Satellite radar interferometry for monitoring and early-stage warning of structural instability in archaeological sites

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Satellite radar interferometry for monitoring and early-stage warning of structural instability in archaeological sites

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Abstract

Satellite interferometric synthetic aperture radar (InSAR) monitoring campaigns were performed on the archaeological heritage of the Roman Forum, Palatino and Oppio Hills in the centre of Rome, Italy, to test the capabilities of persistent scatterer interferometry techniques for the preventive diagnosis of deformation threatening the structural stability of archaeological monuments and buried structures. ERS-1/2 and RADARSAT-1/2 SAR images were processed with the permanent scatterers InSAR (PSInSAR) and SqueeSAR approaches, and the identified measurement points (MP) were radar-interpreted to map the conservation criticalities in relation to the local geohazard factors and active deterioration processes. The multi-temporal reconstruction of past/recent instability events based on the MP deformation time series provided evidences of stabilization for the Domus Tiberiana as a consequence of recent restoration works, as well as of persistent deformation for the Temple of Magna Mater on the Palatino Hill and the structures of the Baths of Trajan on the Oppio Hill. Detailed time series analysis was also exploited to back monitor and understand the nature of the 2010 collapse that occurred close to Nero’s Golden House, and to establish an early-stage warning procedure useful to preventively detect potential instability.

Keywords: persistent scatterer interferometry, structural monitoring, monuments, conservation, Rome

(Some figures may appear in colour only in the online journal)

1. Introduction

The susceptibility of archaeological heritage to deterioration processes is necessarily linked to its nature of ‘ruin’ and related conservation history. Further contribution can also be derived from the local geohazard factors and the structural relationship with the surrounding context and foundation stratum. Archaeological monuments are frequently found within natural environments, on which past/recent phenomena and/or human actions might have produced (in)direct impacts, in several cases worsening the former stability condition.

These conservation issues can be of particular concern, especially for the management of sites characterized by a high density of heritage concentrated over a relatively huge area. Hence, it might be difficult to ensure a constant and effective ordinary maintenance to prevent structural instability events, especially in times of reduced resources dedicated to preservation activities.

In this regard, the employment of technologies capable of detecting conservation criticalities with a field of view,
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at the same time, covering extended areas of investigation and providing highly detailed information on single elements of interest, undoubtedly represents a powerful tool to define sustainable strategies of heritage management. Among the remote-sensing monitoring techniques, synthetic aperture radar interferometry (InSAR) based on the processing of long stacks of SAR images acquired from space-borne radar sensors (Massonnet and Feigl 1998, Rosen et al 2000) has potential to become a routine non-invasive method for preventive diagnosis of archaeological heritage, at different scales of analysis, from entire site to single monument. The processing approaches referred to as persistent scatterer interferometry (PSI) allow superficial deformation affecting ground and man-made structures to be reconstructed in their temporal and spatial evolution, with millimetre precision on single measure. This is thanks to the identification, within the processed satellite images, of elements on the ground which can generate measurement points (MP) persistent throughout the monitoring period, for which a deformation time series is retrieved.

Recent applications (Manunta et al 2008, Osmanoğlu et al 2011, Cigna et al 2012, Teatini et al 2012) demonstrate how the high selectivity of the PSI in distinguishing unstable sectors from stable ones can lead to an updated mapping of deterioration effects on the exposed elements. The availability of SAR images since 1992 also permits us to back analyse past/recent deformation events, in addition to the monitoring of still active processes.

Cigna et al (2011) and Tapete et al (2012) have recently investigated the benefits of the processing techniques known as permanent scatterers InSAR (PSInSAR; Ferretti et al 2001), for multi-temporal deformation analyses of built heritage sites within urban contexts, with critical discussion of the limits that these approaches encounter when used over vegetated and bare areas. In these terms, advances have been achieved with the development of the new multi-interferogram processing algorithm SqueeSAR by Tele-Rilevamento Europa (TRE; Ferretti et al 2011). The latter facilitates the execution of monitoring campaigns over low-urbanized sites, since the signal of several neighbouring pixels, located in correspondence to areas without elements of particular reflectivity, is collected and processed to generate the so-called ‘distributed scatterers’ (DS). This typology of MP completes the information retrievable from the pointwise radar targets (PS), with consequent advantages in the detection of terrain motions potentially damaging to archaeological ruins.

With the perspective of encouraging further implementation of PSI techniques in cultural heritage sites, this paper is aimed at exploring the capabilities of the PSInSAR and SqueeSAR approaches to monitoring superficial deformation of archaeological monuments, which can be correlated to phenomena of structural destabilization and/or ground instability. Site-specific radar monitoring campaigns were carried out on the Palatino Hill–Roman Forum site and the archaeological park of the Oppio Hill in the centre of Rome, the latter including the hypogean structures of Nero’s Golden House. Historical (1992–2000) and recent (from 2003 up to 2010) image archives acquired, respectively, by ERS-1/2 and RADARSAT-1/2 satellites were adopted to produce updated maps of the conservation criticalities, and the observed displacements were correlated with the local geohazard factors. The results of the back monitoring of the collapse that occurred on 30 March 2010 close to Nero’s Golden House are discussed in light of the potentials of the PSI techniques for warning activities. A time series-based warning procedure is proposed here, by exploiting the recognition of acceleration phases, trend inversions and/or displacement anomalies within the deformation time series of the identified MP. Such deviations from the stability trend are analysed, in the role of potential precursors of near future deformation, for their scope for an effective preventive diagnosis. Hence, instability phenomena are detected at an early stage of their evolution (‘early-stage warning’), before they can completely develop and produce irreversible damage to the exposed heritage.

2. PSI techniques

In the last two decades, satellite missions like those of the European and Canadian Space Agencies (ESA and CSA) have created historical SAR image archives, acquired over huge areas on the ground and covering long time intervals. Nowadays, they represent precious reservoirs of information useful to reconstruct the evolution of the stability condition of monuments and historical buildings, as also recently demonstrated by Zeni et al (2011) by means of differential InSAR. New acquisitions still continue increasing these archives, which are exploited for a wide variety of applications, such as monitoring of land surface and tectonic motions (Amelung et al 1999, Hilley et al 2004, Bianchini et al 2012, Bürgmann et al 2006, Meisina et al 2007, Lu et al 2011), natural hazard/risk assessment (Corsini et al 2006, Cigna et al 2011, Gigli et al 2012) and evaluation of impacts due to human activities (Cabrals-Cano et al 2010, Righini et al 2011).

