Multi-Scale MT-InSAR Techniques for Structural Health Monitoring: Applications to the Italian Cultural Heritage Context

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ABSTRACT

In recent years, the number of applications of Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) techniques for structural health monitoring (SHM) purposes has constantly raised. One of the main advantages that MT-InSAR can provide is the possibility to analyze wide areas, such as entire cities or archaeological sites. Thus, several interferometric algorithms have proven to be particularly valid when applied in urban contexts, considering the high reflectivity provided by the structures. In addition, the growing availability of high-resolution SAR satellite constellations, such as the Italian COSMO-SkyMed and the German TerraSAR-X, allows obtaining significantly accurate measures and detecting high density of Measurement Points (MP). Consequently, sufficiently detailed information on single structures can be recorded, permitting to perform both urban scale and local scale analyses. On the other hand, several drawbacks are still present, mostly related to the hardly post-processing processes needed. Indeed, beside the technical difficulties that can be encountered during the analysis (e.g. geocoding errors and noisiness in the time series), an expert interpretation of the results is still required to avoid misinterpretation of data. Anyway, considering both advantages and disadvantages of the technique, MT-InSAR undoubtedly represents a very cost-effective tool in the structural monitoring field.

In this paper, MT-InSAR applications for structural monitoring on the Italian Cultural Heritage context are presented. The analyses have been conducted at both urban and local scale, processing images acquired by COSMO-SkyMed constellation in Stripmap mode (~3 meters resolution). First, spatial interpolation algorithms have been implemented to estimate the overall deformations at urban scale. Subsequently, the attention has focused on some of the main cultural assets of the case-study cities, investigating the MPs detected on the structures themselves. In this work, three cities are presented as case-studies: Verona, Padova (North Italy), and L'Aquila (central Italy). For each city, a specific Cultural Heritage structure has been selected for the local scale analysis, namely the Roman Arena in Verona, the Scrovegni Chapel in Padova, and the Civic Tower in L'Aquila. All these monuments have been monitored by traditional SHM techniques for years, with the possibility to correlate and validate on-site and satellite data.

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INTRODUCTION

The MT-InSAR technique involves the use of multiple SAR (Synthetic Aperture Radar) images acquired over time, each of which contains data on the surface deformation at a particular moment in time. By comparing these images, changes in the surface deformation can be detected and quantified. One of the advantages of MT-InSAR is its ability to detect small deformations over a wide area, making it useful tool for monitoring natural hazards including landslides, earthquakes, and volcanic activity. In addition, the launch of new satellite missions with improved SAR capabilities, such as Cosmo-Skymed, has made possible the application of MT-InSAR to monitor man-made structures such as bridges, dams, and buildings [1–4].

This research presents MT-InSAR applications for structural monitoring in the context of the Italian Cultural Heritage, at both urban and local scale. COSMO-SkyMed acquisitions have been processed through Persistent Scatterers algorithm (PS-InSar) to obtain dataset of Measurement Points (MPs) over the cities, containing information about displacements along the satellite Line of Sight (LOS). The applications of MT-InSAR presented in this study highlight its versatility in different scenarios. In regions characterized by moderate to low seismic activity, such as Padova and Verona, it provides significant value for regular and routine maintenance activities. Moreover, it enables the identification of structures that may be susceptible to critical conditions. Furthermore, during catastrophic events like the one in L'Aquila, MT-InSAR plays a crucial role in emergency management and streamlines the prioritization of operations.

More detailed information about the case studies of Padova and L’Aquila can be found in [5] and in [6].

MATERIAL AND METHODS

Study Areas and Structures

Padova is a city in northern Italy, located in the Veneto region. It is one of the oldest and most important cultural centers in Italy, with a significant history dating back to Roman era. One of the most famous landmarks in Padova is the Scrovegni Chapel, also known as the Arena Chapel. It is famous for its stunning frescoes painted by the Italian artist Giotto, which cover the inner walls and vault.

Figure 1. The city of Padova and the Scrovegni Chapel

Verona is a city in northern Italy, located in the Veneto region. The city is known for its beautiful architecture, historic landmarks, and rich cultural heritage. One of the most famous landmarks in Verona is the roman amphitheater, also known as Arena. The structure, built in the 1st century AD, is one of the largest and best-preserved ancient roman amphitheaters in the world, able even today to seat up to 20000 spectators.

