Monitoring the surface deformation of Mt. Etna with ERS-SAR images

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Abstract

The main goal of this paper is to show how satellite SAR data can be exploited to get surface deformation measurements of an active volcano like Mt. Etna. In particular it is shown that small baseline SAR interferograms are suitable for an accurate imaging of ground deformations with mainly continuous patterns in space. The Mt. Etna deformation occurred during the eruptive event of the July 2001 is shown as a nice and interesting result of this technique applied to ERS-2 data. However, whenever small ground deformations are limited to isolated points or concentrated across lines (e.g. active faults) a more sophisticated analysis should be carried out by means of the Permanent Scatterers (PS) technique. The slip of the eastern flank of Mt. Etna observed by ERS-1 and ERS-2 satellites in 40 repeated passes from 1995 to 2000, is used to show the PS technique potential.

1. Introduction

Differential SAR interferometry (DINSAR) has been widely and successfully used during the last 10 years for monitoring land motion of large areas with centimetric accuracy [Massonnet et al. 1995] [Hanssen 2000]. Most of the results have been achieved thanks to the impressive amount of SAR images provided by the two ESA satellites ERS-1 (1991-2000) and ERS-2 (since 1995). The precise orbit and attitude control of ERS-1 and ERS-2 are at the basis of the successful generation of thousands of interferograms and land motion maps.

At the beginning of 2001, ERS-2 platform attitude control had problems. As a consequence, the generation of SAR interferograms became impossible. A back-up attitude control system has been then activated and tuned by the ESA-ESRIN and ESOC staff, and in June 2001, the interferometric capability of ERS-2 (in gyroless mode) has been practically recovered.

The first ERS-2 SAR interferometric test in gyro-less mode has been carried out at Polimi in cooperation with T.R.E. on Mt. Etna using 3 images taken in June, July and August 2001. Notwithstanding the residual attitude problems, clear (and impressive) surface deformation maps of the Etna volcano connected to the eruptive event of the July 2001 have been determined. The achieved results are presented in the next section. They clearly show the capability of DINSAR to monitor extended ground deformation when the following requirements are met:

(i) ground and orbital conditions allow high coherence on wide areas;

(ii) the interferometric signal due to the ground deformation is much larger than that due to atmospheric changes.

In 1999, to overcome these limiting factors of DINSAR (lack of spatially extended coherence and atmospheric artifacts), an alternative processing of SAR images, the Permanent Scatterers Technique (PST), has been developed, tested and validated at Polimi. The theoretical principle behind the PST will be briefly summarized in the third section without entering the technical details that can be found in [Ferretti et al. 2000] [Ferretti et al. 2001]. In the framework of the GNV project on the “DEVELOPMENT AND APPLICATION OF REMOTE SENSING METHODS FOR THE MONITORING OF ACTIVE ITALIAN VOLCANOES”, the PST has been used to measure the average Line Of Sight (LOS) ground deformation that affected the eastern flank of Mt. Etna in the 5 years period from 1995 to 2000. The results achieved along two N-S sections crossing the eastern flank of Mt. Etna are analyzed in the third section.

2. Etna Deformation occurred during the July 2001 Eruption

Two SAR images obtained from the ERS-2 acquisitions in gyro-less mode on 11 July - 15 August 2001 over the Mt. Etna have been used to get a differential interferogram across the eruptive event of July 2001.

The following digital signal processing steps have been carried out:

