Satellite-based preventive diagnosis: use of Persistent Scatterer Interferometry on cultural heritage sites in Italy

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Abstract

We exploited ERS-1/2 and ENVISAT Persistent Scatterer Interferometry (PSI) datasets of the Italian Extraordinary Plan for Environmental Remote Sensing (EPRS-E), to analyse ground motions over two Italian cultural heritage sites. The deformation patterns over the archaeological site of Capo Colonna in Calabria Region, confirmed the persistent exposure of the ruins to regional-scale land subsidence, with up to 5-10 mm/yr motion velocity observed for the Column. Similarly, a high level of conservation criticality was assigned to the church of San Romolo in the countryside settlement of Bivigliano, Northern Tuscany. The strong correlation between the observed structural damages, PSI data and the pre-existing landslide maps highlighted the need of updating the inventory, redefining the boundaries of the landslide which actually threatens the preservation of the historical building.

Keywords: *Persistent Scatterer Interferometry, radar-interpretation, deformation patterns, time series analysis, cultural heritage*

1. Introduction

Effective strategies for preventive conservation of monuments and sites are increasingly based on selective identification of unstable and critical sectors. The detection of superficial effects as indicators of ongoing/upcoming deterioration processes is a key element to preventively discover structural weakness, and to promptly activate warning procedures, especially over huge areas of investigation. Among the currently used satellite radar-based methods, the multi-interferogram algorithms of Persistent Scatterer Interferometry (PSI) were here selected to carry out a set of feasibility tests, to verify whether these techniques can actually become routine remote sensing tools to back monitor deformation affecting historic built environments and cultural heritage. Site-specific analyses were performed by exploiting the nationwide PSI datasets derived from ERS-1/2 and ENVISAT data acquired in 1992-2010 over the entire Italian territory, and made available within the Extraordinary Plan for Environmental Remote Sensing (EPRS-E), promoted by the Ministry of Environment, Territory and Sea. The two case studies of the archaeological site of Capo Colonna in Calabria Region, Southern Italy, and the countryside settlement of Bivigliano, Northern Tuscany, are discussed in this paper as demonstrative examples of the benefits retrievable to identify key areas of concern for the conservation, and to update the condition report of monuments.

2. Methodology

To perform our study, we interpreted the PSI data of the of ESA's C-band sensors onboard ERS-1/2 (1992-2000) and ENVISAT (2003-2010) satellites (Table 1), already processed in the framework of the EPRS-E project (National Geoportal 2012a-b) by means of, respectively, the PSInSAR technique (Ferretti *et al.* 2001) and PSP-DIFSAR approach (Persistent Scatterers Pairs - DIFferential InSAR; Costantini *et al.*, 2000).

The multi-spatial/temporal analysis was performed following the procedure of "PSI-based rapid mapping and deformation analysis", and related "scale of conservation criticality" [1], developed by Tapete and Cigna (2012) specifically for purposes of preservation of monuments and cultural heritage sites. In particular, deformation time series were exploited to reconstruct the evolution of past/recent structural instability, according to the method referred to as "back monitoring" (Cigna *et al.*, 2011), adapted to structural monitoring and early stage warning of cultural heritage sites by Tapete *et al.* (2012).

Site	Satellite	Geometry	Time interval
Capo Colonna	ERS-1/2	Ascending	27/03/1995 – 17/10/2000
	ERS-1/2	Descending	18/06/1992 – 17/12/2000
	ENVISAT	Ascending	24/06/2003 – 27/07/2010
Bivigliano	ERS-1/2	Descending	24/04/1992 – 27/11/2000
	ENVISAT	Ascending	16/10/2003 – 27/05/2010
	ENVISAT	Descending	10/02/2003 – 28/06/2010

Table 1: *Summary of the PSI datasets analyzed over the sites of Capo Colonna and Bivigliano, Italy.*

3. Results

3.1 Satellite evidences of subsidence and cliff instability in Capo Colonna

The archaeological site of Capo Colonna occupies the head of a promontory overlooking the Ionian Sea, SE of Crotone, and derives its name from the unique column (the Column) still standing on site of the former Greek temple dedicated to the goddess Hera (Figure 1). Located at the margin of a composite terrace (Figure 1c), at about 15 m a.s.l., the site is undermined by sea erosion which triggers rockfalls and collapses (Chiocchini, 2000). Subsidence historically affects the entire promontory as well.

The ERS (1992-2000) data reveal active subsidence over the whole promontory (Figure 1A), with a homogeneous deformation pattern with displacements away from the satellite in the descending dataset in June 1992 – December 2000 (Figure 1A). Average Line Of Sight (LOS) velocity (V_{LOS}) of -6 mm/yr and a definite trend away from the satellite are recorded since May 1995 for the PS located within the archaeological site. Going westward inland, V_{LOS} increases up to -10 mm/yr. Comparison of PS distribution with lithological and marine terraces maps highlights that subsidence is mainly concentrated over the calcareous terrace, which constitutes the foundation of the archaeological structures.

