Ground Motion Services and Monitoring of Movements of the Earth's Surface with InSAR – Present Developments and Perspectives

Bodenbewegungsdienste und Monitoring von Bewegungen der Erdoberfläche mit InSAR – Aktuelle Entwicklungen und Perspektiven

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Summary
Radar interferometry has experienced an enormous development during the past decades. Presently, it is the only measurement technique capable of observing ground motion on regional and even continental scale with sufficient point density to highly precise areal monitoring tasks. Thus, it is, besides observation of single objects, predestined for performing wide area surveying tasks. Currently, many authorities, companies and other stakeholders have a strong interest to use InSAR for their purposes. Also, the State Agency for Spatial Information and Rural Development (LGL) in Baden-Württemberg has undertaken first steps to establish a corresponding organizational entity and is thereby supported by the Geodetic Institute Karlsruhe (GIK). There are two core questions: For which tasks of LGL can InSAR be used efficiently and in an economic way? Should data be processed by themselves or can those of the German Ground Motion Service (BBD) or European Ground Motion Service (EGMS) serve as basis for proprietary products? The present article sheds light on these questions from an overarching perspective by giving an overview on developments of wide area monitoring, discusses several existing services and collects experience from literature. It concludes with an outlook on new possibilities, that future SAR missions will provide.

Keywords: radar interferometry, wide area monitoring, ground motion, geodetic spatial reference, ground motion cadastre

Zusammenfassung
Die SAR-Interferometrie (InSAR) hat während der vergangenen Dekaden eine enorme Entwicklung erfahren. Sie ist derzeit das einzige Vermessungsverfahren, das in der Lage ist, auf regionalem und sogar kontinentalem Maßstab Bodenbewegungen mit ausreichender Punktdichte zu beobachten, um flächenhafte, hochgenaue Monitoringaufgaben erfüllen zu können. Damit ist sie neben der Beobachtung von Einzelobjekten dazu prädestiniert, großflächige Überwachungsaufgaben wahrzunehmen. Aktuell besteht bei vielen Behörden, Unternehmen und anderen Akteuren ein großes Interesse, InSAR für ihre Aufgaben zu nutzen. Auch das Landesamt für Geoinformation und Landentwicklung (LGL) in Baden-Württemberg hat erste Schritte unternommen, eine entsprechende Organisationseinheit aufzubauen, und wird dabei vom Geodätischen Institut Karlsruhe (GIK) unterstützt. Dabei stellen sich zwei Kernfragen: Für welche Aufgaben des LGL kann InSAR nutzbringend und effizient eingesetzt werden? Sollen Daten selbst prozessiert werden oder können solche des Bodenbewegungsdienst Deutschland (BBD) oder European Ground Motion Service (EGMS) als Grundlage für eigene Produkte verwendet werden? Der vorliegende Artikel beleuchtet diese Fragen aus einer übergreifenden Perspektive, indem er einen Überblick über Entwicklungen des großräumigen Monitorings gibt, einige bestehende Dienste diskutiert und Erfahrungswerte aus der Literatur zusammenträgt. Er schließt mit einem Ausblick auf neue Möglichkeiten, die zukünftige SAR-Missionen eröffnen werden.

Schlüsselwörter: *Radar-Interferometrie, Wide Area Monitoring, Ground Motion, Geodetic Spatial Reference, Ground Motion Kataster*

1 Ground Motion Monitoring with InSAR

Synthetic Aperture Radar (SAR) allows to measure displacements of the Earth's surface. Present spaceborne SAR satellites move on a sun synchronous orbit with an inclination near 90°. The sensor emits microwave signals perpendicular to its orbit and with a look angle usually in the range of 20° to 70° (see Fig. 1). The antenna records the returning signal and its run time. The run time is determined by the acquisition geometry, the position and nature of the backscattering mechanism and atmospheric delays. That is, if the position of the sensor were the same for each acquisition, the backscattering resulted from a point-like scatterer, the atmospheric delay would likewise be the same and the sampling of the run time would be sufficiently fine, the differences in run time would allow to calculate the displacement of the scatterer in line of sight by simple dividing the difference of run times by two times the speed of light.

