

# Radar interferometry-based approach to assess damage patterns induced by the climate-driven geohazard of soil shrinkage

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**ABSTRACT:** Old buildings and historic sites worldwide are increasingly vulnerable to climate change impacts, particularly as extreme weather events become more frequent and severe. For example during droughts, shrinkage of water-sensitive, clayey soils can cause differential settlements and structural damages, threatening the stability and preservation of these sites. To protect vulnerable structures and assess this geohazard, the study explores the application of radar interferometry as a high-resolution tool to detect vertical displacements up to a few millimeters' accuracy. The workflow combines multi-temporal radar imagery analysis using persistent scatterers and on-site data assessment, such as structural damage mapping and crack pattern monitoring. Two historical churches in southwestern Hesse, Germany, serve as case studies: the protestant church of Massenheim and the catholic church of Hochheim am Main. They represent sites with assessed and documented soil shrinkage-related damage. The churches demonstrate complexity through multivariate crack patterns and ancient foundation structures with varying depths and construction phases, while their cultural heritage value emphasizes the importance of effective preservation strategies. A persistent scatterer analysis was carried out using 60 satellite images per case study over monitoring periods between 2019 and 2023. The results show a strong correlation between radar-detected displacements and crack monitoring data in the Massenheim case, validating southward movement patterns of the building wall located in the west. Furthermore, seasonal movement patterns related to precipitation cycles were identified. Unfortunately, no clear correlation between PS data and crack development could be detected for the Hochheim church. The presented study shows how incorporating radar interferometry into traditional geotechnical approaches can improve the spatial and temporal resolution of structural displacement monitoring, while also broadening the analysis of climate-driven deformation processes.

**KEYWORDS:** soil shrinkage, radar-interferometry, historical buildings, building damage, climate change.

## 1 INTRODUCTION

Changing weather patterns increasingly threaten the integrity of cultural heritage, such as historical buildings (Philips 2015). Building materials and surrounding soil can be substantially altered in their strength and physical condition e.g. by variation of moisture levels (Sesana et al. 2021; Jones et al. 2020). To ensure the preservation of these vulnerable structures, the use of cross-disciplinary approaches can be helpful, such as the combination of geotechnics and remote sensing.

Climate change impacts on historical buildings occur in a variety of ways (Brimblecombe et al. 2011). Ranging from extreme high or low precipitation resulting in floods or droughts, over seasonal fluctuation of humidity, causing for example salt damage, to higher local wind speeds leading to greater structural loads (Brimblecombe 2014; Insana et al. 2021; Morilla et al. 2022; Mosoarca et al. 2017). This contribution focuses on drought-induced settlement, which can result in cracks in cultural heritage sites.

Shrink-prone soils are typically clay-rich and contain shrink-susceptible clay minerals such as montmorillonite, which belongs to the smectite group. The influencing factors of this phenomenon are multifaceted but are all linked to the change in soil water content. Any changes in the 'soil water ecosystem', for example through drainage, infiltration or root water uptake, can trigger volumetric changes of soil minerals. Typically soil shrinkage happens very locally, e.g. only in one corner of the building, potentially leading to differential settlement of the affected structure.

To detect vertical and horizontal movements, radar-interferometry is a well-known tool. In the field of geotechnical analysis, it is mostly used to detect lateral movements such as landslides and slope failures, but also subsidence on a larger scale (Ansar et al. 2021). Urban environments with their man-made structures are particularly well suited to the use of persistent scatterer interferometry for using radar satellite data (Ferretti et al. 2001). In urban areas there are typically many

temporarily persistent scatterers, which possess good characteristics regarding radar reflectance and temporal coherence. The movement of these PS in vertical and lateral direction is evaluated in time-steps, prescribed by the satellite acquisition dates.

The use of radar interferometry techniques to preserve archaeological and cultural heritage sites has already been explored in several studies (Drougkas et al. 2020; Tapete & Cigna 2012; Zeni et al. 2011; Zhou et al. 2015), mostly for settlement analysis but also for structural health monitoring (Mele, 2023). Of less attention was subsidence specifically induced by soil shrinkage.

