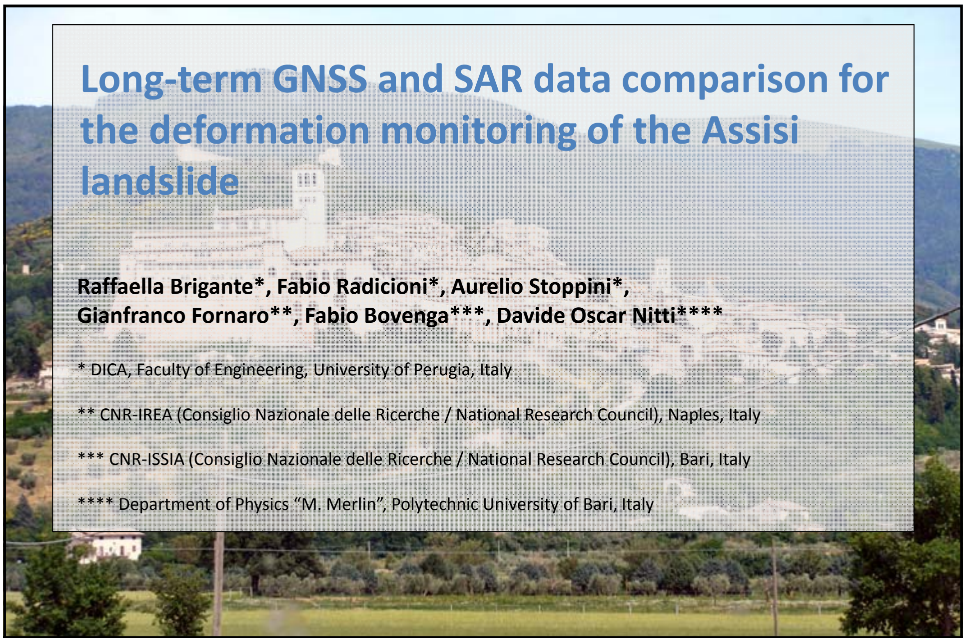

Long-term GNSS and SAR data comparison for the deformation monitoring of the Assisi landslide

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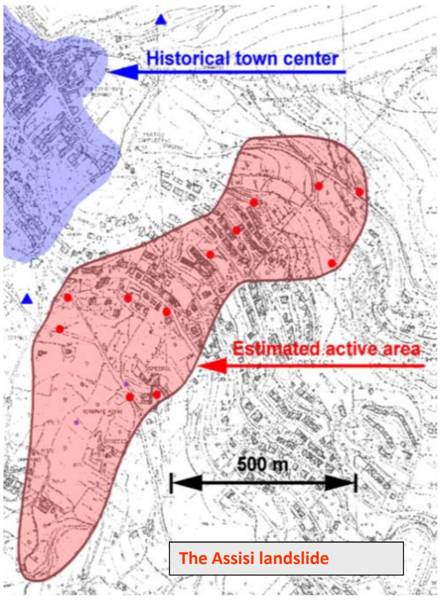


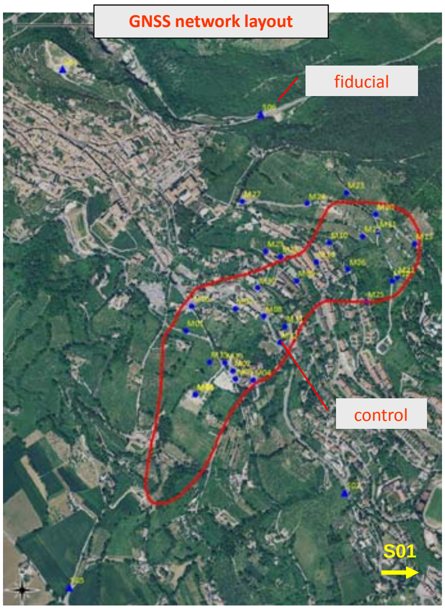
Introduction

The Assisi landslide interests an expansion area of the town, built up since the years 1950-1960 **completely outside of the historical town center**.
The slope has an average inclination of ~21%.
At the start of building activity the landslide was not noticed.
The urbanization caused changes to the regimen of the surface waters, deviating and covering ditches and streams.
Around 1970 the first evidences an active landslide showed, in the form of growing damage to buildings, 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 (figure).

