HIGH RESOLUTION MONITORING OF CAMPI FLEGREI (NAPLES, ITALY) BY EXPLOITING TERRASAR-X DATA: AN APPLICATION TO SOLFATARA CRATER

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ABSTRACT

Geodetic monitoring of Campi Flegrei caldera, west of Naples (Italy), is carried out through integrated ground based networks and space-borne Differential InSAR (DInSAR) techniques, exploiting the SAR sensors onboard ERS1-2 (till the end of their lifetime) and ENVISAT satellites. Unfortunately, C-band sensors give no information when dealing with very low deformation rates and very small deforming areas.
To overcome these problems, we decided to use TerraSAR-X from DLR, a high resolution SAR sensor operating in the X-band, starting in December 2009.
TerraSAR-X Spotlight scenes covering the main part of the Campi Flegrei caldera and centred on the Solfatara crater were used for a DInSAR analysis, using DLR's InSAR software.
Starting from this period, many field surveys highlighted a strong fumarolic activity in the Solfatara - Pisciarelli area [1], so geodetic and geochemical observations were strongly increased.
Furthermore, the growing stack of High-Resolution Spotlight TerraSAR-X data processed using the Small Baseline Subset Algorithm (SBAS) as described by Berardino at al. [2], allowed getting information for a bigger area and data from ground based networks could be integrated.
First results of the SBAS processing and the combination of different observation techniques are presented.

1. INTRODUCTION

Ground deformations in volcanic areas are supposed to be a precursory phenomenon of volcanic activity, as they are likely related to the uprising of magmatic bodies towards the surface, which could finally turn into an eruption.
Deformations appear sometimes in a very small order, at least at the beginning of the volcanic process, requiring therefore very accurate surveying techniques in order to be detected.
In this paper we will show recent results on the Campi Flegrei caldera (Fig. 1), a volcanic and densely populated area located west of Naples and characterized by continuous ground deformation (bradyseismic activity) related to its volcanic nature.
In particular, we will focus on the Solfatara - Pisciarelli area, which is seat of strong fumarolic activity in the last years. For this reason we also take into account some information from geochemical measurements. [3].
The geodetic monitoring of the area has been historically carried out by the Osservatorio Vesuviano [4],[5],[6],[7], presently the Naples branch of the Istituto Nazionale di Geofisica e Vulcanologia (INGV-OV) by ground based networks (levelling, EDM, gravity, tide-gauge, tiltmeter), shown in Fig. 1.
Since the end of the nineties, space geodetic techniques (GPS, InSAR) have been exploited as well [8], [9], [10].
Regarding InSAR data, the time coverage of new space-borne sensors is increasing dramatically after the launch of the new satellite constellations with only a few days revisiting time.
Geodetic data already helped to model the bradyseism deformation source (e.g. [4], [5], [6], [7], [10]).

Figure 1. Geodetic networks of Campi Flegrei

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2. GEODETIC MEASUREMENTS

2.1. Levelling measurements

Some levelling lines of the present network were already available at the end of the sixties, allowing to follow the time evolution of the bradyseismic crises of the years 1969-1972 and 1982-1984 [4], [7] and also the recent uplift events clearly are visible on the altimetric benchmark 25A (Fig. 2), located in the maximum deformation area [11], [12].

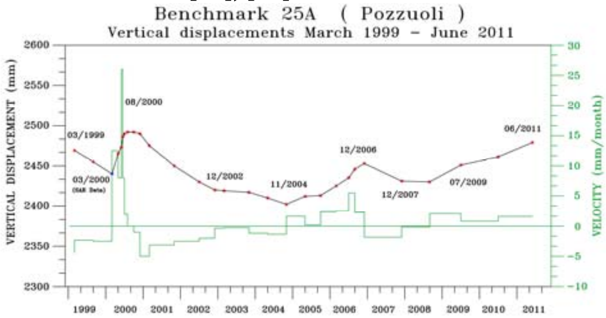


Figure 2. Height variations (black) of benchmark 25A and ground monthly velocity (red) from 1999 to 2011

