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Subsidence of Campi Flegrei (Italy) detected by SAR interferometry

A. Avallone and A. Zollo
Università "Federico II"- Dipartimento di Scienze Fisiche, Napoli - Italy

P. Briole
Institut de Physique du Globe, Paris - France

C. Delacourt
UCBL & ENSL, Laboratoire de Dynamique de la Lithosphère, Lyon - France

F. Beauducel
Osservatorio Vesuviano, Napoli - Italy

Abstract. Seven ERS SAR images of the Napoli area acquired from 1993 to 1996 were used to create six differential interferograms. Although the ambiguity height of the selected couples is high, because of the adverse characteristics of the area, the interferograms exhibit a relatively low level of coherence, even for couples sampling short time intervals. According to the estimated accuracy, no deformation is observed on Vesuvio volcano. The best interferogram, corresponding to the period Feb. 14, 1993 - Apr. 3, 1996, shows that the centre of the Campi Flegrei caldera, near Pozzuoli harbour, subsided by about three fringes (84 mm) during the three years interval. This result is consistent with the value of 28 ± 2 mm/year obtained from routine levelling surveys over the same period in the same area. The deflation that started after the 1983-1984 seismic and inflation crisis is thus still significant. The modelling of the fringe pattern, assuming a spherical deflating source within an elastic half-space medium, predicts a source centred about 800 m Southwest of Pozzuoli at a depth of 2.7 $\pm$ 0.3 km. For the studied time window, the maximum subsidence predicted by the model is 25 mm/year.

Introduction

DInSAR (Differential Interferometry - Synthetic Aperture Radar) has proven to be a powerful technique for the monitoring of several environmental phenomena. High spatial sampling (with decametre ground resolution) of DInSAR technique allows the study of a wide range of surface deformations (hundreds of metres up to thousands of kilometres) with a sub-centimetre accuracy [*Zebker et al.*, 1994]. For example, spaceborne radar interferometry has shown its utility in landslide detection [*Fruneau et al.*, 1996] and in mapping seismic deformation [*Massonnet et al.*, 1993; *Stramondo et al.*, 1999] as well as volcano deformation [*Massonnet et al.*, 1995; *Briole et al.*, 1997, *Lanari et al.*, 1998, *Sigmundsson et al.*, 1997, *Lu et al.*, 1997]. Here, we use the DInSAR method to examine the present days ground deformation occurring around the city of Napoli (Southern Italy), especially in the volcanic area of Campi Flegrei where two ground inflation events, accompanied by seismic swarms, occurred in 1970-1972 and 1982-1984 [*Scandone et al.*, 1991].

Campi Flegrei area is a complex volcanic landform located approximately fifteen kilometres West of Napoli, Southern Italy (Figure 1). The inner caldera presents numerous explosive eruptive vents that are framed by the rim of the Quaternary explosive caldera, which has a diameter of about 12 km and is 40,000 years old [*Aster et al.*, 1992]. The caldera is flanked on the east by Vesuvio volcano and on the west by the volcanic islands of Ischia and Procida. As suggested by the results of the several geological and geophysical surveys, which have been performed in the region [*Lirer et al.*, 1987; *Scandone et al.*, 1991], the Campi Flegrei area is a volcano-tectonic depression, a caldera, created by a subsidence of this area due to several collapses during the last 35,000 years of volcanic activity. After the Neapolitan Yellow Tuff (NYT) eruption (about 12,000 years ago), the successive eruptive episodes occurred only within the caldera structure and frequently along its rim, giving arise sometimes to intracalderic collapses and sometimes to significant uplifts. Following the

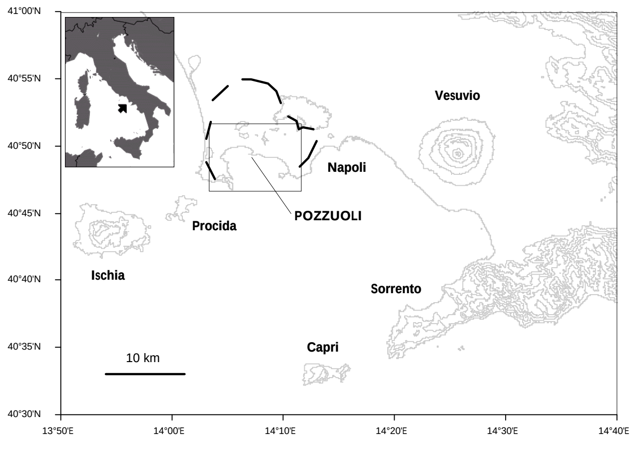

Figure 1. Location of the investigated area: topography of the region of Napoli and Mt. Vesuvio (200-m contour lines). Inset selection corresponds to the Campi Flegrei area used for modelling (Pozzuoli Bay). The black thick line represents the inland caldera rim.