The landslide

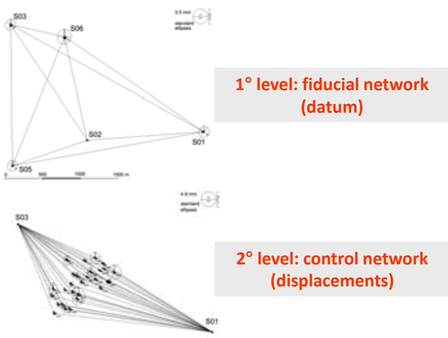
is of a gravitational type (*translational creep*). The **sliding surface** has an average depth of some tens of meters, with a maximum of about 60 m. The moving formation consists of a debris mass flowing over a stable bedrock.
The area has been **monitored** since 1970-1980 with geotechnical techniques and a conventional geodetic network (angles and distances). The geodetic monitoring was interrupted at the mid 80s for its excessive cost and practical difficulties.
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 in the attempt to slow down the motion or possibly stop it. 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, but the works have undergone interruptions and delays for technical and administrative reasons, and are still in progress.

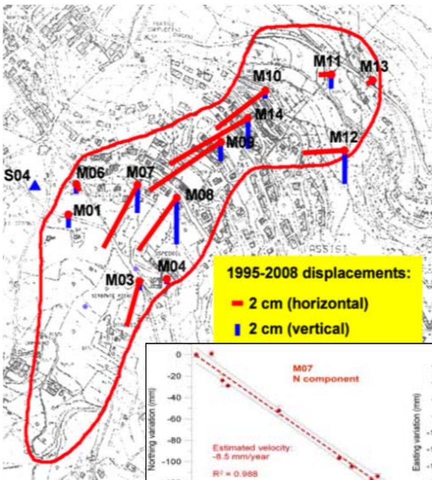


The GNSS network

The Assisi GNSS network in its initial configuration (1995) included 6 reference or "**fiducial**" points located in geologically stable sites (S01 to S06), and 14 "**control**" points in the landslide area (M01 to M14).
In 2006 the network was densified adding 16 control points (M20 to M35). The present configuration includes **28 control points and 5 fiducial points**.
The measurement are performed with **GPS/GLONASS double frequency geodetic receivers** in **static** mode, with 2 hours sessions at a sampling rate of 5 seconds.



GNSS displacement vectors



GNSS network results

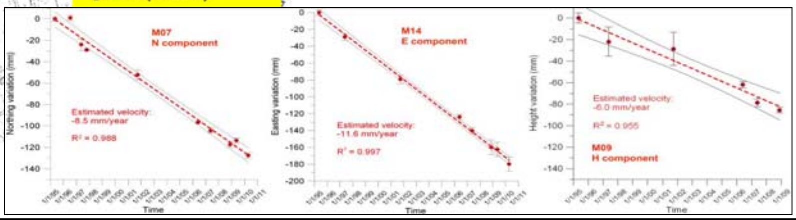
Comparing the 3d coordinates derived from subsequent measurement campaigns, the **displacement vectors** for the control points are computed and statistically tested as effective displacements.

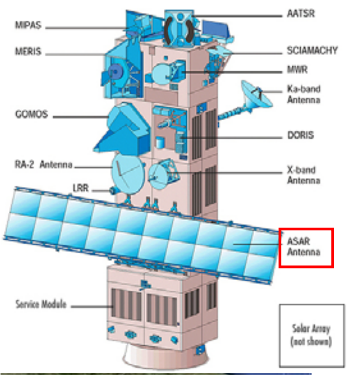
Figure shows the 1995-2008 displacements for the first 14 control points (complete observation set).