1 Precise estimation of the attitude of the satellite (Doppler centroid) for each image and phase preserving focusing.

2 Common band filtering both in azimuth and slant range [Gatelli et al. 1994].

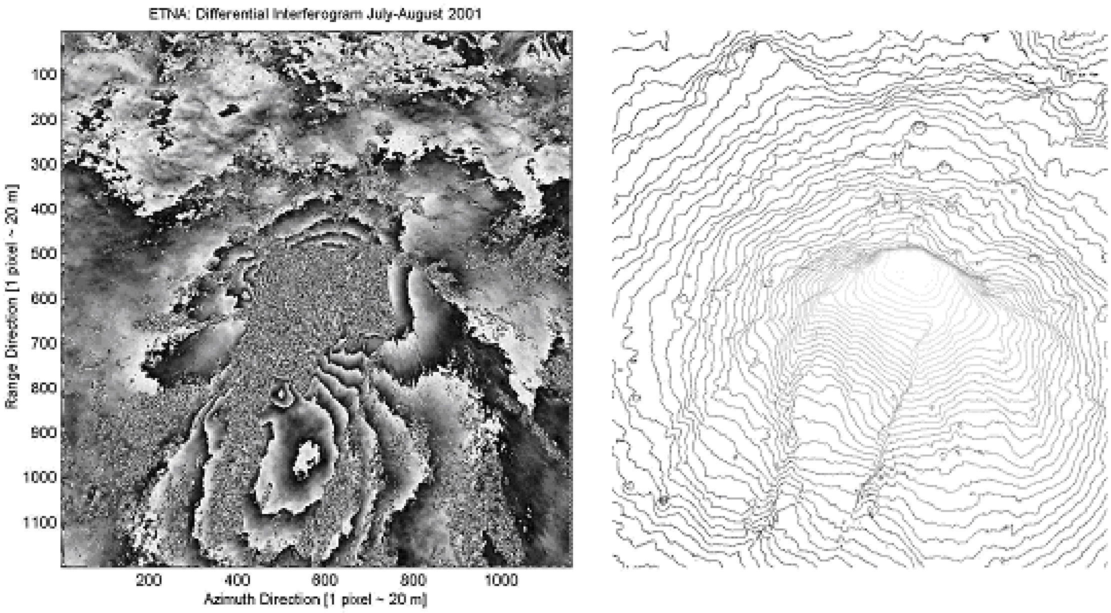

Figure 1 Left: differential interferogram generated with the two ERS-2 SAR images taken on July 11 and August 15, 2001 (SAR coordinates: range, azimuth). A deformation fringe pattern is clearly visible close to the main faults that cross Mt. Etna and on the Valle del Bove (lower part of the map). Each fringe corresponds to a ground displacement of 2.8cm along the SAR LOS (about 23 deg. off-nadir). Right: Contour lines of Mt. Etna DEM (SAR coordinates).

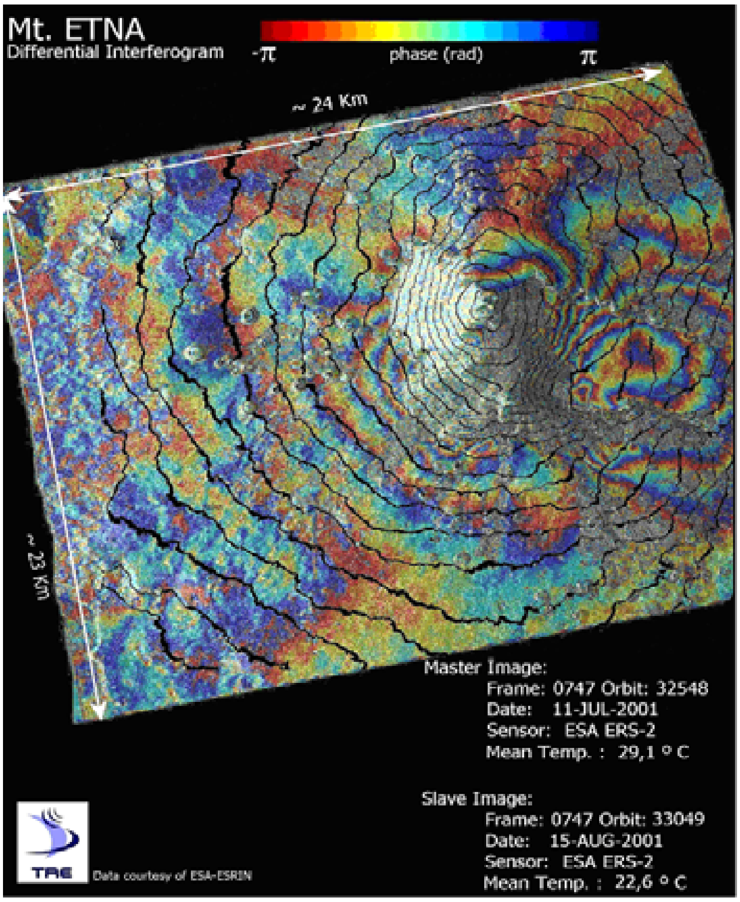

Figure 2 Geocoded differential interferogram generated with the two ERS-2 SAR images taken on July 11 and August 15, 2001. Each fringe corresponds to a ground displacement of 2.8cm along the SAR LOS (about 23 deg. off-nadir). The contour lines of Mt. Etna DEM are shown in black.

