Fusion of BIM and SAR for Innovative Monitoring of Urban Movement – Towards 4D Digital Twin

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Abstract

Digital Twin has gained significant attention for future urban management. Since 2020, Building Information Modelling (BIM) has become the standard for high-rise buildings and infrastructures in Germany. Our project BIMSAR is to combine BIM data and SAR-derived movement for urban movement monitoring. The so-called persistent scatterer (PS) points are extracted from a SAR image stack based on PSI. These PS-points, considered pseudo-substructures of buildings, contain geoinformation such as geographic position and movement estimates. They are integrated into the BIM models for various self-contained units like façades and roofs. This fusion step is implemented by machine learning, employing a novel distance metric adapted through dimensionality reduction. To provide a user-friendly analysis tool, the fused data are displayed in 4D (position + movement) on a GIS-based platform, along with other geodata, e.g., geological maps, hydrological maps, underground mining structures. This paper shows the current results around Ahlen in Ruhr region, where many damages to buildings, bridges, and highways are associated with the abnormal deformation. We created the BIM models ourselves by converting open-source 3D models, adhering to Industry Foundation Classes (IFC) format. The SAR data contain Sentinel-1, TerraSAR-X, and PALSAR-2 for a cross-analysis. The primary application is to assist stakeholders with an early warning system to evaluate whether unusual or long-term deformations cause structural damages and thereby threaten the safety of life and property. We demonstrate some examples towards this application.

1. Introduction

According to the German Federal Ministry for Digital and Transport, Building Information Modelling (BIM) has become the standard for high-rise buildings and infrastructures in Germany since 2020. The concept of Digital Twin has also gained significant attention for future urban management. As passionate pioneers, EFTAS, together with Technische Hochschule Georg Agricola and University of Stuttgart, lead an innovative project BIMSAR, funded by the German Federal Ministry for Economic Affairs and Climate Action. The link to the project website is: https://bimsar.eftas.services/. Our goal is to integrate BIM, SAR and subsurface data to achieve a city-wide building monitoring at a fine scale, such as for change detection, deformation analysis, and early-warning of building damage (Figure 1). This combination of a 3D-BIM-Model with SAR-derived information creates a 4D Digital Twin.

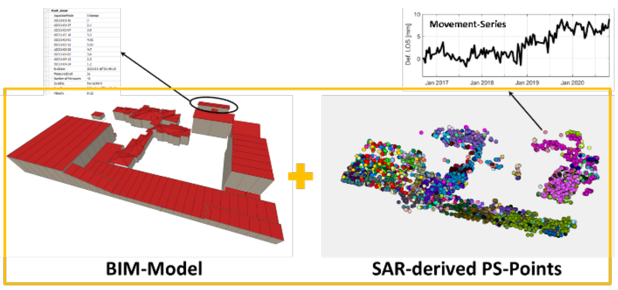

Figure 1. To integrate BIM- and SAR-Data for an innovative building monitoring.

BIMSAR encompasses four aspects. The first is to create a BIM city for Ahlen. The most widely used BIM format is Industry Foundation Classes (IFC) (ISO 16739-1:2018) (Figure 2). This format ensures compatibility with most software, open-source tools, and platforms. Using free LoD2 data from North Rhine-Westphalia, we have developed a semi-automated conversion process to generate IFC data with minimal manual adjustments. Second, the ground movement are estimated via PSI from Sentinel-1 (C-Band), TerraSAR-X (X-Band), and PALSAR-2 (L-Band). Movement analysis is conducted using Sentinel-1 (C-band), TerraSAR-X (X-band), and PALSAR-2 (L-band) data. The cross-analysis of these SAR sensors provides a comprehensive understanding of the post-mining ground movement. Additionally, relevant geodata such as geological maps, hydrological maps, and underground mining structures are integrated to enhance the analysis. Third, the BIM models and movement information are merged into 4D data. This fusion is implemented using machine learning techniques, with plans for continuous enhancement through advanced AI methodologies. Lastly, all the results, including the BIM models, ground movement analysis, and fusion outputs, are incorporated into a GIS-based platform. This platform is designed to be accessible via standard web browsers, ensuring user-friendly interaction and broad accessibility.

