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Exploring InSAR Capabilities for Bridge structural health monitoring using TerraSAR-X and Sentinel-1 Data

Maciej Kwapisz[1], Vazul Boros[1], Karl Heinz Gutjahr[2], Ivana Hlvacova[3], Cesar Martinez[4], Stefan Schlaffer[5], Juraj Struhar[3], Alois Vorwagner[1]
[1]AIT, Giefinggasse 2, 1210 Vienna, Austria
[2]Joanneum Research, Steyrergasse 17, 8010, Graz, Austria
[3]GISAT, Milady Horakove 57, Praha 7, Czechia
[4]Red Bernard, Ernst-Melchior-Gasse 24, 1020 Vienna, Austria
[5]GeoSphere Austria, Hohe Warte 38, 1190 Vienna, Austria
email: maciej.kwapisz@ait.ac.at, vazul.boros@ait.ac.at, karlheinz.gutjahr@joanneum.at, ivana.hlavacova@gisat.cz, cesar.martinez@bernard-gruppe.com, stefan.schlaffer@geosphere.at, juraj.struhar@gisat.cz, alois.vorwagner@ait.ac.at

ABSTRACT: Remote sensing, in particular multi-temporal Synthetic Aperture Radar interferometry (MT-INSAR), is becoming an operational technique for landslide and subsidence monitoring, and it shows significant potential as an effective tool for bridge monitoring as well. In this case study, the possibilities of MT-INSAR-based structural health monitoring were demonstrated on a motorway bridge in Austria. The bridge is a perfect test object to compare the achieved accuracy due to the availability and good coverage of TerraSAR-X and Sentinel-1 data in combination with an in-situ deformation monitoring system. Due to the overlapping period of one year, a statistical evaluation of the obtained deformations along the bridge could be made. Another topic addressed in this contribution is the modelling of typical bridge deformation patterns, which are primarily caused by thermal expansion of the bridge. To detect critical displacement patterns, it is therefore necessary to separate the thermal component from the critical one. After completing this step, we applied and evaluated newly developed algorithms that detect changes in bridge deformation patterns and raise alarms when necessary. Furthermore, an interesting comparison was made between processed Sentinel-1 time series as provided by the Copernicus Land Monitoring Service via the European Ground Motion Service (EGMS) and the custom processing of the area of interest exclusively, utilizing site-specific temperature data.

KEY WORDS: Bridges, InSAR, MT-InSAR, Structural Health Monitoring, Sentinel, TerraSAR-X, thermal displacement.

1 INTRODUCTION

The transport infrastructure and its structures must be functionally intact, provide reliable performance and guarantee the safety of road users. Above all, this requires high standards for engineering structures such as bridges in terms of resistance to impacts, durability and sufficient fulfilment of requirements on structural safety. Other important aspects include low maintenance costs, few service interventions and cost-efficient operation over the entire life cycle.

In addition, the tasks of infrastructure operators with regard to their facilities have shifted from new construction to the maintenance and repair of existing structures or their replacement with new ones. The combination of an ageing infrastructure with limited financial resources makes this a very challenging task. For example, 50% of Austrian/German/Swiss motorways are now over 40 years old and most bridges are about to undergo major maintenance.

As of today, the condition of bridges is mainly determined by on-site inspections (visual inspections and close on examination). The main advantage of this method is the use of experienced personnel with knowledge of the historical development of the structural condition. Bridge monitoring systems with sensors are only used in special cases. A comprehensive, sensor-based examination of all structures is currently too time-consuming and costly to be used across the entire transport network.