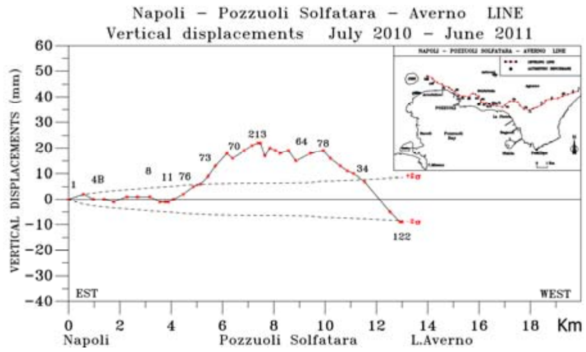


Figure 3. Height variations along the "Solfatara line" (in the upper box) in the period July 2010 – June 2011

The Campi Flegrei levelling network presently consists of 350 altimetric benchmarks on about 140 linear km and is organized into 15 loops [13]; the whole network is measured annually, whereas the most important lines, as the "Solfatara line" (Fig. 3), are usually measured twice per year.
Measurements carried out in June 2011, compared with the ones from July 2010, highlight a further uplift phase with maximum values on the benchmark 213 (+22 mm) close to Solfatara - Pisciarelli.

2.2. GPS measurements

Since 2000, several GPS permanent stations have been set up in the Neapolitan Volcanic District [9] and the present NeVoCGPS (Neapolitan Volcanoes Continous GPS) network consists of 29 stations, 13 within Campi Flegrei area (Fig. 1). All stations are managed by remote control and operate with a 30s sampling rate.
For real-time monitoring, a completely automated system has been realized for data downloading, quality control, storage and processing in order to get time series of the displacements along the 3 components (North, East, Up) for each station [14].
In the period of TerraSAR-X acquisitions (December 2009 - March 2011), the 4 GPS stations located within the selected frame all show a small uplift from April to October 2010 (Fig. 4).
RITE station records the maximum vertical displacements of about 1.5 cm, whereas the other stations exhibit smaller vertical displacements (up to 1 cm at ACAE and SOLO). All the GPS stations also show significant horizontal displacements.