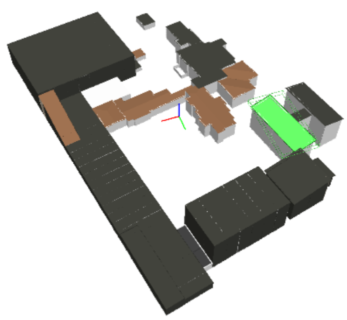

Figure 2. BIM model conforming to IFC format that we created.

Our approach is detailed in Section 2, which covers the overall workflow, BIM creation, PSI processing, and fusion methodology. Section 3 showcases our results, focusing on the validation and analysis of the SAR-derived movement data in conjunction with the geodata. The examples are provided to illustrate the integration of the fused data, highlighting the cases of abnormal ground movement and corresponding structural damages. The features of the GIS-based platform are also presented in this section. Finally, Section 4 summarizes our works and outlook, including the plan for future phases of the project.

2. Methodology

The so-called persistent scatterer (PS) points are extracted from a SAR image stack based on PSI. These PS-points, considered pseudo-substructures of buildings, contain geoinformation such as geographic position and movement estimates. They are integrated into the BIM models for various self-contained units like façades and roofs. This fusion step is implemented by machine learning, employing a novel distance metric adapted through dimensionality reduction. To provide a user-friendly analysis tool, the fused data are displayed in 4D (position + movement) on a GIS-based platform, along with other geodata, e.g., geological maps, hydrological maps, underground mining structures.

2.1 PSI Movement Estimation

PSI (Crosetto et al., 2016; Devanthéry et al., 2014; Kampes, 2006) processes a time series of SAR images to detect PS-points, which are characterized by coherent signals reflected from a (ground) patch of a certain size (dependent on image resolution). Here a PS-point can be interpreted as a measurement point. Man-made structures are therefore potential PS-points. Different kinds of movement are derived from these PS-points such as cumulative time series and mean velocity. The commercial and open-source software including ENVI, SARscape, IDL, etc. are bundled to build the main processing chain. ENVI, a specialized software of remote sensing, provides basic tools of image processing such as import, export, display, format conversion, and so on. The core algorithms of PSI are implemented in SARscape. We programmed versatile functions by IDL especially for calibration, refinement, quality control, and analysis. In addition, we also worked with GMT, Python, GDAL, SketchUp, and ArcGIS to map and analyse our products.

2.2 Fusion of BIM Data and PS-derived Movement

Our approach first identifies clusters of PS-points that are spatially connected and exhibit similar movement behaviour, indicating that they belong to the same structural component of a building. Detecting these clusters allows us to delineate different structural elements and systematically exclude outliers—such as points with significant spatial displacement—that deviate from the common movement patterns. After filtering, the refined clusters are mapped to the corresponding building elements within a BIM model, thereby enriching the movement history dataset. This integration facilitates a more detailed analysis of potential shear stress induced by non-uniform motion.

The process begins by preliminarily associating points with specific objects (in this case, buildings) through a simple intersection with their slightly buffered footprint geometry. To effectively manage the high dimensionality of the data, we apply Uniform Manifold Approximation and Projection (UMAP), a non-linear dimensionality reduction technique (McInnes et al., 2018).

This method reduces the original dataset, consisting of temporal information and three-dimensional positional data (xyz), into a lower-dimensional, three-dimensional representation while preserving its essential structure. To achieve this, we employ a distance metric proposed by (Schneider and Soergel, 2021), which integrates both the correlation of movement patterns and Euclidean distance. This approach ensures that points exhibiting similar movement behaviour remain proximate in the reduced space, thereby enhancing the effectiveness of clustering.

Following dimensionality reduction, we apply the Hierarchical Density-Based Spatial Clustering (HDBSCAN) algorithm (Campello et al., 2013) to identify clusters of points based on their spatial proximity and movement similarity. HDBSCAN is particularly well-suited for this task as it allows for variable cluster densities and effectively distinguishes meaningful clusters from noise, thereby improving the robustness of the segmentation process.

Once the clusters are established, each cluster is assigned to its corresponding BIM element by matching its centroid to the nearest BIM component using a minimum distance criterion. This ensures that the detected clusters are accurately mapped to the building's physical structure, enabling a more precise analysis of localized deformations and their potential impact on structural integrity.