With specific reference to the InSAR data stacks analysed in this paper (table 1), the space-borne radar sensors collect SAR imagery according to their specific right-looking acquisition geometry, while moving along their orbits in N–S and/or S–N directions (namely, respectively, descending and ascending modes). The frequency with which they come to re-observe the same scene of view (repeat cycle) is roughly monthly, thereby configuring a temporal resolution particularly suitable to monitor phenomena characterized by deformation velocities up to a few tens of centimetres per year (e.g., for landslides, extremely slow to very slow velocities (Metternicht et al 2005)). Movements not perceivable with the naked eye can be revealed, with displacement estimations only along the radar line of sight (LOS).

For object-oriented analyses the spatial resolution on the ground of SAR imagery is quite a fundamental parameter, which is strictly dependent on the satellite acquisition mode. Nominal ground-range resolution spans from 8 m for RADARSAT-1 fine beam mode 3 (F3) scenes, to 25–30 m for ERS-1/2 and RADARSAT-1/2 standard beam mode 3 (S3) imagery (table 1). Such values, combined with wide image frames (coverage up to hundreds/thousands of square
kilometres), encourage the processing of these satellite data for cultural heritage applications. In particular, two distinct spatial scales of analysis can be achieved:

- Monitoring at ‘entire site scale’, highly indicated for archaeological sites, historic centres, hilltop settlements and, more generally, monumental complexes considered in their entirety, either enclosed or distributed over huge areas, to detect both phenomena active at regional scale and instability localized on single sectors.
- Monitoring at ‘single monument scale’, focused on group(s) of monuments, even single archaeological structures, whose displacement field can also be assessed in relation to the (in)stability of the surrounding context and foundation substratum.

In both cases, a level of conservation criticality is assigned for each sector of the monitored area, with regard to the urgency of the stabilization and consolidation works to be executed.

### 2.1. PSInSAR analysis

As mentioned above, PS are pointwise MP corresponding to elements backscattering the microwave wavelengths coming from the space-borne sensor, which are found as being persistent within the sequence of the processed images, by virtue of their geometric configuration and constancy of their dielectric properties. Regarding the physical nature of the PS, Perissin and Ferretti (2007) have demonstrated that built-up areas can be satisfactorily monitored by means of PSI techniques. Buildings, metallic structures, infrastructure, light poles, electric power lattice towers and antennas are typical urban targets, as well as rock outcrops and boulders in suburban and natural contexts.

Feasibility analyses carried out by Tapete and Cigna (2012) over different cultural heritage sites located in Southern Italy have recently highlighted that monuments, architectural elements and archaeological remains emerging or sparse on the ground (e.g., columns, column drums, fallen architraves) can generate PS. The spatial distribution of the latter can result in their being particularly emphasized in the final output of the PSI processing, especially if they are identified within areas surrounded by vegetation, in correspondence to which no PS are generally found. The geographic coordinates and height value associated with each PS are essential for a correct spatial localization of its electromagnetic barycentre, thereby clarifying if the detected LOS displacements are attributable to the monitored masonry structure and/or its foundation substratum.

The estimation, along the LOS, of the displacement field is strictly related to the specific acquisition geometry and the mode by which the imagery is collected by each satellite. At a certain latitude, this geometry can be described by two angular values: orbit inclination (\(\alpha\)), the angle measured between the N direction and the satellite orbit; and look angle (\(\theta\)), the angle formed by the LOS and the vertical direction (figure 1(a)).

Deformation analysis is performed by comparing consecutive coherent acquisitions and estimating, along the LOS, the displacement (\(\Delta d\)) having affected the radar target in the elapsed time (\(\Delta t\)) (figure 1(b)). Negative values of the LOS displacements correspond to downwards moving PS, i.e. movements whose LOS component is going away from the satellite. Vice versa positive values indicate LOS displacements towards the space-borne sensor.

Typical deterioration phenomena, to which the LOS displacements detected for archaeological structures can be referred, include: toppling and loss of verticality (figure 1(b), case 1), collapses (figure 1(b), case 2) and structural destabilization due to ground instability (figure 1(b), case 3). Additionally to the deformation analysis of the exposed heritage, the detection of superficial motions of terrain covering hypogean/buried structures can inform about conservation criticalities active at depth (figure 1(b), case 2). Similarly, a wide spectrum of natural instability phenomena can be monitored, such as landsliding movements, slope dynamics, rock block detachment, ground expansion, clayey soil swelling, subsidence, etc., which might produce non-negligible impacts directly on the monitored monuments (Tapete and Cigna 2012).

Based on these capabilities, the deformation analysis is actually performed on both built and natural environments, provided that a sufficiently dense MP spatial distribution is obtained over the area of interest.

### Table 1. Main characteristics of the processed data stacks: \(\lambda\), wavelength; \(\theta\), look angle; \(\alpha\), orbit inclination; Asc, ascending; Desc, descending; F3, Fine Beam Mode 3; S3, Standard Beam Mode 3.

<table>
<thead>
<tr>
<th>Site</th>
<th>Data stack</th>
<th>(\lambda) (cm)</th>
<th>Orbit</th>
<th>Mode</th>
<th>(\theta) (°)</th>
<th>(\alpha) (°)</th>
<th>Repeat cycle (days)</th>
<th>Nominal ground-range resolution (m)</th>
<th>Time interval</th>
<th>N. images</th>
<th>Processing technique</th>
<th>Average MP density (MP km(^{-2}))</th>
<th>PS/DS ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RSAT-1</td>
<td>5.6</td>
<td>Asc</td>
<td>F3</td>
<td>41.3</td>
<td>−8.1</td>
<td>24</td>
<td>8</td>
<td>07/03/2003 - 01/10/2009</td>
<td>81</td>
<td>PSInSAR</td>
<td>1832(^a)</td>
<td>–</td>
</tr>
<tr>
<td>Oppio Hill</td>
<td>RSAT-1</td>
<td>5.6</td>
<td>Asc</td>
<td>F3</td>
<td>41.8</td>
<td>−8.1</td>
<td>24</td>
<td>8</td>
<td>07/03/2003 - 22/02/2010</td>
<td>87</td>
<td>SqueeSAR</td>
<td>3033(^b)</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>RSAT-1</td>
<td>5.6</td>
<td>Desc</td>
<td>S3</td>
<td>35.2</td>
<td>+12.3</td>
<td>24</td>
<td>30</td>
<td>15/03/2003 - 22/08/2009</td>
<td>84</td>
<td>SqueeSAR</td>
<td>1223(^b)</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>RSAT-2</td>
<td>5.5</td>
<td>Desc</td>
<td>S3</td>
<td>36.1</td>
<td>+12.4</td>
<td>24</td>
<td>25</td>
<td>28/06/2008 - 18/06/2010</td>
<td>21</td>
<td>SqueeSAR</td>
<td>1676(^b)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

\(^a\) Value expressed as PS km\(^{-2}\).