Figure 2. The city of Verona and the Roman Arena

L'Aquila is a city located in the Abruzzo region of central Italy. The city is known for its beautiful historic center, which is dominated by the Spanish Fortress. Unfortunately, the city is also known for the devastating earthquake that struck the city in 2009, causing significant damage and the loss of over 300 people. Many historic buildings in the city's center were severely damaged or destroyed, including the Civic Tower. The tower is part of the Palazzo Margherita complex and is the seat of the municipality. Like many other buildings in L'Aquila, the Civic Tower of Palazzo Margherita was damaged during the seismic events. The tower suffered significant structural damage to the base, which has undermined its stability. Since then, efforts have been made to restore the tower. The restoration works have included stabilizing the structure and repairing the damages.

Figure 3. The city of L’Aquila and the Civic Tower

SAR Data Sources and Processing

Several SAR images acquired over the study areas by COSMO-Skymed constellation were processed through PS-InSAR algorithm [7,8]. This multi-temporal SAR method is based on the detection of Permanent Scatterers (PS), which are characterized as coherent radar signal reflectors such as structures, infrastructure, antennas, etc., and minimize atmospheric influences while improving displacement accuracy. For all the PSs detected information about the displacement velocity and displacement time series along the Line of Sight (LOS) of the sensor are obtained.

TABLE I. Analyzed SAR dataset.

Case study	Orbit direction	Monitoring period	N. of images
Padova	Ascending	Mar 2012 – Dec 2021	139
Verona	Descending	May 2012 – Dec 2021	156
L'Aquila	Descending	Sep 2010 – Feb 2013	34

To investigate urban deformation, the irregular pointwise distribution of PSs is converted into a continuous map through the spatial interpolation method IDW (Inverse-Distance-Weighting) [9]. Subsequentially, PSs detected in proximity of the case study structures are inspected in terms of displacement velocity and displacement time series.

RESULTS

Urban Scale

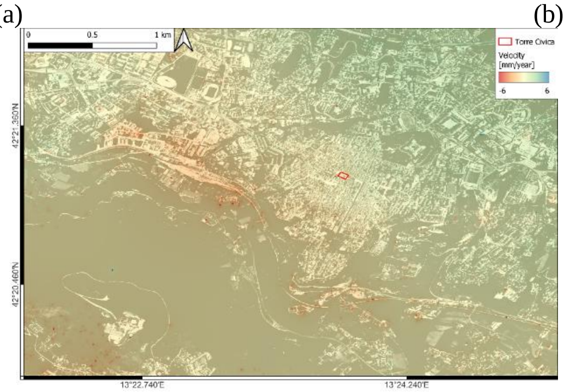
Figure 4 (a) shows LOS displacement velocity interpolated maps of Padova area. A very low displacement rate is detected in correspondence of the city center, with most of the values of the area lying within the considered stable range (± 1.5 mm/year). Higher velocity values appear on different areas in the suburbs, especially in the industrial area in the south-east part of the city, and on infrastructures, such as the northern part of the beltway. The surrounding area of the Scrovegni chapel, despite the proximity to a waterway, presents a very stable condition, with a displacement velocity maximum value of 0.5 mm/year.

As per Padova, the city center of Verona (Figure 4 (b) reveals a very low velocity displacement rate, with the majority of the area characterized by displacement velocity values within the stability range. More intense velocity values can be detected in the northern part of the city, in correspondence with the major beltway, with values reaching 3 mm/year. The area surrounding the Arena, essentially in the exact center of the city, does not show any significant displacement velocity values.

Figure 4 (c) presents LOS displacement velocity interpolated maps of the city center of L'Aquila. In this case, the seismic events occurred just before the observation period, triggered some deformations that involved different parts of the city and lasted for the entire observation period. Indeed, several areas with high displacement velocity can be detected, with values up to 7 mm/year. The area surrounding the Civic Tower, shows an overall stable behavior, however, several pixels with significant velocity values can be identified, including one in correspondence of the tower itself.

