MINERVA: AN INSAR MONITORING SERVICE FOR VOLCANIC HAZARD

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ABSTRACT

MINERVA (Monitoring by Interferometric SAR of Environmental Risk in Volcanic Areas) is a small scale service demonstration project financed by ESA in the Data User Programme framework.

The objective of the project is the design, development and assessment of a demonstrative information service based on the interferometric processing of images acquired from either the ASAR instrument on board ENVISAT-I or SAR instruments on board ERS1/2.

The system is based on a new approach for the processing of INSAR data, which allows to optimize the quality of interferograms spanning from 35 days up to several years, and to merge them to generate a single solution describing the temporal evolution of the ground deformations in the examined risk area. The system allows to update this solution each time a new SAR image is available, and constitutes therefore an innovative tool for monitoring of the ground displacements in risk areas. The system has been implemented and demonstrated at Osservatorio Vesuviano (Naples, Italy), which is the institution responsible for monitoring the volcanic phenomena in the Neapolitan volcanic district, and for alerting the Italian civil authorities ("Protezione Civile") in case such monitoring activity reveals signals of imminent eruptions. In particular, the MINERVA system has been used to monitor the ground deformations at the Phlegrean Fields, a densely populated, high-hazard zone which is subject to alternate phases of uplift and subsidence, accompanied often by seismic activity.

1 INTRODUCTION

The capability of DInSAR (Differential SAR Interferometry) techniques for monitoring land displacement is well proven. This technique allows generating ground deformation maps of the observed area by exploiting the phase difference of two SAR images acquired at different time and from slightly different orbits.

The phase of an interferograms includes the following contributions [1]:

- Topography. It is due to the different acquisition geometry and can be removed using a Digital Elevation Model (DEM).
- Atmosphere. It consists in a low (spatial) frequency noise. It can be removed considering its spatial and temporal characteristics.
- Reflectivity. It is due to the different scattering characteristics of the resolution cells.
- Ground deformation. It gives information about deformation occurred between the two acquisition. Only deformation along Line of Sight (LOS) direction can be detected through this system.

Moreover, when a data set of SAR images acquired over the same area are available, the temporal evolution of deformation phenomenon can be studied and a deformation sequence can be generated by applying a least square algorithm to the deformations maps obtained from interferometric pairs.

2 THE NEAPOLITAN VOLCANIC DISTRICT

The Neapolitan Volcanic District includes three active and potentially dangerous volcanic systems: the Somma-Vesuvius volcanic complex, the Phlegrean Fields and the island of Ischia.

The dangerousness of these volcanoes, the high exposed value (about three million people living in the whole area) and the vulnerability of the area, make the Neapolitan District one of the areas at the highest volcanic risk all over the world.

One of the “precursory” phenomena of a volcanic eruption is represented by ground deformations, induced by magma ascent towards the surface.

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Geodetical monitoring is now typically carried out by ground networks (i.e.: GPS, leveling), allowing measurements with centimetric and/or sub-centimetric accuracies. The drawback of such a surveillance system is the availability of an information related only to the layout of the networks, avoiding to highlight possible migrations of the deformation field outside them. Moreover, depending on the uneven morphology of some volcanic structures and/or (on) the impossibility to approach the volcano to carry out instrumental measurements during pre-eruptive and eruptive phases, remote sensed data become the only recordable one and, therefore, the only useful information.

Remote sensing techniques are a powerful mean for the surveillance of active volcanic areas; in particular, spaceborne SAR *(Synthetic Aperture Radar)* technique allows precise monitoring over large areas with a good temporal coverage, depending on the revisiting times of the satellites now available.

The use of images acquired in more than 10 years of mission by the SAR sensors on board the ESA (European Space Agency) platforms allows therefore to carry out a detailed study on the temporal evolution of ground deformations in active volcanic areas, as in the case of the Neapolitan Volcanic District.

