Monitoring Terrain Deformations at Phlegrean Fields with SAR Interferometry

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ABSTRACT

The terrain deformations in the Neapolitan area of the Phlegrean Fields have been studied by means of SAR interferometry (INSAR). The area, located near Mt.Vesuvius, is subject to strong volcanic activity, as testified by the continuous alternation of phases of strong uplift with periods of slow subsidence. Since 1985 the area is undergoing subsidence. A set of interferograms from ERS data has been generated, on different time intervals, covering the period 1995-1999. The deformations resulting from these interferograms have then been combined in a least squares sense to solve for a deformation model for the four years considered. The resulting deformation model, in very good agreement with the results from pre-existing levelling measurements, shows, for the first time, a spatially continous deformation pattern of the area.

Introduction

The aim of this research is to demonstrate the applicability of INSAR as an effective tool for long term monitoring of deformation processes. The importance of long term monitoring is particularly evident in the area considered for this study, i.e. the Phlegrean Fields, a high risk volcanic area near Neaples (Fig.1).

The Phlegrean Fields caldera is located in the NE part of the Phlegrean Volcanic District, which includes also the volcanic fields of the islands of Procida and Ischia. From the geological point of view, the caldera is mainly formed by volcanic rocks and secondly by clastic sea sediments; from the structural point of view, the present configuration is the result of two principal collapse events, respectively related to the eruptions of the Campanian Ignimbrite

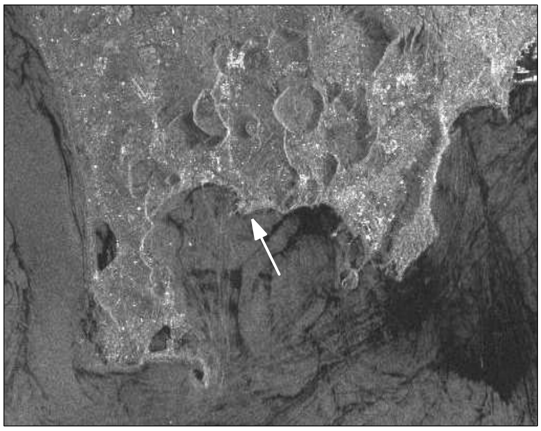

Figure 1: ERS amplitude image of the Phlegrean Fields area. The arrow indicates the location of the city of Pozzuoli.

(37.000 years ago) and of the Yellow Green Tuff (12.000 years ago) [1]. At present, the magmatic system is still active, as testified by the Mt. Nuovo eruption in 1538, the recent bradyseismic crises of 1969/72 and 1982/84 and the diffuse fumarolic and hydrothermal activity. Strong vertical displacements have been registered during these last two bradyseismic crises, which were also always accompanied by continuous seismicity. During the first crisis (1969/72), a maximum ground uplift of about 170 cm was recorded in Pozzuoli. From 1972 to 1974, the ground subsided of about 22 cm while, during the next eight years, there were no significant changes: in this time interval no seismic activity was recorded. From 1982 to 1984 the seismic activity started again, coupled with a strong uplift which reached a maximum of about 180 cm, again in the Pozzuoli area. Since January 1985, the Phlegrean Fields are undergoing a subsidence phase, interrupted only at the beginning of 1989 and in August 1994 by two short periods of uplift, both coupled with seismic activity. At the moment, the ter-

Table 1: ERS images of Campi Flegrei considered for the generation of the interferograms.

Ers1/2	orbit	frame	date	day no
Ers 1	19563	2781	12–4–1995	d1
Ers 1	21066	2781	26–7–1995	d2
Ers 2	1894	2781	31–8–1995	d2a
Ers 2	2896	2781	9–11–1995	d3
Ers 2	6904	2781	15–8–1996	d4
Ers 2	9409	2781	6–2–1997	d5
Ers 1	30585	2781	21–5–1997	d6
Ers 2	10912	2781	22–5–1997	d6
Ers 1	31587	2781	30–7–1997	d7
Ers 2	13417	2781	12–11–1997	d8
Ers 2	17926	2781	24–9–1998	d9
Ers 1	40605	2781	21–4–1999	d10
Ers 2	20932	2781	22–4–1999	d10

rain is subsiding with a mean velocity estimated in about 0.4 cm/month.