\(^b\) Value expressed as (PS + DS) km\(^{-2}\).
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2.2. SqueeSAR analysis

Although the presence of vegetation still remains a limit for the identification of MP, the SqueeSAR algorithm, recently developed by TRE as an advance of the PSInSAR technique (Ferretti et al 2011), widens the field of applications, because it allows MP to be also retrieved in correspondence to bare soil, sparsely vegetated land and debris/earth accumulations.

The basic principle of the technique consists in collecting the signals coming from neighbouring image pixels characterized by similar reflectivity values, and processing them all together. In this way, the noise is significantly reduced and the quality of the displacement estimations is improved, obtaining MP which are comparable to PS, but referred to all the pixels adopted to generate them (figure 2). This type of MP is called DS, and each of them is given with a value of the ‘effective area’ (EA), usually much less than 1 ha, to the electromagnetic barycentre to which all the detected LOS displacements are to be attributed.

The main advantage of the SqueeSAR relies on the fact that the DS are provided additionally to the PS. Hence, the overall MP density is expected to increase over the monitored area. This capability undoubtedly opens it up to potential exploitation for monitoring of archaeological sites characterized by low density of exposed masonry structures sticking out from the ground, as well as archaeological findings spread over rural contexts. Further usefulness can arise for structural monitoring of buried heritage, in light of the higher probability of identifying MP in correspondence to soil and covering terrains, whose superficial deformation can be correlated to inner instability and/or collapses of subterranean environments (figure 1(b), case 2).

3. Case studies

The experimentations presented in this paper were carried out on the heritage of the central archaeological area of Rome. Two distinct radar monitoring campaigns were respectively focused on the Palatino Hill–Roman Forum site and the park of the Oppio Hill, located W and N of the Colosseum (figure 3). These test sites are representative of the following types of cultural heritage context:

1. Archaeological areas, characterized by spotted vegetation and outcropping rock substratum, with relatively high density of structures and ruins sticking out from the ground, built both on valley and hilltop positions.
Figure 3. Aerial view of the Palatino Hill, Roman Forum and Oppio Hill in the centre of Rome, with details of: (a) joints affecting the Lionato Tuff outcrops; (b) hazardous superimposition of subterranean cavities and unstable structures; (c) collapse of the Farnesian Walls that occurred in November 2005 and (d) collapse close to Nero’s Golden House on 30 March 2010. The reference points \( r_1 \) and \( r_2 \) selected during the PSInSAR and SqueeSAR processing over the two sites are also shown as green dots.

(2) Archaeological areas, highly vegetated, with isolated structures, preserved for most of their former architecture, and subterranean environments buried under covering terrain.

In the first case, the PSInSAR technique was employed to process the SAR image archives, while the SqueeSAR algorithm was considered more suitable for the second test site. This was due to the reduced density of the exposed structures of the Oppio Hill and the need to detect deformation of the terrain covering the hypogean rooms of Nero’s Golden House.

3.1. Palatino Hill and Roman Forum

Among the seven hills of Rome, the Palatino Hill and the neighbouring Roman Forum contain the most important remains dating back from the 8th century BC to 5th century AD, among which are the structures of the imperial palaces and temples built by the Roman emperors. After the Roman Empire’s fall and centuries of abandonment and robbing of construction materials, the hilltop was arranged as gardens by the Farnese family in the 16th century, and only with the excavations started in the second half of the 19th century were the Roman structures re-discovered by archaeologists (Heiken et al. 2005). This historical succession of artificial filling and removal phases, combined with huge quarrying activity within the tuff strata constituting the bedrock, contributed to worsen the overall stability of the site. The hazard level is currently particularly high along the slopes, with huge joints affecting the Lionato Tuff outcrops on the western corner of the hill (figure 3(a)). Several collapses and block toppling events that occurred in the past testify to the chronic instability of the area, which is also characterized by local superimpositions between subterranean cavities and exposed buildings, the latter having lost their original architectural continuity (figure 3(b)). Similar hazards affect the northern slope of the hill, where a collapse damaged an entire sector of the Farnesian Walls in November 2005 (figure 3(c)), and a progressive opening has been recorded in the last few years in correspondence to the cracks of the brick masonries of the Domus Tiberiana.

3.2. Oppio Hill and Nero’s Golden House

Originally the SW spur of the Esquiline Hill, the Oppio Hill hosted a luxurious pavilion of the famous ‘Domus Aurea’ (Golden House), the suburban-type villa built by the Emperor Nero in 64 AD in the centre of Rome. After Nero’s death and damnation, most of the decorations covering the brick-faced concrete architecture were stolen and the entire pavilion was filled with earth and rubble by the Emperor Trajan in 104 AD, to create an artificial substructure for the overlying baths (Sciortino and Segala 2005). Nowadays the Oppio Hill is a public park (figure 3), and the archaeological ruins of the Baths of Trajan are inserted within trees and vegetation, as a consequence of the 1930s interventions by Antonio Muñoz. In terms of geological setting, the hill does not show particular elements of instability, except for the well-known susceptibility to fracturing of the Lionato Tuff, especially when it outcrops (Funiciello and Giordano 2005). Indeed, the main hazard factors are to be found in the weathering processes affecting the exposed architectural surfaces, and the structural
destabilization of the archaeological system created by the superimposition of covering terrain and buried structures. In this regard, the collapse, which occurred on 30 March 2010 and destroyed about 60–80 m² of the vault ceiling of a gallery located beneath the Oppio garden very close to Nero’s Golden House (figure 3(d)), confirms the urgency of mitigation works to reduce the impacts due to water seepage and tree root damages.

