Long-term GNSS and SAR data comparison for the deformation monitoring of the Assisi landslide

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Key words: GNSS, SAR, InSAR, deformation monitoring, landslides

SUMMARY

A relevant part of the Assisi urban area (central Italy), built up after 1950 and located outside of the ancient town center, is interested by a landslide characterized by a slow rate of movement, which has caused important damages to buildings for an accumulation effect in time. The movements of the soil surface have both a horizontal and a vertical component.

A GNSS network for deformation monitoring purposes has been established over the area since 1995, connecting by means of a baseline network the moving region with stable geologic formations located well outside of the landslide body. Further (1999), a leveling network has been added to improve the definition of the vertical component of the motion field. Surveys of both GNSS and leveling networks have been carried out in time, with an approximately annual cadence, until the actuality. Time series of coordinates and heights spanning along the observation period (1995-2010) are hence available for the network points.

The Assisi landslide area has also been investigated by means of satellite SAR interferometry InSAR: the data here presented derive from the analysis of ENVISAT ASAR data spanning in time from 2003 to 2010, thus with a 7-years overlapping with the GNSS and leveling surveys, which make possible a comparison.

The comparison has been made for each GNSS marker with the surrounding InSAR scatters, trying to take into account local topological effects when possible. A good agreement between the results of the different techniques has been found in most cases, and a deeper analysis of the movement field and the landslide edge is derived from the complete set of data.

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1. SHORT DESCRIPTION OF THE CASE UNDER STUDY

The study refers to a landslide interesting a urban expansion area of the Assisi town, built starting from the years 1950-1960. The area is located completely outside of the historical town center, at a distance of some hundreds of meters from the ancient city wall.
The landslide interests a slope with an average inclination of about 21%, where at the time of the first building activity the signs of a ground motion were not noticed, in default of exhaustive geological studies. The urbanization of the area caused relevant changes to the flow regimen of the surface waters, deviating and/or covering existing ditches and streams. Around 1970 the first phenomena clearly attributable to an active landslide started to show, in the form of growing damage to buildings (initially attributed to local foundations failures), but also retaining walls, pipelines and street paving.
The area was investigated from a geological-geotechnical point of view, reaching the conclusion that it was interested by an active landslide with a surface extension of about 50 hectares, and individuating an estimated perimeter of the moving area (fig. 1). The landslide is of a gravitational type (*translational creep*). The sliding surface has been individuated from inclinometers data at an average depth of some tens of meters, with a maximum of about 60 m. The moving formation consists of a debris mass flowing over a stable bedrock composed of marl, sandstone and limestone.
The area has been monitored since the years 1970-1980 with geotechnical techniques (drillings, inclinometers, piezometers, etc.), and a conventional geodetic network (angles and distances). The geodetic monitoring was interrupted at the mid 80s for its excessive cost and practical difficulties due to obstruction of the visuals caused by buildings and trees. Since 1995, the Perugia University (with the contribution of CNR in the early years) has established a GNSS control network over the area, integrated from 1999 on by a leveling network. GNSS and leveling campaigns have been performed since then with an about annual cadence up to the actuality.
Since about 1980, stabilization works have been undertaken on the landslide area by the Assisi municipality and other public subjects, in the attempt to slow down the motion rate or possibly stop it at all. In the initial phase most works have interested the surface water regimen, and not directly the deep sliding surface. A more effective intervention campaign, consisting on the draining of deep water, has started in 2006 by the *Provveditorato Interregionale alle Opere Pubbliche per la Toscana e l'Umbria* (Department of Public Works for Tuscany and Umbria), but the works have undergone interruptions and delays for technical and administrative reasons, and are still in progress.

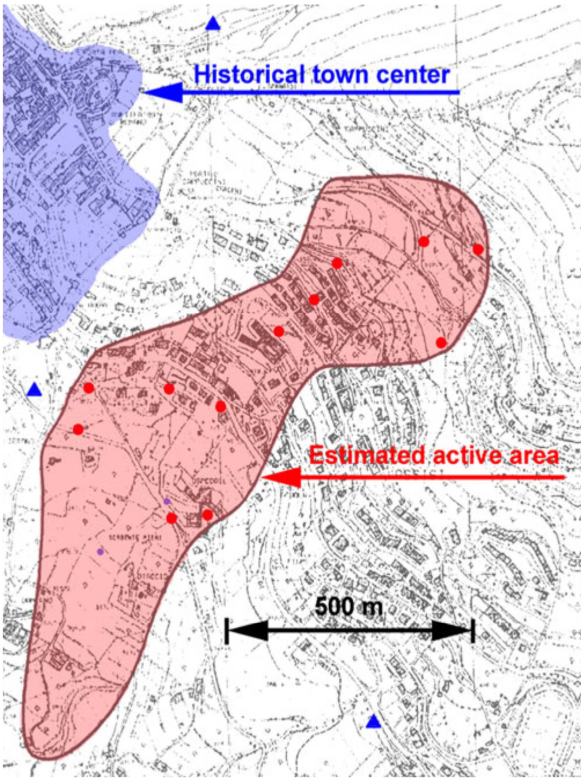

Fig. 1 – The Assisi landslide and its location with respect to the town center; triangles and dots and represents respectively GNSS fiducial and control points (see further paragraphs)

2. PREMISES AND SCIENTIFIC BACKGROUND

2.1. InSAR techniques and their application to the study of ground deformations

Thanks to the all-weather, day-night and even retroactive capability to detect and quantify accurately ground surface deformations, Synthetic Aperture Radar Interferometry (InSAR) techniques appear attractive for landslide hazard investigations and possibly for alert purposes (Colesanti and Wasowski 2006; Corsini et al. 2006; Cascini et al. 2010; Bovenga et al 2012).