The already potentially high volcanic risk of the area is further increased by the fact that it is populated by about two million people. A continuous monitoring of the precursory phenomena (increase of seismicity, variation of temperature and chemical composition of the fumaroles, ground deformations) is therefore extremely important in terms of civil protection of the area. Surveillance is performed on a regular basis by means of precision levelling campaigns, whose results are integrated with those from other topographic techniques (e.g. tiltmetry, GPS)[3].

Although such techniques are able to allow a point positioning with sub-centimeter precisions, however, they have the disadvantage of providing informations related to a discrete number of points. As it will be shown in this paper, in this sense SAR Interferometry can be a valid integration of the traditional techniques, allowing an areal estimation of the deformation field in the area and a more dense sampling in time of the monitoring.

Interferometric and levelling dataset

A set of 13 ERS images has been considered for the generation of 21 interferograms spanning different time intervals, as shown in the scheme of Fig.2. The characteristics of these images are given in Tab.1, where their corresponding dates have been labelled in chronological order. Notice that Tandem pairs,

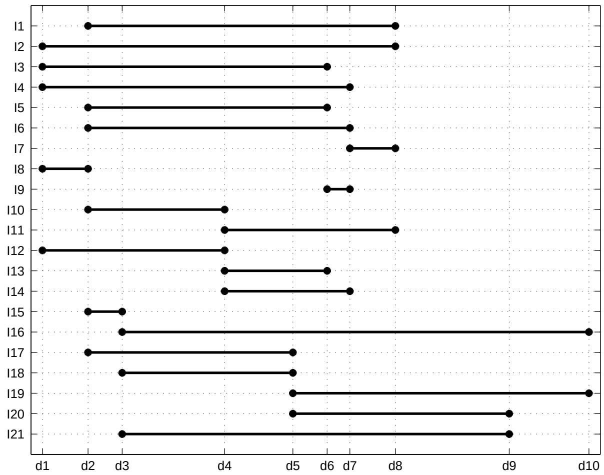

Figure 2: The set of interferograms used for the modelling of the deformations

since they differ of only one day, have been given the same day number. Additionally, a Tandem interferogram has been generated with the pair of orbits no.30585/10912 to be used as reference topography for the differential method ([2]).

As for the levelling data used for the comparison of the results, they consisted of 4 datasets from measurement campaigns performed in January 1995, March 1996, March 1997 and Februari 1998. The deformations estimated from the levelling data were obtained by linear piecewise interpolation in time of these datasets. Unfortunately, the levelling data from the last campaign of 1999 were not yet available, so the comparison with Insar results has not been possible for interferograms extending beyond Februari 1998.

Deformation analysis

The first step was the determination, in each generated interferogram, of the resulting vertical deformations. The differential method has been applied for this purpose, using the Tandem interferogram for estimating the topography in the area. This interferogram has a perpendicular component of the baseline of about 100 meters. The absolute deformation was then computed taking as reference value the phase value at a point of fixed coordinates, the same used as reference for the levelling measurements. More precisely, the mean phase value computed on a square area of size 0.004 degrees around the levelling point coordinates was taken as the zero-

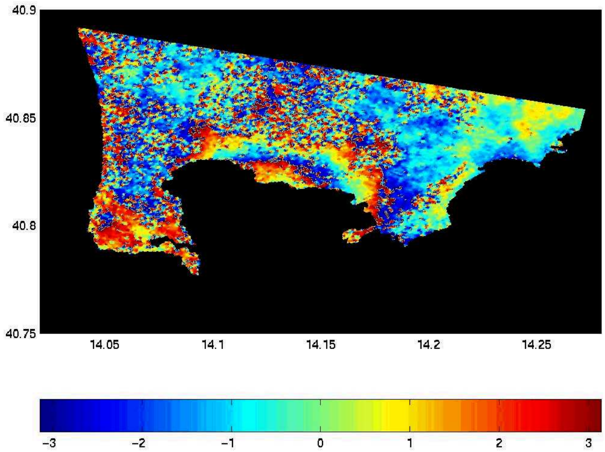

Figure 3: Geocoded phase image of interferogram I_{10} (time interval: 31–8-1995/15–8–1996)

