# MONITORING THE CAMPI FLEGREI CALDERA BY EXPLOITING SAR AND GEODETICAL DATA: RECENT RESULTS AND FUTURE APPLICATIONS

**P. Berardino [(1)], S. Borgström [(2)], I. Aquino [(2)], F. Casu [(1)], C. Del Gaudio [(2)], R. Lanari [(1)], M. Manunta [(1)], M. Manzo [(1)], A. Pepe [(1)], S. Pepe [(1)], G. P. Ricciardi [(2)], C. Ricco [(2)], E. Sansosti [(1)], G. Solaro [(2)], P. Tizzani [(1)], G. Zeni [(1)]**

*[(1)] Istituto per il Rilevamento Elettromagnetico dell'Ambiente - Consiglio Nazionale delle Ricerche, via Diocleziano 328, 80124 Naples (Italy), Email: berardino.p@irea.cnr.it*
*[(2)] Istituto Nazionale di Geofisica e Vulcanologia - Osservatorio Vesuviano, via Diocleziano 328, 80124 Naples (Italy), Email: sven@ov.ingv.it*

## ABSTRACT

Geodetical monitoring of the Campi Flegrei caldera (Naples, Italy), has been historically carried out by ground networks giving an information related only to a certain number of measuring points; this limitation can be greatly relieved by exploiting the space-borne DInSAR which allows to extract the geodetic information on wide areas, with a good time coverage in comparison with the mean repetition time of the campaign measurements.
In this work we will show recent results on Campi Flegrei, obtained by using all the ENVISAT ASAR available data from both ascending and descending orbits.
The processed data revealed that the uplift phase of Campi Flegrei, which became very clear in summer 2005 with an average velocity of about 2.8 mm/year, has definitely reduced the uplift velocity since spring 2007. This conclusion is consistent with independent deformation measurements carried out by the Vesuvius Observatory (INGV-OV).
Differences, in terms of limits and potentialities of DInSAR with respect to classical geodetic techniques and vice-versa and the way they can be compared/integrated, is still a very interesting matter of debate suggesting, as an optimal solution for monitoring purposes in active volcanic areas, the integration of all the available techniques.

## 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 can (or cannot) turn into an eruption. Deformations appear sometimes with a very low amount, at least at the beginning of the volcanic process, requiring therefore very accurate surveying techniques in order to be detected.
Besides the ground monitoring networks, that allow very high accuracies in the deformation measurement, Differential Synthetic Aperture Radar Interferometry (DInSAR) is well suited in this case, allowing to investigate ground deformations with centimetre to millimetre accuracy by exploiting the round-trip phase components of Synthetic Aperture Radar (SAR) images relative to an area of interest.
In this work we will show recent results on the Campi Flegrei (Phlegrean Fields) caldera, a volcanic and densely populated area located to the west of the city on Naples (Italy) and characterized by continuous ground displacements (bradyseismic activity) related to its volcanic nature.
The geodetical monitoring of the area has been historically carried out by the Osservatorio Vesuviano (Vesuvius Observatory) of the Italian National Institute for Geophysics and Volcanology (INGV-OV) by ground networks, as shown in Fig. 1.

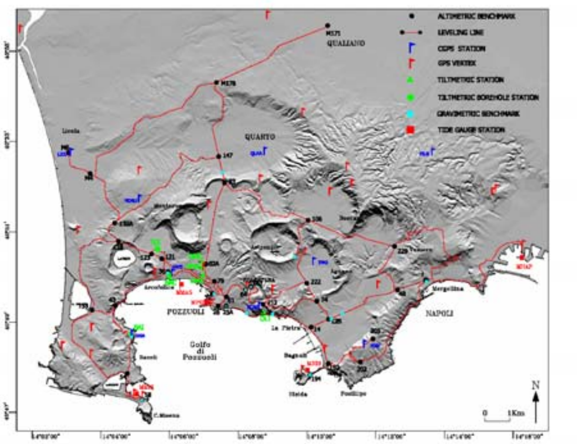


*Figure 1 - Geodetical networks of Campi Flegrei*

In particular, some levelling lines of the present levelling 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, with a maximum value of the vertical displacement in both cases of more than 170 cm (Fig. 2), recorded over an altimetric benchmark (benchmark

25A, see Fig. 1) located in the maximum deformation area.