Accordingly, this study focuses on the application of radar interferometry to the geohazard of soil shrinkage and evaluates its potential to enhance traditional approaches to damage assessment. Therefore, two case studies of historical churches were investigated: the Catholic Church St. Peter and Paul in Hochheim am Main (Hochheim) and the Evangelical Church in Massenheim, a district of Hochheim am Main. On-site data will relate to radar-derived displacement measurements, which enables the analysis of deformation patterns and facilitates a more detailed discussion of soil shrinkage effects.

## 2 MATERIALS AND METHOD

### 2.1 Radar satellite data

Satellite images acquired using Synthetic Aperture Radar (SAR) are independent of cloud cover or daylight and can penetrate vegetation. This makes them highly suitable for monitoring buildings and ground movements. The data used in this study is collected by the TerraSAR-X (TSX) mission, with a maximum revisit period of 11 days and SAR imagery in StripMap mode with a spatial resolution of three meters.

The images available for the study sites were acquired in ascending orbit mode with a right-looking antenna geometry. The incidence angle at the image center is 21.5° for the

Massenheim case study and 35° for the Hochheim case study. The signal polarization used is HH (horizontal transmit, horizontal receive). A dataset of 60 TerraSAR-X images per case study ensures sufficient temporal resolution to monitor deformation trends over the respective study periods. The time span covered for Hochheim extends from 2019 to 2022, while in the Massenheim case study the data had to be divided into two periods from 2019 to 2021 and 2022 to 2023 due to limitations in radar data availability.

## 2.2 Persistent scatterer analysis

Persistent Scatterer Interferometry (PSI) by Ferretti et al. (2001) is one advanced Interferometric-SAR (InSAR) technique that enables the detection and monitoring of millimeter-scale ground displacements over time. In difference to conventional InSAR methods, which rely on image pairs, PSI uses time series of at least 20 radar images to minimise atmospheric influences and improve displacement accuracy by using persistent scatterers (PS). These are typically man-made objects with high reflectance and phase stability, such as building roofs, corners or pavements. Output parameters for each PS include coherence, displacement per acquisition and mean velocity. The coverage of PS can vary greatly depending on the observed area and potential backscatter. Therefore, in order to achieve a higher reliability in the evaluation of the displacements, a coherence value greater than 0.9 was chosen in this study.

Data processing was carried out using the *SARscape* module within ENVI 5.7 software. Then, the Interferometric Stacking module was used for the persistent scatterer analysis. An input digital elevation model with a spatial resolution of approximately 30 meters (SRTM 1) was used for this analysis. Post-processing of the satellite data was conducted utilizing *QGIS* (v3). Used digital orthophotos were provided by the Hessian Administration for Land Management and Geoinformation.

## 2.3 Damage assessment

Damage patterns caused by soil shrinkage of clayey soils depend on one hand on structural characteristics of the building, such like age, foundation type and foundation depth. On the other hand, soil shrinkage is primarily driven by water extraction mechanisms. As these mechanisms are prone to occur rather locally, the risk of building damage due to differential settlement or inclination is relatively high, compared to other drought-driven climate factors like e.g. groundwater lowering. Additionally, multiple water-related influencing factors can act simultaneously, making it challenging to detect and separate their individual contributions. Factors impacting soil moisture may include leaking or defect sewage pipes, anthropogenic groundwater extraction like pumping, new intentional or unintentional drainage facilities or water uptake by vegetation.

It is also not uncommon that surrounding structures affect the damage, such as (newly) sealed surfaces or retaining structures with possible change of drainage conditions. The integration of remote sensing data, such as ground displacement analysis, can complement the interpretation process. Furthermore, it should be assessed whether the inclusion of radar interferometry enables the differentiation of the individual damage contributing factors.

## 2.4 Methodological approach

The integration of satellite-based data can serve as a valuable supplementary tool for evaluating structural damage and potentially distinguish between different contributing factors. The high temporal and spatial resolution have a significant advantage over ground-based measurements, as they enable the

detection of temporally detailed deformation patterns across larger areas without the need for manual measurements of individual movements or cracks. Adding this extra layer of information to the damage assessment is particularly important for historical buildings, where a well-informed solution strategy is crucial.