1.1 InSAR for bridges

Remote sensing, particularly multi-temporal synthetic aperture radar interferometry (MT-INSAR), has a strong potential to be utilized for bridge monitoring. In this context, the advantages of MT-INSAR are the large spatial and the dense temporal coverage (4-12 days, in the case of the Sentinel-1 constellation) of SAR data, the possibility of retrospective bridge monitoring and the fact that many bridges can be semiautomatically monitored at the same time. Furthermore, MT-INSAR techniques allow for the monitoring of slow movements that are often not apparent in visual inspections. But it is precisely the slowly occurring deformation patterns that play a major role in the assessment of the structural health of bridges. This could be shown by retrospective InSAR-based measurements of the bridge in Genoa (Italy) [1] after its collapse. First signs of critical deformation were identified several months/years in advance. However, [2] analyzed the same data sets as in [1] with two independent MT-INSAR methods and found no pre-collapse displacements in their consistent results, leading them to deeply disagree with the findings of [1]. In the reply, the importance of innovative research in the emerging field of InSAR applications to civil engineering structures is highlighted.

1.2 Motivation

The main focus of the study is to demonstrate the case study of the accuracy of the vertical deformation measurement of bridges based on MT-InSAR processing using Sentinel-1 and TerraSAR-X data. This was achieved by direct comparison with in-situ measurements for a selected motorway bridge in Austria. Although several such studies have been carried out [3], there is still a need to include more examples to increase their statistical significance. The conceptual basis of a flagging system to distinguish between normal bridge movement behavior resulting from environmental conditions and

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abnormal behavior that may indicate structural damage is described here. Accurate bridge temperature is an important issue for this task. Therefore, different data sources on environmental conditions have been investigated and their influence has been analyzed.

1.3 Description of the chosen bridge and its in-situ measurement system

The bridge structure G46 is an integral bridge on the A2 Süd Autobahn of Austria, located in the south of Graz consisting of two identical structures, each carrying one traffic direction. It was built in 1969 and has a steel structure: a box girder with an orthotropic deck. The bridge is designed as a single-span composite frame, where the reinforced concrete columns support a steel beam with a span of 88 meters. It rests on non-inspectable lead bearings, presenting a challenge for direct inspection and assessment. Shortly after the completion, a sloping on the longitudinal beams was noticeable. A hydrostatic leveling monitoring system was installed in 2015 to monitor the structural integrity over time. Together with geodetic measurements, there was a confirmation of this sloping that is particularly relevant in the northern beam. A second monitoring system was then installed in 2018 which was complemented in 2020 with a redundant hydrostatic leveling system.

Hydrostatic levelling is a monitoring system used to measure relative displacements in the vertical direction. By interconnecting different liquid vessels, it is possible to use fluid pressure sensors to measure the movements of these vessels and the structures that these are attached to. This allows for very precise measurements over long distances and obstacles, that provides the relative vertical position between the sensors with accuracy under the millimetric scale.

RED Bernard installed two independent hydrostatic levelling systems each in one of the independent structures. These are installed in the abutment and the midspan of the bridge, which provides data about the displacement of the center of the bridge, taking the abutments as fixed points. An overview of the bridge and the sensors installed is shown in Figure 1.

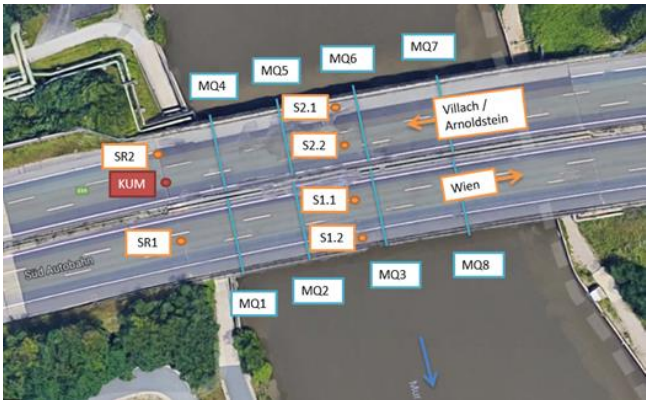

Figure 1. Highway bridge selected for the case study with schematic layout of the measurement system.