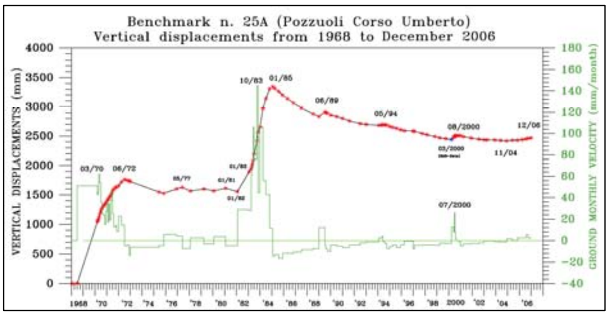


*Figure 2 - Height variations in time of the benchmark 25A and ground monthly velocity from 1968 to 2006*

From January 1985 the Campi Flegrei caldera is undergoing a subsidence phase, with only short uplift events recorded with about quinquennial frequency, very short in time (4 months at the most) and not affecting the last twenty-year trend of the area. Such short crises were pointed out from their very beginning only by the continuous tiltmetric network.

## 2. THE 2005-2006 UPLIFT EVENT IN CAMPI FLEGREI

Between May and June 2004 we recorded the beginning of a new uplift phase, initially pointed out by the tiltmetric stations and afterwards confirmed by the levelling measurements carried out from November of that year.
To further investigate the uplift occurring in Campi Flegrei area, also SAR data processing was carried out in the frame of a scientific agreement between INGV-OV and the Institute for the Remote Sensing of the Environment of the Italian National Research Council (IREA-CNR), focused on the geodetical monitoring of the Neapolitan Volcanic District via an integration between DInSAR and classical geodetic techniques.

## 3. DINSAR DATA PROCESSING

In this work we refer to the Small BAseline Subsets (SBAS) technique [1], which relies on the use of small baseline differential SAR interferograms and on the application of the Singular Value Decomposition (SVD) method. This technique can generate deformation velocity maps and ground deformation time-series of the area of interest; moreover, it has the peculiarity to be able to work at two-scale resolution in order to investigate both spatially large deformation phenomena (with resolutions of about 100m x 100m) [1] and localized displacements that may affect, for example, small areas or single buildings (at the full instrument resolution) [2].

The SBAS algorithm large scale feature has been proved to be well suited for characterizing and monitoring of volcanic phenomena. This has the big advantage of reducing the amount of data to be handled, thus making the whole processing chain more efficient with respect to the full resolution one, while keeping the capability to measure the deformation signal related to the volcanic activity.
Fig. 3 and 4 show the deformation velocity maps and the ground deformation time-series referred to the pixels highlighted with red stars in the maximum deformation area, on the coast-line close to Pozzuoli centre. They were obtained by using all the ENVISAT ASAR available data from both ascending (track: 129 - frame: 810) and descending (track: 36 - frame: 2781) orbits, respectively.

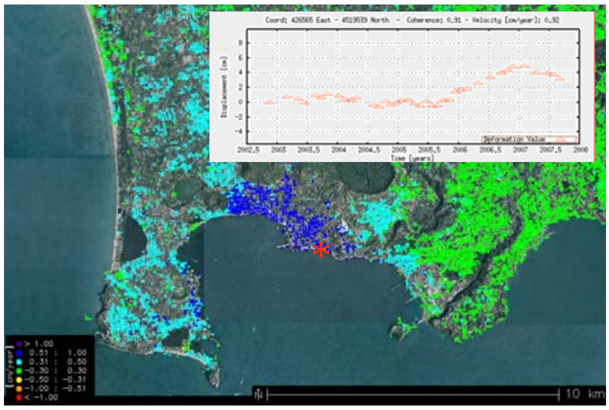


*Figure 3 - Deformation velocity map from ascending data with the ground deformation time-series referred to the pixel highlighted with the red star. ENVISAT ASAR data - IS2 - Time span: 13/11/2002-29/08/2007*

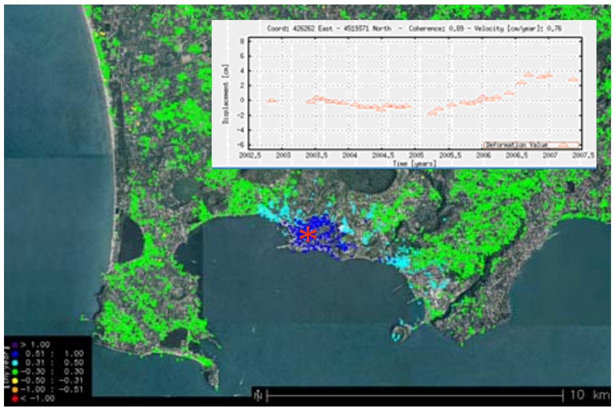


*Figure 4 - Deformation velocity map from descending data with the ground deformation time-series referred to the pixel highlighted with the red star. ENVISAT ASAR data - IS2 - Time span: 07/11/2002-10/05/2007*

The processed data revealed that the uplift phase of Campi Flegrei, which became very clear in summer 2005 with an average velocity of about 2.8 mm/year, has definitely reduced the uplift velocity since spring 2007.
The different behaviour of the deformation pattern pointed out when comparing the two deformation velocity maps, is due to the presence of a well known planimetric component of ground motion, as also reported in [3] from GPS data.
The deformation event highlighted by SAR Interferometry is consistent with the results of independent deformation measurements carried out by the INGV-OV on the monitoring networks of the area, as shown below.

