently studied by the Research Unit FOR 5455: Deformation analysis based on terrestrial laser scanner measurements (TLS-Defo)[2] funded by the German Research Foundation (DFG).

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[2] https://www.tlsdefo.de/

Besides the reference to geodetic networks, GDM strongly relies on refined least-squares parameter estimation (or state-space filtering such as the Kalman filter approach) and subsequent statistical significance tests with respect to possible point movements. To this end, the law of variance propagation is applied to derive the joint variance-covariance matrix of the quantities of interest which is needed for the statistical tests. In addition, the sensitivity of the geodetic network with respect to considered point movements can be assessed and optimized already in the planning phase.

3 Earth observation infrastructure

Earth observation (EO) is one of the key societal interests of the 21st century in order to provide reliable data for informed decision with respect to the so-called grand challenges: (i) causes and effects of global change, (ii) causes and risks of natural hazards, (iii) measures against the loss of biodiversity, habitat and ecosystems functions (Müller and Pail, 2022). For this reason, dedicated EO infrastructures are launched, installed, maintained, operated, exploited and further developed at national and international level.

EO is highly topical also for geodesy; see Kutterer (2024) for a survey on EO and the respective role of geodesy with some considerations and discussions on integrated approaches at global level. From a superior point of view, long-term national, regional and international EO programs such as the European Copernicus system or the Global Earth Observing System of Systems (GEOSS)[3] are the indispensable fundament to serve societal needs. Thus, geodesy and many other disciplines can significantly benefit from and also contribute to these activities.

In this regard, the role and the respective contributions of geodesy to EO are twofold. On the one hand, geodesy provides highly accurate and long-term stable coordinate reference frames at global level which are indispensable as unique metrological basis in EO; see Angermann et al. (2024) for recent activities on terrestrial reference frames and Sánchez et al. (2024a) on the establishment of an international height reference frame.

On the other hand, geodesy contributes to EO by time series of a variety of geodetic parameters such as observation site coordinates[4] [5], Earth rotation parameters[6], Zenith Total Delay (ZTD)[7], or Total Water Storage (TWS)[8]. The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) combines and coordinates respective activities; see Sánchez at al. (2024b) for a detailed description of GGOS.

4 Discussion

The main characteristics of GDM and EO that are relevant for the scope of this presentation were presented and explored in the previous sections. Although there are different goals, backgrounds and traditions in both fields of work, there is a clear topical overlap and an opportunity of beneficially merging for geodetic purposes and beyond.

In case of terrestrial surveying techniques, the availability of respective instruments in the project such as total stations is mandatory. If needed, access to a superior coordinate reference frame needs to be enabled either by control points of authoritative networks or by connection to, e.g., a national GNSS network. In such a case, GNSS also serves as an interface to EO infrastructure.

In case of EO techniques, access to data is possible via the existing respective data infrastructures. This holds for both GNSS (through the available receivers and respective communication devices) and InSAR (through data portals such as the Copernicus Open Access Hub[9]). In this regard, mutual validation – and to some extent calibration – is possible. Nevertheless, integration of the different instruments requires additional work in terms of joint observation modelling together with a physical modelling of the objects and processes of interest.

5 Examples

5.1 Motivation

During the last five years, the GESS group at GIK contributed to several research projects which all show relevant aspects of combining GDM and EO. In the following sub-sections, three of these projects are presented, two of them with a multi-technique

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[3] https://old.earthobservations.org/geoss.php

[4] https://itrf.ign.fr/en/solutions/itrf2020

[5] Kreemer et al. (2018)

[6] https://www.iers.org/IERS/EN/DataProducts/EarthOrientationData/eop.html

[7] https://igs.org/products/#troposphere

[8] https://drought.emergency.copernicus.eu/data/factsheets /factsheet_grace_tws_anomaly.pdf

[9] https://www.copernicus.eu/en/copernicus-satellite-data-access

and multi-disciplinary approach, one of them fully relying on EO for solving a GDM task, in order to illustrate and underline the main outcomes of the previous discussion.

5.2 DAMAST and DAMAST Transfer

In the DAMAST project (and the subsequent DAMAST Transfer project, both funded by BMBF[10]), a consortium mainly consisting of members from geosciences, civil engineering, geodesy and remote sensing cooperated in the regional monitoring of a large hydropower dam in Georgia, mainly looking at induced earthquakes. This project addressed a complex monitoring task with a clear relevance for society in terms of renewable energy supply and safety issues. There is a strong need for a multidisciplinary approach to cover all relevant aspects. In terms of geodesy, data from EO infrastructures are combined for GDM purposes[11].