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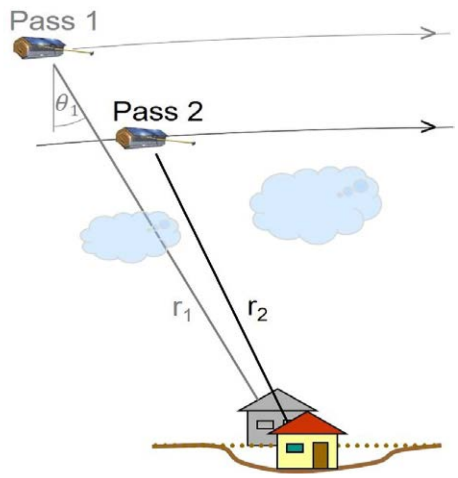

Fig. 1: Acquisition geometry for InSAR. To form an interferogram, two acquisitions taken from the same orbit with the same look angle are needed. θ_1 is the look angle during the first pass of the satellite, r_1 and r_2 are the distances between satellite and scatterer during the first or second pass.

Hence interferograms, that is "differences" of acquisitions, contain information about displacements that occurred between the acquisition times. With algorithms for displacement analysis that use multiple interferograms taken from the same acquisition geometry, it is possible to eliminate the effects of changes of satellite position, atmospheric delay and wrapped phase for the subset of temporally phase-stable scattering mechanisms (point-like or persistent scatterers (PS) and distributed scatterers (DS)) and hence to determine displacements for them. Because of the use of naturally occurring phase-stable scatterers, InSAR is sometimes called opportunistic. The consequence is, that InSAR requires a new view on data collection. There will be data gaps at locations, where measurements are definitely needed. In this case, one has to rely on other methods or to install artificial reflectors. Conversely, a large amount of data on a large area is obtained with a high repetition rate. Thus, e.g., extended infrastructure can be observed, that otherwise for reasons of effort would not be monitored or only in large intervals. InSAR is currently the only measurement technique, which is capable of observing ground motion on regional, national or even continental scale with a sufficiently high point density for accomplishing monitoring tasks.

2 Dynamic evolution of spaceborne InSAR

During the last two decades, InSAR techniques have experienced a rapid development as is visible, e.g., from the at times exponentially growing number of related scientific publications (Wu et al. (2020)). According to Crosetto et al. (2020), this is mainly due to the following factors. SAR data availability has improved a lot with easy access to data hubs via the internet and with increasing number of SAR systems (ERS-1/2, RADARSAT-1, Envisat, RADARSAT-2, TerraSAR-X, COSMO-SkyMed, TanDEM-X, Sentinel-1, etc.). New acquisition modes as well as new methods and algorithms (DS, PS, SBAS, TomoSAR, adaptive Multilooking, PolInSAR) have extended the range of applications and improved the density, quality and reliability of results. With the launch of the first two Sentinel-1 satellites, wide area coverage with a short revisit time of six days had been available until the malfunction of Sentinel-1B and will again be available after the launch of Sentinel-1C. With freely available ESA data and diverse freely available InSAR softwares (DORIS, StaMPS, TRAIN, SNAP, MintPy, ComSAR, …), the research and user communities could grow fast and take part in an accelerating development. In addition, computing continues to become more performant, what allows the processing of ever greater data sets with algorithms of growing complexity. Methods have been developed to apply atmospheric corrections and to use GNSS data to calibrate InSAR measurements, i.e. to transfer the displacements