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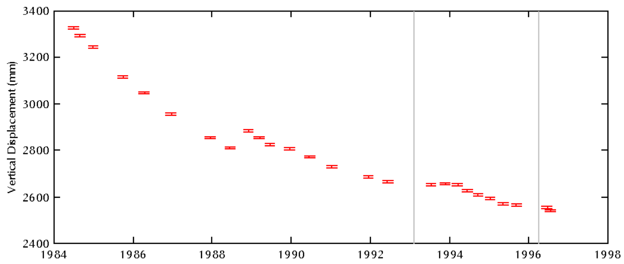

Figure 2. Results of routine levelling surveys carried from January 1985 to January 1997 (Pozzuoli benchmark C25A) [*Osservatorio Vesuviano*, 1998]. A general downlift trend, after the 1982-1984 uplift episode, is observed, and a subsidence of 100 mm is measured in the interval spanned by the DInSAR survey (vertical lines).

last eruption, occurred in 1538 at Monte Nuovo (western periphery of Campi Flegrei), the central caldera subsided, with an average subsidence rate of about 14 mm/year, for over 400 years until approximately 1968, accurately recorded since around 1800 by the progressive sinking of the Serapeo roman market ruins. The shape of measured ground deformation presented an approximately circular symmetry with a maximum subsidence in correspondence of the town of Pozzuoli and sharply decreasing moving outward the centre of the caldera [*Lirer et al.*, 1987]. In the last thirty years two resurgent episodes occurred inverting the previous subsiding trend: the first one from 1970 to 1972 and the second one from 1982 to 1984, followed by a partial recovery of respectively 14% and 30% of the relative uplift [*Berrino and Gasparini*, 1995]. Beginning in early 1983, several months after the start of the ground uplift unrest, an intense seismic activity occurred in the maximum uplift area, characterised by a large number of small magnitude (Ml=1-3) events mainly located in the coastal region surrounding the city of Pozzuoli at rather shallow depths (0-3 km) [*Aster et al.*, 1992]. Successive levelling surveys, performed in the Pozzuoli benchmark from January 1985 to January 1997 by Osservatorio Vesuviano, show that after these two anomalous periods, the area took again a general downlift trend, even with very short and occasional tendency change (Figure 2) which is not documented, and that the process of subsidence is still continuing at a rate that tend to decrease with time. In the time interval spanned by our DInSAR survey (38 months), a subsidence of 100 mm is observed by the standard levelling surveys [*Osservatorio Vesuviano*, 1998].

Interferogram production and analysis

The seven ERS SAR images used in this study correspond to ascending orbits acquired at night (21:17 local time) and span a time interval of more than three years. Among twenty-one possible combinations, we selected six couples with high ambiguity height (listed in Table). The ambiguity height is the amount of elevation change that produces one topographic fringe [*Massonnet and Rabaute*, 1993]. The higher the ambiguity height value is, the lower the sensitivity to topography is. The contribution of the topography was removed using a DEM provided by the Italian Istituto Geografico Militare (IGM) with a 1-arc-second geographic horizontal resolution and an average height accuracy of 10 m. Precise ERS orbits produced either by ESA (European Space Agency) (http://www.esrin.esa.it) or by Delft University (http://deos.lr_tudelft.nl/ers/precorbs) were used.

Most of the interferograms exhibited a low level of coherence, especially on the Vesuvio volcano, on the Sorrento peninsula and to the north and the Northeast of the city of Napoli. There is no clear relation between coherence and ambiguity height, although this is the case elsewhere, for example on Mount Etna (EU project Madviews, final report). It may be due to different causes: intrinsic incoherence which is expected in place with high degree of human modification; the sea closeness, which degrades the interferograms' quality mainly along the coast; the frequent changes of the meteorological conditions between the images acquisition periods, which cause decorrelation in the interferometric phase.