1.4 InSAR Data

One of the aims of the study was to compare the results obtained using different satellites and different processing methods. Both Sentinel-1 (C-band) and TerraSAR-X (X-band) data were used for this purpose. Sentinel-1 data was processed specifically for the area of interest, but the centrally processed level 2a data from the EGMS platform [4] was also employed. Knowledge of the local temperature can improve the accuracy of custom processing. To evaluate this effect, processing was carried out separately using different temperature sources. Those used included global meteorological models, such as ERA5 [5], estimated structure temperature through Virtual Sensing [7][8], based on raster weather data from the GeoSphere data hub [6], and in situ temperature measurements from sensors installed on the bridge surface. TerraSAR-X data was available only from a single orbit and for a limited amount of images/acquisition dates, while Sentinel-1 data is available long-term and from three orbits. For a fair and direct comparison, it was decided to use only one ascending Sentinel-1 orbit (ASC146) for an initial comparison of the quality and quantity of data points. A large stack of data was processed for Sentinel-1 and the final (short) monitoring period was then cropped. An overview of the data used, including time frame, spatial resolution and orbit direction, is given in Table 1.

Table 1. Overview of satellite data used

Satellite (mode)	Sentinel-1 (Interferometric Wide Swath)	TerraSAR-X (StripMap)
Image no.	135	25
Timeline	08/20-08/23	05/22-03/23
Spatial resolution	5x20 m	3x3 m
Orbit direction	Ascending 146	Ascending

2 METHODOLOGY

2.1 Processing of the Sentinel and TerraSAR-X data

MT-InSAR processing was performed in SARproZ(c) software, independently for Sentinel-1 and TerraSAR-X data, listed in Table 1. Topography signal was subtracted using Copernicus DEM [9] and temperature effects were estimated based on in-situ measured, Virtual Sensing or ERA5 temperatures.

After thermal effect subtraction, Sentinel-1 time series (each point individually) were divided into segments with linear displacement and for each temporal segment, the noise level was estimated and segments with too high noise level were indicated as unreliable. Points which are not reliable for at least 3 years were discarded. After the segmentation, the thermal effects were re-added to the data, which was necessary for a direct comparison with the bridge deformations based on the EGMS and with the in-situ measurement, since in both of them the temperature effect is not compensated.

For TerraSAR-X data, the segmentation could not be performed because of too short timeline. As a quality criteria, interferometric temporal coherence was used, and points with coherence lower than a threshold of 0.8 were discarded. Unfortunately, the separation of thermal and permanent displacement was erroneous at the bridge center due to the short timeline: the minimum recommended timeline to reliably separate the permanent and thermal displacement is around 1.5 years [10].

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It shall be noted that in spite of the fact that Sentinel-1 and EGMS resources are calculated using the same satellite data, the processing methodology slightly differs, as well as the criteria for point dropping.
MT-InSAR displacement time series were converted from SAR line of sight direction to vertical direction geometrically, based on the assumption that the displacement is purely vertical. If some points move in a horizontal direction, such a conversion gives incorrect results.

2.2 Clustering of the persistent scatterer (PS) Points on the bridge

The PS points for each of the three configurations (EGMS, Sentinel, TerraSAR-X) were first filtered to contain only points on the bridge based on their geo-location. As expected, the number of obtained PS points varied widely ranging from 34 (EGMS Figure 2a), 86 (Sentinel Figure 2b) up to 368 (TerraSAR-X, Figure 2c). To calculate the vertical deformations of the bridge with respect to its longitudinal coordinate, the PS points were clustered into 7 groups, which were distributed evenly along the bridge axis as shown in Figure 2.