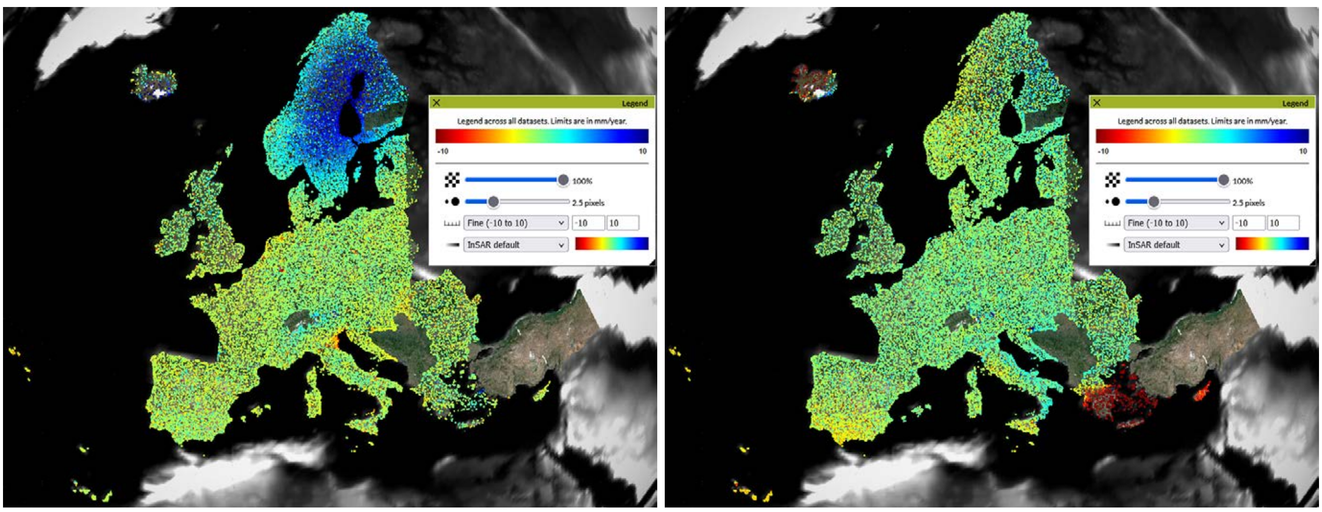

Fig. 2: Displacement rates from viewer of EGMS. Left: Vertical displacement showing e.g. the post-glacial rebound of Scandinavia in blue. Right: East-West displacement presenting e.g. the movement of the Aegean plate in red.

properly into geodetic reference frames. This allows the combination of multiple frames to wide area ground motion products. Nation-wide ground motion maps (e.g. Bischoff et al. 2020, Dehls et al. 2019, Ferretti et al. 2019, Costantini et al 2017, Cuenca et al. 2011), in particular the German Ground Motion Service BBD (Kalia et al. 2017, Kalia et al. 2021), and lately the European Ground Motion Service EGMS (EGMS Documentation 2022) were created (Fig. 2 displays screenshots from the viewer of EGMS). In Germany, regional ground motion services (GMS) were implemented by the surveying authorities of the federal states Saarland (Engel et al. 2022), North Rhine-Westphalia (Riecken et al. 2019) and Lower Saxony (Brockmeyer et al. 2021), which are shaped by a long history of mining and hence of dealing with ground motion.

At this point in time, the potential of InSAR with respect to monitoring of ground motions in general and of infrastructure in particular has been investigated by hundreds of scientific papers that prove its value and discuss its limitations. A transition is taking place, where more and more stakeholders are verifying the benefits of InSAR for their monitoring applications and are seeking to integrate this technique in their workflows. For monitoring of single objects or hotspots, high resolution data offer the most information, but full spatial coverage is not possible in high resolution with existing SAR systems. On the other hand, the resolution of the interferometric wide swath mode of Sentinel-1 does not suffice for certain monitoring tasks, but it provides complete spatial coverage in mid-latitudes. It has many applications in wide area monitoring with its capability of discovering unnoticed phenomena, its use for planning and its capability of risk detection. First systems for wide area monitoring with InSAR (WAMWIN) are operative (Del Soldato et al. 2019, Augmenterra 2024, Rheticus Displacement 2024) and suggest that WAMWIN can be extended to other regions with benefit.

Given the availability of EGMS, BBD and other GMSs, it suggests itself to ask if stakeholders can use them as basis of their own WAMWIN applications or, if not, if the GMSs could serve this purpose after some upgrading. In order to explore this question, WAMWIN is discussed in the next sections and existing WAMWIN solutions are reviewed.

3 Wide Area Monitoring with InSAR (WAMWIN)

The current situation regarding scientific literature on InSAR-based monitoring of infrastructure is that hundreds of case studies have been published, which prove the benefit of InSAR for diverse surveying tasks using different types of SAR data and combine or validate their results with other measurements. Many of these studies use Sentinel-1-data and find that Sentinel-1-data provide useful information. Data with higher resolution provide better coverage with information (points per area or per object) and better accuracy of point positioning. This is very desirable for monitoring purposes. But there is a trade-off between resolution and coverage. High resolution acquisition modes can only observe a small portion of the Earth's surface with repeat pass (mandatory for interferometry). In contrast, with few exemptions Sentinel-1 acquires all data over land with the interferometric wide swath mode. With this strategy, each Sentinel-1 satellite covers every 12 days nearly the complete landmass of the Earth. Together with the free and open data policy and the sustainable acquisition philosophy of ESA that allows to study the past via archived SAR data (ERS-1/2, Envisat, Sentinel-1), this makes Sentinel-1 indispensable, when it comes to wide area ground motion observation on regional, national or even continental scale. Sentinel-1 provides the necessary foundation to build monitoring systems on and – following its launch – WAMWIN has become an important topic.