3 MINEVA-IS OVERVIEW

The goal of MINERVA Information Service is to provide the target User, Osservatorio Vesuviano, with an innovative tool for monitoring of the environmental risk derived from volcanic phenomena in the Vesuvian Area, particularly the subsidence in the Campi Flegrei zone.

The Information Service is able to interact with :

- Service Manager Interface. It is the interface used by the operator in order to manage the system. Through this dedicated interface the operator, in charge of the maintenance and the operations of the Service, sends appropriate commands to the Information Service and receives back data related to the status of the Service.
- User. MINERVA-IS is able to interface the End User. The User sends to the Service requests related to the desired products, and the Information Service makes them available for the user.

The core of MINERVA-IS is the dedicated interface, developed in IDL (Iteractive Data Language) environment. This interface allows to interact with the system and to manage the different software modules implemented, and therefore the processing of satellite data from the raw data to the final product.

Beside service Manager Interface, MINERVA-IS includes various software modules which implement SAR data processing and allow to obtain final products.

An interesting characteristic of the proposed Information Service is the possibility to update deformation maps each time a new SAR image is available. This characteristic constitutes an important innovation that makes MINERVA-IS suitable for monitoring ground displacements in risk areas.

The MINERVA-IS system, in fact, generates a dataset of interferograms starting from a number of SAR Images *[d1…dn]* of the same track and swath. Each newly acquired SAR image is inserted in the data set and all its possible interferometric combinations with the pre-existing images are computed, spanning different, partially overlapped time intervals. The system then merge all the (unwrapped) interferograms with a least-squares approach and produce as a solution a time series of deformation maps which describes the temporal evolution of the displacements with respect to the oldest image.

4 DIFFERENTIAL SAR INTERFEROMETRY ALGORITHMS OVERVIEW

The SAR image processing is a key elements of MINERVA-IS. It consists of different algorithms which allow to generate deformation maps and deformation sequence from either raw or Single Look Complex (SLC) data. Hereafter a brief overview of Interferometric SAR (InSAR) chain is provided.

4.1 Image pre-processing algorithms.

The pre-processing function is used when Envisat ASAR, received using a local satellite ground station (i.e. RAPIDS mobile groundstation), data must be processed. This first step of SAR data processing is needed in order to generate CEOS level-0 file which can be processed by the MINERVA InSAR processing chain.

Two algorithms are exploited in order to pre-process ASAR data. The former converts the received unpacked raw file to a structured raw datafile (it includes synchronisation, reformatting, decompression and discarding non-ASAR data), the letter converts raw datafile to CEOS level-0 format.

4.2 Focusing Algorithm.

SAR raw data are, first of all, focused to a Single Look Complex images. This operation must be very precise in order to preserve phase information to be used in the Interferometric processing. In particular in range direction the observed scene returns are correlated with transmitted pulse replicas. This process is aimed at improving the resolution of focused

image in range direction and it is called *range compression.* In azimuth direction, it is necessary to estimate the Central Doppler Frequency from range compressed data. The algorithms used to focus images in azimuth direction implements both azimuth compression and range migration.
The algorithms used by MINERVA-IS is based on the analytical evaluation of two dimensional SAR System Transfer Function (STF) and its compensation by using Fast Fourier Transform (FFT). [1, 2, 3, 4]

4.3 Registration

This step is usually performed in two stages. The first step, called "coarse co-registration", consists in estimating the relative shift, in both azimuth and range directions, between the two SLC images. The shifts are computed by using precise satellite orbits, and have an accuracy of a few pixels. In a second step, called "fine coregistration", the matching is refined at sub-pixel scale. Small patches extracted from both images are cross-correlated, and the estimated local shifts are used to solve for the parameters of the transformation bringing one of the images (the "slave") to exactly match the other (the "master"). Subsequently, a resampling operation is applied to the slave, i.e. the value of each pixel of the slave is interpolated to give the new value in the applied transformation.