The interferogram which displays the clearest observation of the displacement field (Figure 3) was obtained from two images spanning about 38 months (ERS1 orbit 8290 acquired on 1993-02-14 ERS2 orbit 4993 acquired on 1996-04-03). Its ambiguity height of 182 m lead to a maximum expected errors due to the topography of approximately 1/18 of a fringe (less than 2 mm) according to the 10 m accuracy of the DEM. A large scale fringe, running eastward, due to a residual orbital effect, is observed. Notwithstanding, a deflation signal is clearly visible only in the western part of the interferogram, reaching about three fringes near Pozzuoli harbour, in the centre of the caldera. According to its level of noise, measurement deformation accuracy is estimated to ± 1 fringe ($\pm$ 28mm). The subsidence detected along the line of sight by DInSAR is thus 84 ± 28 mm in 38 months, that corresponds to an average maximum subsidence rate in slant range of 26 ± 9 mm/year. This value is in good agreement with the vertical subsidence rate of 100 ± 5 mm measured by the *Osservatorio Vesuviano* [1998] almost at the same place (benchmark C25A in Pozzuoli) during the same period that would correspond to 90 ± 5 mm along the satellite line of sight or 28 ± 2 mm/year.

Among the six selected couples, the interferograms corresponding to the 1995-1996 interval do not show clearly a fringe, although one is expected from the levelling data. This confirms that the $\pm$ 1 fringe standard deviation assumed for our above estimate is realistic and quantifies the level of detection of DInSAR method in the case of Campi Flegrei area.

Modelling of the deformation source

A simple modelling was performed in order to estimate the location of a source and its associated volume variation (4 parameters), compatible with the observed interferogram. An

Table. ERS images used in this study and ambiguity height of the interferograms. The acquisition date (local time is 21:17), satellite and orbit number is indicated. The track and the frame of the images are 129 and 819 respectively.

	Satellite	ERS1	ERS1	ERS2	ERS2
	Orbit	08290	21159	01486	01987
Orbit	Date				
08290	1993-02-14				
21159	1995-08-01	1130 m			
01486	1995-08-02		164 m		
01987	1995-09-06				
22662	1995-11-14		69 m	120 m	2884 m
04492	1996-02-28				
04993	1996-04-03	182 m			