4. Methodological approach and results

In light of these conservation issues, targeted satellite monitoring campaigns were carried out at entire site scale on both the archaeological areas, by exploiting multi-platform radar imagery of medium spatial resolution and monthly repeat cycle. This temporal sampling frequency was considered sufficient to allow the detection of deformation with average LOS velocity of few millimetres per year, as well as instability events whose destabilization phase, preparatory to the triggering of the phenomenon, presumably takes some time to develop.

The combination of the different data stacks processed and radar-interpreted for each test site (see table 1) was set up according to some criteria, here below briefly reported, which should always guide the data selection during the planning of monitoring activities.

Regarding the historical data, the major constraint can be derived from the absence or incompleteness of SAR image archives covering the study area for the time interval(s) of interest. If available, it is highly recommended to analyse data of the same satellite acquired in both the ascending and descending acquisition geometries. Their combination can facilitate a better reconstruction of the vector components of the real displacements affecting the monitored object on the ground. Nevertheless, the integration of the two geometries can be partially limited by the different acquisition modes with which the two archives were acquired, as well as by the non-perfect temporal overlapping between the monitored intervals and non-perfect spatial overlapping of the identified targets on the ground. This issue is particularly relevant for cultural heritage applications, since the scale of analysis tends to reach the single monument scale and such imagery differences can significantly influence the reliability of the final results.

Similarly, the PSI analysis of multi-platform data is undoubtedly useful, especially if historical data are combined with recent acquisitions. But any comparison is to be executed taking into proper account the difference in the acquisition geometry and temporal coverage. The absence, in more recent data, of a deformation previously detected within an historical data stack does not necessarily imply the stabilization of that movement or its total disappearance. In this regard, a more reliable radar-interpretation of the PSI data can be obtained based on the integration with the ground truth collected during on-site surveys, as well as with updated background information about the monitored monument(s) provided by the local conservators.

Being aware of these potentials and limits, for the PSInSAR analysis over the Palatino Hill and Roman Forum ESA ERS-1/2 images acquired along descending orbits spanning the time interval between April 1992 and December 2000 were selected as historical data, while CSA RADARSAT-1 images acquired along ascending orbits in the period March 2003–October 2009 were used as a more updated data stack. The combination of historical and recent imagery was aimed at the multi-temporal analysis of the displacement field over the entire site, for a total period of almost 16 years. A map with zoning of the conservation criticalities correlated to the local hazard factors was finally produced.

Differently, for the Oppio Hill RADARSAT-1, images acquired along both the orbits, with maximum update on 22 February 2010, were processed by means of the SqueeSAR algorithm to clarify the condition of the exposed monuments and the terrain immediately above Nero’s Golden House. To overcome the temporal gap of these data stacks not covering the occurrence of the March 2010 collapse, the SqueeSAR analysis also included CSA RADARSAT-2 images acquired along descending orbits spanning the period June 2008–June 2010. Hence, a complete back monitoring of the pre- and post-event phases was achieved, and some near future criticalities were preventively detected over the western Neronian structures.

In both monitoring campaigns, the processing was carried out by TRE, who selected the processing strategies and parameters based on the background information concerning the test sites to be monitored, provided by the authors. Indeed, taking into account the nature of the deterioration phenomena and the respective cultural heritage contexts, the estimation of the phase components related to the detected deformation was performed by imposing a simple linear model of phase variation during the PSInSAR processing. Conversely, a deformation model considering also seasonal variations was used for the SqueeSAR processing of both the RADARSAT-1 data stacks acquired for the Oppio Hill. The latter choice was driven by the need to monitor deformation due to swelling/contraction cycles of the covering terrain above Nero’s Golden House, dependent on the seasonal changes of the water content. Due to the extremely reduced number of the RADARSAT-2 images, the seasonality parameter was not employed during their processing, as the seasonality estimation would have certainly been unreliable.

While PS were selected according to the amplitude dispersion criterion and employing a dispersion index threshold of 0.25 (Ferretti et al 2001), the DS were identified by using phase coherence-based criteria (Ferretti et al 2011). The 90 m resolution Digital Elevation Model of the SRTM (Shuttle Radar Topography Mission) by NASA, with linear vertical absolute height error of about 6 m, was initially employed during the processing for the subtraction of the topographic phase components. The latter were then improved through the PSInSAR and SqueeSAR processing to get MP elevations as precise as 0.5–1.0 m for the ERS-1/2 and RADARSAT-1 datasets, and slightly higher values ranging from 1.0 to 2.0 m for the RADARSAT-2 dataset, due to the lower number of scenes and shorter monitoring period of this stack.

For the georeferencing phase, a 1 m resolution orthophoto was used for the PSInSAR monitoring of the Palatino Hill,
while the 2008 orthophoto freely accessible through the WMS service by the Italian Ministry of Environment and Territory of the Sea (METS; National Geoportal 2011) was employed for the SqueeSAR analysis of the Oppio Hill.

Local-type analyses were undertaken to extract the maximum content of information, at the best resolution available. For each detected MP, the processing products included the following:

- Geographic coordinates (longitude and latitude), and height with related standard deviation.
- Annual deformation velocities estimated along the LOS and related standard deviation.
- LOS deformation time series covering the whole monitored period.
- PS coherence, i.e. the quality parameter given as a dimensionless number ranging between 0 and 1, which measures how much the single time series fits with the deformation model selected during the processing.

Additionally, for the RADARSAT-1 datasets processed with SqueeSAR, the following parameters were provided:

- EA of each DS.
- Amplitude and phase of the deformation seasonal component with related standard deviations.

For both PSInSAR and SqueeSAR processing the reference points were purposely positioned in areas not only characterized by sufficiently high phase coherence distribution, but also geologically and structurally stable, to avoid any influence due to recent/active local deformation. The two points are respectively located on the southeastern side of the Palatino Hill, close to the Baths of Maxentius (geographic coordinates: LAT: 41.886; LON: 12.487) and on the northern part of the Oppio Hill (LAT: 41.894; LON: 12.498), as shown in figure 3.