The Enguri Dam (Georgia) is located in the Caucasus about 50 km east of the Black Sea, NNE of Zugdidi (~35 km) and to the north of Jvari (~10 km). It is part of the Enguri HES: Hydroelectric power station (partly located in Abkhazia) and plays an important role in power supply for western Georgia. This dam is the world's second highest concrete arch dam, with a height of 271.5 metres. An expected source of deformations is the change of water level in the range of 100 m.

The projects DAMAST and DAMAST Transfer aimed to make a contribution to the systematic reduction of hazards at water reservoirs as well as to their long-term and efficient operation. The objective was to develop monitoring concepts that can also be transferred to other dams in comparable locations. DAMAST was dedicated to the long-term efficiency of reservoir operation and to avoid the construction of replacement storage with its high costs.

The geodetic contribution comprised continuous and campaign GNSS measurements on the dam and in its vicinity. The remote sensing contribution was threefold: (i) the high-frequently repeated capturing of the surface of the dam using ground-based SAR (Rebmeister et al., 2022), (ii) the analysis of InSAR satellite data of the dam and its environment, and (iii) the capture and analysis of long-range TLS data of the dam (which is work in progress). See Fig. 1 for an overall sketch of the respective configuration.

This presentation addresses GNSS and InSAR. Fig. 2 and Fig. 3 show representative results for the motion of observation sites on top of the dam. They are in a range of about 6-8 cm as observed with GNSS and PSInSAR, respectively. Here, both observation techniques independently provide valuable quantitative information in good consistency.

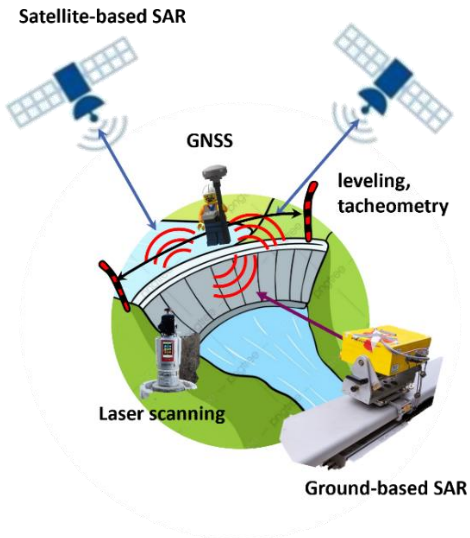

Fig. 1: Multi-technique approach for local and regional dam monitoring combining terrestrial technique and EO capabilities

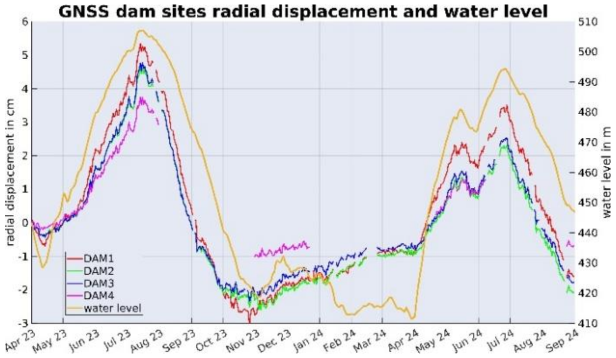

Fig 2: Horizontal motion of GNSS observation sites at the top of the Enguri dam (left vertical scale), mainly induced by water level changes between April 2023 and September 2024 (right vertical scale)

Note the different lengths of the time series as well as the interruptions of the GNSS data. This is due to the continuous availability of Copernicus Sentinel 1 data since mission start which was used for the

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[10] German Federal Ministry of Education and Research

[11] https://www.damast-caucasus.de/779.php

derivation of the PSInSAR results. After failure of Sentinel 1B in December 2021, the repetition rate reduced from six days to twelve days. In contrast, the GNSS time series are shorter, since the observation of GNSS data on the dam started in 2023. In addition, they suffer from several interruptions which could not be recovered on short notice. Thus, the longer PSInSAR time series comprise nine seasonal cycles whereas GNSS covers at present nearly two seasonal cycles only.