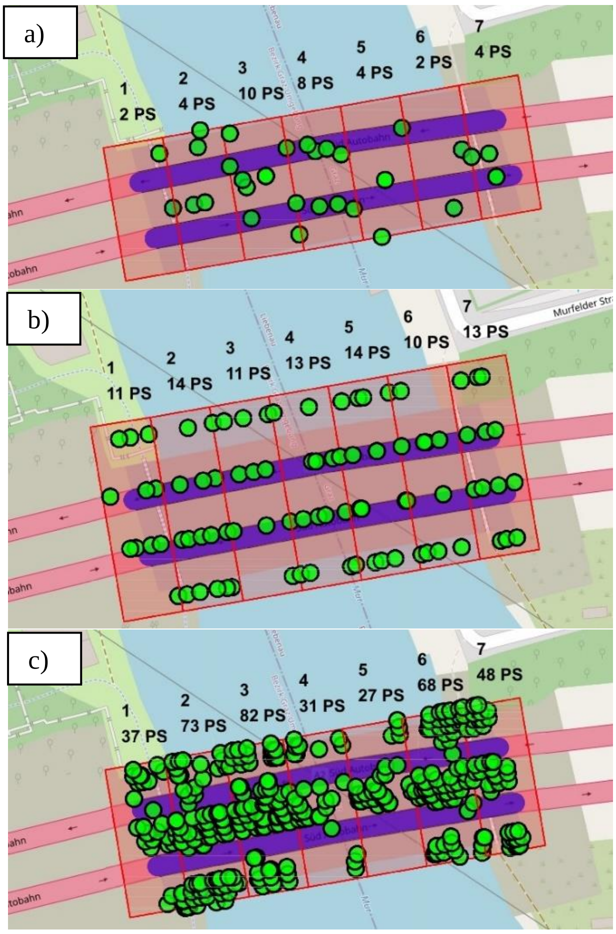

Figure 2. PS Points with the background form OpenStreetMap (OSM), a) EGMS, b) Sentinel-1, c) TerraSAR-X

A time history of the deformation for each cluster was obtained as an average of these points, corresponding to the bridge deflection for that area. This approach is based on the assumption that the points in this area move together, which is approximately true for a bridge deck, neglects however the effects of torsion along the bridge axis. This has been additionally testified with TerraSAR-X data, as there are enough PS points to divide each area further into three clusters across the width of the bridge. If the bridge had been subject to torsional deformations, it would have been visible, but none were observed.

Once the clustering was complete, the PS points were reselected based on the correlation matrix, which is a table showing the correlation coefficients between all PS points within a zone. The correlation coefficient is a statistical measure that expresses the extent to which two PS points are related. It ranges from -1 to +1, where +1 is a perfect positive correlation, -1 is a perfect negative correlation and 0 means no predictable relationship between the points. We estimated, that to classify a PS point as correlated with the others, it must be correlated with at least 1/3 of all points with a threshold of 0.5. It should be noted that this approach is case sensitive and must be carefully adapted when used for other bridges.

This step would be particularly important for bridges with many PS points underneath, as it would help to distinguish which points were on the bridge. In this case there is mostly water, where no PS points are present. Nevertheless, the use of this criteria helped to discard single points without any correlation to the others, which could be caused by the reflection of a non-structural element with some additional movement that does not reflect the deformation of the bridge.

The next step was to calculate a median value for each cluster based on the selected data points, including time series. This greatly reduced the noise of the PS points, removed the outliers and produced a smooth time series as can be seen in Figure 3.

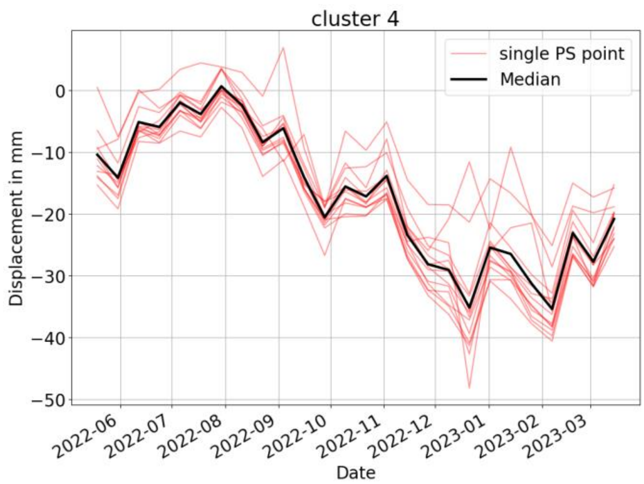

Figure 3. Calculation of the time – series for a cluster in the mid span for EGMS data.