4.1. MP identification

In terms of MP spatial distribution, both the PSI approaches provided satisfactory values of MP density (see table 1), with optimal coverage over the monitored areas, whose extent was approximately 0.75 km² for the Palatino Hill–Roman Forum site and 0.31 km² for the Oppio Hill. As expected from the better spatial resolution dependent on the acquisition mode, higher MP density values were found for the data stacks acquired in Fine Beam Mode 3 (F3) than those in Standard Beam Mode 3 (S3).

Although the comparison is inevitably limited by the difference in the extent and typology of the monitored areas and the number of the processed SAR images, it is to be noted that the significant increase of MP density obtained for the RADARSAT-1 F3 ascending data processed for the Oppio Hill is higher than the corresponding data analysed for the Palatino Hill. This improvement was certainly brought thanks to the employment of the SqueeSAR algorithm.

It is also interesting that, over the same area, the highest value of the PS/DS ratio was found for the RADARSAT-1 F3 ascending data, characterized by the best spatial resolution and the longest SAR image archive. Conversely, for the corresponding S3 descending data stack, this ratio actually halved, reaching a value of about 1, which means a DS number almost equal to the PS one. Despite the reduced available imagery, a sufficiently high MP density was also retrieved for the RADARSAT-2 S3 descending data. Nevertheless, a relevant decrease of the identified PS is appreciable, with an overall predominance of the DS.

Far from being a mere numerical disquisition, these calculations have a direct impact on the final results of the deformation analysis and the correctness of the MP radar-interpretation over an archaeological site, especially with regard to the real value of the information provided by the DS. Also, a higher and more distributed MP density generally allows a PSI analysis to reach a better coverage over all the sectors of the monitored site, with the possibility of identifying non-negligible localized deformation in peripheral or unexpected areas.

Parallel to these quantitative considerations about the MP spatial distribution, the datasets of the identified MP were evaluated in terms of coherence values associated with each deformation time series. Even if the same false alarm rate was used during the processing of all the stacks (equal to $10^{-3}$; Ferretti et al 2001), the MP coherence threshold, i.e. the parameter used to discriminate the discarded MP from the accepted ones, took on the value of $\sim 0.45$ for the ERS-1/2 and the three RADARSAT-1 datasets, while $\sim 0.76$ for the RADARSAT-2 over the Oppio Hill. The latter value was likely due to the shorter temporal interval and lower number of scenes of the processed stack. For both ERS-1/2 and RADARSAT-1 MP over the Palatino Hill and Roman Forum site, the coherence value that occurred most frequently (modal value) was 0.55, with only 25% of the identified MP assuming coherence values $\geq 0.70$. This suggested that the linear deformation model only partially represented a good fit with the recent/ongoing instability processes affecting the archaeological site, as also confirmed by the examination of the distribution of the single LOS displacement records within the MP time series. On the other hand, we observed higher values of coherence for the MP identified with the SqueeSAR processing of both the ascending and descending RADARSAT-1 stacks over the Oppio Hill (MP coherence modal values of 0.82 and 0.85, respectively). These values confirmed that the deformation model considering the seasonal component is reasonably more suitable to describe the deformation patterns affecting the archaeological ruins of this site.

Standard deviations of the annual LOS deformation velocities of the MP identified over the Palatino Hill and Roman Forum ranged between 0.48 and 0.56 mm yr$^{-1}$ in the ERS-1/2 dataset. They also highlighted lower variability of the velocity estimates for the RADARSAT-1 data (0.09–0.37 mm yr$^{-1}$), thanks to combined effects of better ground-range resolution, shorter repeat cycle and related temporal frequency of acquisition (cf table 1). Over the Oppio Hill, MP annual LOS deformation velocities were characterized by values of 0.10–0.36 mm yr$^{-1}$ for the RADARSAT-1 datasets (S3 and F3). As expected, lower number of scenes and shorter
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Figure 4. MP spatial distribution of: (a) ERS-1/2 descending (1992–2000) and (b) RADARSAT-1 F3 ascending (2003–2009) data for the Palatino Hill and Roman Forum, with identification of deformation patterns, the notation of which is reported in (c). (d) Map of the conservation criticalities produced combining PSI-based classification of the state of activity of the detected deformation and multi-hazard assessment. The blue squares indicate the sectors of the Domus Tiberiana and the Temple of Magna Mater.

4.2. Mapping of conservation criticalities

The zoning of areas subjected to conservation criticalities is performed based on the spatial analysis of the MP distribution in comparison with the location of the monuments (figure 4). In this way, it is possible to clarify if significant deformation has taken place during the monitoring period in correspondence to elements of cultural value, their surroundings and/or their foundation substratum.

Following the terminology proposed by Tapete and Cigna (2012), the detected deformation is here distinguished into the categories of ‘macro-pattern’, ‘micro-pattern’ and ‘localized deformation’. These deformation typologies are respectively defined in relation to the decreasing spatial extent of clusters of neighbouring MP which show common LOS displacement trends and/or average LOS velocities associable with the same phenomenon. While a macro-pattern is usually extended over an entire site or monument, a localized deformation can even correspond to a single PS. Nevertheless, the latter is to be unequivocally demonstrated as being pertinent to the monument of interest and not to an un-related element.
Figure 5. (a) MP spatial distribution of RADARSAT-1 F3 ascending (2003–2009) data for the sector of the Temple of Magna Mater, corresponding to the area 3 in figure 4(b). Time series show (b) LOS displacement trends away from the satellite and (c) acceleration phases, the last of which occurred at the end of the monitoring period. (d) View of the archaeological structures affected by the detected deformation.

For the Palatino Hill and Roman Forum, the PSInSAR analysis of both historical and recent archives did not reveal any deformation macro-pattern that referred to an instability phenomenon extended to the entire site (figures 4(a)–(c)). Hence, the hypothesis of an overall subsidence process previously feared by the local conservators (Ascoli Marchetti 2009) was not confirmed. On the other hand, both the data stacks indicated the diffuse presence of localized deformation and some enclosed micro-patterns, with an increase of the latter observed in the RADARSAT-1 (2003–2009) data, especially in the western sector of the Roman Forum (figures 4(b) and (c)).

Most of the PS showed LOS displacements away from the satellite, with a spatial distribution suggesting that the main threat to the preservation of the archaeological structures is to be found in the local structural relationships between the exposed masonries, the foundation substratum and the anthropogenic fill. This correlation is clearly perceivable in the map of the conservation criticalities (figure 4(d)), which combines the following:

- The PSI-based zoning of the critical areas, still subjected to deformation, and those classified as stabilized.
- The hazard susceptibility, with specific reference to ground and slope instability (i.e. toppling, cavity collapses, collapses/subsidence, landslides).
- The geomorphological features of the hill and the alluvial valley.