This has led to different GMSs, to studies and concepts regarding monitoring systems and to first operational monitoring systems. Yet, the amassed wealth of data is only used to a small degree for operational purposes of authorities, infrastructure operators or other stakeholders. Compiling huge amounts of displacement information can only be the starting point. The next logical step is to extract and interpret the information that is contained in these data.

A GMS product may comprise millions to hundreds of millions of measurement points (MPs). To each measurement point belongs a time series of several hundreds of measurement values. Data mining techniques and meaningful visualization are needed to analyse, which phenomena are reflected in these numbers. Then, the information has to be made usable. Stakeholders have to be informed about the situation via reports or bulletins (e.g. indicating the necessity of in situ checks). Results have to be stored in a database.

Thus, a complete WAMWIN comprises the following steps:

1. wide area InSAR processing,
2. generation of information layers,
3. a transition from pointwise information to areal information, in case first categorization,
4. export of relevant information to some GIS,
5. interpretation by InSAR and surveying experts taking other data sources into account, assigning categories regarding level of required action, risk, etc.,
6. generation of a report/bulletin to stakeholders plus storing of information in a data base,
7. if necessary, the stakeholders take action.

3.1 Operative WAMWIN

In this section, three operative WAMWIN services that are based on Sentinel-1 data are discussed. For illustration, we present one of them in some detail.

In Tuscany, where about 117000 landslides are known and further geohydrologically caused movements occur, a monitoring system based on Sentinel-1-data has been established (Raspini et al. (2018), Del Soldato et al. (2019)). The workflow is as follows:

1. Every 12 days, an InSAR displacement analysis is automatically updated with the SqueeSAR (Ferretti et al. 2011) algorithm. PS as well as DS are exploited.
2. Based on the updated time series an anomaly detection is performed, which delivers indications for significant accelerations of movement that occurred during the last 150 days. In doing so, not movements of clusters of MPs are analysed.
3. As next step, the reported anomalies are reviewed by a team of experts, which uses different sources of information for the interpretation.
4. The experts classify the anomalies.
5. For each municipality, a classification is carried out, which considers anomalies and their relevance (to assess, if e.g. settlements or infrastructure are endangered).
6. A monitoring bulletin is prepared and distributed to the authorities.
7. In case critical situations are reported, an in-situ investigation that comprises a risk assessment is executed by regional or local authorities within a few days.

The WAMWIN in Tuscany is provided by TRE Altamira and processed with SqueeSAR. It uses the capability of InSAR to detect evidence of possibly problematic movements on a very large area. The automatically generated warnings are interpreted by experts with the help of further sources of information. The results are reported to stakeholders and lead to in-situ investigations if necessary.

A more comprehensive approach is taken by the WAMWIN service of Augmenterra (Augmenterra 2024, Dörfler 2024). Every half year an update of a ground motion map that covers a time period of three years for the whole territory of Austria is generated based on Sentinel-1-data with the help of SqueeSAR. For different pre-defined object types (e.g. buildings, road or railway segments, dam segments, power poles, lift pylons), an assignment of high-quality points to objects is performed with the proprietary MatchSAR algorithm. Every object gets assigned to one of three displacement classes (no significant displacement, significant displacement, accelerated displacement). Clients pay for an area of interest, for which they can access the classification map and further information in the AUGMENTERRA OBSERVER. The main benefit from client perspective is a risk assessment on large area. Equipped with the displacement information, the client performs further analyses. Clients are infrastructure operators as ASFINAG, road maintenance departments of the federal states, ÖBB (Austrian Railways), APG (Austrian Power Grid AG), as well as some ski resorts.

A third operational service developed from the Sentinels Benefits Study "Highways Management in Italy", performed by the European Association of Remote Sensing Companies and funded by the EU and ESA explored "how regularly updated maps showing the movement of the land can be used by organizations such as ANAS (old denomination: Azienda Nazionale Autonoma delle Strade) and other road operators, to improve their management of the road network" (Sawyer et al. 2022). The InSAR expertise was provided by Planetek. The data were processed with the SPINUA algorithm of GAP, a technology partner of Planetek, including PS and DS. Exemplifying several study cases and performing an estimation of economic benefits; the value of InSAR for planning of works could be demonstrated. As a result, Planetek introduced Rheticus Safeway, a service that provides regularly updated nation-wide maps of ground movement based on Sentinel-1 data together with risk assessments and ANAS is now using Rheticus to

