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Cultural heritage, landslide risk and remote sensing in Italy

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Abstract Italy is the country that owns most of the world cultural heritage and is affected by a very large number of landslides widespread throughout its territory. Aim of the work is to define a methodology, developed on GIS platform, in order to assess cultural heritage exposed to very slow and extremely slow mass movements using: SAR data, the Italian Cultural Heritage database and the Italian Landslide Inventory. The methodology has been developed at provincial level and tested on Macerata province. A single building approach has been also performed on six cultural heritage. The proposed methodology could be applied to all cultural heritage sites in Italy to identify priorities and plan field surveys, detailed studies and monitoring systems.

Keywords Landslide, Cultural Heritage, Remote sensing, PSIn-SAR, Italy;

Introduction

Italy is the country that owns most of the world cultural heritage as it's clear from the list of sites of inestimable value to humanity, prepared by UNESCO under the Convention concerning the protection of the world cultural and natural heritage ratified in 1972. The Italian territory is also particularly prone to natural hazards such as landslides, floods, earthquakes, volcanic eruptions, subsidence and coastal erosion which undermine the protection and preservation of cultural heritage. Since early 90's the capability of Synthetic Aperture Radar (SAR) Interferometry technique (Gabriel et al. 1989; Massonet et al. 1993; Massonet and Feigl 1998) have been exploited to study surface displacement and deformation due to different geohazard. In particular, the multi-image Permanent Scatterers SAR Interferometry (PSInSAR^{TM}) technique (Ferretti et al. 2000, 2001), developed by Politecnico di Milano and licensed exclusively to Tele-Rilevamento Europa (TRE), has showed its capability to provide information about ground deformations over wide area with millimetric precision, making this technique suitable for both wide and site scale investigations. (Colesanti et al. 2003; Colesanti and Wasowsky 2004; Hilley et al. 2004; Ferretti et al. 2005; Dixon et al. 2006; Tamburini et al. 2010; Rucci et al. 2010).

Scope of this work is to define a methodology, developed on GIS platform, in order to assess cultural heritage exposed to very slow/extremely slow mass movements using satellite remote sensing data in addition to the Italian Cultural Heritage database (*Carta del Rischio del patrimonio culturale*) and the Italian Landslide Inventory *(Progetto IFFI)*.

Material and data source

Italian Cultural Heritage database

The Cultural Heritage database, prepared from 1992 by the Central Institute for the Conservation and Restoration, contains 100,258 cultural heritage divided into three categories: Architectural Heritage, Archaeological Heritage and Modern Containers of artworks. It has been realized collecting, geo-referencing each cultural heritage and compiling the vulnerability data sheet (e.g. state of preservation).

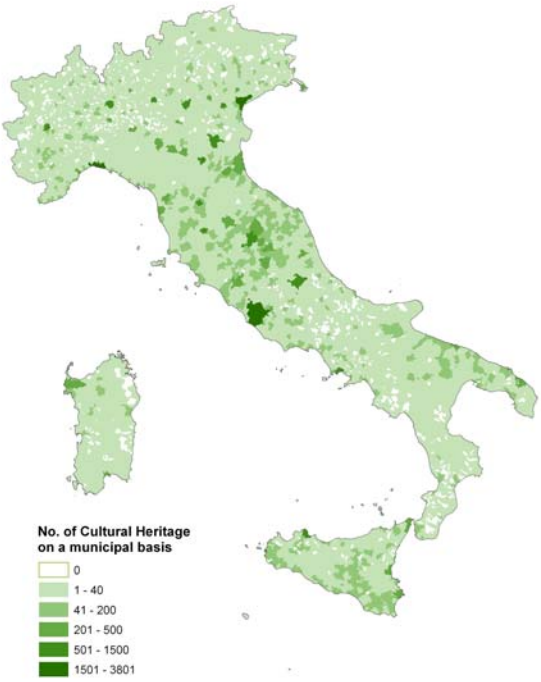

Figure 1 Italian Cultural Heritage density at municipal level

The Italian Landslide Inventory

The Italian Landslide Inventory, realized from 1997 by ISPRA (Italian National Institute for Environmental Protection and Research) and the Regions and Self-Governing Provinces of Italy, identifies and maps the landslides occurred within the national territory. It contains more than 486,000 landslides affecting an area of about 20,800 km², equal to 6.9% of Italian territory.