SAR-imagery will be tested for its ability to detect displacements in structural elements and to identify and quantify horizontal wall inclinations. Additionally, to support the deformation study, crack monitoring from the Massenheim case study will be compared with the relative displacements of the PS itself. Furthermore, the analysis will investigate whether specific influencing factors related to soil shrinkage can be identified in the satellite imagery processed on persistent scatterers. Particular attention is given to the weather patterns and the influence of nearby vegetation (primarily trees) on soil moisture, while an indication of this influence can be seen in seasonally varying ground movements (Biddle, 1998, p. 68).

## 3 STUDY AREA

### 3.1 Protestant church of Massenheim, Hesse

The protestant church is located at Massenheim, Hesse, a district of Hochheim am Main. The building history of the church can be split into two epochal construction phases, one around 1580 mainly covering the tower on the eastern part and one around 1760, where the nave was extended by 6.5 m to the west. Several renovations and repairs, both structural and cosmetic in the interior or the exterior, took part, as well as a foundation excavation in 1980. The church is founded on the north, south and east on strip footings 1 m wide and 2.1 m deep, and with a depth in the west of 0.5 m (Beroya-Eitner et al. 2022). The church is surrounded by trees on the south- and northwest portal, as well as southeast.

#### 3.1.1 Damage patterns and site investigations

The generally severe damage is on the west wall of the building, see Figure 1. Damage first occurred in 1930 and was documented between 1930 and 1960 in the masonry on this west wall. Structural issues persisted through to 2001, when the cracks were extensively repaired. However, they reappeared in 2003, affecting both the interior and exterior of the west wall this time. Due to concerns about the structural integrity, a further investigation into the cause of the problem was initiated (Beroya-Eitner et al. 2022).

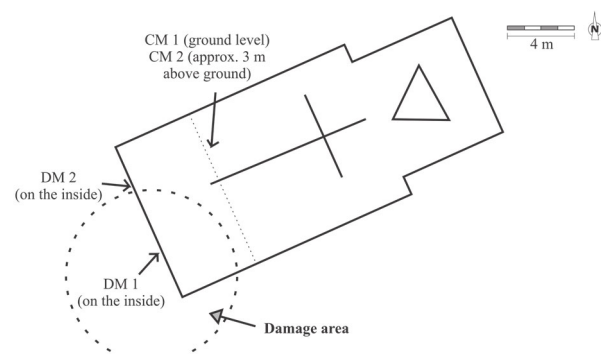


Figure 1. Top view of the protestant church in Massenheim with damage area and monitoring locations (DM 1 and DM 2). Modified after Beroya-Eitner et al. (2022).

Accordingly, site investigations including laboratory tests were carried out between 2003 and 2021, where three layers could be identified: a top layer with backfill material (mainly silty clay with sand and fragments of building material) and a thickness of 0.5 to 2.5 m, a middle layer with reddish silty sand and a thickness of 0.5 to 2.5 m as well as a third layer consisting of fat clay of approx. 8 m thickness.

The silt content of the topmost layer has a plasticity index of 19 %, which corresponds to a medium swelling potential, and a water content of 15 % (Beroya-Eitner et al. 2022). The middle layer is non-plastic and shows a water content of 9 %. The water content of the lowest clay layer is higher with 29 to 32 %, while it is considered highly plastic shown by a plasticity index of 47 to 54 %. Due to that, it is expected to have a high shrink-swell-susceptibility, also incorporating the XRD-results revealing a considerable amount of smectites with 16 to 26 % per weight. No groundwater was encountered in any of the boreholes (Beroya-Eitner et al. 2022).

The outcome of the damage assessment in Beroya-Eitner et al. (2022) stated that non-uniform shrinkage-induced settlement, most likely occurring within the susceptible fat clay layer, is the primary cause of the observed cracking on the west wall. Additionally, observed cracks on the floor are parallel to the slope face indicating a creeping towards downhill. The presence of nearby trees was not excluded as a contributing factor to the soil shrinkage.