4.4 Generation of Interferometric products.

Once the two SLC's are registered, the interferogram is generated by multiplying one image by the complex conjugate of the other and the phase of the resulting complex image, the interferometric phase, is extracted. In addition, the corresponding interferometric coherence image is also generated. This is a measure of the normalised correlation between the two images and therefore is considered as a quality map of the interferometric phase image.
Usually the interferometric products are "multilooked", i.e. averaged on a certain window, in order to increase the signal-to-noise ratio. Of course, this will also cause a loss of resolution; as an example, the typical average factors used with ERS SAR systems are 4 for range and 20 for azimuth, leading to a final resolution of about 100 x 100m.
Since the so-obtained interferogram is related to both the topography and the ground deformation, a subsequent topography correction operation is performed. Precise orbital information and a Digital Elevation Model (DEM) are used to calculate the topography-related "synthetic fringes" which are then subtracted from the interferogram.

The measured interferometric phase is only the fractional part of the phase difference, i.e. a value in the interval $[-\pi,\pi]$ (or $[0,2\pi]$). In order to have the total amount of the phase difference, the correct number of integer phase cycles has to be estimated; this operation is referred to as "phase unwrapping". There are several algorithms for phase unwrapping, based in general on an estimate of the phase gradient, followed by an integration of this gradient performed through minimisation of an appropriate, global (possibly weighted) norm. Coherence and multilook amplitude images are often used for weighting function selection as they contain the information about the location of unreliable estimates of the phase gradient.
The algorithm used by the MINERVA system is described in [5] and allows us to efficiently unwrap interferograms also in conditions of low coherence

4.5 Geocoding.

The final step of the InSAR (Interferometric SAR) processing is the compensation of geometrical distortions intrinsically present in any SAR image and essentially related to the scene topography. By using the topography information and precise orbit data, it is possible to calculate the transformation mapping the SAR grid into a geo-referenced cartographic grid (usually UTM). This transformation is then applied to all the interferometric products, which are then resampled.

4.6 Deformation sequence calculation.

The task of the MINERVA-IS is the computation of a deformation sequence, i.e., a time ordered sequence of maps that indicate the amount of deformation since a reference starting time (usually the date of the first SAR acquisition). To this end, the processing described insofar needs some little adjustment and a post-processing least-squares deformation sequence computation (also known as "database approach").
We start our description from SLC images of the considered area.
First of all, one of the available SLC's is elected as the Database Master. All the available SLC images are coregistered and resampled with respect to this master, thus guaranteeing that all the intermediate and final products match the same master pixel co-ordinate grid at sub-pixel level.
Interferograms are then formed by complex-multiplying these Database Slave images with each other in all the possible interferometric combinations, i.e., those having small enough baselines. The resulting interferometric products are then phase-unwrapped and converted into deformations values in centimetres along the satellite line-of-sight direction. Since each phase unwrapping procedure provides a relative deformation map, an absolute calibration is then necessary. This

calibration is usually carried out by identifying a stable point (i.e., affected by no deformation) inside the investigated area and using it as reference (zero deformation) point in each deformation.
After the unwrapped interferograms have been adjusted the least squares adjustment is performed to compute a time series of deformations relative to a reference image.

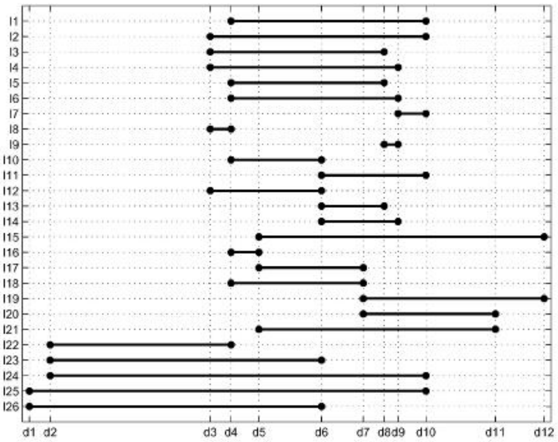


Fig. 1. Diagram showing the interferograms formed for the interferogram time series analysis. The ordinate axis gives the interferogram number, while the abscissa shows the "day" number for each SAR image.