2.3 Normal bridge deformation patterns

A critical task for MT-InSAR bridge monitoring and damage identification is the recognition of normal bridge deformation patterns resulting from environmental influences. This movement must subsequently be subtracted from the measured deformations to obtain a clear pattern. This step is not required when using the SARproZ(c) software mentioned above, as the estimation (and subtraction) can be performed within MT-

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InSAR processing. However, it is essential for EGMS data or other MT-InSAR processing algorithms that do not automatically include it.

There are two common approaches to achieve this: data-driven and model-based. Both are effective in achieving the goal, but each has some advantages and limitations. Mostly, the first one is used and only when the time series is not long enough, the model-based one is employed.

In this study, we combined these approaches by identifying the normal bridge deformation pattern from the data and cross-checking it with an adapted finite element (FE) model. In this way, a link can be established between the single PS point approach and the whole bridge deformation shape. This approach requires two steps, which are described below.

The first step is to relate the deformation values calculated for each zone, as described in the previous section, to the structural temperature. If the data set is too short (less than 1.5 years), as may easily happens with commercial data (such as TerraSAR-X), this can be done with EGMS data (Figure 4). The structural temperature can be obtained either from in-situ measurements, if available, or by using the Virtual Sensing method developed by AIT [7][8]. If none of the above is accessible, the air temperature can be used, but a lower accuracy has to be accepted.

In the second step, a simple FE model was created, although only limited information about the cross-section geometry was available. In case of the examined integral bridge the longitudinal extension was restrained on both sides by very stiff elastic spring elements. To verify the temperature induced deformations, a uniform temperature was applied to the model and the deformations in vertical and horizontal directions were extracted for the same zones as defined for MT-InSAR processing. This was valuable for the decomposition of the Line of sight (LOS) deformation described in the next chapter and for the plausibility validation of the MT-InSAR results.

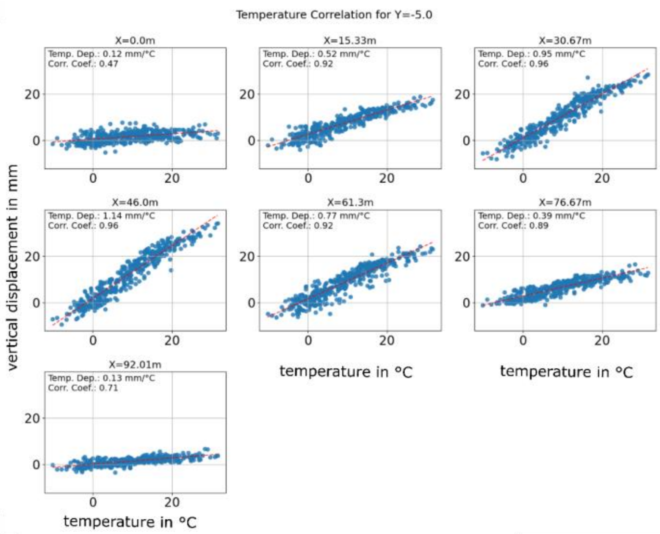

Figure 4. Thermal bridge deformation for each cluster based on EGMS.

In this way, not only the influence of temperature on the movement of each PS point was identified, but also the bridge deformation shape. The latter can be used to validate the deformation over the entire length of the bridge if enough PS points are available.

2.4 LOS decomposition

The decomposition of d_{los} into $d_{vertical}$ requires in general either both ascending and descending orbits or prior knowledge of the horizontal bridge movement based on normal bridge deformation patterns [3]. The analysis described in the previous section has shown that the temperature induced movement of the bridge is almost exclusively in the vertical direction. Therefore, the decomposition of d_{LOS} into $d_{vertical}$, which is of interest in this case, can be simplified to equation (1).

$$\dot{d}_{vertical} = \frac{d_{LOS}}{\cos(alpha_{incidence})} \quad (1)$$

2.5 Flagging system

In this study, we developed a method to detect abnormal bridge deflection. The purpose of this system is to identify bridges that require additional on-site inspection, rather than immediately triggering an alarm or leading to bridge closure based solely on MT-InSAR results. This approach ensures that potential structural issues are carefully evaluated before taking further action.