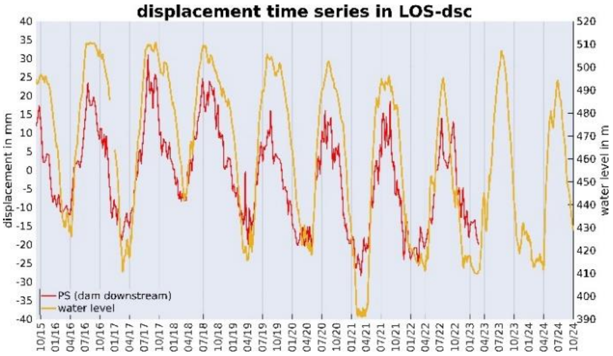

Fig 3: Motion of a PSInSAR point at the top of the Enguri dam in Line-of-Sight direction of the descending orbit (left vertical scale), mainly induced by water level changes between October 2015 and October 2024 (right vertical scale)

In case of future funding, the next working step should address a causal approach based on the joint modelling of the various geodetic instruments and EO infrastructure together with an integrated model of the dam (derived from a computational mechanics approach) in its physical environment (derived using a computational geosciences approach).

5.3 SAMUH2 Project

The SAMUH2 project (funded by BMWK[12]), focuses on research regarding use of underground gas storage facilities for hydrogen storage. In this project, the societal relevance is concerned with both energy supply and safety issues. At GIK, concepts are being developed to monitor surface deformation above these facilities, with a focus on the salt cavern field Epe in the North-Western part of Germany.

Epe has the second largest storage capacity for natural gas in Germany and consists of 114 caverns, more than 50 currently used for gas storage by different companies. The pressure difference to the surrounding rock causes the caverns to converge which results in a complex deformation regime on the surface. To accurately describe such a displacement field, high temporal and spatial coverage is needed, which is why a multi-disciplinary and multi-technique approach (see Seidel et al. (2024) for further reading) including a numerical modelling of the subsurface dynamics is applied for monitoring Epe.

Here, GNSS and precision levelling data are combined with multitemporal InSAR as the main observation technique. Copernicus Sentinel-1 SAR data of four tracks (two ascending and two descending) are processed as time series of up to eight years with a combined approach of persistent and distributed scatterer techniques to obtain high spatial coverage even in the rural area of the cavern field.

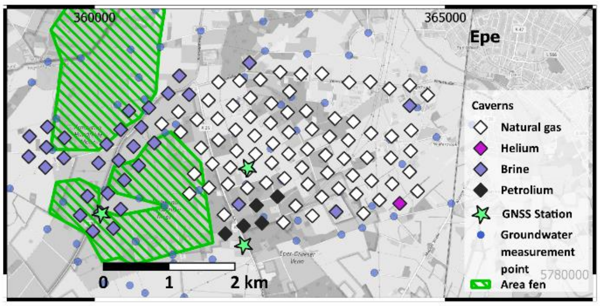

Fig 4: Map of the cavern field in Epe with a distinction of the different cavern types and including observation sites and the fen area (from Seidel et al, 2024)

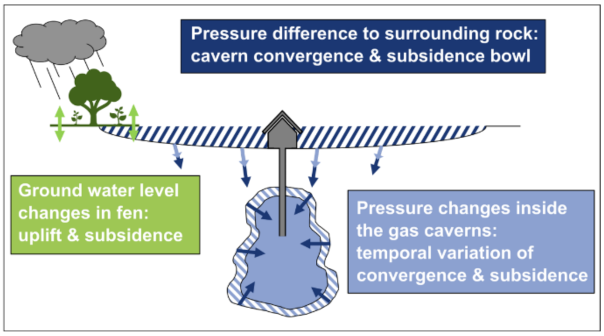

Fig 5: Physical situation of a typical cavern as starting point for a geophysical modelling of the site surface deformation (from Seidel et al., 2024)

Fig. 4 gives an impression of the spatial distribution of the different types of storage caverns which leads to a rather complex deformation field. The respective situation and the related challenges are explained in Seidel et al. (2024). Fig. 5 illustrates a

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[12] German Federal Ministry of Economic Affairs and Climate Action

modelling approach for the main sources of surface deformation at Epe. Displacements are mainly induced by cavern shrinkage, but groundwater changes in certain areas of the cavern field create a superposing signal. Having such a model aids the accurate processing of the time series in terms of unwrapping the phase and separating the deformation from other contributions of the phase of the InSAR data.

Surface displacement results show a spatially irregularly shaped subsidence trough above the cavern field that is slowly expanding into the built-up area of the city Gronau, even though currently at very small rates. Displacements at the centre of the field fluctuate from 1-6 cm/year depending on the cavern usage. The deformation patterns derived from PSInSAR and DSInSAR are confirmed both by GNSS time series and levelling data. In this regard, the project work mainly relies on InSAR techniques.