### 3.1.2 Damage monitoring

Following the continued crack growth after the renovation in 2001, displacement (DM) and convergence (CM) monitors were installed to evaluate movement behaviour. Between 2004 and 2016 no significant movements were observed (see also Beroya-Eitner et al. (2022)), leading to stop monitoring and starting renovation on the affected west wall. Afterwards, only two convergence monitors remained in operation. However, in December 2019 large deformations were observed again (see Figure 2), why the monitoring was resumed.

At that point, movement was presumed to be in downslope direction, as the lateral movement of 6 mm at DM 2 and 8 mm at DM 1 was recorded, along with a vertical movement of 5 mm at DM 1. Since October 2020, only DM 2 remained operational due to a technical defect at DM 1.

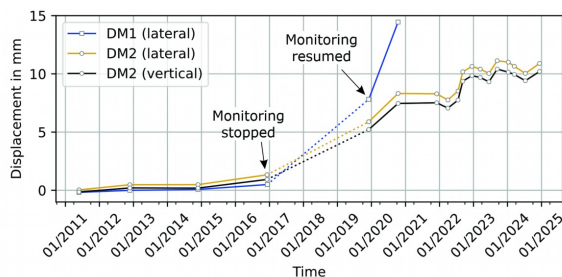


Figure 2. Displacement Monitoring movement over time at different measurement points, shown in Figure 1.

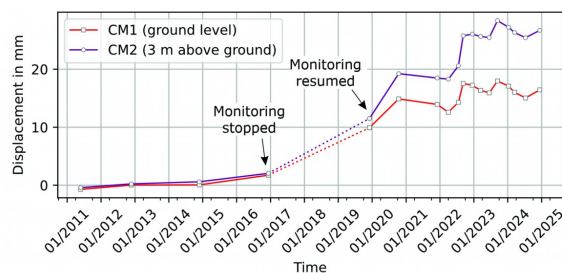


Figure 3. Convergence monitoring movement over time at different measurement points, shown in Figure 1.

Only one year later, in December 2021, measurements started to have been conducted at quarterly intervals. This allowed the measurement of seasonal crack displacements with an increased movement starting in April 2022 and stabilization during the following winter months 2022/2023. Onward movement in summer 2023 and summer 2024 are of smaller magnitude than the previous ones. The same measurement intervals and patterns are valid for the convergence measurements shown in Figure 3.

### 3.2 Catholic church of Hochheim am Main, Hesse

The Catholic Church of Hochheim am Main, Hesse stands with an east-west orientation at the southern part of the village. It was built around 1730 on the foundation leftovers of a previous church. Several inner and outer cosmetic repairs were carried out as well as structural reinforcement starting 1990 for the nave ceiling and the façade due to insufficient roof structure that time. Furthermore, a renovation of the retaining wall laying on the eastern and southern part of the church was carried out in 2014 due to severe moisture patterns with salt efflorescence and plaster damage. No detailed information exists on the church's foundation, but it is assumed to be strip footings, with a known foundation depth underneath the sacristy of 3 meters.

#### 3.2.1 Damage patterns and history

Crack formation is primarily concentrated in the northeastern part of the building, resulting in two main cracks: one in the ceiling of the sacristy and another as a vertical crack along the nave wall, west of the church tower, as illustrated in Figure 4 (Landesamt für Denkmalpflege, no date).