The flagging system was based on a data-driven approach in order to be flexibly adaptable to different types of bridges. The proposed system is designed to distinguish different classes of bridge displacement behaviors based on the time series of $d_{vertical}$:

- no trend or breakpoint,
- linear trend,
- one or more breakpoints,
- accelerating trend (i.e. at least one breakpoint and two different downward trend slopes $\beta_{t2} < \beta_{t1}$, where t2 > t1 and β_{t1}, $\beta_{t2} < 0$). β_{t1}, β_{t2} denote the slopes of the model segments before and after the breakpoint.

A data-driven approach assumes that normal bridge deformation patterns can be derived from the deformation time series as described in section 2.3. However, this may not always be the case as MT-InSAR time series may be too short to assume a pattern to be stable. In this study, only the Sentinel-1 time series was used as the displacement time series derived from TerraSAR-X was too short. Additionally, the flagging system provides for the possibility of applying user-specified thresholds on linear trends and total displacement. In order to minimise noise the PS points were grouped according in seven segments along the length of the bridge.

3 RESULTS

3.1 Influence of the temperature accuracy on MT-InSAR results

For data-driven methods to estimate/subtract temperature effects, temperatures at the acquisition times are necessary and their accuracy directly influences the (temporal) noise of the final time series of each point, and in some cases (especially those with shorter timeline), also other results, such as the displacement or estimated thermal dilation coefficient.

Results achieved using in-situ and Virtual Sensing temperatures are comparable, as the average differences between these two temperature sets is 0.7 degrees and the

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maximum difference is 3.1 degrees (acquisition time for this data is 5PM UTC).

The differences between Virtual Sensing and ERA5 temperatures, on the other hand, (compared in a different processing not considered here), are much higher: average of 2.5 degrees and maximum 5.2 degrees (even if the acquisition time for this case was 5AM UTC).

If the number of images is high enough and the monitoring period long enough to provide numerical stability of separation between linear and thermal displacement components (at least 1.5 years according to [10]), the temperature inaccuracies (if not systematic in time) influence only the noise, i.e. the estimated point quality, which may slightly influence point density.

If temperature accuracy is lower but the number of points is high enough to provide for statistical processing, and the thermal dilation is also significant, higher accuracy can be achieved by temperature refinement procedure [10].

3.2 Comparison with in-situ measurements

To compare the accuracy of the three data sets considered, the recalculated values of vertical bridge deformation in the mid-span (zone 4) were compared with the in-situ measurement. A period of time from May 2022 to April 2023 was selected, which was common to all data sets. The direct comparison is shown visually in Figure 5, where green dots represent the in-situ measurements, while the red curve shows EGMS, black Terra-SAR-X and blue custom processed Sentinel-1 data. The normal bridge deformation patterns were not removed from either the reference in-situ or the InSAR data. If it was already subtracted during the MT-InSAR processing, it was added afterwards for the purpose of this comparison.

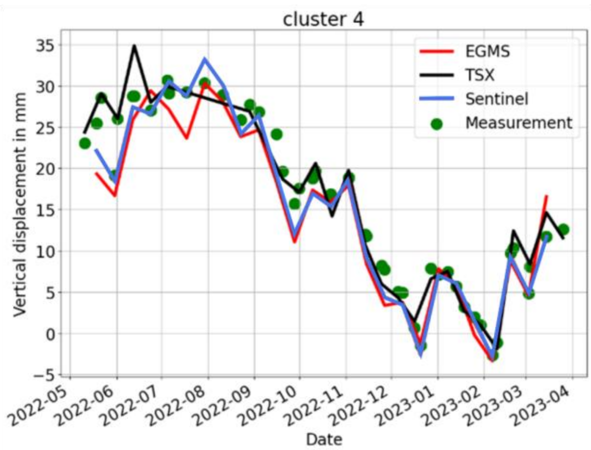

Figure 5. Comparison between the reference measurement (green dots), EGMS (red line), TSX (black line) and Sentinel (blue line) for the central segment of the bridge

The differences between each InSAR data set (EGMS, Sentinel-1 and TSX) and the reference were statistically analyzed and the resulting standard deviations are shown in Table 2. To compare the InSAR data with the reference measurements, first the mean value is calculated for all the Persistent Scatterer (PS) points belonging to the cluster associated with the location of the reference measurement. This mean value represents the average displacement derived from the InSAR dataset for that area. Next, any offset between the two datasets is removed to align both to the same baseline. Once aligned, the mean value obtained from the selected InSAR cluster is then subtracted from the corresponding reference measurement. This difference reflects the deviation between the two datasets at the reference location. Finally, the standard deviation of these differences is calculated to quantify variability and assess consistency between InSAR-derived values and reference data.