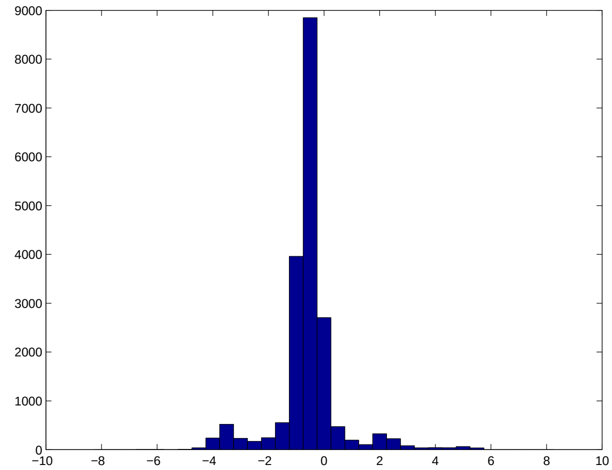

Figure 4: Histogram of a linear combination of 3 interferograms forming a closed loop: the maximum is clearly shifted with respect to zero

deformation value and subtracted from the whole interferogram. The resulting deformations from the interferogram were then validated by comparison with the deformations interpolated from the levelling data on the same time interval. All the interferograms show a similar deformation pattern, extending radially from the Pozzuoli area, see for example Fig.3. Moreover, all the interferograms revealed to be in good agreement with the interpolated deformations from the levelling, in terms of relative deformations. However, some of them showed unrealistic values of absolute deformations, suggesting the presence of a bias in the reference value. Such a bias could be caused by effects like, for example, atmospheric disturbances or differences in soil moisture, but also by phase unwrapping errors. The reference point in fact is located outside the deformating zone, which in most interferogram is almost completely surronded by uncorrelated areas. It is therefore possible that in the passage through these decorrelated areas phase unwrapping is subject to errors. In order to solve for these biases, a procedure based on the comparison of the interferograms has been applied.
An interferogram suspected to be biased was compared with other two ones forming with it what we can call a ”closed loop” in time. Let us suppose that three images are taken at subsequent days A B and C, and that the interferograms AB, AC and BC are formed. If, for example, interferogram AB is suspected to be biased, then it is compared with interferograms BC and AC by considering the linear combination AB+BC-AC, which should give as a result zero. So, for example, the difference of I_1 and I_2 should be equal to the interferogram labelled as I_8, giving the deformations occurred between days $d1$ and $d2$ (see scheme in Fig. 2). Due to the presence of noise in the three interferograms, a noise caused by all different effects and which we can assume to be random, the linear combination of the deformation values will not be overall zero, but its histogram should show anyway a clear maximum around the zero value in absence of a general bias. Therefore, if the histogram is centered at another value (see Fig.4), this means that the suspect interferogram is indeed biased, and the value can be considered as an estimate of this bias and subtracted from that interferogram. With this procedure, all the 21 interferograms generated were checked for the consistency of their deformations, and when necessary corrected.

The series obtained were then adjusted in a least squares sense. The first day (12-4-95) has been taken as reference and the deformations at each of the other nine days with respect to this day have been found as solutions of the problem

$$y = Ax$$

with:

$$y = [I_1, ..., I_{21}] \qquad x = [X_{d2}, ..., X_{d10}]$$

respectively the set of interferograms and the (unknown) deformations at the nine remaining days.

Note that the interferograms $I_{15,\ldots,21}$ do not have images in common with $I_{1,\ldots,14}$. In order to be able to solve the whole set as a unique least squares problem, the day $d2a$ has been assumed to coincide with $d2$, i.e. 31–8–1995. Of course, this introduces in interferograms $I_{15,\ldots,21}$, an error in the estimate of the deformation. This error is equal to the subsidence occurred between the two days and, from the interpolation of the levelling data, results to be approximately 0.5 cm.

Results

The deformations (in cm) resulting from the least square adjustment are shown in Fig.5. The images have been masked for the sea, while the sparse black areas on the land are those which could be not solved for, due to the presence of decorrelation noise. Each image represents the deformations, in centimeters, at one of the nine considered days with respect to the reference day $d1$ (12–4–1995). As expected, the deformation has a radial pattern centered on the east part of the city of Pozzuoli. On the maximum time span considered, i.e. on the period April 1995–April 1999, the measured maximal deformation amounts to about -18 cm, with a standard deviation estimated at the level of 0.4 cm. Although the maximal deformation remains localized in the same area, right to the east of Pozzuoli, the pattern however changes slightly in the course of time, and the deformation seems to extend from the coast to the inland in the east direction. The mean subsidence rate results to be indeed of the order of about 0.4 cm/month, however variations are noticeable in the deformation rate. In the period August 1996–May 1997 the subsidence seems in fact to slow down with respect to the preceding period, increasing then slightly from May 1997 up to April 1999. A denser coverage of interferometric data in time however would be needed to solve for more days and permit a better assessment of the deformation rate changes.