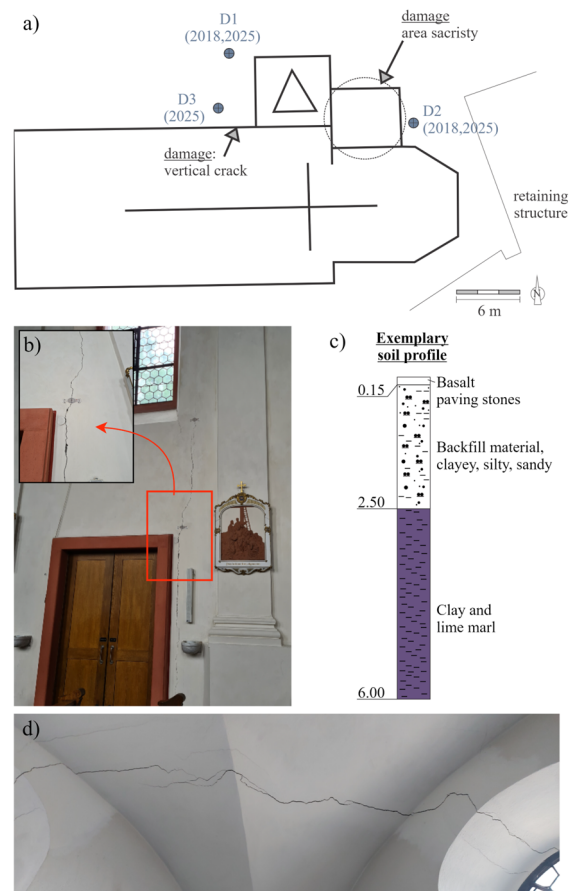


Figure 4. Damage patterns in the catholic church of Hochheim, with a) damage and soil investigation locations (D1, D2, D3) in top view. Modified after LfD (no date) b) picture and detail of vertical crack (photo from 2024); c) soil profile (2025) at location D1 (BGS 2025); d) crack in ceiling of sacristy (photo from 2022).

The vertical crack exists at the inner and outside wall and evolves from the door up to the window and the ceiling. According to the buildings administration, increased crack propagation was observed in the sacristy, at a pre-existing crack present for some years, during the summer of 2018. That is why detailed investigations into the cause of the problem were carried out, leading to damage reports and site investigations. A crack reparation of the damaged area in the sacristy was carried out in 2020. Further crack propagation was detected in summer 2022 in the sacristy, as well as a new vertical crack in the northern part of the nave.

### 3.2.2 Site investigations and damage patterns

Site investigations in 2018 included two core drillings (see D1 and D2 in Figure 4) and light penetration soundings up to 7 m depth. A second investigation followed in 2025 to further assess the situation with three core drillings accompanied by light penetration soundings up to 6 m depth (D1 to D3). Water content was measured on samples of all drillings, and no groundwater was encountered. No further investigations on clay minerals or swelling potential were carried out. The subsurface mainly consists of two layers: a top layer of backfill material extending to 2.7 m below surface and beneath that, a layer of tertiary clay and lime marl continuing to the full depth of the drilling.

The outcome of the damage assessment showed a settlement causing inclination of the sacristy to northeast. The influence of the shrink and swell-prone soil on the damage patterns was confirmed by the water content testing on the site investigation probes, with low values near the damaged areas at the sacristy and the tower. Furthermore, the retaining structure supporting the church terrace in the southeast could have an influence on the church's movement, especially after the retaining wall maintenance work in 2014, which may have changed the hydraulic conditions in the soil.

## 4 RESULTS

For the two described case studies of the churches in Massenheim (MH) and Hochheim am Main (HO), it was assessed, how radar interferometry can contribute to analyse the damage patterns and to identify the damage contributing factors.

### 4.1 PS movement analysis Massenheim

The PS on the western part exhibits a pattern of settlement towards the south, as shown in Figure 5. The data covers two time periods, from July 2019 to June 2021 and February 2022 to August 2023. This observation is consistent with the on-site damage assessment as well as the findings reported in Beroya-Eitner et al. (2022), both of which indicated a southward movement of the west wall.

As crack monitoring is conducted less frequently than radar acquisitions, the analysis will focus on comparing the relative displacements of the corresponding data points.

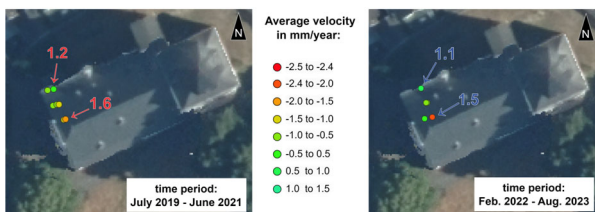


Figure 5. Overview of PS coverage for MH case study and average velocities in the Line of Sight per PS for two evaluated time periods.