2.3 GIS-based Platform

The platform is built on the Piero Framework (https://giro3d.org/), a fully configurable open-source application designed for the visualization of various 2D and 3D geospatial formats. Within this platform, we integrate and display multiple datasets, including point clouds and IFC-based building models. Additionally, the viewer supports the incorporation of various geospatial data sources, such as Web Map Services (WMS) and GeoJSON files, enabling a comprehensive and interactive analysis environment. This flexibility ensures that users can seamlessly overlay and compare different datasets, facilitating an in-depth evaluation of urban structures and environmental changes.

3. Results

3.1 Post-mining Ground Movement

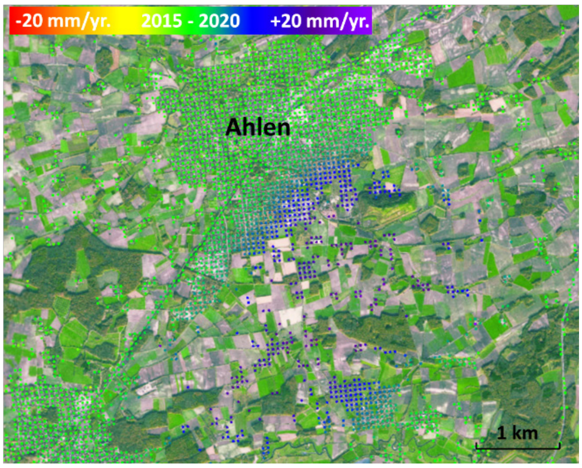

Figure 3. EMGS vertical movement map (Yang et al., 2023) in post-mining Ahlen (51°45′48″N 7°53′28″E). Time period: February 2015 to December 2020. Positive and negative velocities, uplift and subsidence. Each target point represents the centre of a patch of 100 m × 100 m. Copyright © EGMS. All rights reserved.

The main area of interest is around the city of Ahlen, near the Ruhr area, Germany, which has been strongly affected by post-mining ground uplift due to the mine water rebound (Yang et al., 2023). The coal mining in Ahlen (Figure 3) on the edge of Ruhr area, Germany was active since 1909 and abandoned in 2000s. During the active period, the groundwater was pumped out, which together with the underground extraction of material leaded to subsidence as expected. After mine closure, the pumping stopped, so that the water level continued to raise due to precipitation and groundwater flow. Consequently, the ground uplifted as the ground layer swelled. Between 2015 and 2020, the data from EGMS exposes an area of ground uplift spanning almost 6 km × 6 km, with uplift rates reaching up to 20 mm/yr. To our knowledge, most of the residents were not informed about this uplift scenario. The consortium in BIMSAR briefed the city administration of Ahlen about the up-to-date movement up to end of 2021.

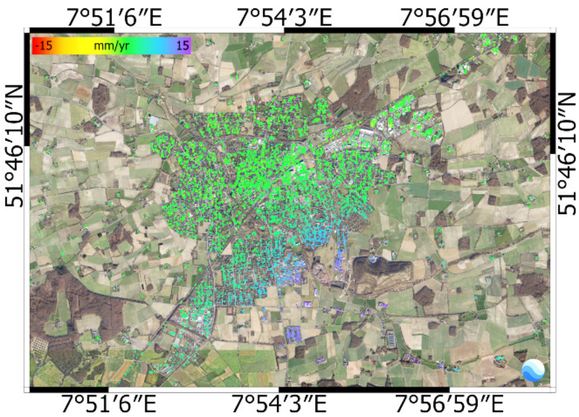

Figure 4. PSI vertical movement map derived by Sentinel-1 in post-mining Ahlen (51°45′48″N 7°53′28″E). Velocity is scaled between -15 mm/yr. and 15 mm/yr. Time period: January 2018 to December 2021. Each target point represents the centre of a patch of 5 m × 15 m. Positive and negative velocities, uplift and subsidence.