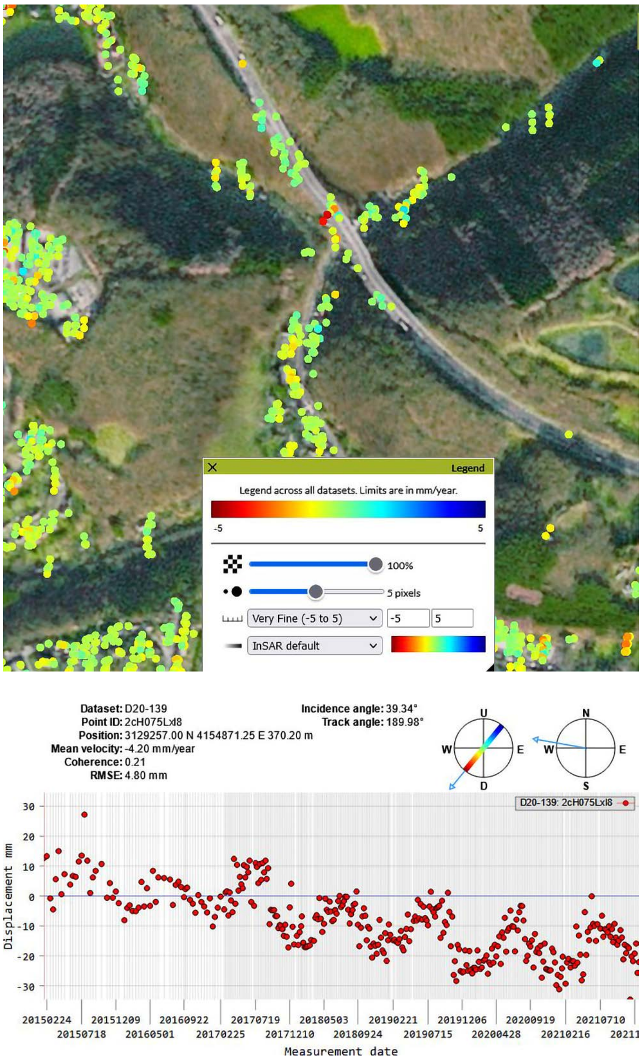

Fig. 3: Screenshot from EGMS viewer, path 139 of descending orbit. Above, three red points are visible on the viaduct of A45 over the Rahmede. Below, the time series of one of the red points is displayed. It shows a seasonal pattern, which suggests that it is actually situated on the bridge. In summer 2017, a distinct subsidence sets in. During surveillance work of the bridge in December 2021, severe damages were found and lead to the immediate closure of the bridge. In May 2023, it has been blasted. As EGMS is available since autumn 2022, this observation came too late to be of use.

assess risk and adapt road designs to reduce the danger for Italian motorways, tunnels and bridges. Although Sentinel-1 data are the basis for the product, the study remarks that monitoring of bridges and tunnels requires higher resolution data, but Sentinel-1 can be used to obtain indications and trigger the acquisition of higher resolution data.

As illustration of what has been said, Fig. 3 gives an example of a motorway bridge, where EGMS could have provided a useful early warning that would have led to an early detection of a severe damage. But the example also demonstrates some of the limitations of bridge monitoring with Sentinel-1. 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.

The examples of these operational services show that Sentinel-1-data are suitable for WAMWIN, when used for area related planning or generation of warnings. However, monitoring of e. g. bridges is challenging and can be done, if at all, with high resolution data only. The described services achieve a better coverage by including DS in their processing. Updates are delivered every 12 days for Tuscany, every half year by Augmenterra and maybe monthly by Rheticus Displacement (2024).

3.2 Concepts and Studies

There is also a number of studies and concepts in the literature that at least include the initial steps of WAMWIN. Most of them address monitoring of landslides or of linear infrastructure.