Subsidence remains active even after 2000, as observed from the PSP-DIFSAR analysis of the ENVISAT ascending dataset (2003-2010) (Figure 1B). In the central part of the promontory, the spatial distribution of the V_{LOS} shows higher values than in the coastal area, with values ranging from -5 to -13 mm/yr. Hence, contribution from local groundwater pumping, which overlaps onto the effects of local geology, cannot be ruled out. Three localized micro-patterns were identified on the following sectors of the archaeological site: 1) Column and Temple A; 2) balneum and building M; 3) Capo Nao Tower and St. Mary Sanctuary (Figure 1C). Within sector 1, the Column and the surrounding basement show displacements with average V_{LOS} of -4.8 mm/yr and two different accelerations recognizable within the PS time series, respectively, in the periods June 2004 – August 2005 and June 2008 – March 2009. Similar acceleration phases characterize PS distributed on the nearby foundations of the Temple A. Localized displacements affect both ruins and ground at the SW corner of the balneum and the area of building M (sector 2), with average V_{LOS} of -5.6 mm/yr and same changes in displacement trend as those in the PS time series identified on the architectural structures of Capo Nao Tower and the church (sector 3). Movements away from the satellite, with V_{LOS} up to -4.3 mm/yr, were detected along the rock cliff. These displacements can be reasonably attributed to the combination of land subsidence and rock slope instability.

[1] The term "conservation criticality" refers to natural and/or human-induced factors, conditions and dynamics which can bring to the triggering of deterioration processes, and more generally to key areas of concern for the conservation of the area of investigation.

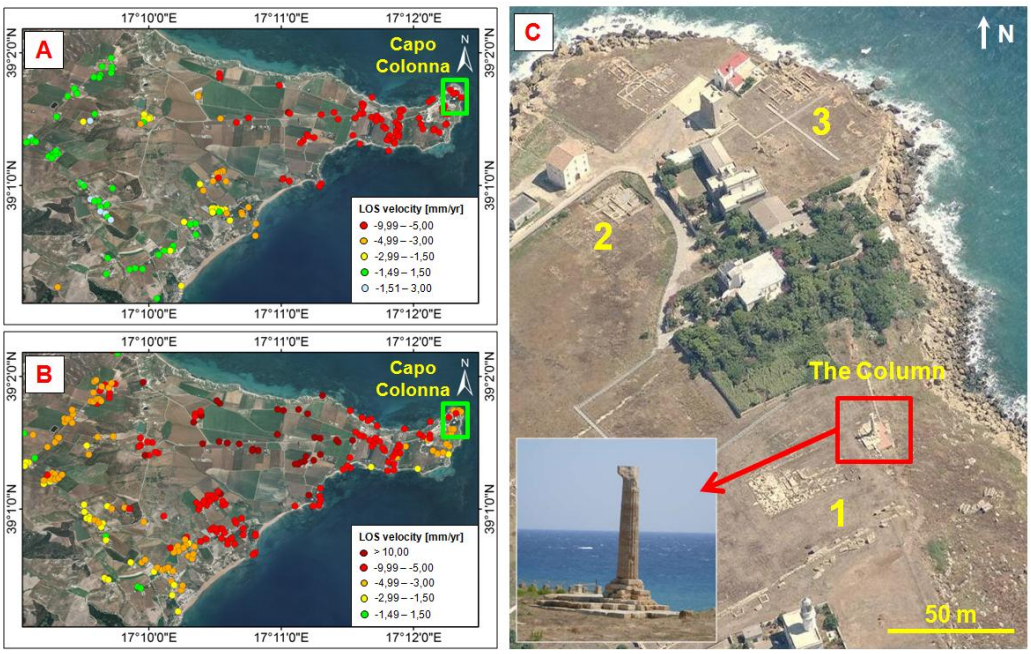

Figure 1: *Subsidence macro-pattern detected over Capo Colonna promontory: A) ERS descending data (1992-2000); B) ENVISAT ascending data (2003-2010). Deformation affects the archaeological ruins in the sectors: 1. Column and Temple A; 2. balneum and building M; 3. Capo Nao Tower and St. Mary Sanctuary.*

3.2 Landslide impacts on the heritage of Bivigliano imaged by PSI data

Sited 20 km north of Florence in the municipal territory of Vaglia, the countryside settlement of Bivigliano preserves fine examples of rural historic heritage, among which the Romanesque parish church of San Romolo. Geologically, several landslide bodies are reported over the village in the Regional Geological Map (*Carta Geologica Regionale* – CGR) Sheet 263120 at the scale 1:10,000. Due to landslipping, in modern times the old cemetery of the village was moved to the present place (Figure 2).