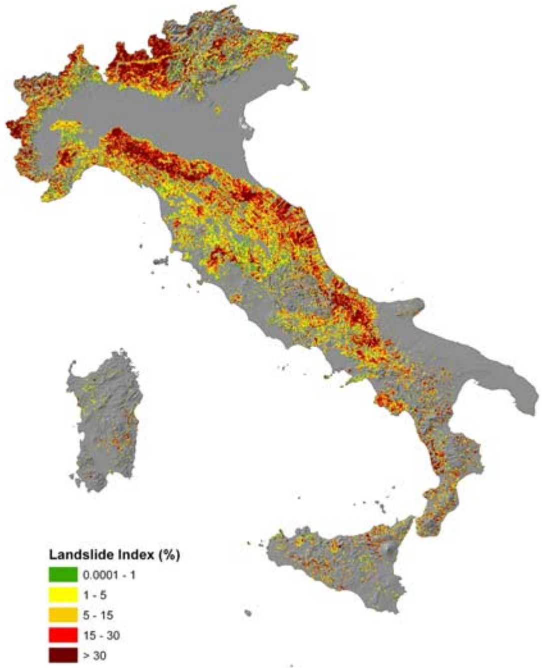

Figure 2 Landslide Index derived from the Italian Landslide Inventory

Satellite SAR data

For this study, SAR scenes acquired by ERS (ESA) and RADARSAT satellite CSA covering respectively the 1992-2001 and 2003-2010 time periods, were processed using the SqueeSAR™ technique. SqueeSAR™, the second advanced generation of PSInSAR™ technique (Ferretti et al., in press), allows quantitative, high precision, multiscale monitoring of surface deformation, by exploiting long temporal series of satellite SAR data acquired over an area of interest, during a specific time period. The technique leads to identification and exploitation of stable natural reflectors, that keep almost the same electromagnetic behaviour in all the radar images acquired at different times, where very precise displacement information can be retrieved. SqueeSAR™ displacement measurement are made in the sensor's line of sight (LOS), that is the sensor to target direction, and are spatially related to a ground point of known coordinates, called reference point, and temporally related to the first image's acquisition date. The output of a SqueeSAR™ analysis consists on a database of measurement points (MP): PS (permanent scatterers) and DS (spatially distributed scatterers). The database contains for each point the ground target's position, the LOS displacement's annual average rate and the displacement's time series.

Methodology

The present work aims at defining a methodology for the identification of architectural, archaeological and monumental sites exposed to very/extremely slow mass movements (Cruden and Varnes 1996). Thanks to its capability to detect millimetre level displacements over long periods and large areas, SqueeSAR™ analysis is complementary to conventional methods of landslide investigation and monitoring in order to improve and complete the information on very slow and extremely slow phenomena evolution. Furthermore, as a consequence of the availability of satellite data archives covering almost two decade, surface displacement time series calculated for all the radar benchmarks identified make it also possible to change the scale of the analysis from wide to site, allowing an in depth study of the evolution of single instability phenomena, identifying buildings potentially damaged and even verifying the efficiency of remedial works.

The main limitations of the SqueeSAR™ technique are that it cannot measure deformation along the North-South direction since these movements are parallel to the satellite orbit; vegetation prevents to identify stable radar targets and consequently to estimate ground deformation patterns; theoretically, on a single isolated radar target the measurement of displacement between two single acquisitions along the sensor-target direction are limited to a fraction of the wavelength (5.6 cm for C-band ERS and RADARSAT satellites); precision of velocity measurements decrease with the increase of the distance from the reference point which is assumed to be stationary.