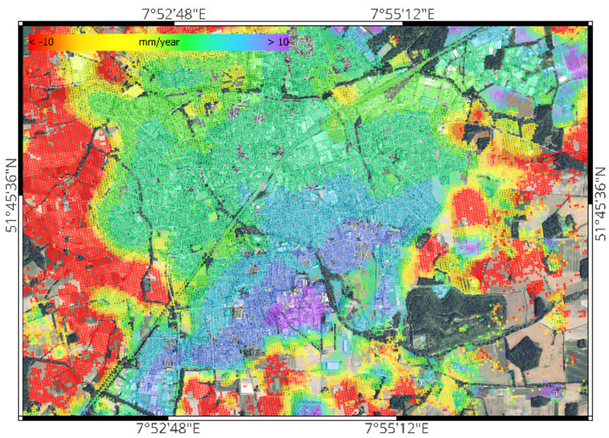

Figure 5. DSI vertical movement map derived by Sentinel-1 in post-mining Ahlen (51°45′48″N 7°53′28″E). Velocity is scaled between -15 mm/yr. and 15 mm/yr. Time period: January 2018 to December 2021. Each target point represents the centre of a patch of 30 m × 30 m. Positive and negative velocities, uplift and subsidence.

The vertical movement maps of our PSI and Distributed Scatterer Interferometry (DSI) products, derived by Sentinel-1, around Ahlen are shown in Figure 4 and Figure 5. Thanks to the a priori information provided by EGMS, we received a reasonable result in our first computation. Such a cost-effectiveness benefits especially commercial project. To be comparable, both movement data were anchored to a stable area (≈ 0 mm/yr.) chosen from EGMS as reference. Our PSI result shows the same velocity pattern as seen in EGMS (Figure 3). This is a strong hint that our processing should not contain significant errors. The first noticeable feature in our DSI result is a larger coverage of target points. This gives us the possibility to analyse the movement, missing in EGMS and our PSI product, in particular over the fields and vegetation covers. Various kinds of movement were subject to different reasons or mixed causes. We explored the causes of the ground movement, if any, in the field and the potential correlation to pedology, hydrology, agriculture, etc. Our previous studies pioneered this topic and concluded some interesting findings (Yang and Müterthies, 2021, 2020).

The ground movement derived from TerraSAR-X data reveals a significant uplift in the southeast near a former underground mine (Figure 6). Our on-site investigations confirmed that many damages to buildings, bridges, and highways correlate with the abnormal deformations observed in SAR data. Using the Sliding Spotlight mode, a resolution finer than 1 meter was achieved for an individual PS-point. These PS-point clouds were hence fused with the BIM data and served as test subjects on our platform. The detected movements were validated against levelling data from North Rhine-Westphalia, revealing only minor differences between the two datasets. However, due to temporal and spatial gaps in the validation process, a conservative statement is recommended when interpreting the accuracy.

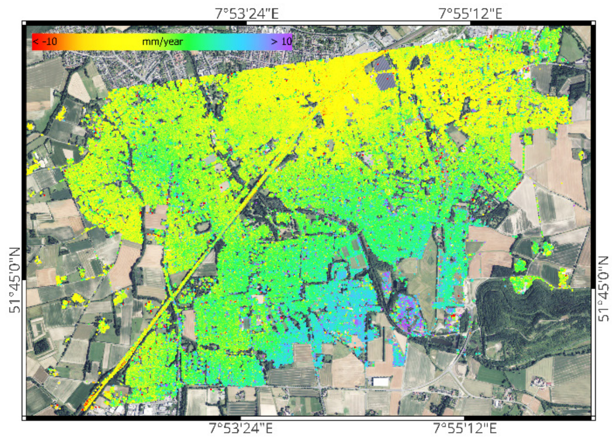

Figure 6. Ground movement around Ahlen, derived from TerraSAR-X data via PSI.

ID	Levelling (2020 - 2022)	TerraSAR-X (2022 - 2023)	Diff
169	5.0 mm/yr.	5.2 mm/yr.	0.2 mm/yr.
234	1.0 mm/yr.	0.6 mm/yr.	0.4 mm/yr.
231	0.5 mm/yr.	1.0 mm/yr.	0.5 mm/yr.
193	0.0 mm/yr.	-1.2 mm/yr.	1.2 mm/yr.
185	0.0 mm/yr.	0.6 mm/yr.	0.6 mm/yr.

Table 1. Comparison of Vertical Velocity: Levelling vs TerraSAR-X.