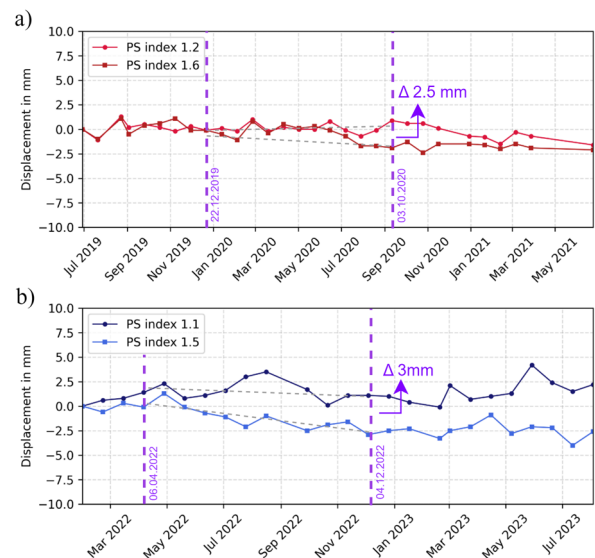


Figure 6. Relative vertical movement of two PS on the west wall evaluated on the moving discrepancy over time periods from a) July 2019 to June 2021 and b) Feb. 2022 to Aug. 2023

Evaluated for two PS on the west wall, the most northern and the most southern one in Figure 5 show a vertical displacement difference of 2.5 mm from December 2019 to October 2020 (see Figure 6a) and of 3 mm from April 2022 to December 2022 (see Figure 6b).

Comparing these with the crack monitors in Figure 2, DM2 recorded for the first period a displacement of 2.2 mm in vertical and 2.4 mm in lateral direction, while the more southern located DM1 shows a significantly larger movement at the crack edges of 6.6 mm. In accordance, the convergence monitors in Figure 3 show an increase in deformation with a difference between the measurement points of 4.2 mm in October 2020.

The increased inclination from north to south is clearly visible in both measurements. A similar magnitude is evident when comparing the relative crack opening movements at DM2 and DM1 with the corresponding PS-derived displacements.

This behaviour is also evident from April to December 2022, with DM2 showing movements of 2.9 mm laterally and 2.8 mm vertically. The inclination is apparent, and the magnitude of the movements matches that observed by the crack monitors and the PS movements.

To assess environmental influences on surface displacements, the relative vertical movements of persistent scatterers (PS) are correlated with precipitation data. Seasonal variations, particularly between summer and winter, affect subsurface processes such as shrinkage and swelling.

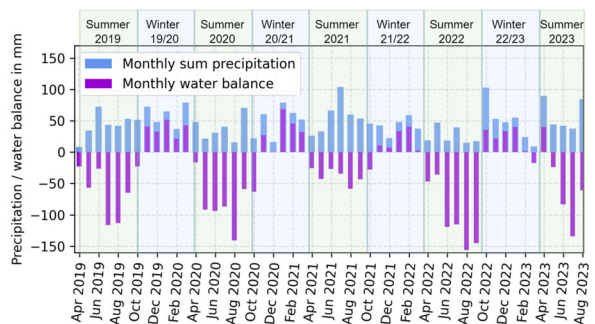


Figure 7. Monthly precipitation (blue) and water balance (purple), calculated as the difference between precipitation and potential evapotranspiration, based on data from the DWD weather station Frankfurt (station ID 1420).

The weather patterns between 2019 and 2022 are shown in Figure 7. It can be observed that the already derived subsidence from April 2020 to September 2020 corresponds to a period with long-lasting low precipitation and high evapotranspiration. Comparing these with the PS located on the western wall in Figure 8a, it can be seen that the dry weather period first influenced the more southern PS and, with a delay of a couple of months, also affects the more northern PS. Similar pattern is seen during summer 2022 in Figure 8b. Furthermore, the data link reveals a tendency toward subsidence during drought, but no link between wet periods and building heaves could be detected. If this trend continues, the settlement is expected to progress further over time.