An early work was from Meisina et al. (2008) and uses ERS-1 and ERS-2. It classified landslides in Piedmont, Italy. The results served to update a GIS data base of the Regional Environmental Protection Agency (ARPA). Later, Di Martire et al. (2017) updated a land slide inventory for the whole Italian territory with help of COSMO-Skymed data. The great majority of landslides (77 %) have not been recognized by InSAR, but only during field surveys. In contrast, about 11 % of the landslides could not be detected in the field, but only by InSAR. Ferlisi et al. (2021) used COSMO-Skymed data to quantitatively estimate the risk of repair costs posed by slow-moving landslides for the road network of Campania, Italy. Infante et al. (2018, 2019) developed an Integrated Procedure for Monitoring and Assessment of Linear Infrastructures Safety (MONALISA), a concept for an automatic vulnerability analysis for roads in Campania, Italy, based on COSMO-SkyMed data. Delgado Blasco et al. (2019) set up a processing chain based on freely available software (SNAP and StaMPS) and Sentinel-1-data. Roads, railways, bridges and buildings can be extracted with help of shape files from OpenStreetMap. The exported data subsequently can be post-processed in a GIS. The authors applied their workflow to greater Rome. Likewise, Rome was the test case of Orellana et al. (2020). The product was mean velocities per segment for the highways. Results based on COSMO-SkyMed data were compared to results based on Sentinel-1-data. The authors conclude that the amount of PS detected by Sentinel-1 is sufficient to provide valuable information on the general state of the network and could be useful for planning of maintenance work.

Macchiarulo et al. (2021) presented a semi-automatic method that combines PSInSAR with procedures for damage assessment for the case of subsidence caused by tunnel boring. A damage class is assigned to each building. The classes are visualized in a map. Test case is the Crossrail tunnel in London using COSMO-SkyMed. In Macchiarulo et al. (2022a) warnings for road networks are generated with help of an automatic integration of InSAR-measurements in a GIS-based infrastructure inventory. As test cases, the Los Angeles highway and freeway network and the Italian motorway network were studied using Sentinel-1.

Chang et al. (2017) presented a concept study that went on trial basis through a country wide railway monitoring for the Netherlands. As products, maps of displacements along railways, quality information for the MPs as well as a classification according to displacement pattern were generated. The authors pointed out that an automatic detection of risk requires the knowledge of experts in order to define suitable criteria for classification and generation of warnings.

SAR4Infra (2023) supports "German land surveying authorities by providing an automated risk map for traffic infrastructures, which complements their in-situ measurements". Another application is addressed by Alberts et al. (2021). Levelling of the Dutch height system is performed in a cycle of ten years. The paper suggests to optimize the levelling cycle by measuring areas with ground motion more often than stable areas. For their test case RADARSAT-2 data were used, but the authors suggest to base the operational product on a nationwide ground motion map based on Sentinel-1-data.

These concepts and studies demonstrate the value of Sentinel-1 for WAMWIN and provide a good source of inspiration for setting up new services.

3.3 Concepts based on BBD/EGMS

Only two of the studies and concepts (SUMO4Rail, EO4Infrastructures) regarding WAMWIN that are referenced in this manuscript are based on data of BBD or EGMS.

According to SUMO4Rail (2020), "SUMO4Rail aims at a concise evaluation of the German ground motion service (Boden-Bewegungs Dienst – BBD) deformation products with dedicated consideration of the requirements of the Eisenbahn-Bundesamt (German Federal Railway Authority, Germany – EBA) including the valorization of these deformation products …". GAF AG (2024) states "In SUMO-4Rail, GAF AG is responsible for the further processing and adaptation of BBD basic data, in particular component decomposition, determination of areas of active movement as well as classification based on the use of geological, hydrological and topographical basic data for the assessment of risks in logistics chains, especially regarding railway and port infrastructure.". Unfortunately, it seems that none of the project results were published. For EO4Infrastructures at least the final report (EO4Infrastructure Team 2022) is available on the internet and shares the main insights of the project. The study was a collaboration of the railway companies SNCF (France), RFI (Italy) and DB-Netze (Germany) with the earth observation service providers e-GEOS, TRE-Altamira and GAF AG. A series of test cases involving SAR (EGMS and also higher resolution data) and electro-optical data (Sentinel-2) was determined and the railway companies defined their requirements for different monitoring tasks.

Here it is noteworthy with regard to an upgrading of EGMS/BBD, that for some of the ground motion monitoring tasks a monthly update of products was demanded. In the conclusions, this was reduced to requiring quarterly updates. Regarding the assessments and conclusions of the railway companies with respect to ground motion maps, the two main statements are: 1. EGMS data are useful for the end users, although some limitations were identified, and 2. the use of ground motion maps poses difficulties (e.g. because of the high number of MPs). Because of the latter, "value-added products in terms of identification and classification of the critical sections/anomalies" and reports were considered desirable. For more details, see EO4Infrastructure Team (2022).