The methodology has been applied on a province territory and on six cultural heritage located in 5 sites (Fig. 3).

Figure 3 Location of the test site (in blue) and location of the selected province (in yellow).

Provincial approach

The provincial approach consists of a preliminary analysis of a large number of cultural heritage aimed at identifying those exposed to landslide risk.

The cultural heritage (mentioned below as CH) have been preliminary processed passing from point to polygon geometry through generation of a 30 meters buffer. The landslides classifiable as slow movements (*sensu lato*) have been extracted from the Italian Landslide Inventory: rotational/translational slide, slow earth flow, complex landslide referring to rotational/translational slide evolving in slow earth flow, lateral spread, deep-seated gravitational slope deformation and areas affected by numerous shallow landslides in mostly clay and flysch deposits. It is necessary to consider that the SqueeSAR™ technique could be partially applicable depending on the landslide rate of movement. More in detail, the proposed methodology is not applicable to all CH falling within or near the landslides not included in the mentioned data extraction (e.g. rockfall/topple, debris flow, unclassified type of movement). The CH localized in hilly mountain area have been distinguished from those falling in plain areas, using a model derived from the DEM 20x20m (Trigila and Iadanza, 2008). CH inside or within a distance of 20 m from the extracted landslides have been then selected. The distance of 20 m allows to take into account landslide evolution. Finally different SAR datasets have been processed according to the images availability over the province area.

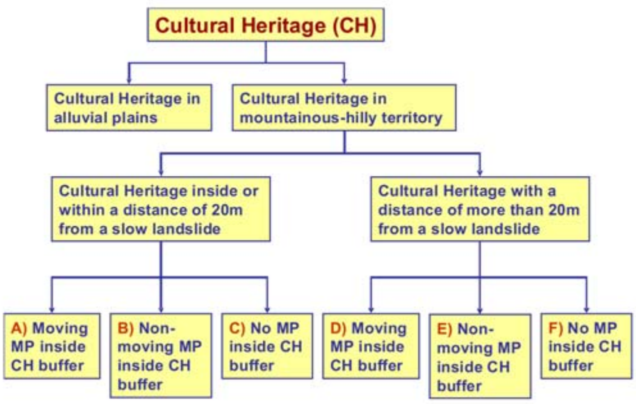

Figure 4 Flow chart of Provincial approach (MP stands for measurement point)

On the basis of the results of the SqueeSAR™ analysis, for CH located inside or next to a landslide, three cases are possible: A) at least one moving MP, in the CH buffer, characterize by LOS mean annual displacement rate above a significant threshold; B) non-moving MP with the displacement rate below threshold; C) no MP into the CH buffer (Fig. 4). The velocity threshold, in absolute value (positive or negative values correspond to motion towards or away from the satellite), has been defined equal to 2 mm/year + 2σ, where σ is the maximum standard deviation of all MP average velocities of the dataset in order to take into account the precision of measurements related to each dataset processed with SqueeSAR™ technique.

In case A, the landslide is active and there is a high probability that the CH has been damaged. In order to assess the reliability of the information, a more detailed analysis should be performed (see single building approach). In case B, the landslide could be inactive during the monitored period, unless the movements cannot be measured with SqueeSAR technique because the rate of movement is greater than the measurable threshold (phase unwrapping errors) or the deformation occurs along the north-south axis. However a landslide reactivation could involve the CH in the future. In case C no MP have been identified in the CH buffer and no information about displacement can be analyzed. In case B, there may be moving MP outside the CH buffer which indicate that the CH neighborhood is stable but other portions of the landslide are active and could involve the CH due to advancing or retrogressive evolution of the landslide. In case B and C the landslide state of activity should be evaluated through the integration of other sources of information (e.g. field survey, in situ monitoring).