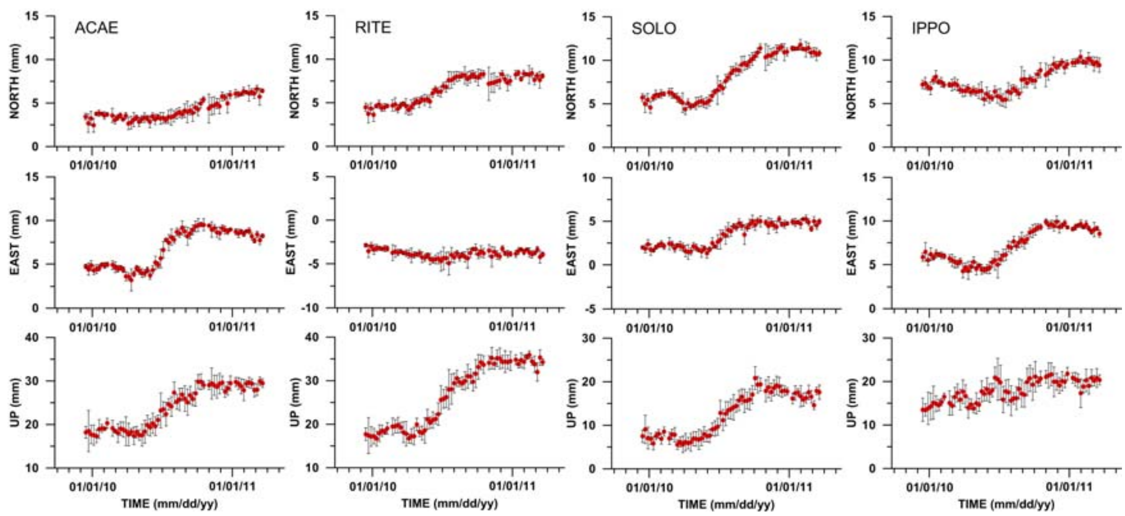
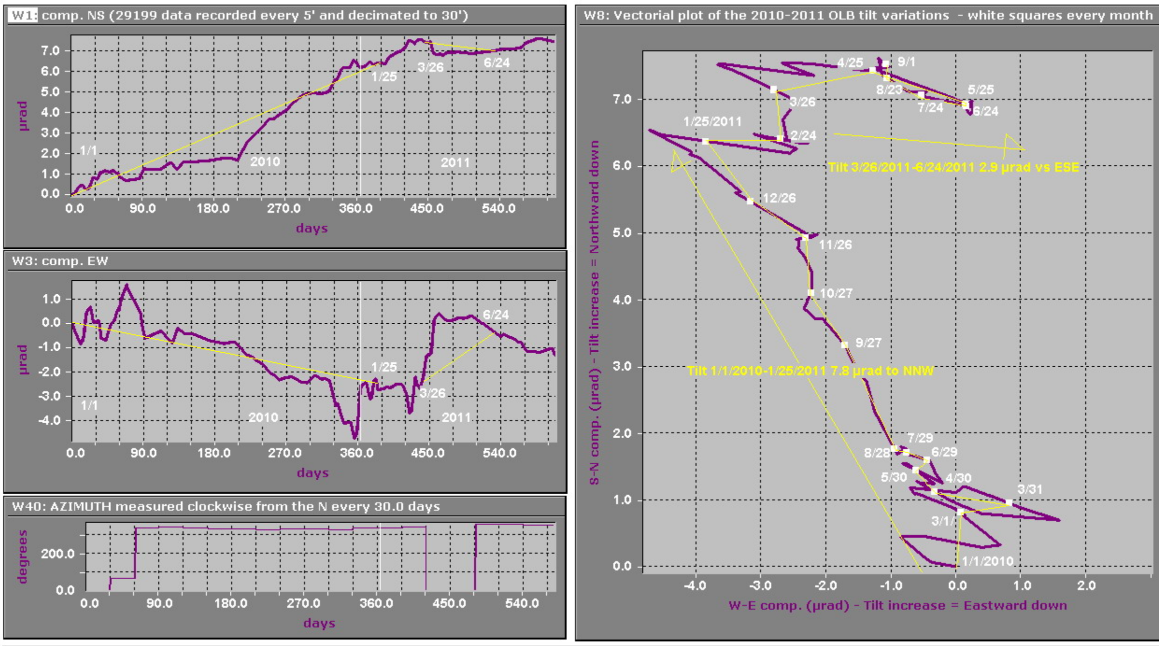


Figure 4. GPS time series of weekly coordinate changes, from December 2009 to March 2011 (along North, East and Up directions) for the stations located within the selected TerraSAR-X frame

2.3. Tiltmetric measurements

The tiltmetric network consists of 8 stations (6 surface sensors and 2 boreholes, Fig. 1), equipped with a temperature sensor with 0.1 °C resolution. Tilt variations are measured along the NS and EW directions, with a resolution of 0.1 µrad [15] [16].
In Fig. 5, in the first two windows on the left, the thermal decorrelated data of the NS and EW tilt components are shown in purple. The soil thermal component has been removed by a statistical approach.
In the window on the right the resultant vector of the decorrelated sequences is shown in purple; white squares indicate every 30 days marks.
Yellow lines indicate tilt vectors in the two periods 01/01/2010-01/25/2011 and 03/26/2011-06/24/2011; in the first period the ground is tilted 7.8 µrad towards NNW, indicating a NNW subsidence (SSE uplift) while in the last period the tilting is 2.9 µrad towards ESE, due to uplift in the west direction.