At the scale of entire site, the multi-temporal analysis of the PS spatial distribution of both the ERS descending (1992-2000) and ENVISAT descending (2003-2010) datasets highlights the persistence, from the historical period (1992-2000) to the recent one (2003-2010), of an extended deformation macro-pattern covering most of the residential sectors of Bivigliano, with LOS displacement field mainly characterized by movements going away from the satellite. Correlation between the spatial distribution of most the identified PS clusters and the presence of landslide bodies is inferred based on the boundaries and extent of the landslide phenomena mapped in the above mentioned CGR.

In this environmental context, the worst situation was found for the Church of San Romolo (Figure 2). ENVISAT descending (2003-2010) data show a clear deformation micro-pattern over the entire complex of the church (Figure 2a). All the five identified PS, including the one which appears stable, share a common LOS displacement trend going progressively away from the satellite, with V_{LOS} reaching the maximum value of –2.7 mm/yr and a total LOS displacement up to –20 mm over approximately seven years (Figure 2b). The recent history of the church and on site inspections validate the analyzed PSI data. During the monitoring period (1992-2010), several interventions of stabilization and consolidation were carried out by the local authorities and heritage bodies. Nevertheless, new cracks recently opened and currently cross over the pavement in front of the main entrance of the church. Also, new fissures progressively developed on the brick floor inside the church, starting from the main entrance and reaching the middle of the nave and the southern wall, as well as huge cracks which run on both the exterior and interior façades (Figure 2c). Curiously, looking at the landslide inventory reported in the CGR, the boundary of an 'active slide' runs close to the church, but does not include it (red dashed line in Figure 2a). Based on the PSI data and ground truth, it seems reasonable to propose a modification of the landslide boundaries, to be extended also to the area of the church, as well as the execution of detail ground investigations preparatory to the design of appropriate consolidation works, to be performed both at the level of the unstable ground and the deteriorated structures.

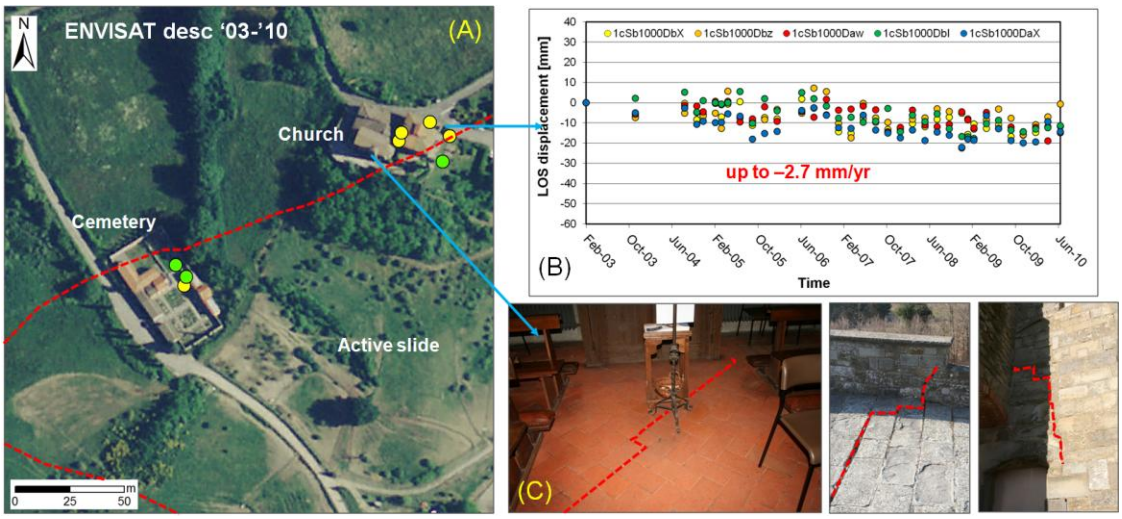

Figure 2: (A) *ENVISAT descending (2003-2010) PS V_{LOS} over the Church of San Romolo and the cemetery of Bivigliano, and examples of deformation time series (B) . Severe cracks affect the exterior and interior wall surfaces and floor of both the cemetery and the church of San Romolo (C).*

4. Conclusions

The performed radar feasibility tests prove the suitability of PSI data for deformation analyses at both the scales of entire site and single monument. Although the PSI data here radar-interpreted were not formerly processed for cultural heritage applications, they were of sufficient quality to detect ongoing instability processes affecting cultural heritage and monuments of the analyzed sites. The conservation criticalities discovered over the archaeological site of Capo Colonna highlight a worsening of the impacts of the regional-scale active subsidence and an increased susceptibility of the ruins to cliff instability, finding a good agreement with risk mapping reported in the Hydrogeological Setting Plan for Capo Colonna promontory, which classifies them as landslide-prone areas. Benefits of PSI data to improve existing mapping products, inventories and condition reports of monuments have been also demonstrated for the case of Bivigliano. Radar mapping was essential to retrieve evidences of landslide activity as natural cause of the damages observed in the last years in the church of San Romolo.

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