Table 2. Comparison with in-situ measurement

data set	Std. deviation in mm
EGMS	3.8
Sentinel	2.1
TSX	1.7

The bridge deformations from the in-situ measurement are only given for the mid-span, so only these values were available for comparison. Therefore, a FE model of the bridge was used to perform a plausibility check on the deformed bridge shape that results from the MT-InSAR analysis. First, it was slightly updated to match the deformation in the center of the span by adjusting the stiffness of the constraining springs at the bridge abutments. Next, several TerraSAR-X acquisition times were selected and structural temperatures were calculated for each date and time. These temperatures were then applied to the FE model and the resulting bridge deformations were extracted and plotted as a solid line in Figure 6. Equivalent bridge shapes resulting from the TerraSAR-X data were plotted with the dashed line and the in-situ measurements with a point. The colors were kept the same for each date to enhance visual comparison. Not only does the mid-span deformation match very well between the FE model, reference measurement and MT-InSAR, but also the shape over the entire length of the bridge is similar. This demonstrates very high quality of the bridge deformation measurement obtained by MT-InSAR processing.

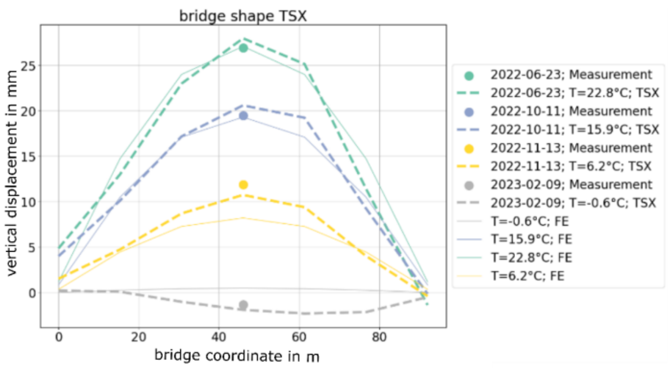

Figure 6. Comparison of the bridge shape according to FE Model (solid line), TSX (dashed) and reference (dots)

Once the direct comparison of the three datasets was complete, the analysis was repeated for the remaining two Sentinel-1 orbits. To obtain the total vertical deformation for each zone, the average of the results from each orbit was calculated after interpolation between acquisition times. In this way a combined EGMS and Sentinel-1 solution was obtained.

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In addition, a combination of Sentinel-1 and TerraSAR-X data was derived for a total of four orbits. All three options for zone 4 (mid-span) were again compared with the reference measurement and the resulting standard deviations are shown in Table 3.

Table 3 Comparison with in-situ measurement for all available orbits

data set	Std. deviation in mm
EGMS	1.7
Sentinel-1	1.4
Sentinel-1 + TSX	1.3

The use of multiple orbits greatly improved accuracy, especially for EGMS. It is also evident that locally processed Sentinel-1 data can give better results than centrally processed EGMS, although both are based on exactly the same radar data. This is particularly true for the single orbit approach shown in Table 2. A novel combination of Sentinel-1 and TerraSAR-X data could improve the quality even more, but as the standard deviation is already very small, it does not bring that much improvement. It is expected that for bridges with scarce Sentinel-1 coverage the enhancement would be much more significant.

3.3 Flagging system

The developed algorithm for the flagging system was then applied to the processed data for each zone. This step allowed us to automatically evaluate potential anomalies in the bridge deflection and determine if the bridge may require further field inspection.