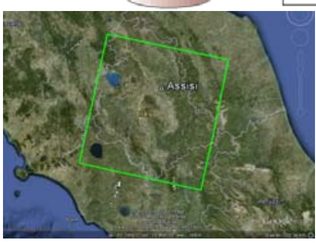
The planimetric vectors show a field of movements in agreement with the landslide characteristics: a *creep*, where the upper layers of the soil slowly slide on a stable formation at a depth of some tens of meters.

The maximum displacements are located in the central part of the landslide body, and their direction follows approximately the maximum slope line.

The **coordinate time series** (below) show an almost **linear** trend, with maximum velocities of about 1 cm/year.







SAR data analysed

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 20m by 5m** 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).

The 7-years overlapping with GNSS measurements allows a **validation** of the **displacements derived by InSAR processing**.

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May 6-10 2012
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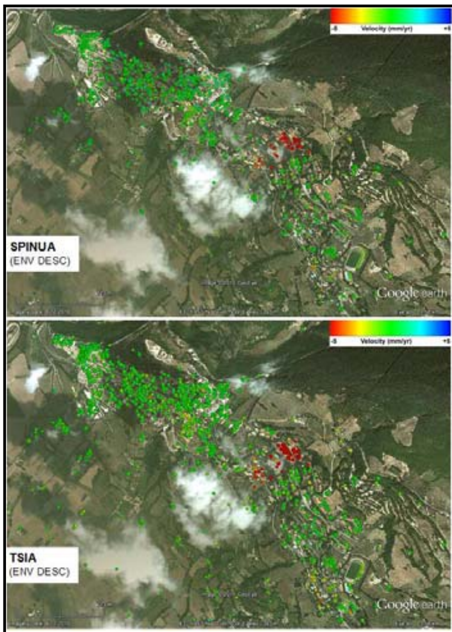


InSAR processing

The ASAR data processing has been performed by means of **two different approaches**, **SPINUA** and **TSIA**.

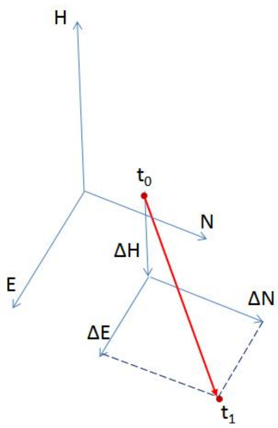
The **SPINUA** algorithm is a Persistent Scatterers Interferometry (PSI) like technique originally developed with the aim of detection and monitoring of coherent PS targets in non- or scarcely-urbanized areas (Bovenga et al., 2004, Bovenga et al., 2006). It has been further updated to deal with wide 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.

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 has been performed using spatially averaged data, in addition to the threshold on the baselines, to mitigate the effects of decorrelation. For the large scale has been adopted a **tomographic processing** (Fornaro et al., 2009), that improves the performances in the detection and monitoring of scatterers with respect to the classical (phase only) PSI techniques.

The two different approaches have given **similar results**

GNSS, Leveling, InSAR: different techniques, different results

GNSS, Leveling and InSAR are three different techniques which contribute in different ways to the investigation of a ground deformation phenomenon such as a landslide. Each of the three techniques has its own peculiarities, including some advantages and drawbacks. The best solution for an accurate description of a complex phenomenon like a landslide is an **integration** of more techniques.



GNSS

GNSS positioning (normally in **static post-processed** mode for monitoring purposes) provides absolute **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 (figure). The **displacement vectors**, in other terms.

As counterpart, the monitoring regards **only a small number of markers**, which for economical reasons are normally quite **sparse**. Thus, the description of the **motion field** resulting from GNSS only data is **not continue** and an **interpolation** is necessary between the surveyed points.