Most of the critical areas are interestingly located along the W–SW sector of the Palatino Hill (figure 4(d)), where the site-specific multi-hazard assessment led us to recognize a high susceptibility to toppling for the ancient retaining walls erected by the Romans and the Farnese family to stabilize the hill slope, as well as to structural damages for the buildings located above the subterranean corridors and tuff quarries.

In this regard, the comparison between the ERS-1/2 (1992–2000) and RADARSAT-1 (2003–2009) data highlights a worsening of the instability localized over the areas of the Temple of Magna Mater and St Anastasia church and Via dei Cerchi (respectively, areas 3 and 4 in figures 4(a) and (b)). Based on the recent deformation, the alert level was raised for these sectors, by classifying them as deformation micro-patterns rather than the previous identification as localized deformation.

In particular, the time series analysis for the downwards moving PS located close to the Temple of Magna Mater shows average annual LOS deformation rate up to $-3.3 \text{ mm yr}^{-1}$ away from the satellite, and acceleration phases with LOS velocity up to $-20.2 \text{ mm yr}^{-1}$ concentrated in the last year of the monitoring period (figures 5(a)–(c)). The persistence since 1992, even the worsening, of the deformation is reflected by the ground truth collected during on-site surveys (figure 5(d)). Some walls have lost their verticality, while shoring interventions have been installed as provisional measures to prevent collapses and block detachments. Crack
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patterns and evidences of instability are also surveyed on the inner surfaces of the corridors carved in the tuffs.

Further criticalities were identified in areas, over the Palatino Hill, highly susceptible to cavity collapse, as well as in sectors of the Temple of Saturnus and the Arch of Septimius Severus in the Roman Forum (respectively, areas C and D in figure 4(b)), with PS showing significant acceleration phases up to $-6.8 \text{ mm yr}^{-1}$ in the period March 2003–August 2005. The location of these criticalities in areas with contacts of different lithological units (see figure 4(d)) does not exclude a geological component for the detected deformation.

Despite the limits that the radar sensors usually encounter in the displacement detection in correspondence to steep slopes and north-facing surfaces (Casagli et al. 2010), precious information was retrieved for the structures of Hadrian’s Substructures of the Domus Tiberiana, sited along the N–NW side of the Palatino Hill (area 1 in figures 4(a) and (b)). Based on the historical data, this sector was the most unstable in the period 1992–2000, with average LOS deformation rate of the downwards moving PS up to $-6.1 \text{ mm yr}^{-1}$ (figures 6(a) and (c)). It confirmed the critical situation reported by Scarpelli et al. (1997), who correlated the extended cracks of the arcade piers with the hypothesized progressive sliding down of the monument towards the Roman Forum, due to the geotechnical properties of the soft clayey silt on which it was founded.

Differently, the RADARSAT-1 data (2003–2009) show stable PS localized in correspondence to Hadrian’s Substructures and the top of the archaeological complex, without significant LOS displacement phases recognizable within the respective time series (figure 6(b)). Such clear evidence of relative stability over a sector previously classified as unstable is particularly remarkable, in light of the restorations carried out on the lower arcades and the inner structures of the Domus Tiberiana in the 2000s (Archaeological Superintendence of Rome 2006). Deep consolidation and anchorages, as well as reconstruction of the partially/totally lost architectural elements along the Via Nova, were executed to strengthen the base of the monument (figure 6(d)). Taking into account the above-mentioned limitations affecting such a type of comparison, the stabilization of the Domus Tiberiana observed in the recent data can be reasonably put in relation to these restoration works and assumed as an indirect proof of their consolidation effectiveness.

A further element supporting this interpretation is provided by the presence of two isolated downward moving PS, respectively located on the rear structures along the Clivus Victoriae (the ancient road running behind the front arcades of the Domus Tiberiana) and east of the arcade façade, i.e. in areas not yet with restoration (figure 6(b)). Their time series highlight the occurrence of a sequence of differential displacement phases and related trend inversions, which indicate an unstable condition for these areas, and suggest the need to execute targeted interventions.

As a general remark related to the above discussed time series and those presented in the subsequent figures, it is worth noting that, despite the presence of noise observable in the

Figure 6. MP spatial distribution of: (a) ERS-1/2 descending (1992–2000) and (b) RADARSAT-1 F3 ascending (2003–2009) data for Hadrian’s Substructures of the Domus Tiberiana, corresponding to the area 1 in figures 4(a) and (b). (c) While ERS time series showed LOS displacement trends away from the satellite, RADARSAT-1 data suggest a stabilization (green square in (b)), which can be associated with the recent restoration works carried out to consolidate the base of the monument (d). Localized deformation (yellow PS in (b)) persists in the areas not restored yet.
sequence of single LOS displacement records, the recognition of a perceivable deformation trend over a long temporal interval (at least 5–10 consecutive acquisitions in the case of PSI data with monthly sampling frequency) can be a sufficient element to focus the attention on a certain sector rather than others appearing as relatively stable. Ground truth and background information provided by local conservators may confirm such satellite-based observations, and the reliability of each time series can be consequently assessed. This approach was constantly pursued during the radar-interpretation of each MP time series, throughout the carried out experimentations over the Palatino and Oppio Hills.

4.3. Single monument structural assessment

The multi-spatiality of the PSI approaches actually translates into the possibility of focusing the analysis reaching up to the single monument, with satisfactory results even with medium resolution radar imagery. As for the PSInSAR analysis of the Palatino Hill, this capability was exploited for the SqueeSAR monitoring of the Oppio Hill, to assess the structural condition of the exedra and the still preserved structures of the Baths of Trajan.