	1:YEAR	2:MONTH	3:DAY	4:HOUR/MIN	5:SCALEdays	6:TOT.days	7:TOT.data	8:TILT	9:AZIMUTH		
1:	2010.0	1.0	1.0	0.0	30.0	608.3	29199.0	7.6	352.0		
2:	2011.0	9.0	1.0	700.0							

Figure 5. Working sheet of OLB tiltmetric station showing the decorrelated tilt (01/01/2010 – 06/24/2011)

2.4. Gravity measurements

Precise gravity measurements started on 1981 and, afar from bradyseismic crises periods, are generally carried out twice per year [6], [17], [18].
Presently, the gravity network consists of 28 stations (Fig. 1) all coinciding or close to leveling benchmarks, 7 of them located inside and around the Solfatara crater.
The reference is the absolute station in Naples also belonging to the Italian Zero Order Gravity Network [6]. Two additional absolute gravity stations have been set up in the most active area of Campi Flegrei, namely in La Pietra, along the coastline east of Pozzuoli and in the Accademia Aeronautica, close to the Solfatara crater.
Gravity changes extending over the whole Campi Flegrei show, from the end of 2009 to March 2011, values generally within the expectable error (Fig. 6). The only significant variations occur in the Solfatara area and also show, in general, an opposite behavior in comparison with the rest of the area. Sometimes, significant gravity decreases have also been detected in La Pietra area. These gravity changes are mostly due to seasonal effects and in part, mainly in Solfatara, to the dynamics of the local hydrothermal system [18].
Overall gravity changes on the whole period (in the blue frame) show that the only significant gravity variations (decrease) are concentrated along the eastern coastline, centered in La Pietra. This is the area where during the last bradyseismic crisis (1982-84) gravity residuals have shown mass changes and where usually the maximum gradient of the vertical movements and the maximum horizontal ground deformation occurred [6].
Gravity changes may be due in part to small uplift and in part to fluid motion in a very shallow and limited area.

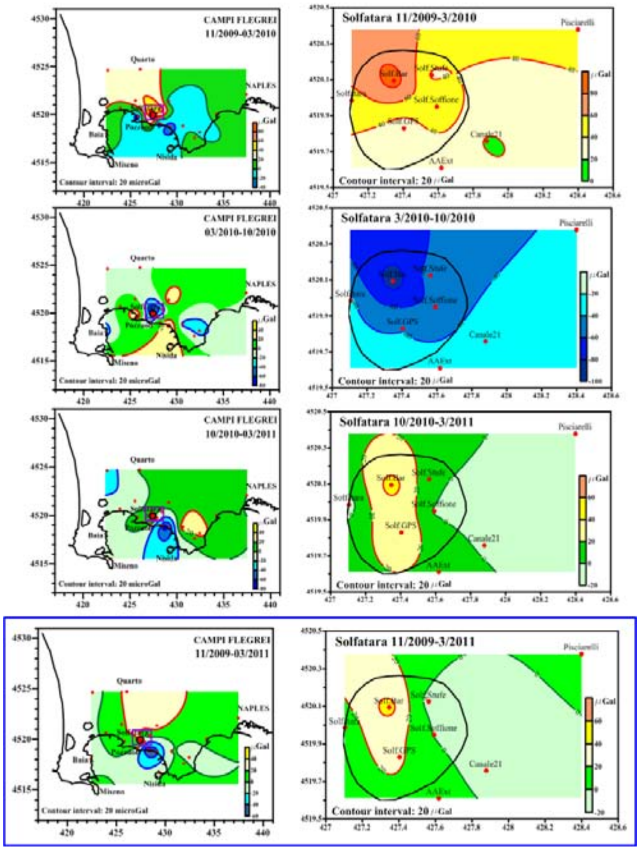


Figure 6. Gravity changes during different time intervals (from 11/2009 to 03/2011) – In the blue frame the overall gravity change on the whole period is shown

3. GEOCHEMICAL MEASUREMENTS

Fig. 7 shows the major events of interest during the last years at the Pisciarelli fumarolic field. These are represented by mud emissions, pools and new vents.