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May 6-10 2012
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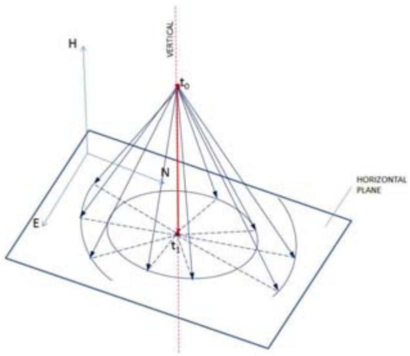

LEVELING

Measurement campaigns 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**.

Figure shows as **the same vertical 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, and its determination is **more accurate** than from GNSS (approximately ±1 mm vs. ± 1 cm).

GNSS, Leveling, InSAR: different techniques, different results

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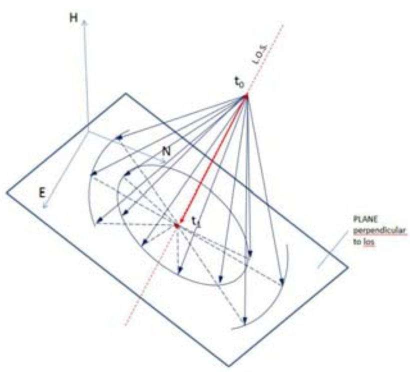


InSAR

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 figure shows: the same deformation on the LOS can derive from $\infty 2$ possible displacement vectors.
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.

GNSS – InSAR Comparison

GNSS and InSAR are different techniques giving different results not only for the 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 the average values can be reasonably assumed as constant.

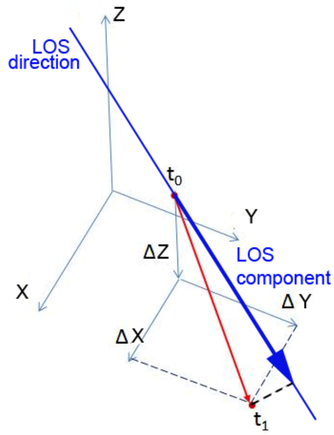
Starting from the GNSS-derived XYZ coordinates time series, the components of the displacement vectors for the control points along the LOS have been derived from the following expressions:

$$\Delta X = X_i - X_0$$

$$\Delta Y = Y_i - Y_0$$

$$\Delta Z = Z_i - Z_0$$

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



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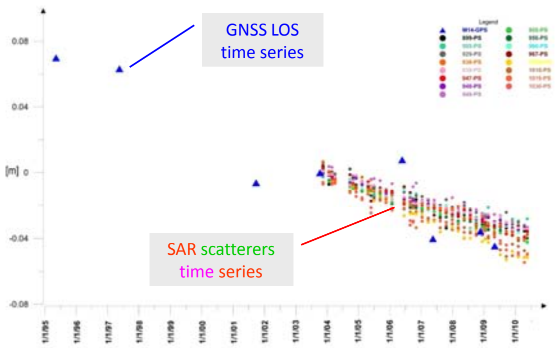
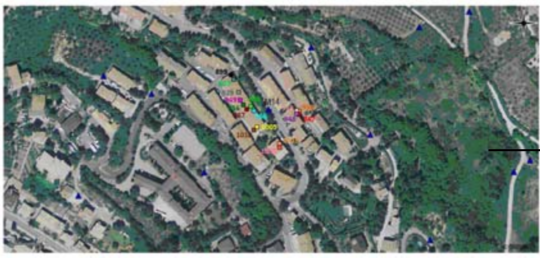


GNSS – InSAR Comparison

The LOS components derived from GNSS data have been compared with those of the **SAR scatterers closest to the GNSS marker (never coinciding)**.

An **alignment of the time scales** has been necessary (i.e. adopting 2003 as common zero epoch for GNSS and InSAR).