An InSAR system measures the phase difference between SAR echoes backscattered from targets on the ground and received by two antennas located at slightly different positions (with a relative distance known as *spatial baseline*). This phase difference is related to the ground elevation of the target, and to the displacement possibly occurred between the acquisition of the two images (Hanssen 2001).

Nowadays, different space-borne SAR data are available for InSAR applications. The European Space Agency (ESA) missions ERS-1/2 and **ENVISAT** archived a big amount of data acquired in C-band (about 5 cm of wavelength) and at medium resolution (5x20 m^2) from 1992 to 2010. This precious archive allows to look back in time searching for instability phenomena almost allover the Earth surface. The **RADARSAT-2** satellite from Canadian Space Agency is still working, providing C-band data with also better resolution than ESA missions.

Finally, the last generation SAR sensors, namely **Cosmo-SkyMed** from Italian Space Agency (ASI) and **TerraSAR-X** from the German Space Agency (DLR), operating on X-band (about

3 cm of wavelength) thanks to the improved capabilities in terms of both resolution (from 3 to 1 m) and revisit time (11 to 4 days), allow significant advances in the achievable accuracy and sensitivity and open new application frontiers.

2.2. GNSS, Leveling and InSAR data integration for landslide monitoring

GNSS, Leveling and InSAR are three different techniques which can contribute in different ways to the investigation of a ground deformation phenomenon such as a landslide.

A common characteristic is that all of them are only capable to give information on the ground surface movements. For a full description of a landslide mechanics, it is necessary to integrate the surface analysis with a subsoil investigation, performed by means of inclinometers and/or other instruments pertaining to Geotechnics.

Each of the three techniques has its own peculiarities, including some advantages and drawbacks:

GNSS positioning (normally effected in static post-processed mode) provides absolutes three-dimensional coordinates of the control points in a well defined datum (ETRF89 for the case under study). The execution of GNSS campaigns repeated in time (the intervals can be regular or not) permits to describe the local motion of the marker points in the most complete way, evidencing the northing, easting and height components of positions, displacement vectors and velocities (fig. 2). As counterpart, the monitoring regards only a certain number of markers, which for economical reasons can not be extremely dense. Thus, the description of the motion field resulting from GNSS only data is not continue and an interpolation is necessary between the surveyed points.

Leveling campaigns, normally performed nowadays with digital levels, provide a one-dimensional information, only referring to the height component of position and displacement. There is no way to derive the planimetric components, so the description of the deformative phenomenon is not complete. Fig. 3 shows as the same vertical deformation component can derive from ∞^2 possible displacement vectors, varying for direction and inclination with respect to the vertical itself.

Planimetric-only movements cannot be evidenced at all. Still, in the case of landslides, the motion almost always includes a vertical component, because the sliding is normally caused by the weight of the moving masses. Thus, a partial description is obtained, but it regards a relevant (often the most relevant) part of the motion.

InSAR also provides a one-dimensional information, in a kind of similar way to leveling, but referring to an oblique direction, the sensor Line Of Sight (LOS). Moreover, the determination is not absolute, but relative, resulting from the interferometric comparison between two images acquired at different epochs. There is no way to derive from single InSAR dataset the effective movement vector in its three components, as fig. 4 shows: the same deformation on the LOS can derive from ∞^2 possible displacement vectors, varying for direction and inclination with respect to the LOS. Deformations occurring on a plane perpendicular to the LOS cannot be seen at all. Thus, the displacement direction and field cannot be recovered by InSAR, unless at least three independent datasets or assumptions on the ground motion are available, which is not common.

The location and density of the controllable points is not predictable. In urban areas the scatterers are often quite dense, but they cannot be placed where the researchers want as with the geodetic methods, unless artificial reflectors are used.

Still with such drawbacks, the InSAR technique has relevant and peculiar advantages:

- a good accuracy on the LOS component, which gives sensitivity and attitude to identify moving areas with respect to surrounding stable regions, and to give alert when a landslide activity is starting or re-starting;
- a high density of controlled points in areas where many scatterers are visible;
- the possibility to investigate what happened in the past, as long as SAR images are available for the study area.

What above discussed leads to an inevitable conclusion: each technique has its own peculiarities and drawbacks, and the best solution for an accurate description of a ground deformation phenomenon comes from an **integration** of the three techniques.

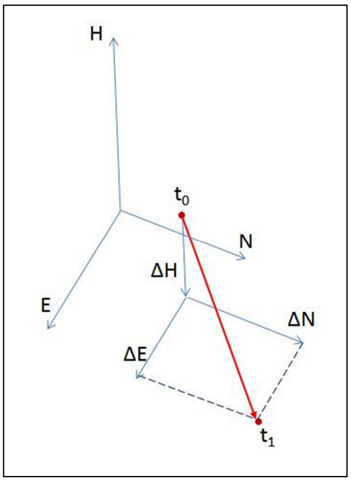

Fig. 2 – The GNSS technique individuates a 3D displacement vector univocally.
Also positions and velocities are computed with all three components.