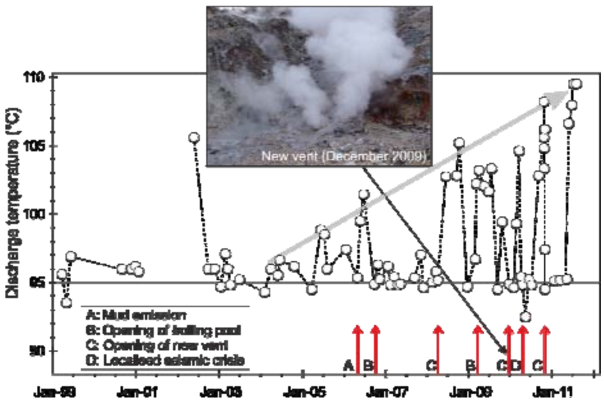


Figure 7. Temperature chronogram (°C) of the Pisciarelli fumarole with major events related to the increasing of the hydrothermal activity (after [3])

Temperature chronogram points show such phenomena increased in the last years, with higher temperatures which overcame the 95°C threshold (boiling point of the Pisciarelli fumarolic fluids) many times during 2010. The photo in Fig. 7 shows the new vent, which opened on December 2009 and was also detected by interferometric observation using TerraSAR-X data [1].

4. SAR PROCESSING

4.1. TerraSAR-X Data

Data basis for the performed processing is a stack of 24 TerraSAR-X High Resolution Spotlight images, covering the time span from 15.12.2009 to 22.03. 2011. The images cover an area of approx. 10 km (range) by 5 km (azimuth) and are centred on the Solfatara Crater, as seen in Fig. 8. The city of Naples is located approximately 9 km to the east of the Solfatara Crater.
All images were acquired in a descending orbit with an incident angle of 39 degrees and single (VV) polarisation.

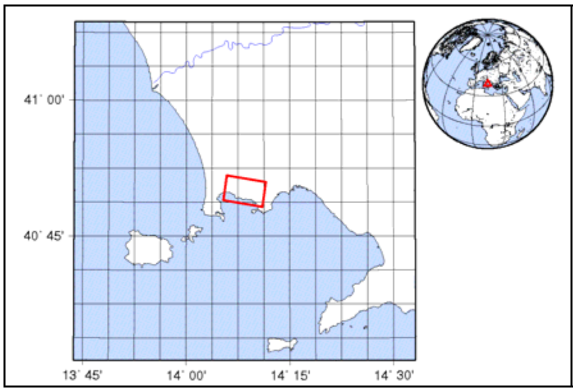


Figure 8. Footprint of used TSX acquisitions

4.2. SBAS Processing

For SBAS Processing, the images were cropped to a region of 4.8 km in range and 3.4 km in azimuth, again centred on the Solfatara Crater. By using the 24 acquisitions, 84 small-baseline interferograms were formed using DLR's interferometric system GENESIS. After the multilooking and unwrapping of the differential interferograms, they were appropriately combined in subsets (Fig. 9 blue), characterized by small baselines, with the goal of limiting spatial decorrelation and provide spatially dense deformation maps.
A Single Value Decomposition Algorithm was used to estimate the deformation for each pixel [2].
No long-term stable point inside the processed area was available as a reference point, so a building carrying a permanent GPS Station (IPPO) with a known GPS-time series was used. The processing results were then corrected for the reference point motion by projecting the known changes of the IPPO station into the Radar Line of Sight (LOS).
Through the SBAS Processing, reliable deformation time series for approximately 30% of the processed area

could be retrieved in the form of 23 deformation maps distributed over the monitored time span (Fig. 10). Using these maps, deformation time series for each processed pixel can be extracted (Fig. 11).