We plan to utilize more than 20 PALSAR-2 images after tasking to conduct a detailed analysis of ground movement. Our initial results, derived from an interim dataset of 14 images, are presented in Figure 7. The remaining images are still within the tasking queue. Our preliminary observations indicate those areas exhibiting significant ground uplift or subsidence, which have been independently verified. However, a comprehensive analysis is currently not feasible, as 14 images are insufficient to generate a statistically robust and reliable movement estimation. The accuracy of our findings will improve as additional SAR acquisitions become available, allowing for a more detailed and validated assessment of the long-term ground deformation trends.

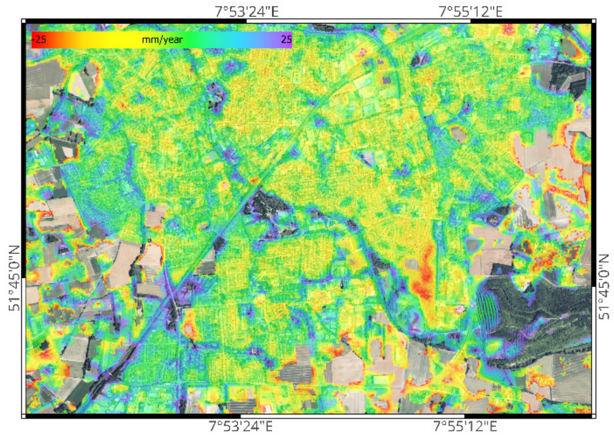

Figure 7. Ground movement around Ahlen, derived from PALSAR-2 data via PSI.

3.2 Movement Monitoring Platform

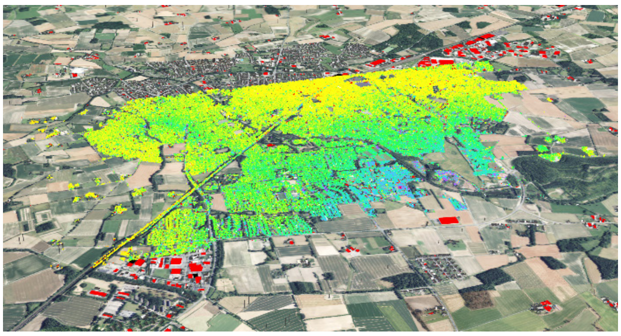

Figure 8. Overview of GIS-based Platform.

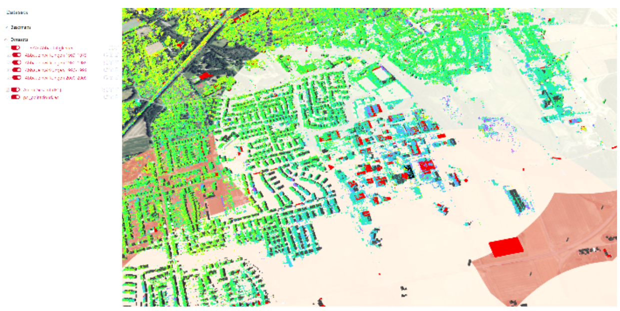

Figure 9. Underground mining areas at different time periods.

The first framework of our platform has been developed as shown in Figure 8. The basemaps from optical images, point cloud, BIM-buildings with fused information, and Geodata like underground mining (Figure 9) are uploaded and displayed together. Three following examples show how we monitor the urban movement in a cost-effective way. The various deformation behaviours of the school buildings are supposed to cause the wall damages and cracks (Figure 10). We can also easily inspect the movement subject to different structures at the train station Ahlen, including main building, railways, platforms, etc. (Figure 11). The last example confirms our finding that the serious ground uplift due to plate movement caused always the highway damage and so endangered the driving safety (Figure 12).

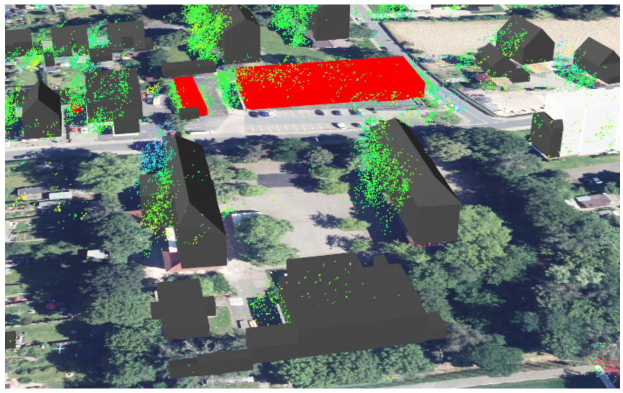

Figure 10. Example of school presented by platform.