(a)

(b)



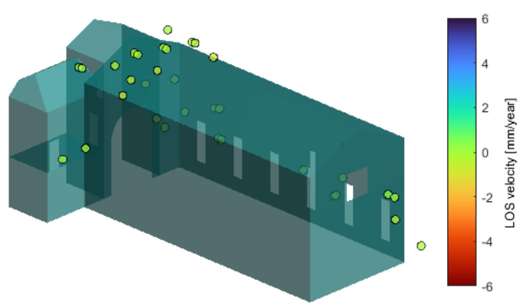
(c)

Figure 4. Displacement velocity interpolated map of Padova (a), Verona (b) and L'Aquila (c)

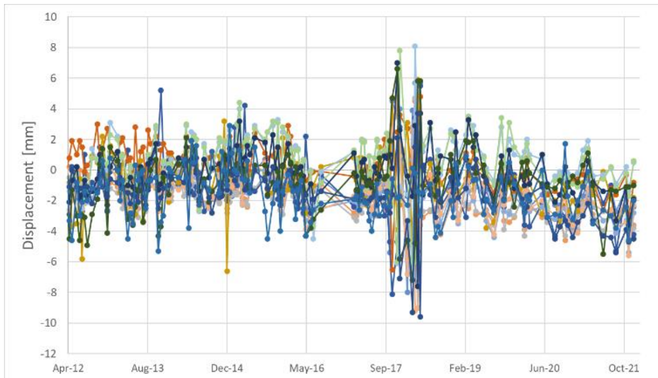
Local Scale

Figure 5 (a) and (b) display the PSs detected in correspondence of the Scrovegni Chapel. It can be noted that the displacement velocities are near zero and no area of the structures highlights unstable conditions. The displacement time series detected on the rooftop, presented in Figure 5(c), also underlines the stable behavior of the structure, with an almost flat trend of displacement recorded during the monitoring period. However, it can be noted that between September 2017 and April 2018, the times series show a very noise behavior, possibly related with the restoration works carried out in the same period.

(a)



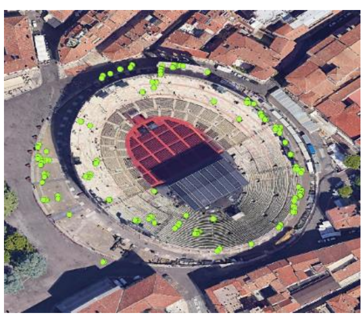
(b)



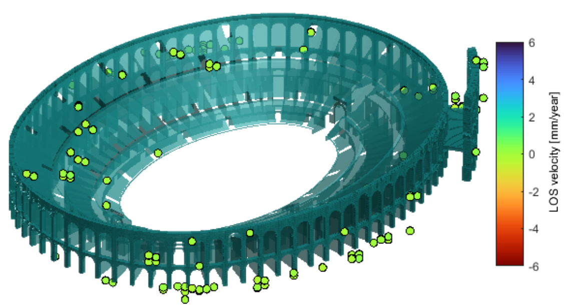
(c)

Figure 5. PSs detected on the Scrovegni Chapel (a, b) and displacement time series of PSs located on the roof (c).

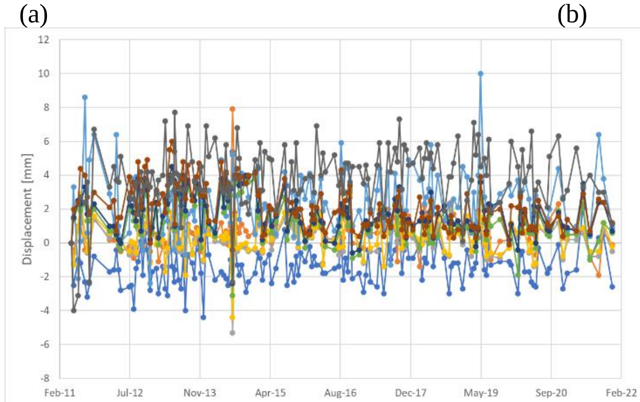
Figure 6 (a) and (b) present the PSs detected in correspondence of the Arena. Also in this case, all the displacement velocity values lie within the stability range. It is interesting to notice that some PSs have been detected also in correspondence of the wing, despite its reduced in-plan dimensions. Figure 6 (c) shows the displacement time series of the PSs detected on the wing. It can be noted that the trend is almost flat. However, it is necessary to highlight that, due to the view geometry of the sensor, the identified displacement trend represent the in-plan behavior of the wing, while the out-of-plan component, that follows the south-north direction, cannot be detected by InSAR analysis.