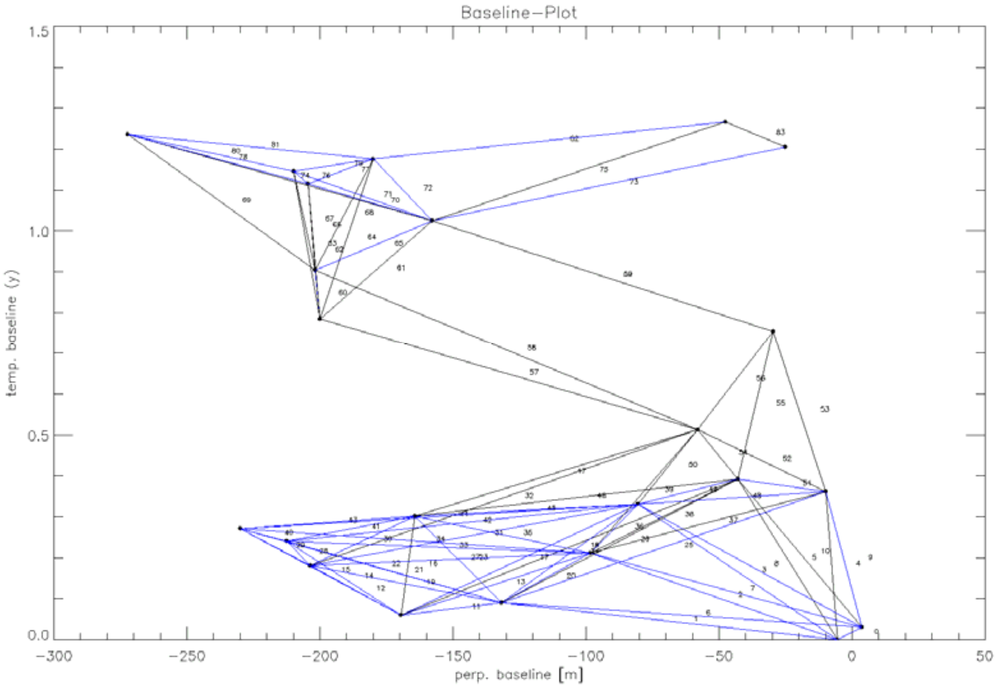


Figure 9. Baseline Diagram for SBAS-Processing

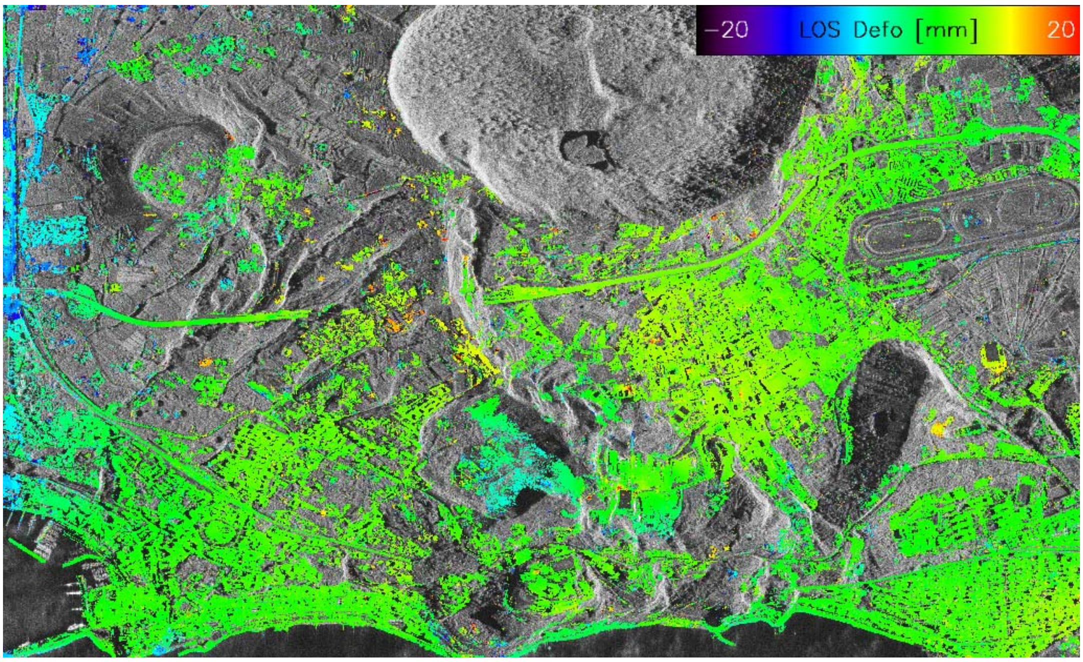


Figure 10. Accumulated deformation map of valid pixels, red showing uplift, blue indicating subsidence, draped over an Amplitude image of the region

4.3. Results

Starting from the end of 2004, the Campi Flegrei caldera exhibits an uplift phase with small accelerations followed by stasis of the phenomenon.

In particular, the vertical component of the ground displacement reached +77 mm in the period November 2004 – June 2011 on the altimetric benchmark 25A (Fig. 2).

As regard to the InSAR results in the interested period, they confirm the general uplift of the whole region of approximately 5mm/y, though different velocities can be observed throughout the processed footprint. Some small areas in the region however, show a different behaviour and can therefore clearly be identified in the last deformation map, shown in Fig. 10.

Conversely, the south–eastern part inside the Solfatara crater shows a different behavior compared with general trend of the Campi Flegrei area.

5. COMPARISON AND INTERPRETATION

Validation of the retrieved times series using GPS stations generally shows a very good agreement of the time series, differences mostly are below 2mm, measured in LOS (Fig. 11).

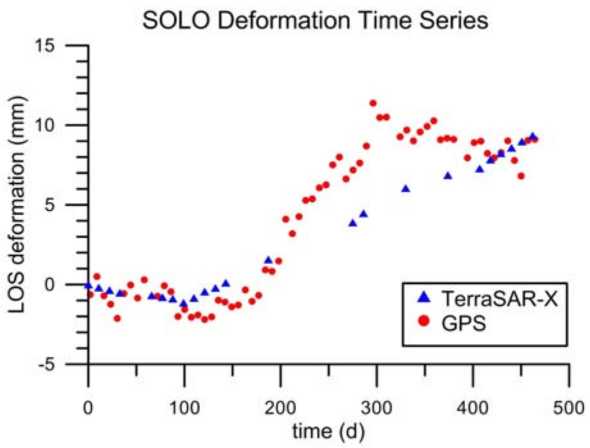


Figure 11. Time series comparison of the SBAS Results and SOLO permanent GPS station

The different behaviour shown inside the Solfatara crater could be likely related to soil compaction phenomena due to degassing events, extremely localized and linked to the presence of the main vent in the south–eastern part of the crater.

Levelling measurements carried out during the last years exhibit a shift eastward of the maximum deformation area, which could be validated through long–term InSAR monitoring, exploiting high resolution X-band data.

As a general comment, we must point out that, in the absence of a strong deformation signal affecting the whole area, very local and shallow deformation events mostly prevail, as in the case of the 2009 Pisciarelli event, pointed out in the 15.12.2009 – 26.12.2009 interferogram.

This paper demonstrates the exceptional suitability of High Resolution TerraSAR-X data and the SBAS Processing for monitoring highly dynamic volcanic systems from space. A well known deformation history, not only point wise, but covering large areas, increases the chances of retrieving data for events at new and up to then unknown positions. This knowledge is critical for understanding the subsurface processes and helps in assessing the risks this volcanic system poses for the surrounding area.

Acquisitions of the Campi Flegrei area will be continued at least until the end of 2011, future monitoring and research will likely happen in the framework of the Supersites initiative, in which the Campi Flegrei are one of the European research sites for volcanoes.

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