3 Sub-pixel registration of the images.
4 Generation of differential interferograms using an available Digital Elevation Model (vertical accuracy better than 7m.- courtesy of Institut de Physique du Globe de Paris).
5 Compensation of different atmospheric profiles with the elevation. Local measurements of pressure, temperature and humidity have been exploited for this sake [Bonforte et al. 2001].
6 Data geocoding.

The differential interferogram is shown in figure 1. Here, a deformation fringe pattern is clearly visible close to the main faults that cross Mt. Etna (including the Pernicana fault that is one of the sites to be monitored in the framework of the GNV project). Each fringe corresponds to a ground displacement of 2.8cm along the SAR Line Of Sight (about 23 deg. off-nadir).

The deformation map generated with these ERS-2 SAR images have been then geocoded in order to facilitate its geophysical interpretation and a comparison with independent ground measurements carried out by the volcanologists of the INGV in Catania. The geocoded differential interferogram is shown in figure 2.

3. The Average Velocity of the Mt. Etna Eastern Flank measured with the PST

The ground deformation analysis carried out by means of the Permanent Scatterers Technique (PST) is conceptually different from that carried out by means of DINSAR and offers many advantages that will be briefly discussed here.

The very basic PST principle can be summarized as follows where ERS, ENVISAT or RADARSAT missions are considered as data sources:

1 Isolated targets that maintain their coherence during the monitoring time interval (Permanent Scatterers) can be identified from a statistical analysis of at least 15 complex SAR images. The requested baseline limit is 15 to 20 times greater than for DINSAR, thus making all the archived SAR images exploitable and minimizing the monitoring sampling interval. Moreover, coher-