Also for the CH with a distance greater than 20 m from a landslide, 3 cases are possible: D) at least one MP is moving in the CH buffer; E) non-moving MP are identified; F) there are no MP in the neighborhood of CH. In case D the movement could be due to either structural problems independent from a landslide (e.g. differential settlement of the building foundations) or to an incomplete landslide inventory (Trigila et al., 2010). More in detail, an active landslide could be not recorded in the IFFI Inventory or mapped with a less extensive perimeter. In case E there is congruity between non-moving MP and the absence of surveyed instability phenomena.

Single building approach

The single-building approach is different from the provincial approach in several aspects: 1) the CH is represented in its real dimension measured on the orthophoto; 2) the position of MP respect to CH is carefully evaluated verifying if they fall directly on the CH building, in the forecourt, or on neighboring buildings; 3) the number of MP and % of moving MP, the standard deviation of velocity, the displacement time series, coherence and noise of each displacement time series are analyzed; 4) the velocity of MP located in the CH neighbourhood are analyzed in order to exclude the possibility that the CH displacements are related to structural problems independent from the landslide; 5) the reliability of the SqueeSAR data and the Italian Landslide Inventory is evaluated using other sources of information as scientific literature and archive data (e.g. AVI - Inventory of areas historically affected by landslides and floods in Italy realised by CNR/GNDCI http://sici.irpi.cnr.it/avi.htm; ReNDiS - Italian national database of landslide and flood mitigation measures by ISPRA http://www.rendis.isprambiente.it/rendisweb/).

Results and discussion

The provincial analysis has been applied to Macerata province since it contains a large number of cultural heritage and it's affected mainly by slow mass movements. Of the total number of 1,331 CH of Macerata, 69 fall into alluvial plains and 1,262 fall into hilly-mountainous areas. Slow movements constitute the 86% of a total of 9118 landslides identified by the IFFI project. More in detail 3,121 are classified as rotational/translational slide, 2,049 as slow earth flow, 773 as complex landslide, 46 as deep-seated gravitational slope deformation and 1,823 as areas affected by numerous shallow landslides (Trigila, 2007). The processing of SAR scenes has identified 155,124 descending MP and 184,115 ascending MP for the RADARSAT dataset.

The Macerata province analysis has provided the following results: 171 CH are within or next to (distance ≤ 20m) a landslide, of which 10 are classified as case A, when at least one moving MP (RSAT ascending or descending) falls in the CH buffer; 145 CH as case B, when non-moving MP fall in the CH buffer and 16 as case C, when no MP falls in the CH buffer.

Of the remaining CH (distance > 20m from a slow or very slow landslide), 26 are classified as case D with at least one moving MP, 991 as case E with non-moving MP and 74 as case F with no MP (Fig. 5).

Therefore, the applied methodology has allowed the identification of 36 cultural heritage (case A + D) on which, as a priority, field surveys and more detailed analysis have to be performed. In case A there is a good accordance between the presence of landslide and the LOS displacement rate of MP in the neighborhood of the CH which may have suffered damages. A detailed analysis is required to verify if the MP fall directly on the CH building, in the forecourt, or on neighboring buildings (see single building approach). In case B no displacements of the CH have been registered during the satellite observed period unless the movements cannot be measured with SqueeSAR technique. Anyway the CH could be affected by a reactivation of the landslide.

Finally 28 CH fall within or near landslides classified as rockfall/topple, debris flow or with unclassified type of movement, collected by the IFFI project that are not considered in this study. These CH require ad hoc studies using other methods of analysis.