SPINUA model

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May 6-10 2012
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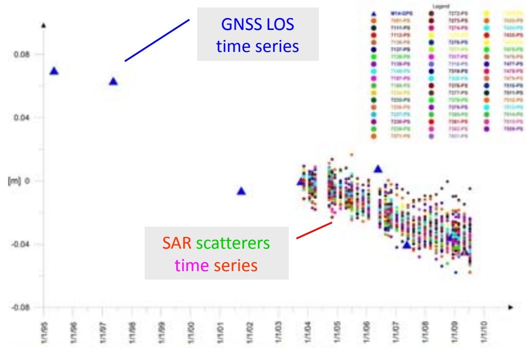

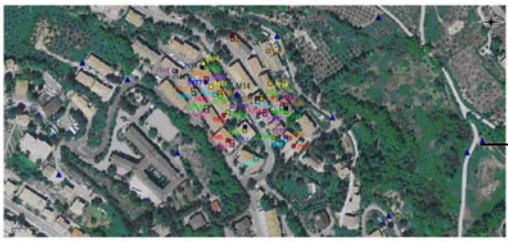

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TSIA model

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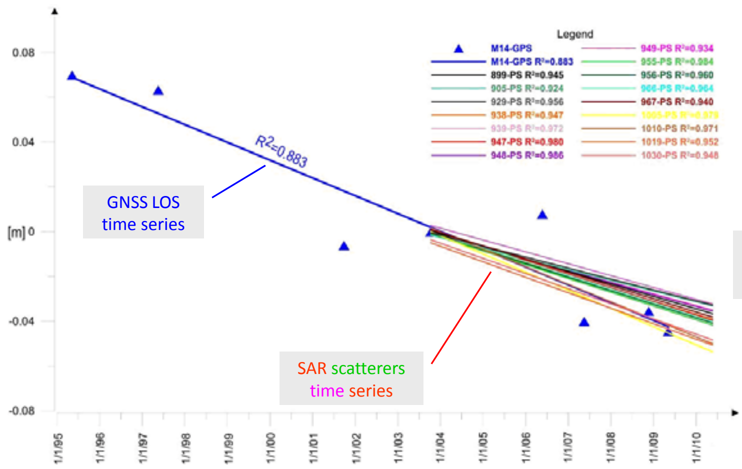
GNSS – InSAR Comparison

For a better understanding of the single points behavior, **linear regressions** have been estimated for both GNSS and InSAR points



SPINUA model

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May 6–10 2012
Rome, Italy

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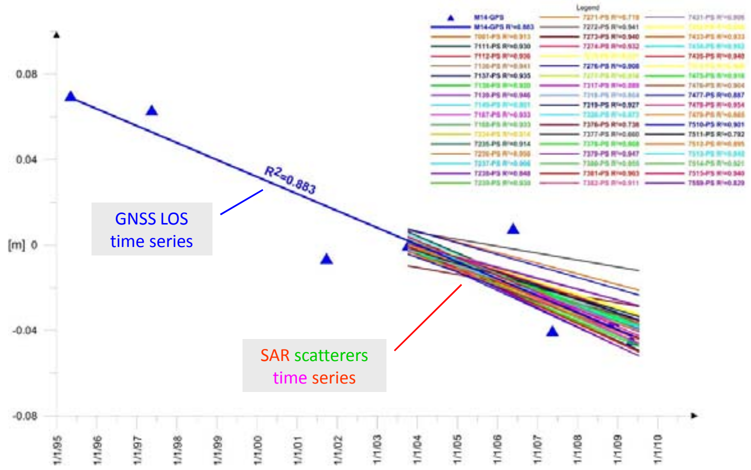