Conclusions

Insar has been demonstrated to be a valid integration of the traditional geodetic techniques in long term monitoring of hazardous areas, provided a sufficiently dense sampling in time of the area is realized. The use of a database of interferograms instead of loose ones permits a check on the consistence of their results, mainly with respect to processing errors, and on the presence of general biases. Moreover, solving for all the deformations as a unique least squares problem provides a picture of the development of the two–dimensional deformation pattern in time.

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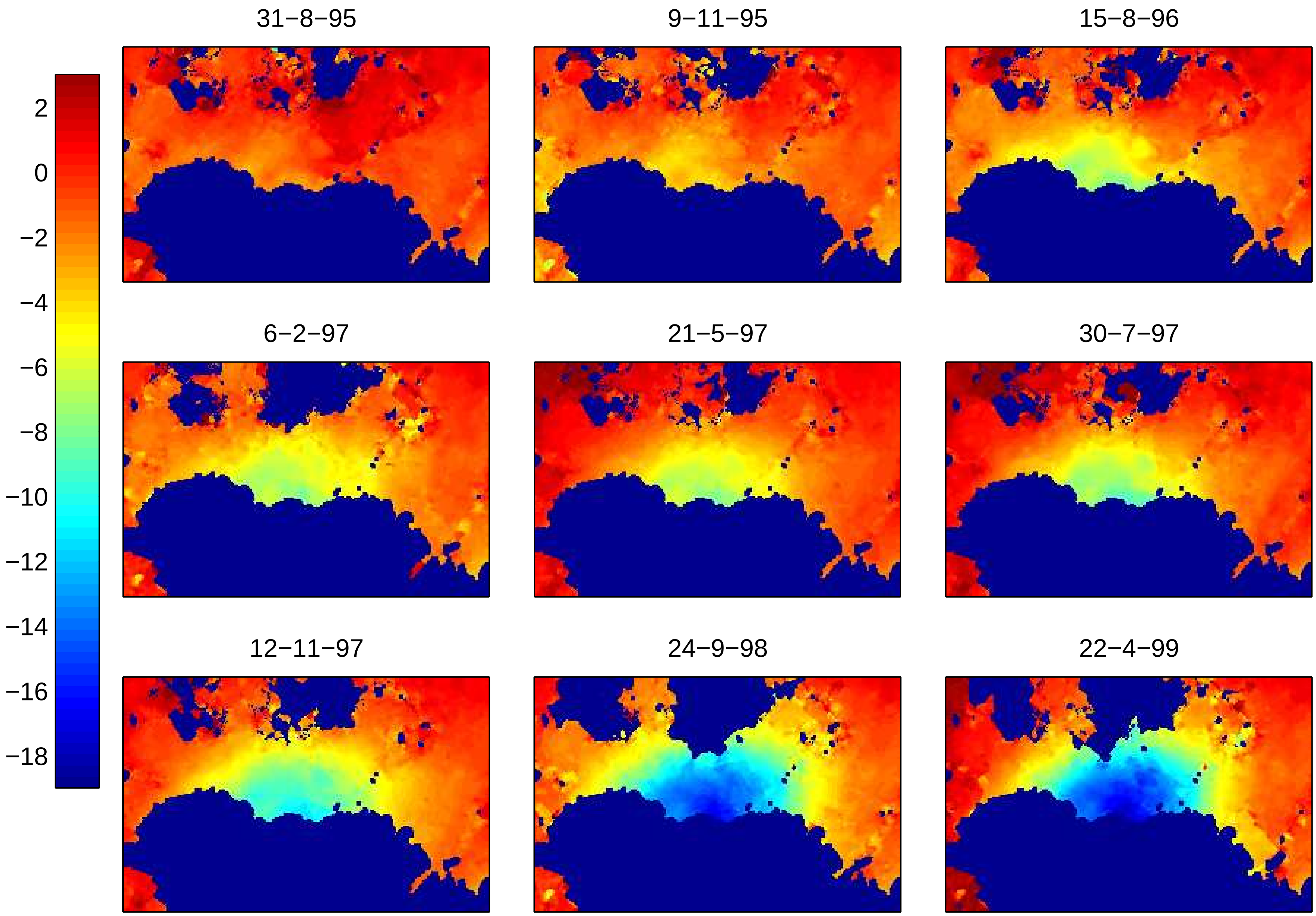

Figure 5: Resulting deformations (in cm.) at the 9 considered days with respect to 12–4–1995