3.4 Existing Ground Motion Cadastres

The surveying authorities of the German federal states are in charge of providing a reliable, high precision integrated geodetic spatial reference that is the basis of land registries, georeferencing of spatial technical data, navigation applications, flood protection and emergency planning. The use of InSAR helps the surveying authorities in maintaining the integrated geodetic spatial reference by informing on ground motion areas. InSAR supports the planning of measurements, allows the reduction of terrestrial measurements and considerably increases the available information by providing areal displacement measurements.

GMSs on the level of federal states have been established in the former German mining regions Saarland, North Rhine-Westphalia and Lower Saxony by the surveying authorities of these states. The foundation of these services is the Copernicus program, which is sustainably operated and established on a permanent basis and whose data are open and free for all users.

In Saarland and North Rhine-Westphalia (NRW), the displacement data are processed by the authorities. Instead, the GMS of Lower Saxony is based on post-processed BBD data. Quality controls are applied and a recalibration using proprietary geodetic data is performed. With help of Kriging interpolation, a displacement map with full spatial coverage is derived. The interpolated data represent well large area mining-induced ground motion, but are less suitable for the monitoring of single infrastructure objects. See Riecken et al. (2019), Brockmeyer et al. (2021) and Engel et al. (2022) for more details.

4 BoBISBaWü

The surveying authority of the state Baden-Württemberg (LGL) intends to complement its portfolio by providing InSAR-based products and services in the frame of a regional ground motion information system (Bodenbewegungs-Informationssystem, BoBIS) for Baden-Württemberg (BoBISBaWü).

4.1 Motivation BoBISBaWü

According to the surveying act of Baden-Württemberg (VermG BW, § 3 Abs. (2)), the realisation of the geodetic spatial reference system belongs to the mission of the authoritative surveying. This holds for position, height and gravity via a network of control points and a satellite-based positioning service (SAPOS). LGL collects and qualifies the data of the control points and stores, provides and submits them in digital form in the Authoritative Control Point Information System (AFIS). In accordance with the requirements of the administrative regulation for the geodetic control network (VwVFP 2008) and the "Richtlinie für den einheitlichen integrierten geodätischen Raumbezug des amtlichen Vermessungswesens in der Bundesrepublik Deutschland" (AdV-Rili-RB 2017), the control network must be maintained and the data kept up to date. For this purpose, the control points are monitored. If needed, they are checked by dedicated geodetic measurements. Changed values of coordinates, heights and gravity are updated in AFIS. Information provided by radar interferometry helps to identify areas affected by ground motion and to coordinate the cycles for the metrological inspection of control points. In this regard, the data of the control points are updated as efficiently as possible. Particularly in the case of height data, which are determined and checked by time-consuming and labour-intensive precise levelling along the 1st and 2nd order levelling lines, great potential is seen in both time and cost reduction resulting from optimized measurement cycles. Moreover, the ground displacements provided by InSAR will support the selection of stable locations for new SAPOS reference stations.

Based on the AAA model of the AdV[1] (AFIS, ATKIS (Official Topographical Cartographic Information System) and ALKIS (Official Land Registry Information System))

1 Working Committee of the Surveying Authorities of the Laender of the Federal Republic of Germany

innovative service products for departments of the state administration and other stakeholders will be possible (AdV 2024). This concerns in particular the surveying of infrastructure, buildings, control points and SAPOS stations. In case of Baden-Württemberg, motorways, federal roads, railways, bridges, dams, geothermal plants, lockages, construction projects, mining areas and uplift caused by oil shale could be monitored.

4.2 Conception BoBISBaWü

As a preparatory step for BoBISBaWü, GIK carried out a comprehensive study on the possible applications of InSAR for LGL including a validation of BBD and EGMS (Even et al. 2024) and a concept for the introduction of BoBISBaWü. Given the dynamically developing environment and some open questions, establishing BoBISBaWü in two stages has been proposed.

During the first stage, starting from data of BBD/EGMS, basic tools and workflows for data handling, quality assurance (verification with other geodetic data, outlier detection, spatio-temporal consistency, …), data mining, data visualization and data management will be implemented. Examples are the generation of additional information layers (activity, anomaly, …) and a functionality that allows extraction of data for defined areas as foundation for the creation of stakeholder specific products. As first such product, active displacement areas will be determined. Specific, ground motions in the vicinity of control points and SAPOS stations will be extracted and analysed. Potential stakeholders will be addressed and invited to cooperate regarding the definition of products tailored to their needs. During the second stage, LGL, GIK and stakeholders will work together to design user specific products and establish the operational workflows.