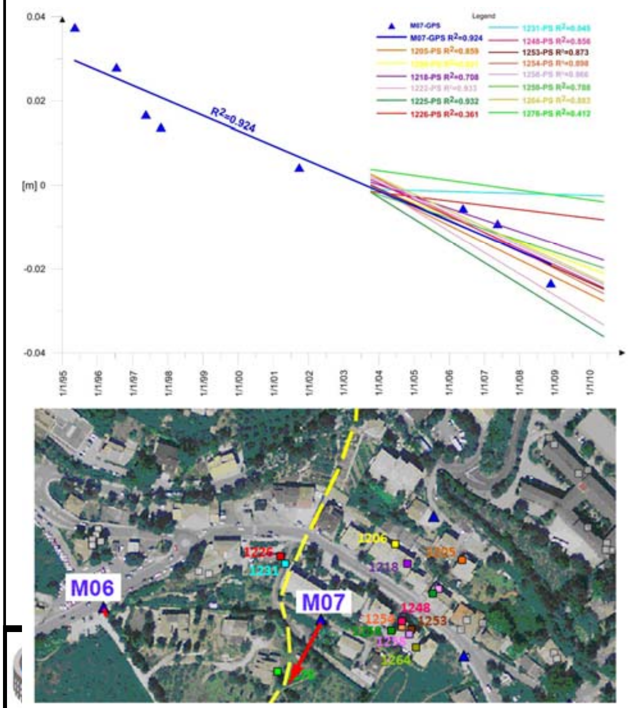

GNSS – InSAR Comparison

For some points local effects can be noticed

The landslide is divided in more contiguous portions with different granulometry and compactness. Moreover, for a landslide in an urban environment the surface motion can be locally influenced by the presence of buildings, retaining walls and deep foundations.

In the figure, the marker M07 belongs to the main “stream” of the landslide, while the western portion (including M06) is almost steady

GNSS – InSAR Comparison

Summary of results (**SPINUA**)

GNSS marker	V_{LOS} (mm/y)	D_m (m)	Velocity differences (mm/y)			
			mean	max	min	RMS
S01	-0.16	688.4	0.04	0.50	-0.93	0.54
S02	0.00	30.08	-0.32	0.09	-1.02	0.59
S03	-0.09	102.6	0.38	0.89	0.09	0.63
S05	1.50	546.0	-2.17	-2.73	-1.72	2.20
S06	0.33	106.0	-0.01	0.70	-0.72	0.58
M01	0.36	93.0	-0.52	-0.29	-0.75	0.57
M03	-0.63	26.6	0.10	0.69	-0.40	0.42
M04	-0.53	21.0	0.45	0.83	-0.12	0.53
M06	-0.90	79.8	0.69	1.70	-0.27	0.87
M07	-3.60	72.4	-0.32	0.84	-1.63	0.83
M08	-7.00	46.4	2.67	4.28	0.73	2.83
M09	-5.80	53.6	-0.01	1.62	-1.14	0.85
M10	-4.00	72.7	-1.62	-1.26	-2.09	1.66
M11	-1.92	118.4	1.30	1.30	1.30	1.30
M12	-5.80	111.2	4.08	5.19	3.47	4.15
M13	-1.05	75.5	-0.67	0.44	-1.28	1.04
M14	-8.00	33.1	1.90	3.17	-0.18	2.11
					RMS mean	1.28

GNSS – InSAR Comparison

Summary of results (**TSIA**)

GNSS marker	V_{LOS} (mm/y)	D_m (m)	Velocity differences (mm/y)			
			mean	max	min	RMS
S01	-0.16	533.2	-1.16	-0.50	-2.06	1.28
S02	0.00	63.10	-0.74	-0.18	-1.49	0.80
S03	-0.09	136.9	-0.19	1.16	-0.97	0.82
S05	1.50	167.4	-2.33	-2.08	-2.51	2.34
S06	0.33	45.0	-0.05	0.06	-0.10	0.07
M01	0.36	109.3	-0.85	-0.01	-1.71	1.03
M03	-0.63	51.6	-0.14	0.80	-1.47	0.60
M04	-0.53	26.2	-0.24	0.70	-1.58	0.63
M06	-0.90	95.9	-0.14	1.23	-1.19	0.75
M07	-3.60	76.1	-2.56	-2.21	-3.17	2.60
M08	-7.00	42.4	1.47	3.11	0.22	1.76
M09	-5.80	67.1	-0.43	11.32	-3.11	2.36
M10	-4.00	82.2	-2.61	0.78	-4.95	2.98
M11	-1.92	159.7	-3.24	-0.19	-6.89	4.16
M12	-5.80	133.8	3.72	5.70	1.34	3.98
M13	-1.05	154.6	-0.71	0.29	-1.60	1.06
M14	-8.00	48.6	1.04	4.72	-0.99	1.64
					RMS mean	1.70