(a)



(b)

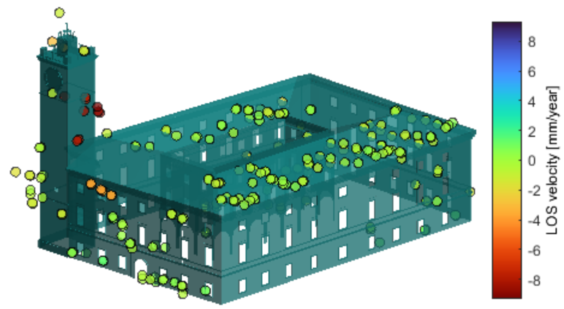


(c)

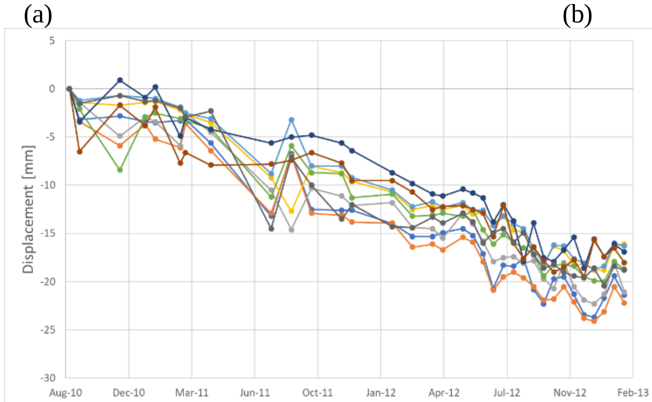
Figure 6. PSs detected on the Arena (a, b) and displacement time series of PSs located on the wing (c).

Figure 7 (a) and (b) show the PSs detected in correspondence of the Civic Tower and the Palazzo Margherita. It is immediately evident the presence of a cluster of PSs with high displacement values located on the north-east wall of the tower, while the remaining PSs, included those detected on Palazzo Margherita, present stable values of velocity. The difference between the velocity identified on the top of the tower and those identified at the base of the tower and on the palace may indicate that a differential movement occurred during the monitoring period, likely involving a rotation of the tower. The displacement time series of the PSs, presented in Figure 7 (c), display a negative trend which can be associated with a movement away from the sensor. This aspect strengthens the hypothesis that a rotation of the tower may be occurred during the observation period.

(a)



(b)



(c)

Figure 7. PSs detected on the Civic Tower (a, b) and displacement time series of PSs located on the tower (c).

CONCLUSIONS

This article discusses the use of MT-InSAR technology for monitoring the structural integrity of cultural heritage sites in Italy. The study analyzes at both urban and local scales images captured by the COSMO-SkyMed constellation. The researchers first implemented spatial interpolation algorithms to estimate overall deformations at an urban scale and then focused on individual cultural assets in Verona, Padova, and L'Aquila. In each city, a specific heritage site was selected for local scale analysis, including the Roman Arena in Verona, the Scrovegni Chapel in Padova, and the Civic Tower in L’Aquila. In the case of Padova and Verona, the urban analysis highlighted how in both cases the city center showed an overall stable behavior, while higher displacement velocity values are detected in proximity of the major roadways. In the case of L'Aquila, instead, the seismic events that affected the area before the monitoring period, resulted in the deformation of several areas of the city center. The local analysis conducted on the single structures for the Scrovegni Chapel and the Arena also showed as the detected velocity displacement values presented moderate values. On the other hand, in the case of Civil Tower, a cluster of PSs with high velocity values was detected, likely indicating a movement/rotation of the structure.

In conclusion, the presented applications of MT-InSAR show its usefulness in various scenarios. During regular periods, as the case of Padova and Verona, it proves valuable for routine maintenance purposes, and with large-scale analysis, it can help identify structures that may be prone to critical conditions. During catastrophic events such as the case of L'Aquila, MT-InSAR aids in emergency management and facilitates prioritization of operations. However, despite the huge potential of MT-InSAR, a fully validation of the data is still to be reached, and, thus, the integration of satellite sensing methods with on-site measuring is advisable to obtain a detailed knowledge of the structural behavior.

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