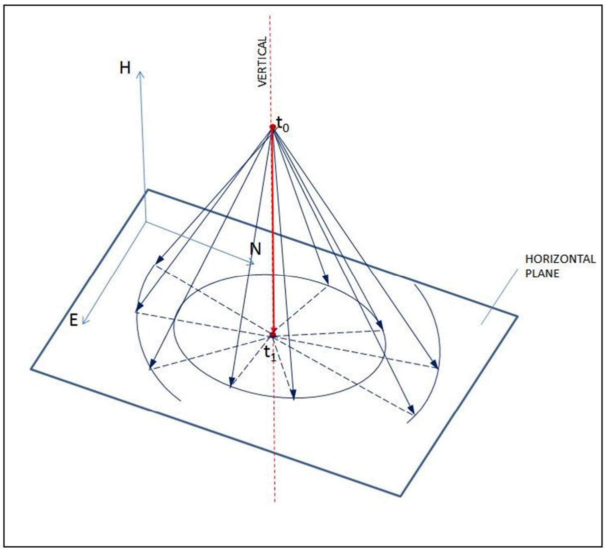

Fig. 3 – Leveling only measures the vertical component of the displacement vector.
There are ∞^2 possible displacement vectors having the same vertical component.

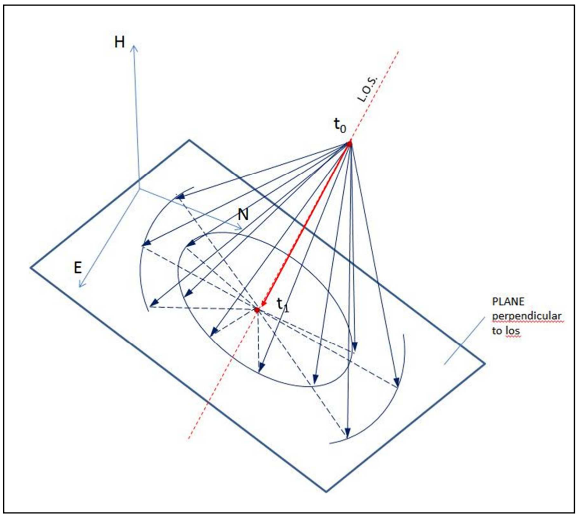

Fig. 4 – InSAR only determines the LOS component of the displacement vector.
There are ∞^2 possible displacement vectors having the same LOS component.

2.3. InSAR validation issues and research objectives

InSAR-based displacements data are currently used in different application fields to aid traditional in situ measurements (GPS, leveling, inclinometers). In order to evaluate the effective accuracy provided by the InSAR techniques, different experiments have been carried out in the past. They compare directly or indirectly the displacements derived by InSAR with those computed through GPS or leveling. Among others, the works of Samsonov et al. (2007) and Henriques et al. (2011) can be mentioned.

This work provides an assessment of the ground displacements derived by InSAR over the Assisi landslide in terms of relative performance (cross-comparison between the two different methods) as well as absolute accuracy (validation) derived by using GNSS measurements. This landslide has been already investigated by processing C-band ERS-1/2 SAR data acquired between 1992 and 2000 (Guzzetti et al. 2009). The present study, besides adding validation and cross-comparison issues, extends the displacement analysis up to 2010 by using both C-band ENVISAT ASAR. In particular for InSAR processing (see chapter 4) have been used both the SPINUA algorithm, which is an independent implementation of the Persistent Scatterers technique, and the TSIA algorithm, which is an alternative coherent-based approach for multi-temporal InSAR analysis. In situ measurements are provided by a GNSS network, and leveling data are also available for a future deepening of the research.

The comparison is performed on small areas, putting into evidence local topological effects when they show. Besides of the InSAR validation and the comparison with GNSS, from the data an hypothesis on the active landslide perimeter is derived.

3. THE ASSISI LANDSLIDE GNSS CONTROL NETWORK

3.1. Network set up and survey campaigns

The Assisi GNSS network in its initial configuration (1995, fig. 5) includes 6 references or “fiducial” points located in geologically stable sites (S01 to S06), and 14 “control” points in the landslide area (M01 to M14). Because of the draw scale, in fig. 5 the vertex S01 falls

outside of the map, about 1.2 km eastwards.
The network was set up and measured for the first time in 1995. Measurement campaigns were carried out with an about annual cadence up to 2001. From 2002 to 2005 the survey activity was temporarily interrupted due to a lack of funding. In 2006 the project was refinanced, and the network was densified adding 16 new control points (M20 to M35), in order to get a better description of the field of movements and replace some damaged or lost markers. The present configuration includes 28 control points and 5 fiducial points.
The campaigns from 2001 on have been performed with GPS/GLONASS double frequency geodetic receivers, the previous ones with GPS only. All the observations have been performed in static mode, with 2 hours sessions at a sampling rate of 5 seconds.

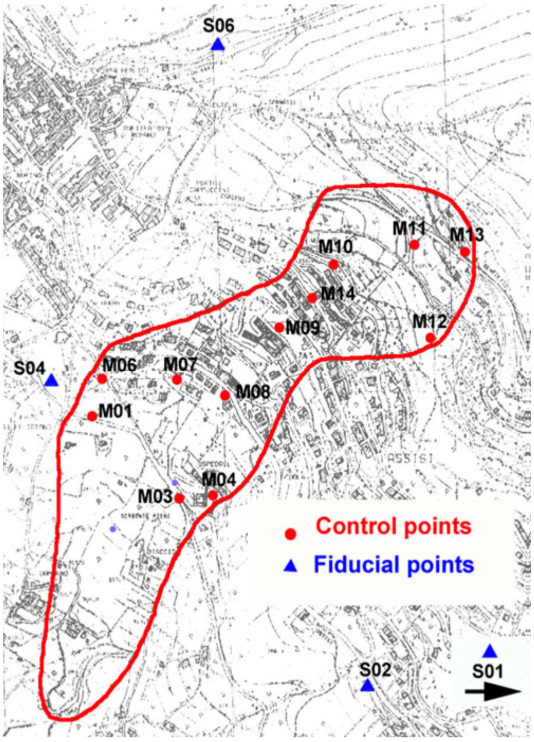

Fig. 5 - Assisi landslide GNSS network, original configuration (1995)