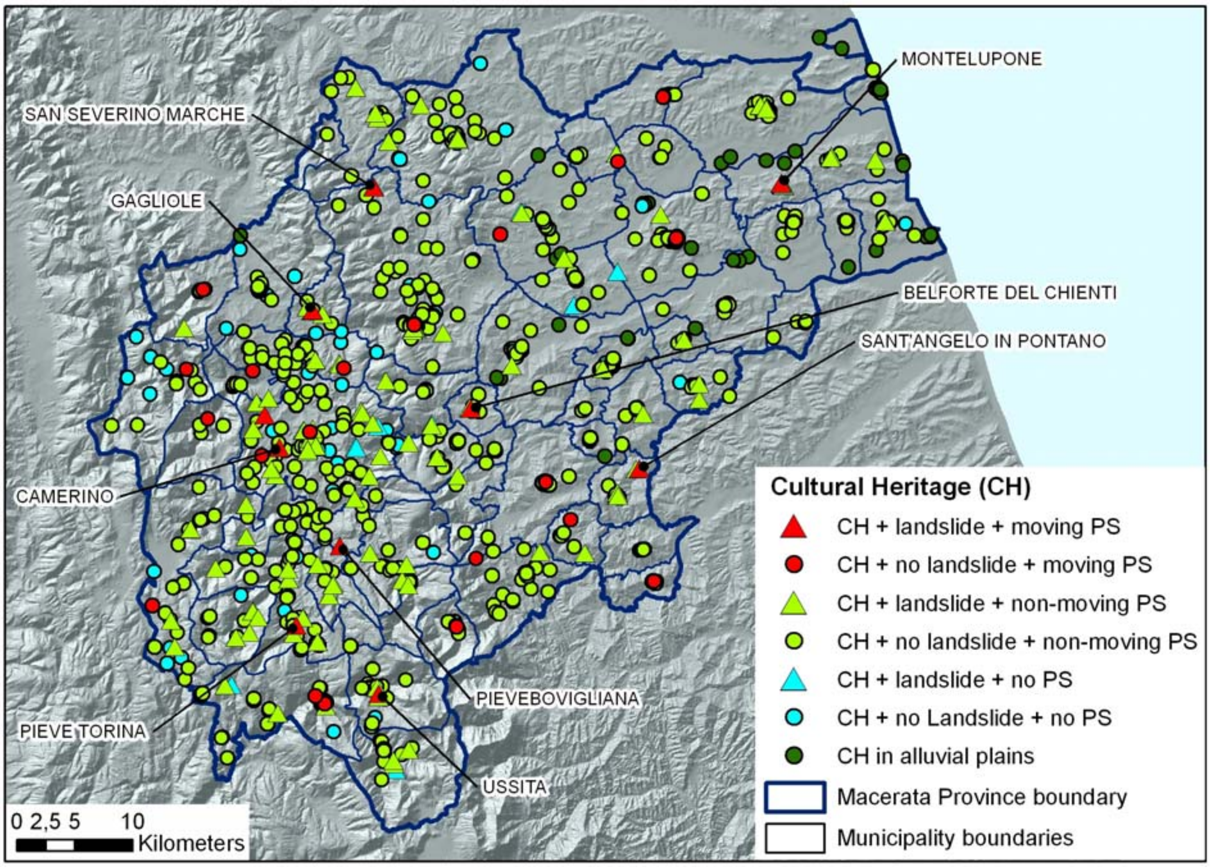

Figure 5 Results of Macerata province analysis

The single building analysis has been performed on 6 CH located in 5 sites. The CH have been selected among those located inside or next to a slow/very slow landslide and that suffered damages in the past (Tab. 1).