GNSS – InSAR Comparison

Summary of results (**TSIA**)

GNSS marker	V_{LOS} (mm/y)	D_m (m)	Velocity differences (mm/y)			
			mean	max	min	RMS
S01	-0.16	533.2	-1.16	-0.50	-2.06	1.28
S02	0.00	63.10	-0.74	-0.18	-1.49	0.80
S03	-0.09	136.9	-0.19	1.16	-0.97	0.82
S05	1.50	167.4	-2.33	-2.08	-2.51	2.34
S06	0.33	45.0	-0.05	0.06	-0.10	0.07
M01	0.36	109.3	-0.85	-0.01	-1.71	1.03
M03	-0.63	51.6	-0.14	0.80	-1.47	0.60
M04	-0.53	26.2	-0.24	0.70	-1.58	0.63
M06	-0.90	95.9	-0.14	1.23	-1.19	0.75
M07	-3.60	76.1	-2.56	-2.21	-3.17	2.60
M08	-7.00	42.4	1.47	3.11	0.22	1.76
M09	-5.80	67.1	-0.43	11.32	-3.11	2.36
M10	-4.00	82.2	-2.61	0.78	-4.95	2.98
M11	-1.92	159.7	-3.24	-0.19	-6.89	4.16
M12	-5.80	133.8	3.72	5.70	1.34	3.98
M13	-1.05	154.6	-0.71	0.29	-1.60	1.06
M14	-8.00	48.6	1.04	4.72	-0.99	1.64
					RMS mean	**1.70**

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May 6-10 2012
Rome, Italy

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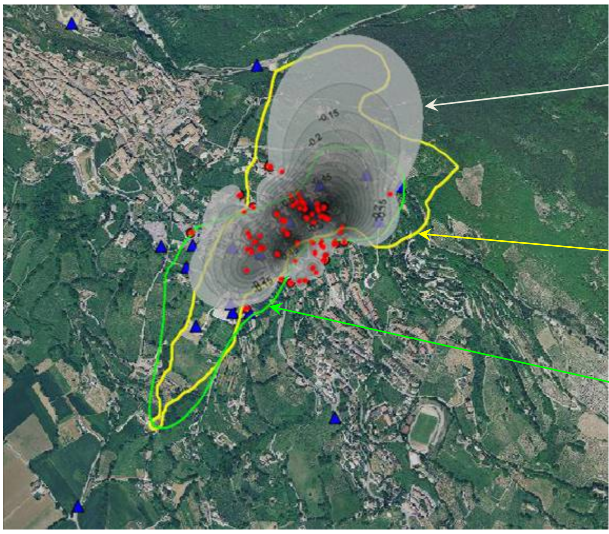
Landslide Perimeter estimation

From a Kriging interpolation on the full InSAR dataset (SPINUA



$V_{LOS} = 0$
contour line

Landslide perimeter
from geology -
geotechnics

Landslide perimeter
from geology –
geotechnics

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Final Remarks (1)

The comparison has generally shown a **good agreement** between the two different techniques, referring to the LOS component of the ground deformations, velocities and time series, confirming a **substantially linear behavior** (sliding velocity almost constant in time) already observed from the GNSS data.

Some local differences can be explained with effects connected to the non homogeneity of the landslide body or to the presence of structural elements (retaining walls, deep foundations).