3.2. Analysis of the GNSS results

Comparing the results of the subsequent campaigns performed on the network, the displacements resulting for the control points (when confirmed as effective displacements by means of the criteria described above – point f) can be analyzed and graphically represented in various modes, in order to describe the field of surface movements of the landslide. The analyses here presented are limited to the points M01-M14, for which the time series of coordinates spans for the longest period (1995 to 2010).
Fig. 6 shows the displacements for the control points referring to the 1995-2008 period (complete observation sets for all existing control points). The planimetric vectors (resulting of northing+easting components) are drawn in red with their effective orientation, while the height vectors are drawn in blue.
The planimetric vectors show a field of movements in agreement with the landslide

characteristics described in the first chapter: a creep, where the upper layers of the soil slowly slide on a stable formation at a depth of some tens of meters. The maximum displacements are located in the central part of the landslide body, and their direction follows approximately the maximum slope line.

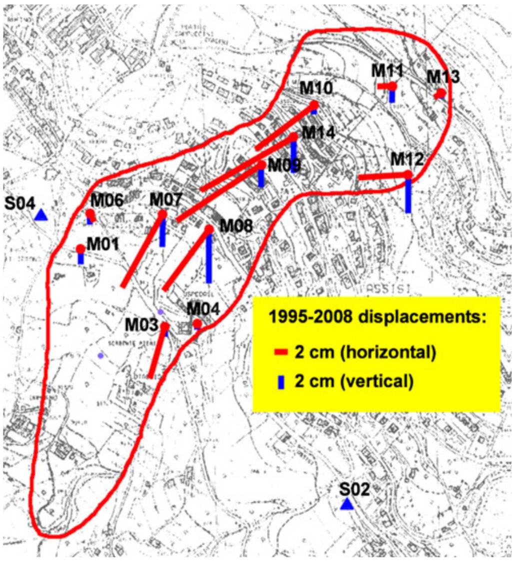

Fig. 6 - Assisi GNSS network, 1995-2008 displacement vectors

A stacking in time of the available solutions leads to coordinate time series, some of which (corresponding to the maximum N, E, H total displacement components among the control points) are shown in fig. 7 as variations from the initial values (set on zero), with error bars at 1σ.

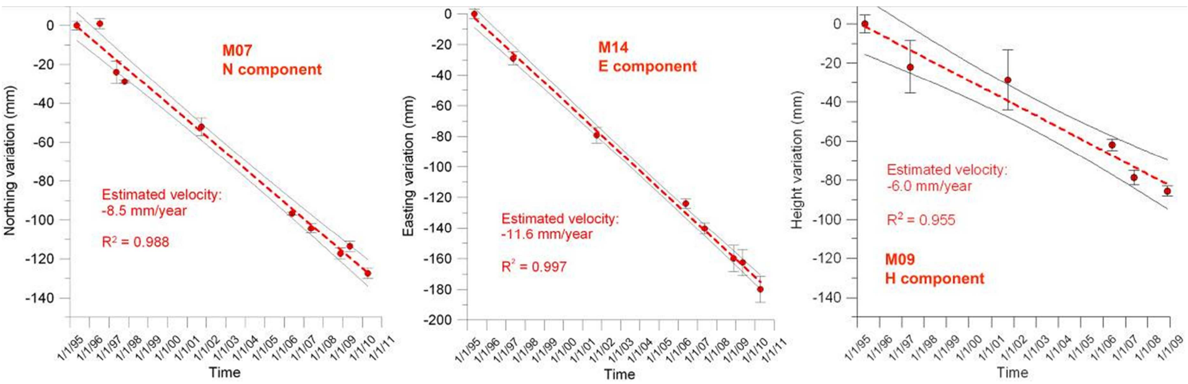

Fig. 7 - Examples of coordinate time series, showing an almost linear behaviour

A linear regression is shown in the graphs with the red dashed line. The squared correlation coefficient R^2 is always very close to the unity, indicating an almost constant velocity (the order is about 1 cm/year) on a long term period. The vertical component, as usual with GNSS observations, is characterized by higher uncertainty and noise than the horizontal components, so the data are more scattered. More details on the GNSS network, its development and processing can be found in Dominici et al. (1998), Cilli et al. (2002) and Fastellini et al. (2011).

4. SAR DATA ANALYSIS

The ASAR sensor onboard of the ENVISAT ESA satellite is active since 2002 acquiring SAR images in C-band (λ = 5.6 cm) with different acquisition modes, polarizations and incident angles. This satellite followed the ERS-1/2 ESA mission ensuring the continuity of C-band data acquired with a revisit time of 35 days and a resolution cell size of about 20 m by 5 m along range and azimuth directions respectively.
The C-band ASAR dataset utilized for the present experimentation consists of 39 STRIPMAP SLCs acquired between October 2003 and May 2010 along descending passes, with mean incident angle of around 23° (Track 531, Frame 2741; Image Swath: IS2; Polarization VV; green frame in Figure 8). The 7-years overlapping with GNSS measurements allows validation of the displacements derived by InSAR processing.

Fig. 8 – Coverage of ENVISAT descending dataset (green frame).