Table 1 Catalogue of the selected case study for the single building analysis

Cultural Heritage	Municipality Province Region	Type of movement (IFFI DB)	Date of landslide triggering	Landslide restoration works	In situ monitoring systems	References and archive data	Satellite and geometry	Satellite monitored period
Church of S. Francesco (ID code: 2ICR00331 10AAAA)	Montelupone (MC), Marche Region	Rotational/ translational slide	XVIII sec. 1928 1954 13/11/1980	1980: two drainage tunnels; 2009-2010: new sub-horizontal drains	1980: inclinometers piezometers and crack gauges; 2010: new monitoring system	ReNDiS Project (ID: 187/08); Cherubini et al., 1983.	ERS 1/2 Ascending	23/08/1992 03/12/2000
							ERS 1/2 Descending	11/06/1992 14/01/2001
							RADARSAT 1 Ascending	04/03/2003 23/09/2010
							RADARSAT 1 Descending	15/03/2003 04/10/2010
Temple of Juno Lacinia; (ID code: 1ICR00031 49AAAA)	Agrigento (AG), Sicily Region	Rotational/ translational slide; Rock fall/topple	Dec. 1976	2007		AVI Project; Cotecchia et al., 2000, 2005.	RADARSAT 1 Ascending	21/03/2003 27/11/2010
							RADARSAT 1 Descending	05/03/2003 11/11/2010
Cathedral of S. Gerlando (ID code: 2ICR00030 940000)	Agrigento (AG), Sicily Region	Rotational slide	1506 1745 1898 28/02/1944 July 1966 Feb. 2006 Dec. 2010 March 2011	1999: micro-piles 2006		AVI Project; ReNDiS Project (ID: 390/09); Cotecchia et al., 2000, 2005.	RADARSAT 1 Ascending	21/03/2003 27/11/2010
							RADARSAT 1 Descending	05/03/2003 11/11/2010
Convent of S. Francesco d'Assisi (ID code: 2RTI07602 24AAAA)	Pietrapertosa (PZ), Basilicata Region	Rotational/ translational slide	1930	1930: masonry buttresses; 2009: landslide restoration works;	1997-1998: inclinometers 1997-1999: piezometers	Coppola et al., 2006.	ERS 1/2 Descending	17/05/1992 20/12/2000
							RADARSAT 1 Ascending	18/03/2003 20/08/2010
Church of S. Maria Assunta (ID code: 2ICR00349 80AAAA)	Gorgoglione (MT), Basilicata Region	Rotational/ translational slide	1973 1980 2003	1988: bulkheads	2004-2005: topographic levelling 2008: crack gauge	AVI Project; Guerricchio & Melidoro, 1990; Pancioli et al., 2009.	ERS 1/2 Ascending	23/05/1992 02/11/1999
							ERS 1/2 Descending	17/05/1992 20/12/2000
							RADARSAT 1 Ascending	18/03/2003 20/08/2010
Church of S. Maria (Rabatana) (ID code: 2ICR00351 950000)	Tursi (MT), Basilicata Region	Rotational/ translational slide	1930 1931 23/01/1972			AVI Project; ReNDiS Project (ID: 031/07); Lazzari et al. 2006, 2010.	ERS 1/2 Ascending	23/05/1992 02/11/1999
							ERS 1/2 Descending	17/05/1992 20/12/2000
							RADARSAT 1 Ascending	18/03/2003 20/08/2010

Regarding the case study of Gorgoglione, the southeast portion of the village, where the church of S. Maria Assunta is located, is affected by a landslide classified as rotational/translational slide in the IFFI inventory. Landslide reactivation has been recorded since 70's documented by scientific papers and archive data (Guerricchio and Melidoro, 1990; Pancioli et al., 2009). The SqueeSAR™ analysis of RSAT ascending data shows that the landslide was active in the period 2003-2010 (Fig. 6 and 7). Although there are no PS on the church building, there are several moving PS on adjacent buildings characterized by an annual average rate of about 15 mm/y and a displacement of about 12 cm cumulated in seven years and five months of monitoring. In 1998 remedial works (bulkheads) have been realized in the main scarp. Recently the church has been consolidated and restored with Programma Operativo Val D'Agri founds (Regione Basilicata, 2010)