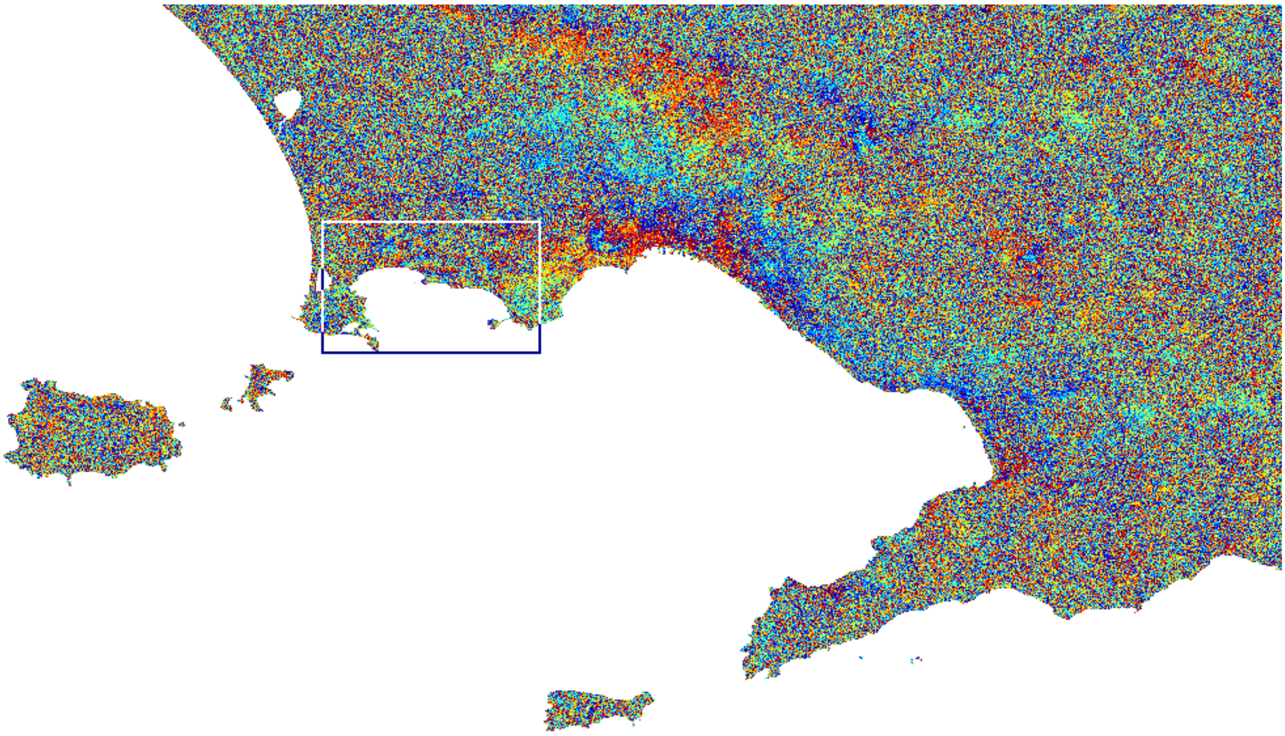

Figure 3. Best interferogram obtained from the phase difference of two SAR images (1993-02-14 and 1996-04-03) (with orbit numbers 8290 and 4993, respectively). Three cycles of phase (fringes) are clearly visible, corresponding to about 84 mm of total displacement along the sensor line of sight. Inset selection puts in evidence the deflating area and the modelled one.

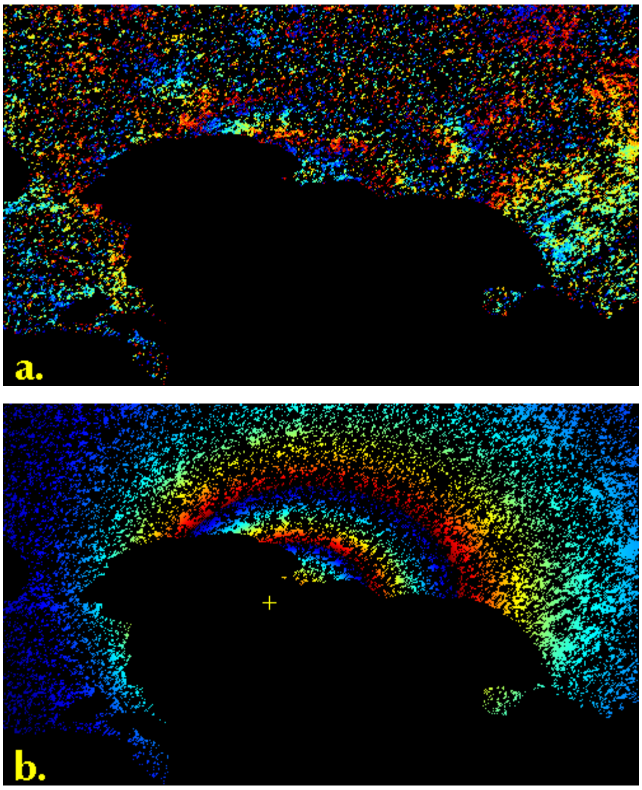

Figure 4. Modelling of the deflation by a source point in elastic half-space (11.6 × 9.4 km area). (a) Data used for the inverse problem (selection of most coherent pixels in the interferogram). (b) Best model found: computed interferogram and location of the 2.7-km deep source (cross).

area of 8’30" Eastern by 5’ Northern (about 11.6 by 9.4 km in UTM local coordinates) that includes the complete Pozzuoli Bay was selected. Original data were filtered in order to keep only the most coherent phase values (pixels with more than 62% of coherence) for the modelling. These data are shown on Figure 4a, representing about 23,000 data (15% of the original data set). Using a point-source model in an elastic homogeneous half space medium [*Mogi*, 1958], we defined the forward problem as a synthetic interferogram equal to the projection of three-dimensional displacement vector on the satellite line of sight, properly scaled and wrapped according to the sensor wave length. Cost function is defined as the misfit between computed and observed phase values (in the least squares sense), and had to take into account phase ambiguity. The best model was found using the gradient search inversion method (about 30 steps for converging), starting with an a priori source located below Pozzuoli. Figure 4b shows the computed interferogram that reproduces the observed fringes pattern and a total of 2.8 fringes for Campi Flegrei. The source was found at 500-m west and 600-m south of Pozzuoli, 2.7 ± 0.3 km depth, and with a volume decrease of 2.5×10^6 m^3. The predicted vertical displacement at Pozzuoli is -78 mm, a value compatible although somewhat less than the observed levelling motion.