The ASAR data processing has been performed by means of two different approaches, SPINUA and TSIA.
The SPINUA algorithm is a Persistent Scatterers Interferometry (PSI) like technique originally developed with the aim of detection and monitoring of coherent PS targets in non- or scarcely-urbanized areas (Bovenga et al., 2004, Bovenga et al., 2006). It has been further updated to deal with wide areas, also densely urbanized. It adopts ad hoc solutions which enable to get fast results, on small areas by processing also scarcely populated stack of SAR images. In particular, a patch-wise processing scheme is developed: The patches (usually covering an area of a few km^2) are selected with the aim to optimize the density and the distribution of potential PS. Their small size allows using locally an approximated model for the atmospheric phase signal and ensures high processing robustness. Final data consist of a precisely georeferenced persistent scatterers database, including average velocity, precise

elevation value, as well as the complete displacement time series.
The TSIA technique is based on a processing chain that performs a sequence of a low resolution (small scale) and a full resolution (large scale) processing. The small scale analysis in this work has been performed via the SBAS algorithm (Berardino et al., 2002). The algorithm uses spatially averaged data, in addition to the threshold on the baselines, to mitigate the effects of decorrelation. The products are: a) the low resolution deformation time series, b) the low resolution residual topography and c) the Atmospheric Phase Delay (APD) stack. The low resolution products are employed to perform a phase calibration of the full resolution images for the large scale analysis. In this work the latter is based on a tomographic processing (exploiting both the amplitude and the phase information) (Fornaro et al., 2009), that improves the performances in the detection and monitoring of dominant scatterers with respect to the classical (phase only) PSI techniques.

5. GNSS-InSAR COMPARISON

As discussed in chapter 2, GNSS and InSAR are different techniques giving different results not only for their completely different approach and data type, but also from a geometrical point of view: GNSS supplies the displacement vectors in three dimensions (geocentric XYZ or eulerian ENH) while InSAR only gives the variations of the component along the LOS.
The LOS direction is known, expressed by its direction cosines with respect to the geocentric XYZ reference system. The cosines are slightly varying from a SAR target to another, but in a relatively small area like that under study average values can be reasonably assumed.
Thus, starting from the GNSS-derived XYZ coordinates time series, the components of the displacement vectors for the control points along the LOS have been derived from the following expressions:

$$\Delta X = X_i - X_0$$
$$\Delta Y = Y_i - Y_0$$
$$\Delta Z = Z_i - Z_0$$

$$\Delta_{LOS} = \Delta X \cdot \cos LOS_X + \Delta Y \cdot \cos LOS_Y + \Delta Z \cdot \cos LOS_Z$$

where the suffix *0* indicates the initial or “zero” values of the coordinates, and the suffix *i* the value at a given epoch *i*.
The LOS components derived from GNSS data as described above for each control point of the GNSS network have been compared with those of the SAR scattering targets located around the GNSS marker, chosen among the closest to it (even if never coinciding with it). The analysis has been effected on the Envisat InSAR data computed with the two different approaches described in the former chapter, for all available epochs (from October 2003 to May 2010), after a realignment of the time scales (i.e. adopting the same zero epoch for GNSS and InSAR).
The comparison is shown in the following graphs (figs. 9 to 12), referring as example to the GNSS point M14, characterized by the highest displacement velocity. In the x-axis the time scale (with the dates), in the y-axis the displacements referred to the zero epoch of the SAR

time series (October 2003). The blue triangles indicates the GNSS-derived LOS values, while the color circles indicates the LOS displacements of the SAR targets, also accompanied by their identification numbers. For each GNSS point the location of the SAR scattering targets is indicated on a portion of the Assisi ortophoto map. For a better understanding of the single points behavior, linear regressions have been estimated for both GNSS and InSAR points. Figures 11-12 show the regression lines for the same data sets of figs. 9-10.