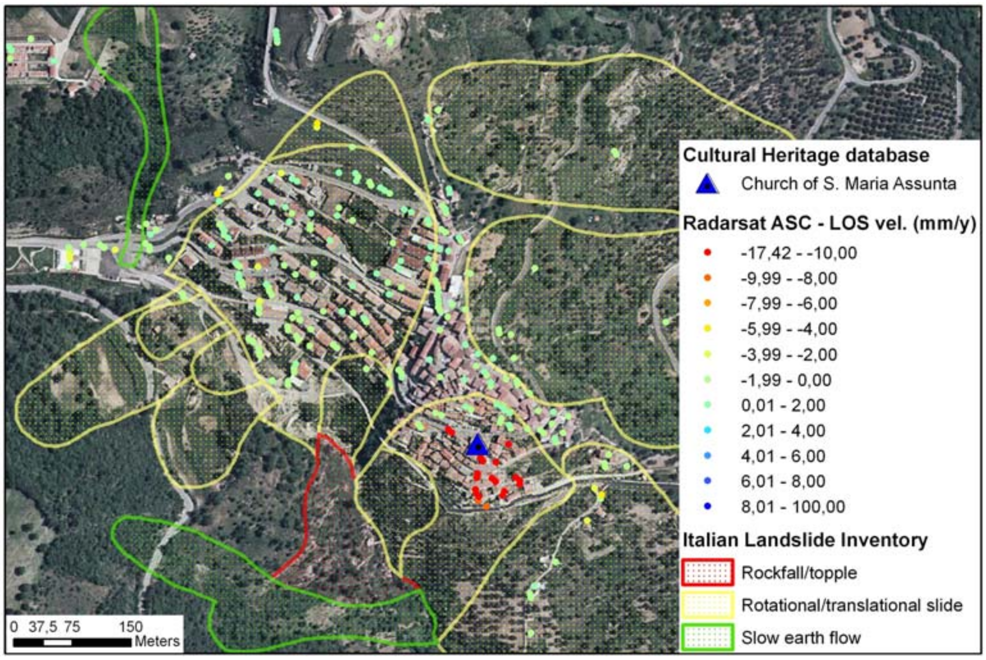

Figure 6 SqueeSAR™ analysis - Church of S. Maria Assunta (Gorgoglione, Basilicata Region)

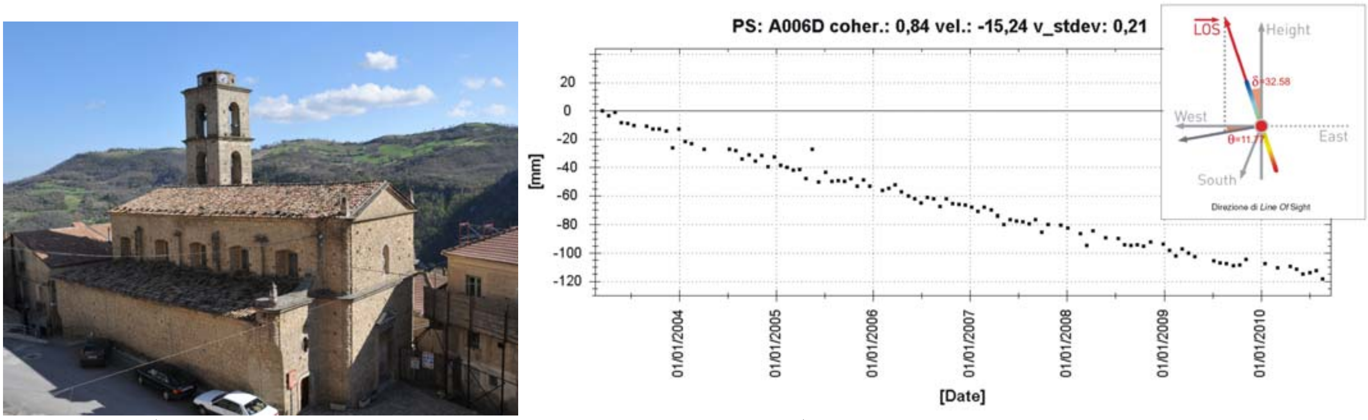

Figure 7 a) Church of S. Maria Assunta after restoration works in 2010; b) displacement's time series of a PS located on a building adjacent to S. Maria Assunta