The PSI-based mapping of the conservation criticalities reports a clear deformation macro-pattern covering the whole apse wall of the central exedra, with significant LOS displacements estimated in the RADARSAT-1 descending data stack in the period March 2003–August 2009 (figure 7(a)). Two downwards moving PS, spatially attributed to the upper-middle part of the masonry, show average LOS deformation rates up to $-1.7 \text{ mm yr}^{-1}$, while one upwards moving PS, located in the lower-middle part of the architecture, has moved with an average annual LOS velocity of $+1.6 \text{ mm yr}^{-1}$ (figures 7(b) and (c)). All these PS are characterized by constant LOS displacement trends, which confirm the persistence and the progression of active deformation. The brick-faced masonry of the apse wall is actually severely fractured, with vertical cracks running from the top to the lower arcades (figure 7(d)). It is reasonable to interpret the obtained satellite data as reliable evidence of the structural effects due to a progressive opening of the fissures, with movements perceived along the LOS, respectively, away and towards the satellite for the two parts separated by the cracks.

A deformation macro-pattern also characterizes the structures of the Cisterna delle Sette Sale, namely the former cistern for water supply of the baths. Comparing both the RADARSAT-1 data stacks with the RADARSAT-2 one, a worsening of the structural condition is recognizable in the period June 2008–June 2010 (figure 8). A PS moving away from the satellite with average LOS deformation rate of $-4.1 \text{ mm yr}^{-1}$, jointly with several DS distributed over the top of the cistern and showing common LOS displacement trends, identifies the entire monument as one of the most unstable sectors of the Oppio Hill in the last two years of monitoring (figures 8(c) and 9(a)). The MP spatial distribution
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Figure 8. MP spatial distribution of: (a) RADARSAT-1 F3 ascending (2003–2010); (b) RADARSAT-1 S3 descending (2003–2009); (c) RADARSAT-2 S3 descending (2008–2010) for the Cisterna delle Sette Sale on the Oppio Hill. Green squares indicate relatively stable sectors, while the red square in (c) marks the deformation macro-pattern detected over the whole monument. Localized deformation is also found on the SW corner of the monument (orange PS in (a)).

Figure 9. Time series of: (a) one PS and four DS RADARSAT-2 S3 descending (2008–2010) identified over the Cisterna delle Sette Sale (cf figures 8(c)); (b) two PS RADARSAT-1 F3 ascending (2003–2010) identified on the SW corner of the western façade of the Cistern (orange PS in figure 8(a)), with a common acceleration phase in July 2004–September 2005.

suggests the occurrence of an overall instability process at the top of the monument, affecting both the southern and northern parts, with major deformation concentrated in 2009, followed by a relative stability in 2010, as observed in the respective time series (figure 9(a)).

The impression of a recent worsening is particularly emphasized by the comparison with the stable values of average LOS velocity estimated over the same area, within the RADARSAT-1 descending data in the period March 2003–August 2009 (figure 8(b)). Further confirmation of existing conservation criticalities is also provided by the localized deformation on the SW corner of the western façade (figure 8(a)), the time series of which show average LOS deformation rates up to $-2.3 \text{ mm yr}^{-1}$ and a common acceleration phase with LOS velocities up to $-16.7 \text{ mm yr}^{-1}$ recorded in the interval July 2004–September 2005 (figure 9(b)).

Although the reduced image archive has inevitably limited the value that can be assigned to the RADARSAT-2 data, the obtained results contributed to highlight the potential criticality of the cistern, thereby supporting the hypothesis of the local conservators about structural instability currently affecting the monument. As an immediate implication, further terrestrial surveys were activated by the Archaeological Superintendence to retrieve the knowledge basis necessary to plan the most appropriate interventions.

4.4. Back monitoring of instability events

The availability of SAR images, which record the condition of the area of interest at the time of acquisition and allow the evolution of deformation to be followed with a certain temporal continuity, actually configures the possibility to perform ‘back monitoring’ of past instability events.

Referring to the definition firstly given by Cigna et al (2011), this term is here specifically adapted to applications on
cultural heritage sites, with the meaning of ‘measurement and reconstruction in retrospect of past deformation events based on the interpretation and analysis of historical data’. The latter are mainly constituted by the deformation time series associated with the MP identified during the PSI processing phase.

A demonstrative example of how this type of back analysis can support the comprehension of the nature of past events is offered by the back monitoring of the collapse that occurred on 30 March 2010, close to the hypogean structures of Nero’s Golden House (figure 10). Despite the limits due to the paucity of the RADARSAT-2 images and the technical differences between the processed data stacks, some interesting considerations can be drawn based on the following PSI results.

The RADARSAT-1 ascending data temporally covering till 22 February 2010, i.e. a few weeks before the occurrence of the event, show a single stable DS, the time series of which does not highlight any acceleration phases and/or deviations from the displacement trend over the whole monitoring period, especially in the months prior to the collapse (figure 10(a)).

Similarly, the RADARSAT-1 descending data, acquired until August 2009 according to an acquisition geometry complementary to that of the previous data stack, led us to identify a single PS, spatially attributable to the southern front of the n. XV and XVI Trajan galleries. Its time series confirms a relative stability throughout the monitoring period, particularly starting from July 2005, without any LOS estimation associable with acceleration and/or worsening of the PS displacement trend (figure 10(b)).

The only element recognizable within the time series of these two MP consists in a slight seasonal trend of the LOS displacements, which is presumably associated with the swelling/contraction cycles of the clayey soils of the terrain formerly covering the collapsed gallery.

Finally, the RADARSAT-2 descending archive, including SAR images straddling the event and the post-event phase, does not show any radar target over the area affected by the collapse (figure 10(c)). As expected from the damages caused by the event, the pre-existing elements on the ground, which have generated MP in the previous data stacks covering the pre-event phase, were totally destroyed, with a complete and irreversible modification of the observed scene.

The absence of any previous deformation trend in the pre-event monitoring data, as well as of acceleration phases and/or deviations from the trend immediately before the occurrence of the collapse, assumable as precursors prefiguring the instability phenomenon, does not support the hypothesis of the predictability of the event, although it could not exclude it at all. Based on these satellite evidences, the collapse appears to be ascribed to the typology of phenomena characterized by immediate and unexpected occurrence, not necessarily preceded by effects perceivable at the surface. Indeed, it is more probable that the failure was caused by coactions of destabilization processes active in the inner structure of the covering terrain during a time interval, the length of which cannot be exactly assessed based on the satellite data. In these terms, the triggering factors are to be found in un-controlled water seepage, the progressive consumption of mortars and the...
disaggregation of the structural elements due to the mechanical actions of tree roots.