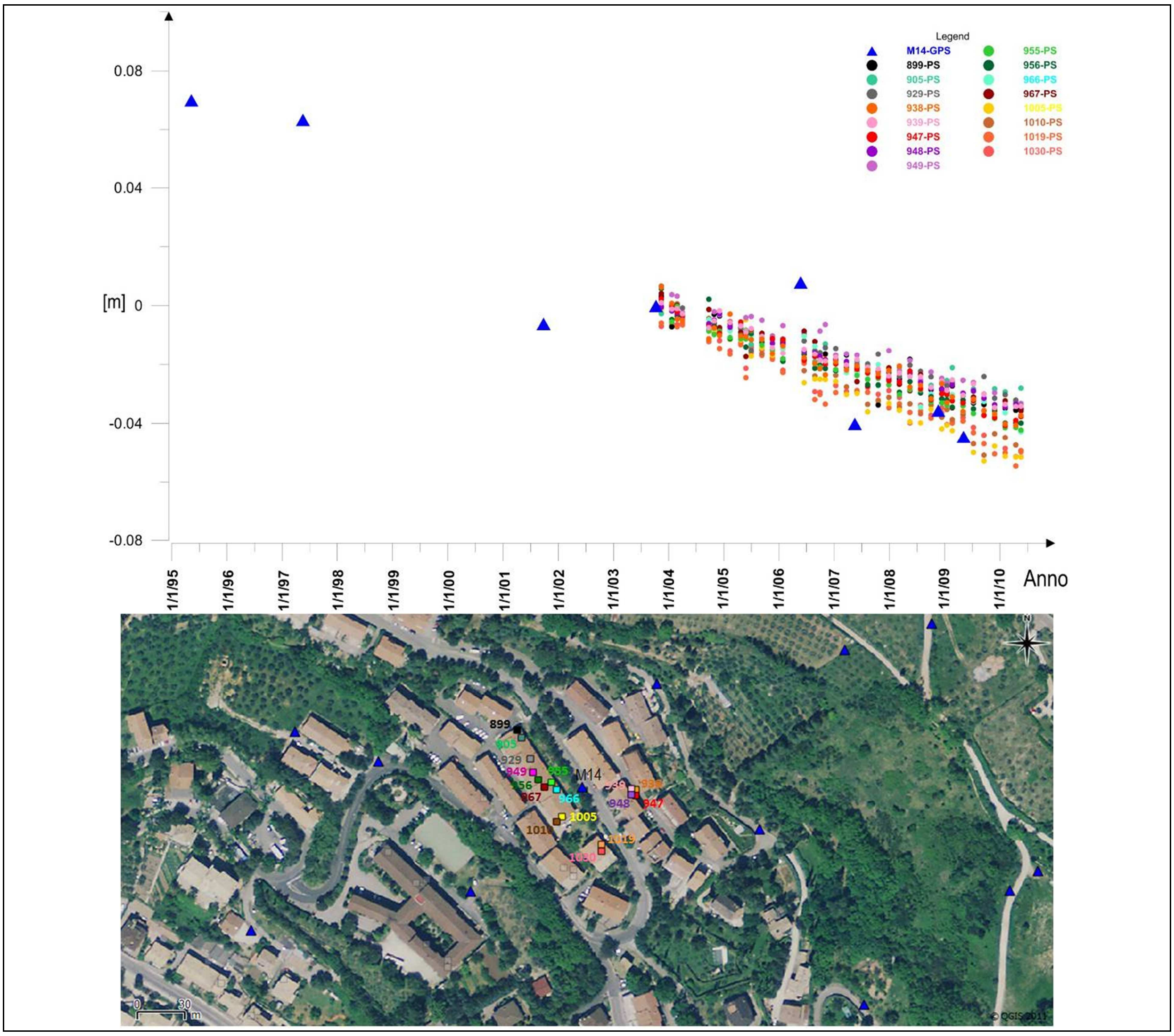

Fig. 9 – LOS displacements of the GNSS marker M14 and its closest SAR scatterers (SPINUA)

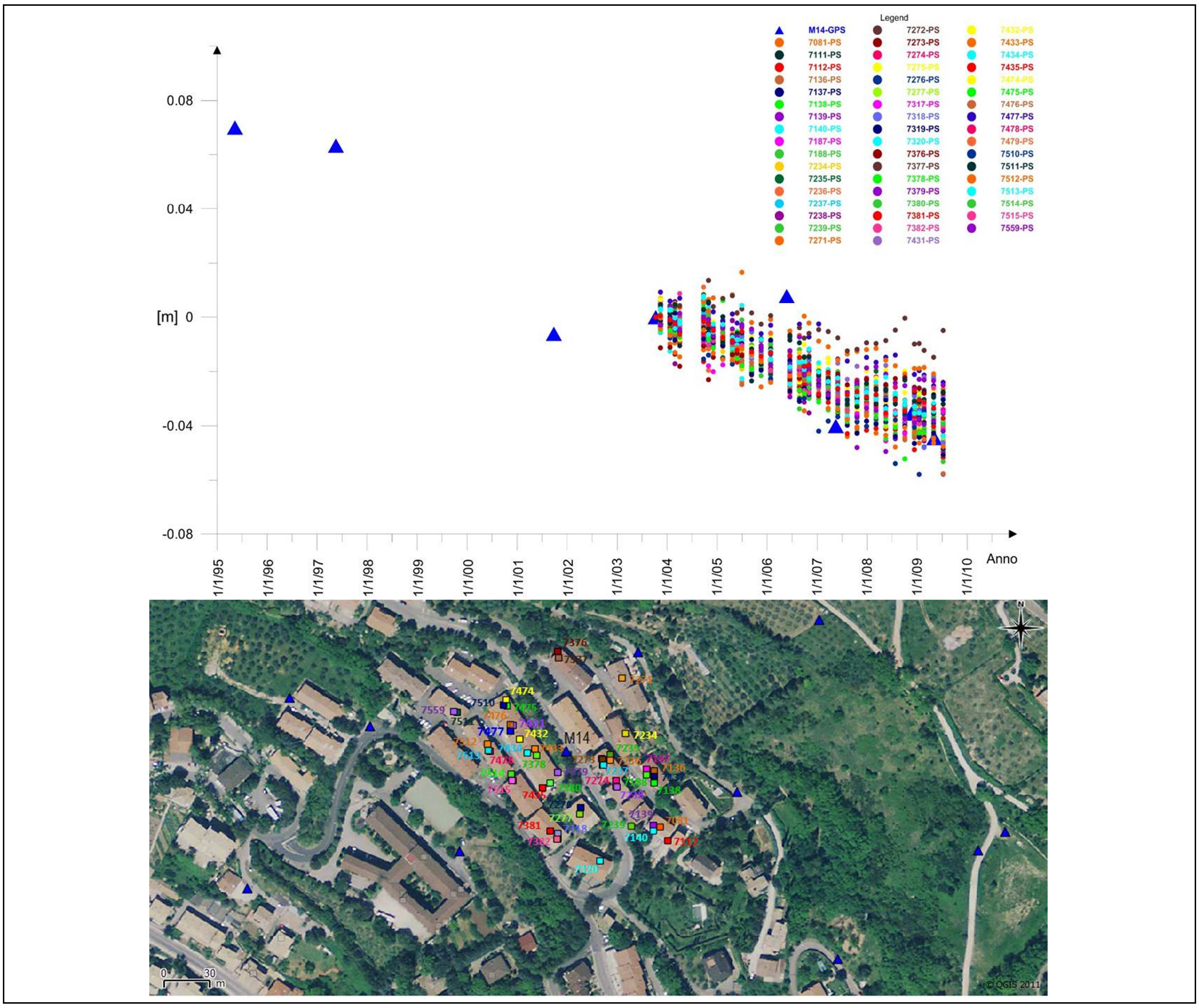

Fig. 10 - LOS displacements of the GNSS marker M14 and its closest SAR scatterers (TSIA)