Regarding the other case studies, the SqueeSAR™ analysis shows non-moving PS on the Church of S. Francesco (Montelupone) and the Temple of Juno Lacinia (Agrigento) in the period 2003-2010. On the Convent of S. Francesco d'Assisi (Pietrapertosa) there are non-moving PS in the period 1992-2010. The presence of non-moving PS on the CH which in the past have suffered damage caused by landslides, documented by literature sources, indicates that the landslide is inactive in the period monitored with satellite data, unless the movements cannot be measured with SqueeSAR technique, or that the stabilization measures have stopped the movement. On the Cathedral of St. Gerlando in Agrigento there are some moving PS near the transept and the north-west corner in the period 2003-2010 (Fig. 8).

There are non-moving PS from 1992-2010 on the building of the Church of S. Maria Rabatana (Tursi). At short distance of about 20 m from the CH there are moving MP near the landslide scarp (2003-2010), which demonstrate the activity of a portion of the landslide (Fig. 9).

Figure 8 Cathedral of S. Gerlando (Agrigento, Sicily Region)

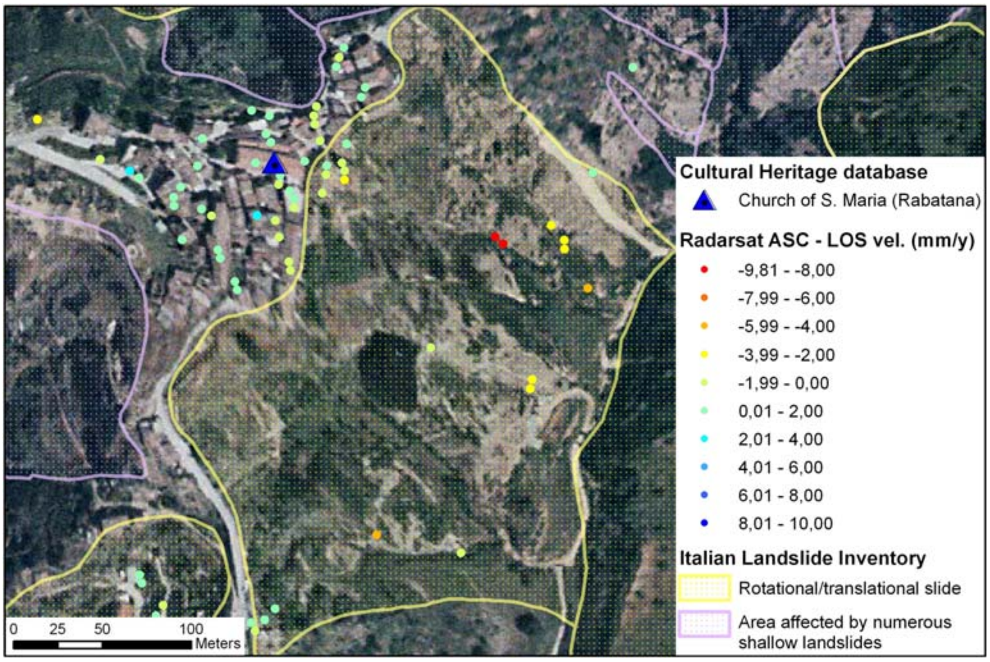

Figure 9 SqueeSAR™ analysis - Church of S. Maria, Rabatana (Tursi, Basilicata Region)

The next steps of the research will concern the estimation of vertical and E-W horizontal displacement component using the vector resulting from the two acquisition geometries (ascending and descending) and the comparison between satellite and in situ monitoring data.

The methodology implemented in this study has allowed to assess the potential and limits of interferometry technique for the identification of cultural heritage exposed to very slow and extremely slow landslides. The proposed methodology could be applied to all cultural heritage sites in Italy and it could provide a useful tool to identify priorities and plan field surveys, detailed studies and monitoring systems, allowing job scheduling of cultural heritage maintenance.

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