The deformations relative to the reference data are found as solutions to the problem:

$$\mathbf{y = Ax} \qquad \textbf{(1)}$$

where $y = [I_1, I_2, \dots, I_k]$ is the vector of the interferometric phase values, and $x = [X_{d2}, X_{d3}, \dots, X_{d4}]$ is the set of unknown deformations at the remaining dates. The system matrix A is the mathematical representation of Fig. 1. For each row (i.e. for interferogram $I_k = X_{dj} - X_{di}$) the values are zero except for the columns corresponding to dates d_i and d_j which are –1 and 1, respectively. This approach has been described in details in [7, 8].
All the deformation sequence images so generated will have the same resolution and contain the same kind of information of the original interferometric data. However, the merging (in the least squares sense) of redundant information from this data permits to minimise the processing errors and reduce the general noise. It also allows us to reduce the temporal decorrelation, which is particularly strong on long term interferograms, by inserting information from shorter term interferograms in order to "fill" decorrelation patches.

4.7 Atmospheric artefacts filtering.

The presence of atmospheric phase components in the deformation sequence signal represents a critical issue because it may significantly reduce the accuracy of the detected deformations and, in some case, completely mask them out.
Therefore, in order to mitigate the effect of these atmospheric artefacts, a filtering operation must be performed on the output of the Least Squares adjustment. The filtering operation is based on the observation that the atmospheric signal phase component is characterised by a high spatial-correlation but exhibits a significantly low temporal correlation [9, 10]. Accordingly, the undesired atmospheric phase component is detected as the result of a three-dimensional filtering operation. In particular, the filtering is implemented as the cascade of a low pass filtering step, performed in the two-dimensional spatial domain (i.e., azimuth and range), and a high-pass filtering operation with respect to the time variable.
For this approach to be effective, a certain amount of data is required, i.e., the signal must have enough temporal length to apply the temporal filtering.
Once the atmospheric phase component has been evaluated, it is finally subtracted from the estimated phase signal.

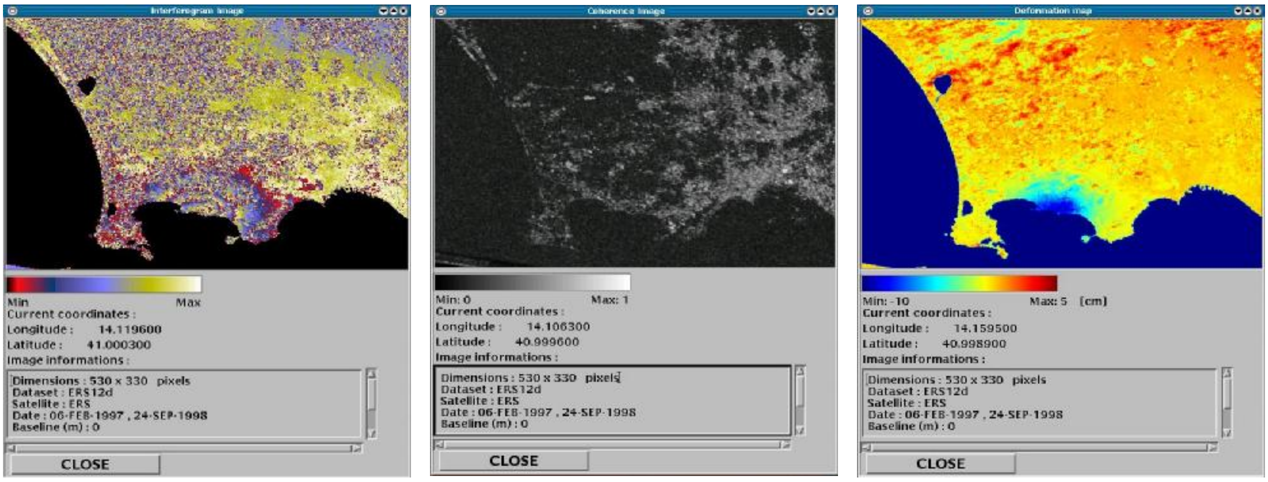
5 RESULTS

MINERVA-IS was used in order to analyse an area characterised by an high volcanic risk compared with the high density of inhabitants: the Phlegrean Fields. This area is is subject to bradyseism, i.e. alternate phases of subsidence and uplift, the latter accompanied by seismic activity.