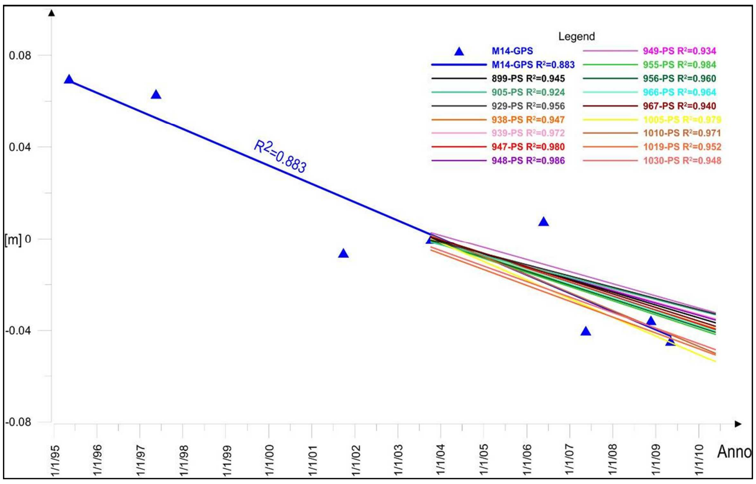

Fig. 11 - Regression lines for the GNSS marker M14 and its closest SAR scatterers (SPINUA)

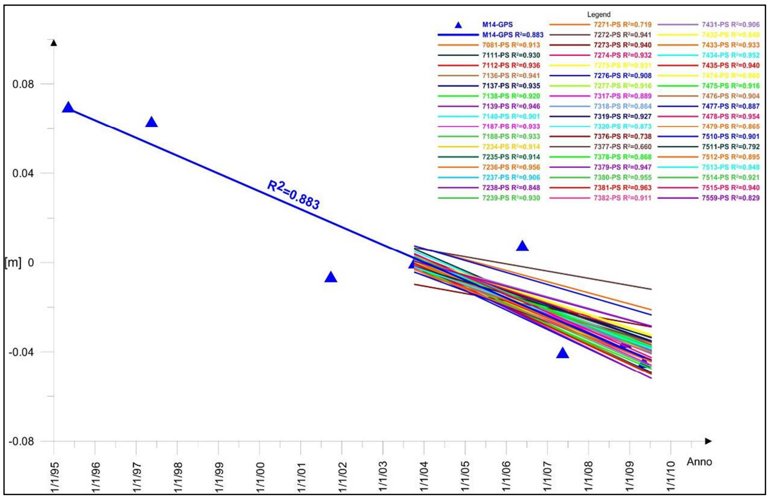

Fig. 12 - Regression lines for the GNSS marker M14 and its closest SAR scatterers (TSIA)

Some local differences can attributed to the fact that GNSS markers and SAR scatterers do not coincide, even if located in the same area. Most SAR scattering points are found to be on the building roofs, while almost all GNSS markers of the Assisi network are mounted to a concrete foundation at the street level. Local differences can also be caused by the presence of retaining walls, deep foundations on poles, and altimetric discontinuities.

6. DEFINITION OF THE LIMITS OF THE ACTIVE LANDSLIDE

A kriging interpolation has been performed on the LOS-component velocities deriving from InSAR-SPINUA data. Its results can be synthesized as a contour map of constant LOS velocities, where the zero-value contour can be assumed as a possible approximation of the active area perimeter.
The contour map derived as above, with the zero-value contour as its external border, has been superimposed in fig. 13 to an ortophotomap of the area, where two hypotheses on the landslide perimeter deriving from former geological studies are also drawn (yellow and green lines). A good general agreement can be noticed. The historical center (some hundreds of meters westwards) is confirmed to be stable from the InSAR data analysis.
The most relevant movements occur in the central area of the landslide body, while the lower part (including the Civic Hospital) shows much lesser displacement velocities.

7. FINAL REMARKS AND FURTHER DEVELOPMENTS

The research here presented had the objective of comparing the results obtained on the deformation monitoring of the Assisi landslide through post-processed GNSS and InSAR, referring to measures spanning over a common time period of about 7 years. The results can also contribute to a validation of the InSAR technique for their application on ground deformation control.
The comparison has requested a preliminary analysis and data treatment because the spatial and temporal resolutions of the two databases were different.
GNSS data were available on the period 1995-2010, while the InSAR dataset here utilized

(from ENVISAT satellite) refer to 2003-2010. The GNSS and InSAR time series were referred to different origins, so an alignment has also been requested.