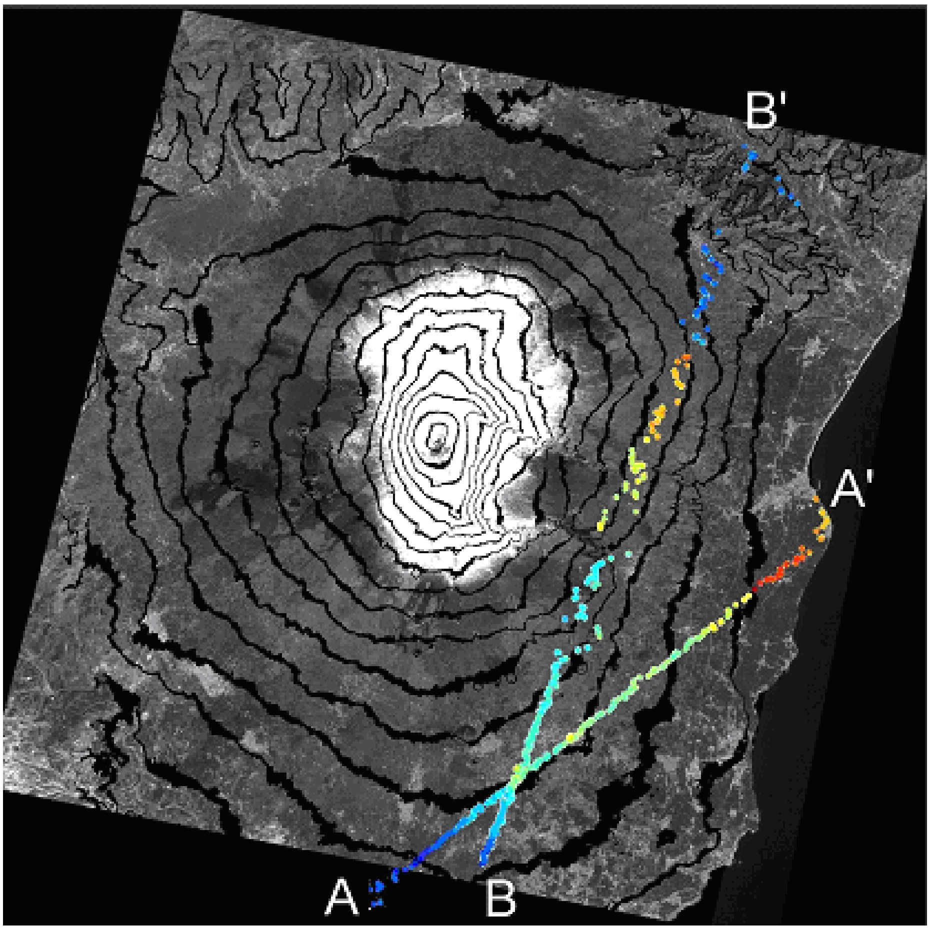

Figure 3 Profiles AA' and BB' crossing the eastern flank of Mt. Etna from South to North along which the average PS velocity has been computed.

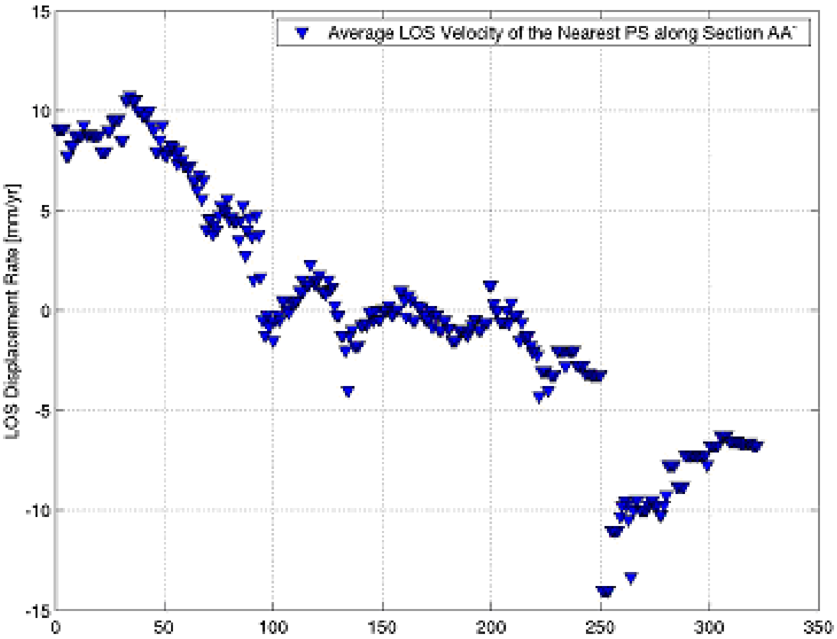

Figure 4 Average LOS PS velocities along the profile AA'. The dispersion of LOS velocities is in the order of 1 mm/year; no averaging of neighboring PS has been carried out. The effects of the non uniform distribution of the PS along the transept contribute to the residual dispersion. Rapid ground velocity variations identify several active faults.