4.3 Next Steps

Currently, it is unclear if BBD/EGMD suffices as data basis for the purposes of all users or if LGL needs to build up proprietary InSAR processing capacities in order to enable more frequent updates of products, to achieve better coverage by advanced processing using DS and temporally coherent scatterers or to observe hotspots with help of higher resolution data. This decision has to take account of several issues: BBD/EGMS are produced by highly accomplished providers. To generate mass products of similar quality is difficult to achieve. This would require the availability of advanced software (open source or commercial) and the ability to make good use of it, that is requiring considerable in-house expertise. Moreover, the requirements regarding staff and hardware would grow, when displacement data were generated by LGL.

As the idea of BoBISBaWü is to provide InSAR related products to other stakeholders, buying services from commercial providers is not considered for the basic products. Though it may be an option for specific cases, like monitoring of hotspots.

5 Next Decade of WAMWIN

Currently, many authorities and operators of infrastructure are verifying the potential of InSAR monitoring for their purposes. But in medium term, it is not efficient if each organizational unit and each stakeholder establishes its own InSAR processing capacities. Hence it can be expected that a consolidation will take place, where depending on the specific organizational, legal, geological, climatic or vegetational circumstances, the generation of InSAR derived products will be performed by a few providers. E.g. in Germany, it would make sense, that for motorways, federal roads or railways nation-wide products are generated, while other tasks fall in the responsibility of the federal states and are best dealt with on this level. The recent announcement that future releases of BBD will be based on displacement data provided by EGMS (Kalia et al. 2023) can be seen as precursor of the coming consolidation. With this prospect, the question is the future role of BBD or EGMS. In light of economic efficiency and of the challenges posed by generating a high-quality wide area displacement product, it would make sense that not every stakeholder across Europe, who wants to use InSAR, processes SAR data himself, but that EGMS provides displacement information that suffices the requirements of most WAMWIN applications and that on this basis stakeholders derive products for their individual application. This would mean that updates of EGMS are required more frequently than once a year. Optimally, temporary PS as well as temporary DS would be processed in order to obtain maximum coverage. In addition, subpixel positioning, where SCR allows, would be beneficial for infrastructure monitoring, as the precise location of observed motion is crucial for interpretation.

Another aspect of the success of WAMWIN is the free and open availability of data. Financing of EGMS as part of Copernicus is guaranteed until 2027 (EU 2024). The continuation of Copernicus beyond 2027 is in preparation. As ESA, starting with ERS-1/2, over Envisat and currently Sentinel-1, has made possible an almost continuous earth observation with SAR satellites, it can be assumed that ESA provides SAR data also after 2027. Apart from Sentinel-1, the coming decade offers exiting new possibilities for InSAR. Presumably from 2029 on, the Harmony mission (Harmony 2023) will complement Sentinel-1 and allow to obtain the North-South component of the displacement field. As the ground resolution will be 100 m × 100 m, not all monitoring applications will benefit. A little bit earlier, 2028, the launch of Rose-L is scheduled (Rose-L 2023). Thanks to the better coherence of L-band in vegetated areas, the extent of the land surface, where displacements can be measured will be enlarged. E.g. monitoring of landslides and of dams will be improved. Like ESA, NASA follows a free and open data policy. NISAR, a combined L- and S-band mission in collaboration with the Indian space agency ISRO will start in 2024 and will bring similar benefits for WAMWIN as Rose-L (NISAR 2024).

6 Conclusions

In this article, we have analysed the current situation of WAMWIN with a view to implementing BoBISBaWü, a new GMS for Baden-Württemberg. The current conditions are favourable. A large number of studies and concepts have explored the use of InSAR for monitoring, first operative services and ground motion cadastres exist and provide a basis of experience that can be used for further developments. In particular, the value of Sentinel-1 for WAMWIN has been proved. ESA follows a sustainable strategy regarding provision of free and open data, is continuously developing its services and is answering to the needs of the earth observation community with devoted missions. This reliable long-term perspective is a foundation for the introduction of new services and products. Given the great interest of authorities and other stakeholders to use InSAR for their purposes, we expect that a widespread use of this technique across Germany/Europe will develop during the coming decade. The surveying authorities with their legal mission to provide geo base information have a central role in this transformation and are the predestined interface between system and service providers on the one hand and the different technical administrations on state level on the other hand. It suggests itself, that they take the initiative and develop novel services that work into the administration, but also create and provide products for and in collaboration with external users.

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