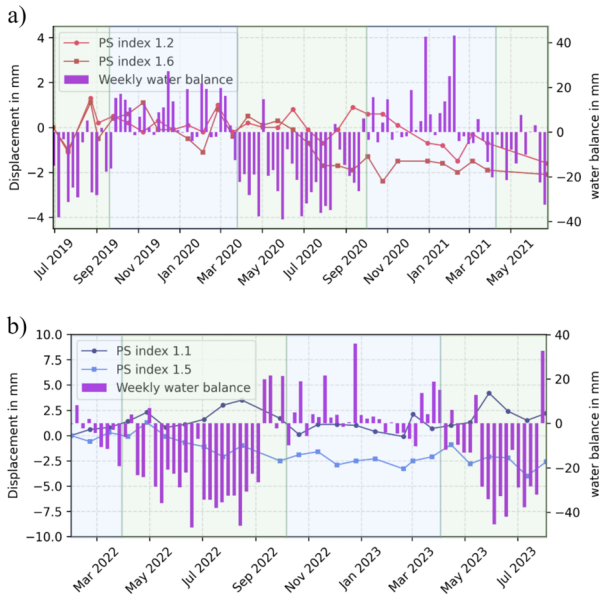


Figure 8. Water balance (purple) calculated by the difference of precipitation and potential evapotranspiration, based on data from the DWD weather station Frankfurt (station ID 1420) combined with the PS and time frames shown in Figure 5.

A clear indicator of vegetation influence on the shrinkage process and thus on ground movements would have been a seasonal pattern of subsidence during summer and in reverse heave during winter, due to the growth periods of vegetation. This pattern was not observed at the MH case study site, which may indicate that vegetation-related water uptake is not a primary cause of the observed crack damage, or that potential heave pressure is not transmitted to the building structure.

#### 4.2 PS movement analysis Hochheim am Main

In contrast to the MH case study, the Catholic church in Hochheim does not exhibit any clear settlement trend or directional movement for the evaluated period from March 2019 to August 2022 based on the PSI, illustrated in Figure 9. As the velocity is derived from displacement over the entire observation period, it is possible that periods of movement in opposite directions may offset one another, potentially masking short-term dynamics.

Therefore, it is necessary to analyse specific time periods and spatial areas separately. As the damage area is located in the northeastern part of the structure, Figure 10 focuses on the differential movements in this zone. There is a seasonal trend apparent. However, starting in summer 2020, the winter recovery phases no longer fully compensate for the increasing discrepancy in summer, resulting in a growing residual deformation visible through winter 2021/22 and summer 2022. Total and differential deformations remain very small.

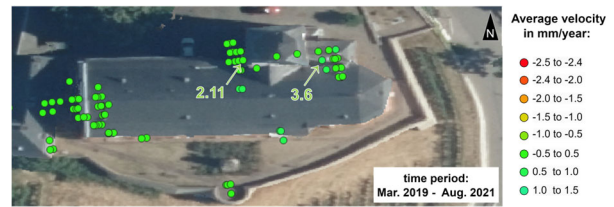


Figure 9. Overview of PS coverage for HO case study and average velocities in the Line of Sight per PS.

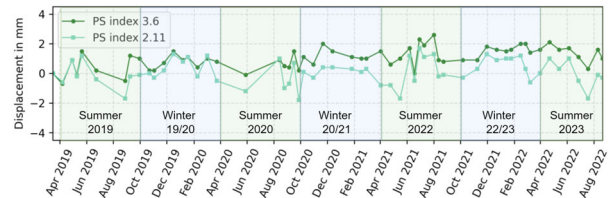


Figure 10. Differential movement of two PS laying in the damage area of the sacristy (3.6) and the vertical crack (2.11), with the evaluated PS highlighted in Figure 9.

Unfortunately, as the dates of the satellite radar visits do not match the existing crack monitoring, a correlation cannot be carried out for this case study.

Since the trees in the churchyard exhibit significant crown volume, potential vegetation influence should be assessed. The resulting seasonal movements are proven by a benchmark PS located at distance of approx. 10 m to the tree north of the church (see Figure 11). Patterns of subsidence and heave of up to 5 mm are visible, following overall a lasting settlement trend. Since such seasonal patterns are not observed at the PS points on the damaged building, based on this study, tree influence as damage cause is unlikely. However, conclusively this must be verified by further measurements, such as long-term ground observations or seasonal soil moisture analysis.