The **RMS difference between GNSS and InSAR LOS velocities** are **less than 1 mm/y** for most points, with exceptions due to local effects discussed above.

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 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 on the sides and at the top and bottom of the sliding body. An approximated perimeter of the active area has been estimated from a spatial interpolation of the velocities field, finding a quite good agreement with landslide perimeters defined on a geological basis.

Final Remarks (2)

This research refers to a particular case, but the reproducible 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 artificial markers, high sensitivity, possibility of going back in time, clear discrimination of active and inactive areas);

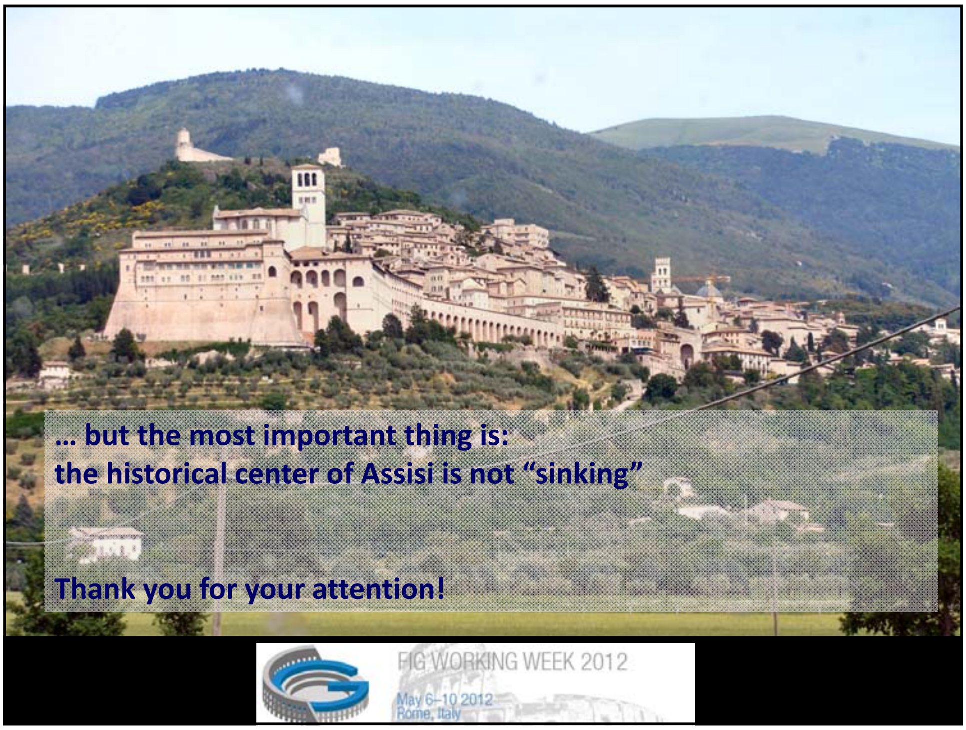
- InSAR only give information on a **one-dimensional deformation component**, the **LOS** (Line of Sight) of the radar pulse, while GNSS gives a complete 3D definition of the displacement vectors and velocities;

- for a **complete 3D description** of a landslide surface motion, defining all planimetric and height components, an **integration of InSAR with GNSS** (and also **leveling**) is possible and appears as a very good solution;

- if the InSAR datasets are subjected to a preliminary analysis to correct the spatial and temporal differences with respect to GNSS, a **good agreement** 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.

FIG WORKING WEEK 2012
May 6–10 2012
Rome, Italy
Radicioni F, Stoppini A, Brigante R, Fornaro G, Bovenga F, Nitti D O:
Long-term GNSS and SAR data comparison for the deformation monitoring of the Assisi landslide


… but the most important thing is:
the historical center of Assisi is not "sinking"
Thank you for your attention!
FIG WORKING WEEK 2012
May 6–10 2012
Rome, Italy