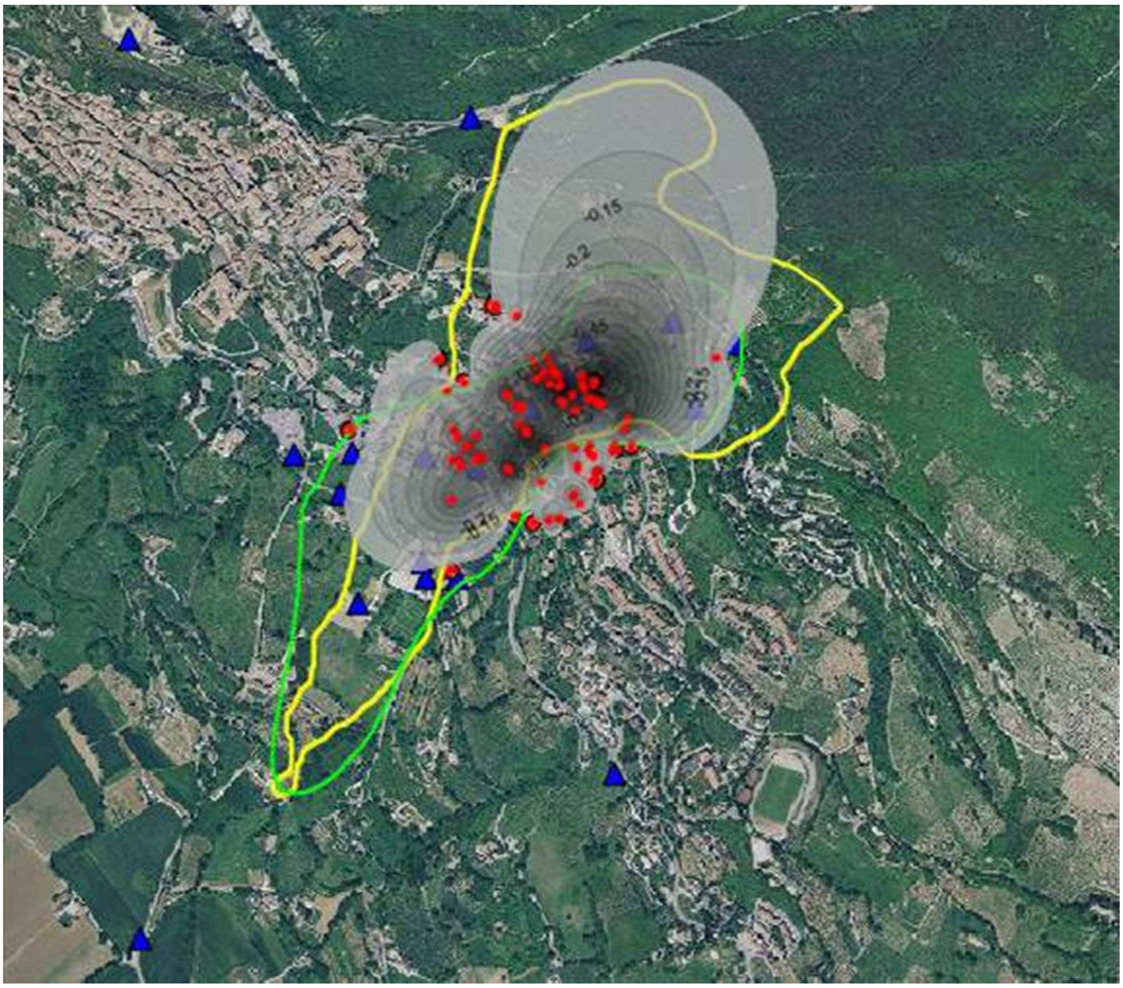

Fig. 13 - InSAR LOS velocity contour lines (V=0 at the external edge) and hypotized landslide perimeter

GNSS data have been computed for relatively sparse points (the network markers) while InSAR data are available for the SAR scatterers, more numerous but never coinciding with the GNSS markers. Thus, the comparison has been effected for small areas surrounding each GNSS marker, considering the closest InSAR scatterers.

Finally, InSAR only gives the LOS (Line of Sight) component of the estimated displacements, while GNSS give a three-dimensional vector. So, a projection of the GNSS vectors along the LOS has been necessary.

Once performed the necessary steps, considering what above, to make the two datasets comparable, the comparison has generally shown a good to very good agreement between the two different techniques, referring to the LOS component of the ground deformations, velocities and time series, confirming the substantially linear behaviour (deformation velocity almost constant) already observed from the GNSS data. Some local differences can be explained with topological effects connected to the non homogeneity of the landslide body, also noticeable from GNSS data only.

The highest deformation velocities along the LOS have been found in the central area of the landslide, with values of about 5 mm/year. Lesser values are found laterally and at the top and the bottom of the sliding body. An approximated perimeter of the active area has been individuated from a spatial interpolation of the velocities field, considering the line at zero velocity, finding a quite good agreement with perimeters defined on a geological basis.
The two analysis methods adopted for the InSAR data (SPINUA and TSIA) also show a very good agreement with each other: even if individuating different scatterers, the LOS deformations and velocities for local areas deriving from the two approaches are substantially the same.
The present research refers to a single area, but the reproducible analysis methods and the results lead to some conclusions which can be attributed a general validity:

- the InSAR technique offers a very useful instrument of analysis of landslide deformations, with some peculiar advantages (no need of markers, high sensitivity, possibility of going back in time, clear discrimination of active and inactive areas);
- InSAR only give information on a one-dimensional deformation component, along the LOS (Line of Sight) of the radar pulse, while GNSS gives a complete 3D definition of the displacement vectors and velocities;
- for a complete 3D description of a landslide surface motion, defining all planimetric and height components, an integration with the GNSS technique (and also with leveling) appears the best solution presently;
- if the InSAR datasets are subjected to a preliminary analysis to correct the spatial and temporal differences with respect to GNSS data, a good agreement with the latter is found.

Further developments of the present research will likely regard an extension of the experimentation on more areas, the analysis of datasets coming from different SAR sensors (COSMO-SkyMed in particular) and a comparison with leveling data, which for their high sensitivity also give a very important contribution to the knowledge of a landslide behaviour.

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Fabio Radicioni graduated cum laude in Civil Engineering at the Ancona University in 1980. In 1988 he obtained his PhD degrees in Geodetic Sciences. From 1990 to 1992 he has been Researcher at the Bologna University, Institute of Topography, Geodesy and Mining Geophysics. Since 1992 he is Associate Professor for the ICAR 06 area (Surveying and Cartography) at the University of Perugia, Faculty of Engineering. Since 2002 he is Full Professor for the ICAR 06 area (Surveying and Cartography) at the University of Perugia, Faculty of Engineering. He is the author of more than 150 scientific papers, published on specialized scientific journals and in the proceedings of national and international conferences.

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