Figure 7 and Figure 8 show linear displacement rates up to 0.6 mm pear year. Displacement rates of this magnitude were deemed too small to flag any of the anomalous behaviors listed in section 2.5. Breakpoints along the time series were detected, e.g., in zone 5, however, the overall displacement trend along the time series is close to zero. Overall, no flags were raised for any of the bridge segments.

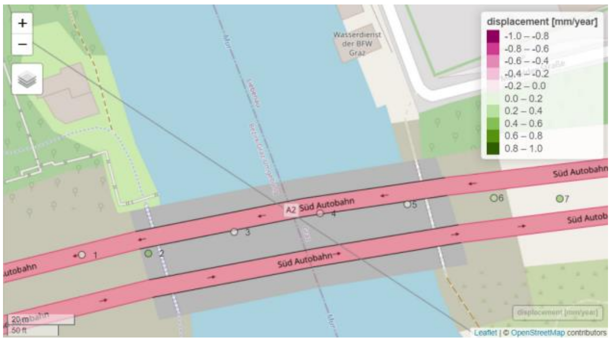

Figure 7 Overview of annual displacement rates for each of the seven bridge segments. OSM is used as background map.

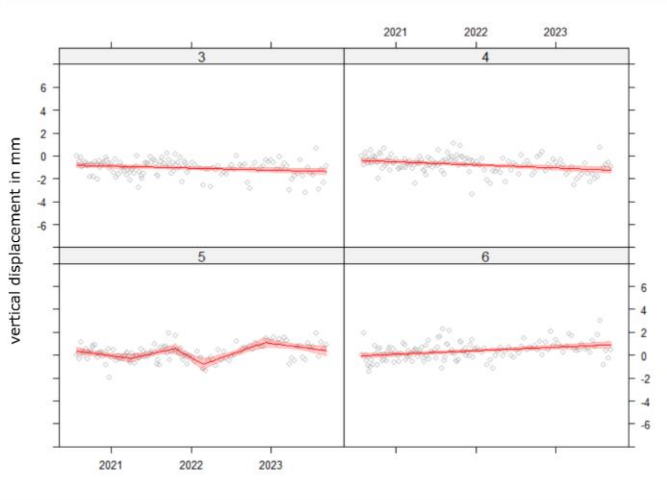

Figure 8 Displacement time series for four segments with fitted trend lines and 95% confidence intervals of the fitted lines.

4 CONCLUSIONS

While MT-InSAR bridge monitoring has certain limitations, it also offers unique advantages. One key advantage is its ability to provide retrospective monitoring when historical data are available, with Sentinel-1 data being available globally from 2015. However, due to its limited spatial resolution, Sentinel-1 data typically provides reliable results only for larger structures. For higher point density and improved accuracy, high-resolution satellite data from sources such as TerraSAR-X or Cosmo-SkyMed are required.

In this study, deformations from in-situ measurements of a highway bridge in Austria were compared with three different InSAR datasets: EGMS, processed Sentinel-1 and TerraSAR-X. As can be expected the number of PS points on the bridge is significantly higher for X-band radar compared to C-band. Nevertheless, the result show, that for the investigated bridge a remarkable accuracy, with standard deviations lower than 2 mm, can be achieved with all three datasets, especially if all available Sentinel-1 orbits are taken into consideration. This result not only highlights the great potential of MT-InSAR-based monitoring for detecting bridge deformations with high accuracy, but also raises the question whether expensive X-band data is required for bridge monitoring or often the freely available Sentinel-1 data is sufficient for this purpose.

To accurately assess actual bridge displacements and distinguish them from normal deformation patterns, thermal effects are estimated and subtracted from the MT-InSAR results. This correction helps to refine the analysis, ensuring that detected displacements more accurately reflect structural behavior rather than temperature-induced variations.

Finally, by implementing the flagging system, an automated method for identifying potentially problematic bridges was developed and demonstrated. However, it is important to emphasize that this approach is not intended to replace on-site inspections. Rather, it serves as a complementary tool that provides additional information to assist in the assessment of bridges that may require further investigation.

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