The capability of MINERVA-IS for the monitoring of Phlegrean Fields and for the analysis of deformation phenomena in this area is well proven. Some of the preliminary results obtain are hereafter illustrated. In order to generate final products over Phlegrean area 16 SAR images acquired from 1995 to 2001 were used.

Generated products are characterised by a spatial resolution of about 100 m and an accuracy or 1 cm.

In Fig. 2 the geocoded differential interferograms, coherence map and deformation map are shown. Deformation map is the unwrapped differential interferogram obtain from the two SAR images acquired respectively 6th February 1997 and 24th September 1998. In this product the atmospheric artefacts are not removed.



Min Max
Current coordinates :
Longitude : 14.119600
Latitude : 41.000300
Image informations :
Dimensions : 530 x 330 pixels
Dataset : ERS12d
Satellite : ERS
Date : 06-FEB-1997 , 24-SEP-1998
Baseline (m) : 0

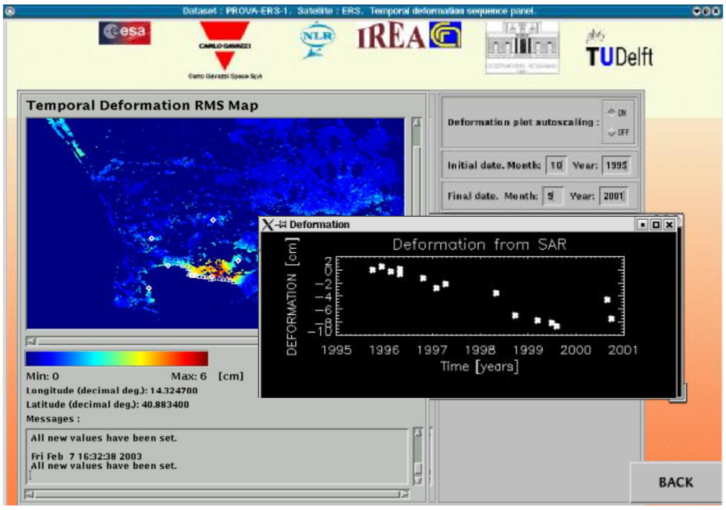
Min: 0 Max: 1
Current coordinates :
Longitude : 14.106300
Latitude : 40.999600
Image informations :
Dimensions : 530 x 330 pixels
Dataset : ERS12d
Satellite : ERS
Date : 06-FEB-1997 , 24-SEP-1998
Baseline (m) : 0

Min: -10 Max: 5 [cm]
Current coordinates :
Longitude : 14.159500
Latitude : 40.998900
Image informations :
Dimensions : 530 x 330 pixels
Dataset : ERS12d
Satellite : ERS
Date : 06-FEB-1997 , 24-SEP-1998
Baseline (m) : 0

(a) (b) (c)

Fig. 2. Interferometric pair 6th February 1997 (master) and 24th September 1998 (slave). (a) Differential interferogram, (b) Coherence map, (c) Deformation map. Atmospheric artefacts are not removed

In Fig. 3 the geocoded multilook RMS deformation map, i.e. the temporal root mean square of the deformation for each pixel of the considered area, and deformation sequence are shown. The RMS map is obtained using all deformation maps available filtered from atmospheric effects. Deformation sequence gives information about the temporal evolution of deformation phenomenon.



Dataset : PROVA-ERS-1. Satellite : ERS. Temporal deformation sequence panel.