Discussion

The spatial extent and geometry of the deformation field, as inferred by the DInSAR, confirm that it is the same area that is displaced during the different events since 1970. The 1982-1984 Campi Flegrei uplift unrest has already been modelled by a point source [*Dvorak & Berrino*, 1991] and a source depth of about 3 km below Pozzuoli was found. This phenomenon can be related to a pressure increase either below the caldera structure or within the loose pyroclastics. It is compatible with the intense seismic swarms that occurred from 1982-1984, indicating that the rock was fracturing at depth of few kilometres. In our case, the few centimetres of subsidence correspond to a pressure decrease value consistent with absence of significant seismic activity from 1993 to 1996 (Osservatorio Vesuviano, intern. report, 1998).

The accuracy of the DInSAR result is significantly lower than the classical precision levelling, but the spatial coverage is much denser (23,000 points instead of a few hundreds). The subsidence interests an area which has the similar extension and geometry of the uplifted area during the recent ground deformation unrest episodes [*Scandone et al.*, 1991], thus suggesting the presence of a common source driving both the short-term ground uplifts and subsidence processes in the inner caldera. Moreover, in the DInSAR image it is possible to note the spatial continuity of the deformation, which is more difficult to detect with discrete GPS benchmarks or even dense levelling measurements.

The proposed source model does not take into account the complex caldera structure of Campi Flegrei. For that, it cannot tell more than a first order information on the source location and volume variation occurred during the period of study. Nevertheless, the relatively good fit and the agreement between our computed source characteristics (horizontal location and depth) and the other geophysical studies results suggest that this modelling reflects some reality of the involved phenomena.

Conclusions

Despite several unfavourable factors and the consequent low level of coherence, DInSAR method has been successfully used for measuring the ground displacement changes in Neapolitan volcanic area. The DInSAR method, applied to radar images in the period comprised between 1993 and 1996, confirms the significant subsidence still occurring in the Campi Flegrei area after the last 1982-1984 seismic and inflation sequence. This subsidence is also observed by classical levelling surveys. The best interferogram, corresponding to the 1993 - 1996 period shows that the centre of the Campi Flegrei caldera subsided by about 26 ± 9 mm/year during this three years interval. This result is consistent with the value of 100 ± 5 mm obtained from the routine levelling surveys carried out by Osservatorio Vesuviano in the same area.

The modelling of the fringe pattern using the *Mogi*'s model predicts a source centred offshore eight hundreds meters Southwest of Pozzuoli at about 2.7 km depth. The modelled volume decrease at depth is 0.8×10^6 m^3/year and the maximum subsidence predicted by the model is 78 mm.

According to the estimated accuracy in the image range ($\pm$ 1 fringe) no deformation is observed on Vesuvio volcano in the three years interval of our study, as already suggested by the comparisons between GPS and DEM data from 1975 to 1996 [*Pingue et al.*, 1998].

Finally, for its own characteristics the Neapolitan area has been an important test for DInSAR and has given the opportunity to understand how the different quality parameters influence the results. Moreover, this work confirms DInSAR potential to detect volcanic ground deformation.

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A. Avallone and A. Zollo, Università "Federico II", Dipartimento Scienze Fisiche, Mostra d'Oltremare, 80125 - Napoli, Italy (antav@na.infn.it, aldo@na.infn.it).

F. Beauducel and P. Briole, Institut de Physique du Globe, Case 89, 4 place Jussieu, 75252, Paris cedex 05, France (briole@ipgp.jussieu.fr, beauducel@ipgp.jussieu.fr).

C. Delacourt, UMR CNRS 8515 UCB Lyon-1 & ENSL, Laboratoire Dynamique de la Lithosphère, Bat 402, Boulevard du 11 Novembre (delac@alto.univ-lyon1.fr).

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