To confirm the suspected source mechanisms from a causal perspective, InSAR time series of all four orbits are combined to retrieve horizontal and vertical deformation components from Satellite line of sight (LOS) vectors and compared with supplemental data of cavern filling levels and groundwater level measurements. The temporal patterns of points in the centre of the cavern field show high correlation with filling levels and therefore pressure change within the cavern, when the annual subsidence trend is subtracted beforehand, as shown in Fig.6. Points in the northern part of the fen, which are assumed to be only lightly affected by cavern due to high distance, show a similar correlation in regard to groundwater level changes, as shown in Fig.7.

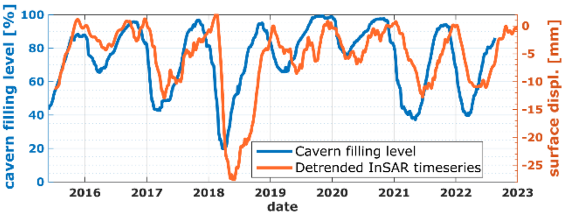

Fig. 6: Relation of the gas filling level and the delayed response the detrended InSAR time series
(from Seidel et al., 2024)

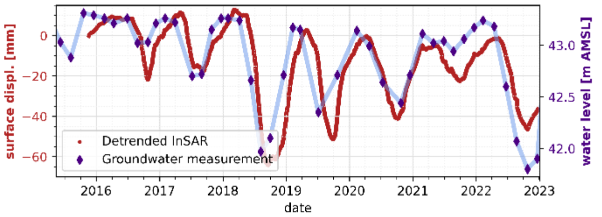

Fig. 7: Relation of the groundwater level and the respective response the detrended InSAR time series
(from Seidel et al., 2024)

Ongoing work is addressing these relations and the effective separation of the effects, which is only possible with the high spatio-temporal coverage of multitemporal InSAR. Future work will focus on the development of a refined geophysical model of the underground situation and the derivation of induced surface deformation.

5.4 BOBIS Project

Finally, within the BoBIS project (funded by MLW[13]) a series of studies is conducted concerning the possible implementation of a regional ground motion information system for Baden-Württemberg (BoBISBaWü) by the State Agency for Spatial Information and Rural Development (LGL). The central questions are, which InSAR-based products can be realized that would complement the portfolio of LGL and what would be the source of InSAR data that are used to derive those products. In the focus is the Sentinel-1 mission, as the only mission that currently provides a regular coverage of whole Baden-Württemberg.

Even et al. (2024a) show both the main conceptual considerations for such as system and an overview on current developments and perspectives of wide area monitoring with InSAR (WAMWIN). The examples of operative services in Italy and Austria demonstrates that WAMWIN based on Sentinel-1 data is useful for monitoring of several types of infrastructure (e.g. roads and train tracks). This suggests that Sentinel-1 data can be used with benefit also in Baden-Württemberg. An important aspect are the requirements for creating a product: frequency of updates, coverage, data quality (e.g. accuracy, noise level). The services provide updates every 12 days (Tuscany) or half year (Augmenterra) and achieve an optimized coverage by including PS as well as DS in their products.

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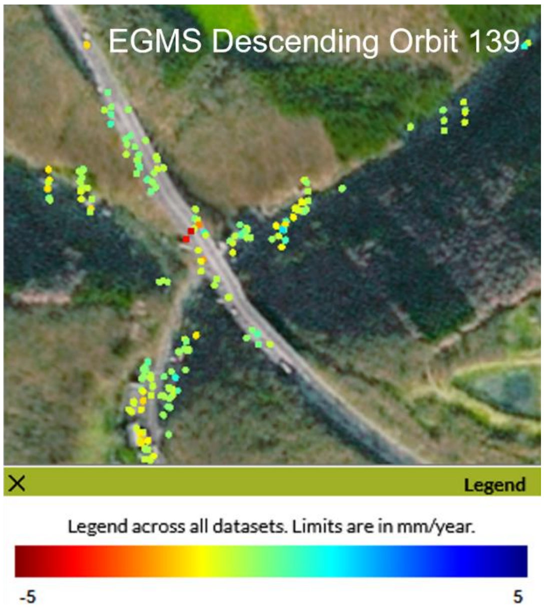
[13] Ministerium für Landesentwicklung und Wohnen, Baden-Württemberg, Germany

Furthermore, the question for a suitable data basis for a regional ground motion information system for Baden-Württemberg was addressed. To this end, the German ground motion service BBD and the European ground motion service EGMS were comprehensively analysed and discussed (Even et al., 2024b). BBD and EGMS were compared with levelling and GNSS data at several locations and for different displacement phenomena. As main conclusions, a good general agreement and good quality of EGMS and BBD were found. An exemption was the cavern field at Epe (see Section 5.3), which is challenging for InSAR because of the pronounced spatio-temporal gradients of the displacement field.