Deformation plot autoscaling : ON OFF

Initial date. Month: 10 Year: 1995

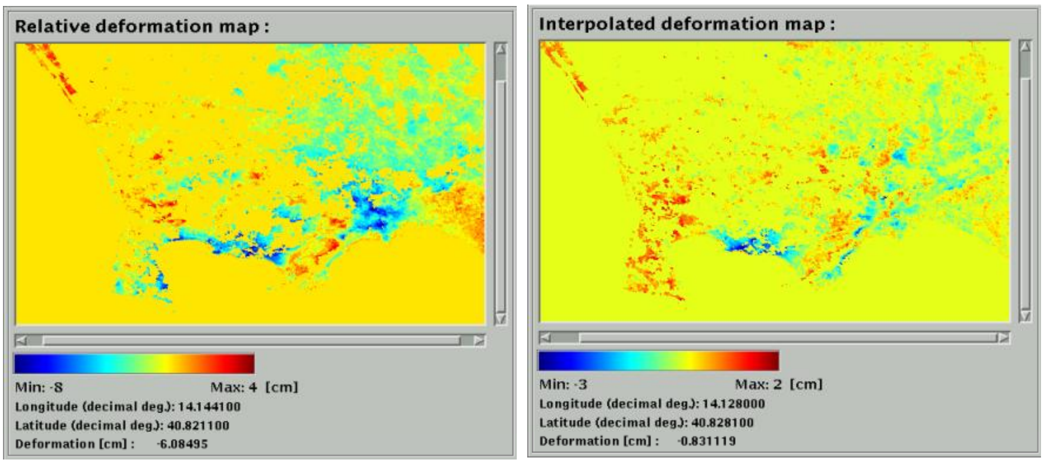
Final date. Month: 5 Year: 2001

Min: 0 Max: 6 [cm]
Longitude (decimal deg.): 14.324700
Latitude (decimal deg.): 40.883400
Messages :
All new values have been set.

Fri Feb 7 16:32:38 2003
All new values have been set.

Fig. 3. Deformation sequence generated by MINERVA-IS

In Fig. 4 Relative deformation map and Interpolated deformation map are depicted. These final products are generated exploiting the dataset available and can be visualised by MINERVA-IS. Atmospheric artefacts have been removed from both maps using atmospheric artefacts filtering approach, previously describe.



Min: -8 Max: 4 [cm]
Longitude (decimal deg.): 14.144100
Latitude (decimal deg.): 40.821100
Deformation [cm] : -6.08495

Min: -3 Max: 2 [cm]
Longitude (decimal deg.): 14.128000
Latitude (decimal deg.): 40.828100
Deformation [cm] : -0.831119

(a) (b)

Fig. 4. Relative deformation map (a), Interpolated deformation map (b). Atmospheric artefacts are removed.

As concern ENVISAT ASAR acquisitions, the number of images available during demonstration phase of the service was not enough. For this reason only results generated processing ESR SAR data are presented. The acquisition of ASAR images will anyway continue in 2004 until a significant set of images will be acquired. Afterward demonstration will be carried out using ASAR ENVISAT acquired from October 2002 until 2004

6 CONCLUSIONS - POSSIBLE USE OF MINERVA-IS FOR SURVEILLANCE PURPOSES

One of the features of MINERVA-Information Service is the possibility to insert geodetical data (GPS, leveling), in order to allow the comparison and validation of interferometric data. Comparison between geodetic and ERS1/2 data was quite encouraging, pointing out comparable ground deformations for the same time intervals.

Future developments of the system will be oriented towards a closer integration between SAR (ENVISAT) data and geodetical data from the I.N.G.V.-Osservatorio Vesuviano (INGV-OV) monitoring networks, with particular reference to GPS continuous data, recorded in *near real time* by a *server* operating in the frame of the INGV-OV Geodesy Team.

The integration of data from different techniques will be a powerful instrument for civil protection purposes, allowing to get a quick and precise information to be provided to local and national Institutions devoted to the management of the emergency in case of volcanic event.

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