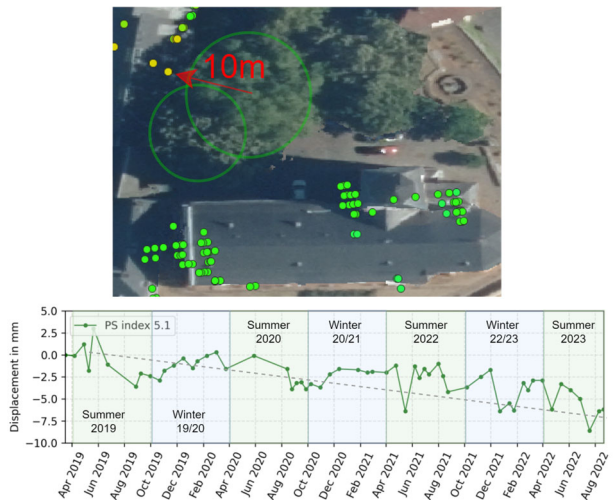


Figure 11. PS located approximately ten meters away from a tree showing seasonal ground movements of a magnitude up to 5 mm.

## 5 DISCUSSION

The combination of crack monitor data with PS-based displacement measurements proved to be helpful in validating observed structural movements and clarifying their overall direction, as shown in the MH case study. Crack monitors typically capture lateral openings directly at the damaged structure, while radar primarily reflects displacements at roof level. This needs to be considered while correlating the results of these two systems. Nevertheless, radar data effectively complement classical point-based methods by enabling area-

wide subsidence analysis with enhanced temporal resolution compared to crack monitors, which are generally evaluated in a defined interval. Furthermore, radar data allows a view back in time, for example if damage is noted for the first time or if the expert is involved at a late moment and no crack monitoring is available. With sufficient radar coverage, full-surface deformation patterns can be assessed independently of crack monitor locations and installation time, which offers a valuable broader context for understanding deformation behavior.

The impact of hydrological changes of the soil on crack edge movements was shown by a correlation between displacement and soil water balance. Seasonal patterns observed between two PS on opposite sides of damage zones showed increased differential movements in summer and partial decreases in winter. Besides moisture changes this could be induced by seasonal temperature variances of the building material. However, persistent displacement differences over time indicate that these seasonal effects overlay longer-term subsidence processes, which indicate soil participation, and which may contribute to ongoing structural damage. In contrast, the seasonal pattern was not clearly connected to the growth phases of vegetation, why no influence of vegetation alone could be identified, possibly due to the domination of other hydrological factors. These results highlight the complexity of deformation mechanisms and the need to consider multiple environmental and site-specific factors in structural monitoring.

The accuracy and reliability of displacement measurements strongly depend on the data characteristics, such as acquisition mode and area coverage. A relatively low magnitude of movements of maximum 7 mm observed in the case studies poses challenges for reliably linking displacement signals to specific influencing and movement characteristics. To improve the analysis, adding an additional dataset in descending orbit mode would provide complementary viewing geometry and additionally enable horizontal displacement assessment. Alternatively, higher-resolution data (e.g. up to 1 m) could enhance detail. Both pieces of data could not be provided by the satellite TerraSAR-X. Future work could also consider integrating other satellite-based methods, for example satellite data including moisture measurement, to further advance structural health monitoring.

## 6 CONCLUSION

Radar interferometry provides a powerful complementary approach for area-wide assessment of soil shrinkage damage in historical buildings. The strong correlation between PS movements and crack monitor readings in the Massenheim case study confirms the reliability of radar data for detecting building-scale deformations. Moreover, this approach combined also movements with environmental factors showing seasonal patterns referring to soil moisture and most likely volume changes. Although some limitations in direct comparability remain, the integration of these methods advances the ability to monitor and understand complex deformation processes, especially needed for cultural valued historical buildings. Therefore, integrating radar analysis with persistent scatterers adds valuable insights to the conventional damage assessment in geotechnical practice.

## 7 ACKNOWLEDGEMENT

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