This assessment finds a solid validation in the results of the inspections carried out by the local conservators immediately after the collapse and, more generally, in the repeated water infiltrations from the vaults of the hypogean rooms of Nero’s Golden House. Caneva et al. (2006) have also demonstrated which impacts on the stability of the buried masonries are progressively produced by the actions of tree roots. In this regard, the methodological approach adopted in the experimentations recently activated by the conservators in Nero’s Golden House confirms that a key point in attempting the solution of the present conservation issues is considering the ‘archaeological structures—covering terrain system’ in its entirety, with a deep analysis of its multiple criticalities and related impacts.

4.5. Early-stage warning (ESW)

What was observed for the area damaged by the 2010 collapse does not imply that such types of phenomena cannot be predicted or preventively discovered when they are not evolved yet. Indeed, this sort of back analysis plays a relevant role for activities of preventive diagnosis in cultural heritage contexts.

ESW actually means the identification of past/recent conservation criticalities at an early stage of their evolution and consequent warning of potential near future instability events, before irreversible damage to the monument(s) can occur (Tapete et al. 2012).

For this purpose, the detailed analysis of the MP deformation time series is essential to recognize deviations from the trend and/or accelerations which can be referred to the (re-)activation of instability phenomena, especially if these LOS displacements are recorded in the last period of the monitoring time interval. The higher the number of SAR images (and related LOS displacement estimations) which constitute this trend, the more alarming these displacement deviations are. In such a case, it is likely to exclude that these displacements are only occasional events.

This type of analysis is particularly useful to discover unstable situations whenever the average LOS velocity values of the identified MP do not seem worrying. It is quite common that an average LOS deformation rate calculated over the entire monitoring period and not exceeding the stability threshold (which is usually fixed at the values of $\pm 1.5$ mm yr$^{-1}$, according to the sensitivity of the PSI techniques) corresponds to a sequence of displacement phases with opposite directions of movement, which give an overall stable value when they are averaged. Such apparently stable MP can actually hide displacement phases within their time series, frequently including the following two situations:

- accelerations with movements keeping the same direction as the previous trend;

Figure 11. (a) MP spatial distribution of the RADARSAT-2 S3 descending (2003–2009) data for the two sectors of the western part of Nero’s Golden House, where the identified MP show acceleration phases in the last year of monitoring (b) and (c), potentially assumable as precursors of near future instability for an area characterized by the partial/total superimposition between buried structures and covering terrain (d).
• deviations from the trend, with LOS displacements which have an opposite direction of movement and configure an inversion of the trend.

In both cases, the level of attention has to be raised, especially if the single and/or group of MP showing these types of displacement trend are located in correspondence to vulnerable areas or elements of cultural value, for which the condition report by the conservators warns about potential structural instability.

An interesting example is offered by the ESW performed for the western Neronian rooms of Nero’s Golden House (figure 11). The time series of the DS identified in the RADARSAT-1 descending (2003–2009) data over the western side of the monument are characterized by a common deviation from the previous trend in the last year of monitoring, with a clear inversion of the displacement direction, from upwards to downwards movement. The average LOS velocity values range from −3.7 to −7.5 mm yr\(^{-1}\) (figures 11(a)–(c)) and the result is quite alarming, since they appear as being still in progression.

Looking at the location of the identified MP, the two areas affected by these movements respectively correspond to a sector of Nero’s Golden House completely covered by the overlying terrain, and to masonry partially exposed and outcropping from the rear covering terrain (figure 11(d)). Both these areas are typologically similar to that damaged by the 2010 collapse, and the satellite evidence of active and progressive deformation movements has encouraged the activation of a specific ESW. Indeed, on-site inspections confirm the presence of deterioration patterns on the brick-faced structures and the appropriateness to assign a high level of criticality to the entire sector.

The time series-based ESW can also be effective to raise the alert about a reactivation of a past phenomenon, which was temporally stabilized or decelerated. This is the case of the already discussed acceleration phases, recognized for the MP identified close to the Temple of Magna Mater, within the RADARSAT-1 ascending (2003–2009) data (see figure 5(c)). A previous acceleration phase developed in 2003–2004 and was followed by a long phase of movements with average LOS velocity of about −1.6 mm yr\(^{-1}\). The occurrence of this new acceleration phase has further contributed to classify the area neighbouring the Temple of Magna Mater as one of the most unstable, and targeted interventions have been consequently designed by the Archaeological Superintendence.

5. Conclusions

The potentials of the PSI techniques for monitoring activities in archaeological sites mainly rely on the direct support which they can provide to the monument conservators in achieving an updated knowledge of the existing criticalities, as well as of the situations of potential instability over huge areas of investigation, coupled with detailed evaluations focused on single structures.

The PSInSAR processing approach and its recent advance, the SqueeSAR algorithm, have proven to be highly suitable for MP identification over different types of archaeological contexts, which is the essential element to performing a reliable and wide-coverage deformation analysis. In particular, as demonstrated for the case studies of the Palatino Hill, Roman Forum and Oppio Hill, the added value of this type of analysis consists in the possibility to retrieve not only information about the displacement field of the exposed heritage, but also evidences of criticalities affecting partially/totally buried structures, as discovered for Nero’s Golden House.

The correlation between the detected displacements and local geohazards found in the case of the Palatino Hill opens to further implementation over cultural heritage sites threatened by natural and/or human-induced deterioration processes. This also encourages the adoption of conservation strategies which include the restoration of the architecture component and, at the same time, the stabilization of the whole system formed by the monument and its foundation substratum.

According to a similar perspective the satellite evidences achieved for the Oppio Hill have to be read, with specific regard to Nero’s Golden House. The prevention of future collapses can be possible only if all the hazard factors are tackled, by executing interventions which deal with the structural issues of both the covering terrain and hypogean environments. The here proposed time series-based ESW procedure represents a promising tool for the preventive diagnosis of instability phenomena, complementarily to constant inspections and targeted terrestrial surveys.

As underlined by many authors, the new satellite missions like the COSMO-SkyMed constellation of the Italian Space Agency and TerraSAR-X of the German Aerospace Center are expected to improve the capabilities in the detection of deterioration processes with faster kinetics, thanks to shorter repeat cycles (up to a few days). Not less useful will be the availability of new SAR acquisitions, such as those which will be offered by the ESA Sentinel-1 constellation in the near future, especially in view of a better planning of the acquisition programmes, which might include the monitoring of archaeological areas spread all over the world among their priorities.

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