## 4. GEODETICAL DATA PROCESSING

Fig. 5 shows the results from levelling measurements carried out along the coast line (see the box in the upper part of the figure) in the period from November 2004 to December 2006: besides indicating the maximum value of the vertical displacement (about 5 cm, recorded on benchmark 25A), the figure clearly highlights the time evolution of ground deformation, from subsidence in November 2004 (referred to May 2004) to uplift till December 2006.

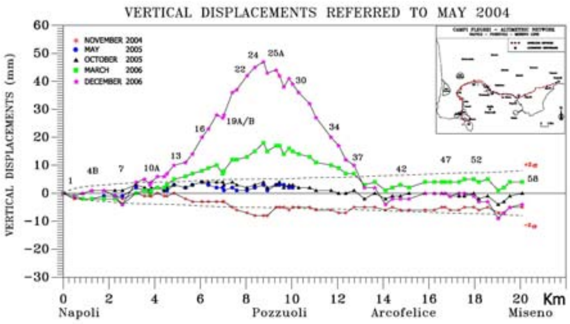


*Figure 5 - Levelling measurements: vertical displacements from November 2004 to December 2006 referred to May 2004 - Coast line*

The results from continuous tiltmetric measurements (Fig. 6) point out the beginning of the uplift event already in the middle of 2004 [4].
The figure shows the signals for the time span 1996-2007 of the N-S and E-W components of the tilt sensor (DMB station, see Fig. 1), besides the temperature, the time azimuth from North of the tilt vector every month with respect to the starting value, the relative histogram and the tilt modulus; the resultant vector of the NS and EW components (previously filtered) has been plotted on the right. Tilt decrease must be interpreted as a subsidence (southward and westward down) otherwise as an uplift.

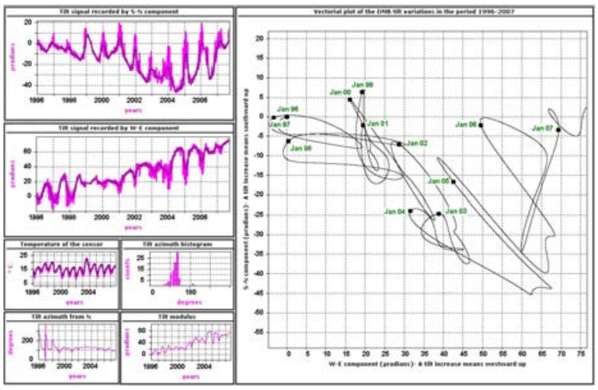

*Figure 6 - Tiltmetric measurements: ground tilt (DMB station) from 1996 to 2007 with the plot of the resultant vector of the NS and EW components on the right*

Besides considering an increasing of the tilt towards East in the E-W sketch of Fig. 6, an inversion of the ground tilt can be clearly seen in the N-S sketch during mid-2004, due to the beginning of the uplift event. The superimposed cyclic component is likely related to local thermal effects.

## 5. DISCUSSION AND CONCLUSIONS

### 5.1. The integration between SAR and geodetical data: some open issues

The geodetic information from ground networks is related only to a certain number of measuring points: this limitation can be greatly relieved by exploiting the space-borne DInSAR technique, which allows to extract an information on wide areas, indicating also eventual migrations of the deformation field outside the layout of the terrestrial networks and therefore the areas to be afterwards selected for setting up new ground networks.
Space-borne DInSAR allows moreover a time coverage better than the classical techniques, considering the revisiting time of the SAR sensors in comparison with the mean repetition time of the geodetic campaigns on periodically measured networks (e.g. 35 days/swath for the ENVISAT ASAR sensor vs. one/two geodetic campaign(s)/year), unless in case of crisis, when classical data sampling is strongly increased.
This is obviously not true when dealing with permanent networks (e.g. continuous GPS), but also in this case we must take into account the generally poor space coverage of permanent stations on the area of interest, due to some economical, technical and logistic reasons.
The recent availability of new SAR data processing strategies, like the Persistent Scatterers Interferometry approach (e.g. SBAS, PS, etc.) has allowed to get (long) time-series of the ground deformation, filling the information gap from classical techniques in the time interval between the campaign measurements and