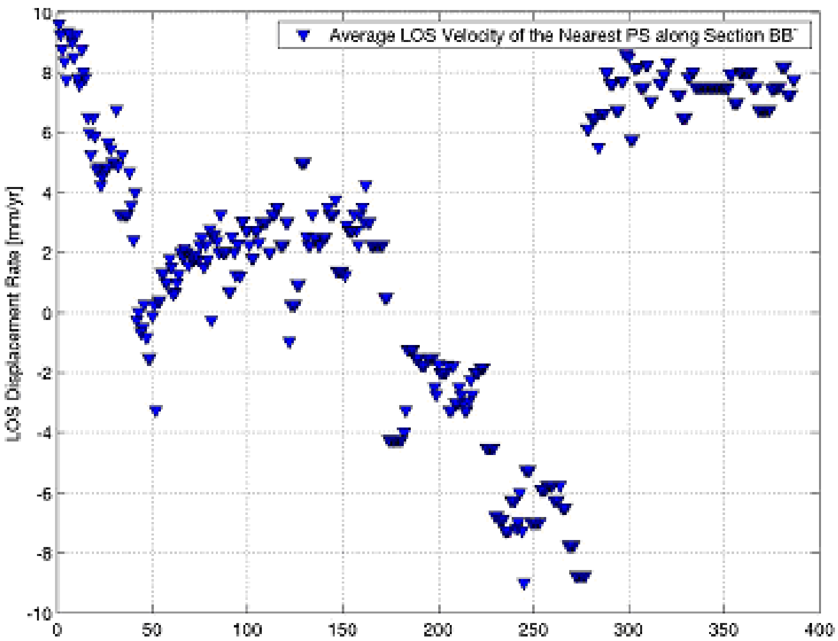

Figure 5 Average LOS PS velocities along the profile BB'. The large ground velocity variation on the right part of the profile corresponds to the slipping of the Pernicana fault. The dispersion of LOS velocities along the profile BB' looks higher than in profile AA'. This is just a visual impression connected to the position of the PS as clearly shown in figure 3; again, no averaging of neighboring PS has been carried out.

ence estimation is done in time with no need of spatial averaging as for DINSAR, thus making possible the identification of isolated coherent targets that would result invisible to DINSAR analysis.

2 The relative elevation of the PSs can be measured with accuracy better than 1 meter thanks to the large baseline dispersion. As a

consequence no reference DEM is needed.

3 Finally, isolated target motion and atmospheric artifacts can be separated by means of a joint space-time data analysis.

The PST has been used to monitor Mt. Etna deformations during the 5 years period of relative low volcanic activity from April 1995 to December 2000. 40 ERS images have been used with normal baselines ranging from -1056 to +1109 meters with respect to the reference orbit. The quality of the information of this data set is shown in the following examples. In figure 3 two profiles AA' and BB' crossing the eastern flank of Mt. Etna from South to North are shown. Figures 4 and 5 show the average Line of Sight velocity of more than 300 PS identified along the two profiles AA' and BB'. The accuracy of the velocity values (computed independently one from the other) can be appreciated from these plots where the vertical scale is expressed in millimeters per year. From a geophysical point of view, these plots clearly show the presence of many active faults splitting the Etna eastern flank in blocks with different slipping velocities. The PS results are currently object of analysis by volcalogists in Catania (GNV) and Paris (IPGP).

Conclusions

Despite its potentialities, conventional Differential SAR Interferometry (DINSAR) analysis is not the solution for a routine monitoring of surface deformation phenomena by means of satellite repeat-pass observations. Atmospheric effects and phase decorrelation strongly limit the use of this technology as a standard geodetic tool. Whenever the SNR is not very high (as in co-seismic displacement fields and ground deformations due to eruptions) only in a multi-image framework it is possible to separate motion components from clutter and noise and to identify radar targets where reliable displacement information can be recovered.

To this end, the ESA-ERS archive represents a unique dataset to study slow geophysical phenomena and to test different multi-temporal data analysis algorithms. This archive is still underused and its value underestimated by the scientific community. We think that all attempts to extract information from this huge dataset should be fostered and promoted. The ESA acquisition policy chosen for the ERS mission was a success: building a consistent and coherent archive will be in the future a "must" for any SAR mission dedicated to Civil Protection and monitoring applications. In order to pass from an academic research activity to an operational tool for ground deformation monitoring, any DINSAR analysis should deal with two essentials issues: (a) high precision and reliability of the measurements: the processing chain should permit a reliable error analysis, also from a mathematical point of view (robust theoretical framework); (b) high data geocoding precision. The first point implies that final users should be provided with data as well as quality controls. The second point addresses the importance of the integration of EO data in GIS packages, now becoming a standard working tool for many user groups.

The necessity to deal with SAR data characterized by lower stability platforms pushed toward the development of new processing strategies that significantly improved the quality of the results both for standard DINSAR analyses and the PS approach.

Its seems indeed that, in the future, interferometric data (ERS-2, ENVISAT, RADARSAT and ALOS) will play a key-role for geodetic measurements and will become a standard tool for monitoring the 3 components of the surface motion. In fact, all three components of the motion are measurable (and not only LOS data) if 23o and 45 o ascending and descending orbit data are available. For absolute motion measurements, synergistic strategies with GPS and GALILEO data can be easily envisaged and are likely to be applied in many fields. Hopefully, volcanologists, geophysicists as well as Civil Protection authorities will be provided with powerful Decision Support Systems that will help in identifying the best actions to be undertaken.

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