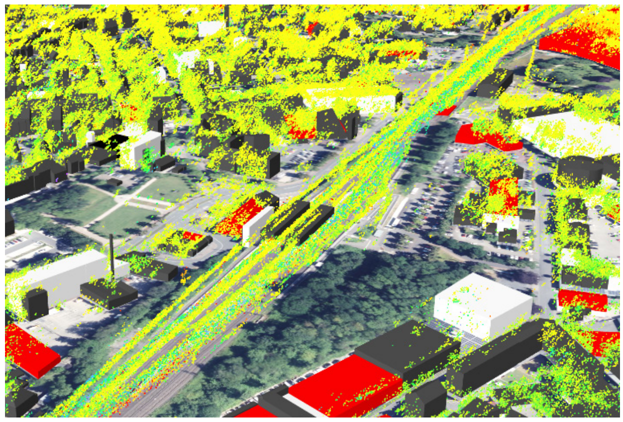

Figure 11. Example of train station Ahlen, presented by platform.

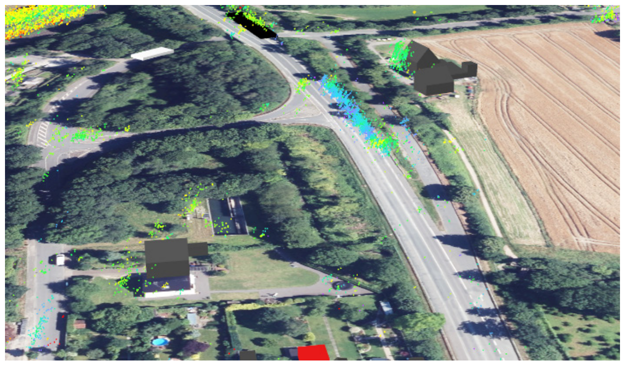

Figure 12. Example of damaged highway, presented by platform.

3.3 Movement Analysis with Geodata

Ahlen has been shaped by over a century of mining activities, particularly through hard coal extraction at the Westfalen I and II collieries (Yang et al., 2023).. Since 1969, the mining operations have been conducted at depths ranging approximately from -1,200 m to -700 m, with the southern part of the city being the primary area of extraction (Figure 13).

Various public geospatial data sources are utilized in the analysis, ensuring a comprehensive assessment of ground movement and geological conditions. The qualitative evaluation of these heterogeneous datasets follows the criteria of ISO Standard 19157-1, which provides a structured framework for assessing data quality attributes. Key sources include the Citizen Information Service of RAG, Geobasis NRW, and the Geological

Survey of North Rhine-Westphalia. Additionally, the public ground movement services from North Rhine-Westphalia (Geobasis NRW), Germany (BGR), and the European Union (EGMS) complement the analysis. The evaluation focuses on general characteristics, qualitative attributes, relevance, and usability to ensure the reliability and applicability of the data for further processing.

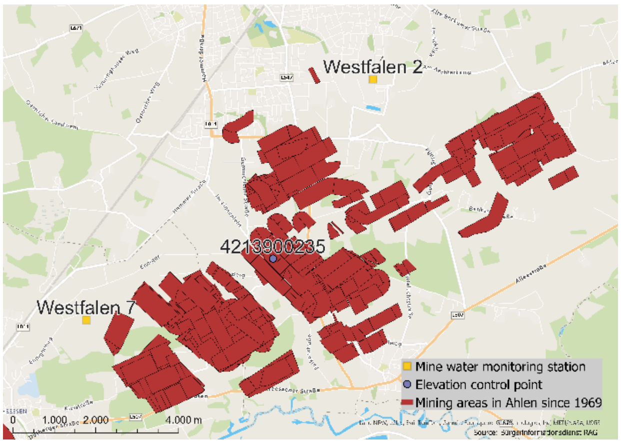

Figure 13. Mining areas in Ahlen. Copyright © Bürgerinformationsdienst. All rights reserved.