In addition, an analysis of coverage was provided for road tracks, motorways and state roads for an area in northern Baden-Württemberg for BBD and EGMS. As for Germany neither BBD nor EGMS are using DS for their products, the central question of (Even et al., 2024c) is if DS could improve the coverage on roads or train tracks. To this end, numbers of coverage are provided for different categories of linear infrastructure (motorways, federal roads, state roads, county roads, train tracks) for EGMS and for data including DS processed at GIK. The analysis does not consider BBD data, as it was recently announced that future releases of BBD will be based on displacement data provided by EGMS.

The obtained numbers show a considerable improvement of coverage, when PS+DS are used and may help to justify the additional effort to use DS during InSAR processing for EGMS/BBD. Consequentially, an upgraded BBD or EGMS that provides displacements for PS+DS could be the data basis for BoBISBaWü. Depending on the application, more frequent updates would be desirable.

Recently, an investigation on the data quality of EGMS was started with a view to adequacy for derived products, e.g., identification of irregular motion. An illustrative example is the Rahmede viaduct in North Rhine Westphalia. Fig. 8 shows a screenshot from EGMS of the viaduct. There are three backscatterers on the bridge (in red), which show an irregular motion deviating from backscatterers in the vicinity. The viaduct was closed in December 2021 after local TLS inspection and it was blasted in May 2023. Fig. 9 presents the time series of one of these backscatterers with some evidence for anomalous displacement starting in 2017.



Legend across all datasets. Limits are in mm/year.

Fig. 8: Line-of-Sight deformation for the Rahmede viaduct in North Rhine-Westphalia with significant point motion of backscatterers on the bridge (in red) between Feb. 2015 and Dec. 2021

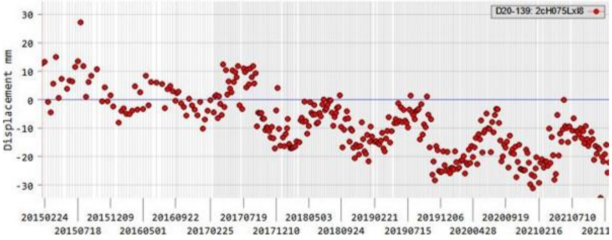


Fig. 9: Line-of-Sight time series of one of the PSInSAR backscatterers on the Rahmede viaduct with both a seasonal periodic and an irregular component between Feb. 2015 and Dec. 2021

Only one of the products of EGMS contained points that showed the critical movement and it were only three points. The exact position of the points is uncertain, although the seasonal pattern indicates that they were on the bridge. While the noise level for the depicted time series is low, we found that EGMS contains many noisy time series. The given example shows that highly relevant information can be found in EGMS, but also that it is difficult to reliably extract this information for very local phenomena because of low coverage, in particular when the quality of the time series is not optimal.

At present, EO techniques are to some extent capable to provide valuable information for GDM in a combined approach. Moreover, on a regional scale, they provide a basis to identify sites of further interest on a remote sensing basis. In this regard, it allows to economically bridge regional and local scales although there is still the need for dedicated improvements so that the ground motion services could regularly provide valid displacement time series for linear infrastructure objects. This can even be extended if ground motion services are becoming a standard component of a national critical infrastructure. This needs to be studied in further detail, in particular with respect to the use of machine learning techniques.

6 Conclusions

EO and GDM are complementary approaches to deal with structural monitoring and geodynamic monitoring. Together with a rigorous free-and open data policy, a sustained EO infrastructure is becoming increasingly important for standard GDM tasks. As shown in this work, EO could be better exploited in combined approaches as it provides the link to a global spatial reference frame and as it is capable to merge local and regional scales. The presented examples underline the potential of the joint use. Nevertheless, dedicated research is needed in terms of a more refined modelling and of a meaningful quantification and propagation of uncertainty for determining a realistic level of consistency of the different components and a realistic level of significance for detecting deformations.

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