highlighting precisely the evolution of the observed phenomena.
However, also the monthly revisiting time of the SAR instruments could not be adequate in case of crisis, as it does not allow following the evolution of an impending eruption. In order to increase the update frequency, SAR data should be acquired by different sensors, besides exploiting the SAR sensors capabilities to image the area of interest from different swaths (e.g. ENVISAT ASAR). Unfortunately, the main limit of this approach is related to possible conflicts with other (not scientific) user requests: in this case the Scientific Community and the Civil Protection authorities should make some pressure on the Space Agencies in order to give them priority in EO data provision.
On the contrary, one of the main drawbacks of DInSAR is due to the temporal decorrelation, affecting sometimes large areas. Besides using Corner Reflectors in case of no or low coherence, a possible solution was recently given to the SAR Community by the use of L-band data, which is suitable for monitoring purposes in active volcanic areas with high deformation rates, but not suited with low deformations, as in the case of Campi Flegrei, requiring a ground displacement of at least 12 cm to get one interferometric fringe.
Again, also the use of the C-band could result sometimes in no information when dealing with very low deformations, as it was in the case of the 2005-2006 uplift event in Campi Flegrei, when only continuous tiltmetric stations were able to detect the beginning of the event on May 2004, pointed out by the ENVISAT ASAR sensor only from mid-2005.
This problem could be overcome in the very next future by using the data of recently launched sensors like TerraSAR-X and COSMO-SkyMed, employing the more sensible X-band.
Anyhow the differences, in terms of limits and potentialities of DInSAR with respect to classical geodetic techniques and vice-versa and the way they can be compared/integrated, is still a very interesting matter of debate suggesting, as an optimal solution for monitoring purposes in active volcanic areas, the integration of all the available techniques.

### 5.2. Final remarks

Ground deformations measurement in the Campi Flegrei area is a crucial point because, according to historical records, deformation seems to precede the beginning of seismic activity during uplift phases and both the energy and the number of seismic events increase at increasing velocity of ground displacement [5].
As a general remark, we must highlight that the comparative analysis between DInSAR and geodetical data referred to the 2005-2006 uplift event is good also if the comparison did not show a clear agreement as it was during the previous uplift recorded in spring-summer of 2000, due to a very slow and irregular trend of the phenomenon at the beginning, which was not initially solved by the C-band ENVISAT ASAR sensor.
The main limitations towards a more precise comparison between SAR and classical data in the area of interest are due to the poor space coverage of the geodetic continuous stations vs. the high space coverage of SAR data, besides the low data sampling of periodic networks, unless in case of crisis.
The difference between the components of ground motion recorded by SAR and classical techniques has been partially overcome when SAR data from both ascending and descending orbits are available, resulting in the possibility to split the data into the vertical and the easting components of ground motion, easily comparable with levelling and/or GPS data. This task was preliminarily carried out for the Campi Flegrei caldera, giving encouraging results and will be further developed in the frame of future monitoring and research activities, as it will be in the case of the Italian Space Agency (ASI) pilot project “Volcanic Risk System”.

## 6. ACKNOWLEDGMENTS

SAR and geodetical data processing was carried out in the frame of the INGV-DPC Project V3_2 - Campi Flegrei 2005-2007 - Research Units: V3_2/01 and V3_2/06.

## 7. REFERENCES

1. Berardino, P., Fornaro, G., Lanari, R., Sansosti E. (2002). A new Algorithm for Surface Deformation Monitoring based on Small Baseline Differential SAR Interferograms. *IEEE Transactions on Geosci. and Remote Sensing* **40-11**, 2375-2383.

2. Lanari, R., Mora, O., Manunta, M., Mallorquí, J.J., Berardino, P., Sansosti E. (2004). A Small Baseline Approach for Investigating Deformations on Full Resolution Differential SAR Interferograms. *IEEE Transactions on Geosci. and Remote Sensing* **42-7**, 1377-1386.

3. Lanari, R., Berardino, P., Borgström, S., Del Gaudio, C., De Martino, P., Fornaro, G., Guarino, S., Ricciardi, G.P., Sansosti, E., Lundgren P. (2004). The use of IFSAR and classical geodetic techniques for caldera unrest episodes: application to the Campi Flegrei uplift event of 2000. *Journal of Volcanology and Geothermal Research*, **133**, 247-260.

4. Ricco, C., Aquino, I., Borgström, S., Del Gaudio, C. (2007). The study of the tiltmetric inversion recorded from July to October 2006 at the

Phlegrean Fields (Naples, Italy). *Annals of Geophysics*, in press.

5. Orsi, G., Civetta, L., Del Gaudio, C., de Vita, S., Di Vito, M.A., Isaia, R., Petrazzuoli, S.M., Ricciardi, G.P., Ricco, C. (1999). Short-term ground deformations and seismicity in the resurgent Campi Flegrei caldera (Italy): an example of active block-resurgence in a densely populated area. *Journal of Volcanology and Geothermal Research*, **91**, 415-451.