For the analysis, the elevation control point 4213900235 was examined (Figure 14). This involved evaluating the cumulative height changes, the ground movement cadastre of Land NRW, the Federal Ground Movement Service, and the EGMS. In addition, the temporal development of the mine water rise at the former collieries and current monitoring points Westfalen 7 and Westfalen 2 was analysed. The temporal development of cumulative elevation change (top) and mine water levels (bottom) in Ahlen is presented. The elevation change analysis is based on multiple data sources, including the NRW Ground Movement Cadastre, Federal, and European services, and reveals shifts in elevation following an initial phase of subsidence. Meanwhile, the mine water levels at Westfalen 7 have been rising continuously since 2000, with an overall increase of approximately 1130 m over the entire observation period. The time series for Westfalen 2, which begins in 2020, exhibits a similar upward trend to that observed at Westfalen 7.

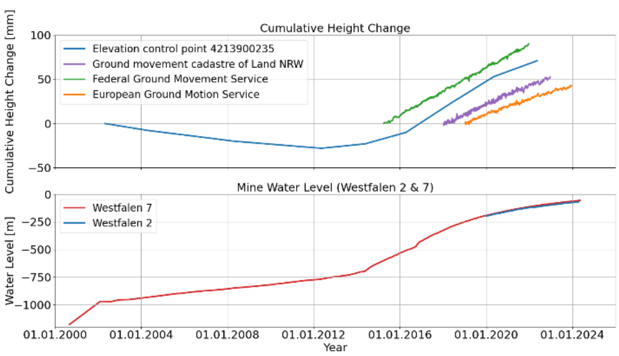

Figure 14. Cumulative height change and mine water levels over time. Copyright © Bürgerinformationsdienst, Geobasis NRW, BGR, and EGMS. All rights reserved.

The cumulative elevation change may exhibit a temporal correlation with the rise in mine water levels, suggesting that the observed ground movement in Ahlen could be linked to increasing mine water levels. While the mine water levels began rising in 2000, significant changes in ground elevation appear to have occurred at a later stage, potentially indicating a delayed response between subsurface water level rise and surface deformation. A more detailed analysis, including a quantitative correlation of both datasets, is required to precisely determine the relationship between mine water rise and surface elevation change.

The future data collection will provide further context and support a comprehensive assessment of these processes. Additionally, the integration of public participation platforms, such as the "Umweltkumpel" initiative by the Georg Agricola University of Applied Sciences, is being considered. This could enhance ground movement monitoring by incorporating citizen-contributed data, thereby improving validation and understanding of local deformation phenomena. Furthermore, the expanded investigations across additional areas in Ahlen will improve spatial coverage, enabling a more detailed assessment of ground movement patterns.

4. Summary and Outlook

This paper presents the BIMSAR project, which integrates BIM and SAR data using machine learning for urban ground movement monitoring. The movement estimates derived from Sentinel-1, TerraSAR-X, and PALSAR-2 data reveal various patterns, necessitating cross-analysis to comprehend the long-term, and complex post-mining deformations. The fusion of SAR-derived movement data with BIM models enhances monitoring efficiency, enabling applications such as assessing building and street risk levels for early warning. All results are visualized on a GIS-based platform, facilitating practical and accessible urban management solutions.

Our future work will prioritize the expansion and enhancement of our platform, ensuring public accessibility to facilitate transparent and efficient monitoring. The primary objective is to streamline the monitoring process by integrating and intuitively visualizing diverse datasets, thereby improving usability for stakeholders. Additionally, we will continue tasking PALSAR-2 acquisitions to expand our dataset, enabling a more comprehensive and refined ground movement analysis.

Our efforts to promote commercial applications have already gained many interests from stakeholders such as municipal governments, real estate companies, and Autobahn GmbH. For example, an early-warning system enables evaluating whether abnormal or long-term deformations might damage structures and threaten the safety of lives and property. Meanwhile, we explore AI-based approaches for geospatial data fusion and movement analysis, particularly regarding effectiveness, efficiency, and automation. We are also working towards realizing Digital Twin to bridge the gap between reality and digital data.

5. Acknowledgement

Our project, BIMSAR, is funded by the German Federal Ministry for Economic Affairs and Climate Action. We extend our gratitude to the Institute for Photogrammetry and Geoinformatics (ifp) for their cooperation during the first phase of BIMSAR. The TerraSAR-X data were provided by DLR for scientific purposes, while the Sentinel-1 data were made available through ESA's Copernicus Program. Additionally, the LoD2 data and levelling measurement from North Rhine-Westphalia are publicly accessible.

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