## VOLCANO MONITORING USING INTERFEROMETRIC SAR

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### ABSTRACT

**At a volcano like Etna, which is under continual scientific observation, differential interferometry using ERS SAR has the potential to become a useful operational tool to monitor surface displacements caused by internal changes in magma pressure and movement. Our approach to achieve this is firstly to create geocoded differential interferograms corrected by a DEM from which surface displacement maps can be derived. Then in conjunction with contemporary ground survey measurements, we can analyse the surface displacements in terms of pressure changes in a 3D finite element model of the volcano and the crust. Preliminary results using ERS-1 and -2 SAR data from September 1995 to June and September 1996 suggest that the volcano expanded over this period. Often it is only the historical lava flows on the flanks of the volcano that supply areas with sufficiently high phase coherence to produce good results. To work well this approach needs a time series of suitable SAR data so that transient atmospheric and surface effects are minimised. We also show that ignoring the topography of the volcano when analysing internally-induced deformation will distort the pattern of apparent surface displacements.**

### 1. INTRODUCTION

The surfaces of volcanoes move in response to the movement of magma within them. Generally speaking, increasing internal magma pressure will make the surface bulge upwards and outwards. Following an eruption of magma at the surface, this deformation will tend to be reversed. The scale of this deformation is centimetric to decimetric over tens of square kilometres, over periods of weeks to years. Hence differential interferometry from spaceborne SAR should be a good means of monitoring such deformation. No other technique will produce such a dense spatial sampling of the displacement field.

There are two obvious monitoring strategies: early warning and forecasting. In the former, relatively infrequently sampled pairs of images (e.g. 0.5 - 1 year separation) at non-erupting volcanoes could be checked to detect any signs of deformation. At volcanoes with established observatories a more intense observation programme (e.g. every 35 days) could be integrated with other observations to analyse the internal behaviour of the volcano.

This study is concerned with the latter strategy applied to the Etna volcano in Sicily. Etna has been the focus of most work on this technique to date because it is the most active European volcano with an observatory. A substantial volcano-wide deflationary signal was detected from ERS-1 data and reported by Massonnet et al. (1995) for the 1992-93 period during and after a major lava flow eruption. Briole et al. (1997) also showed from the same data that a much more localised deformation anomaly was correlated spatially with earlier lava flows from 1986-89, suggesting that post-emplacement stress relaxation was responsible. There are 2 main elements to our approach, though the results presented here are preliminary. First, we create differential interferograms using repeat-pass pairs of ERS-1 and ERS-2 SAR images and map them onto ground range coordinates. Then we validate and compare these interferometric observations with contemporaneous field survey observations and 3-D finite element models of surface deformation due to magmatic/tectonic stress variations at depth.

### 2. SAR DATA AND PROCESSING

ERS-1 and-2 SAR data for Etna were chosen from the ERS-1 phase G (1992-93), the tandem experiment ( May 1995- May 1996) and the ERS-2 period (May 1996-present). The relevant data from ERS-1 phase G were discussed by Massonnet et al. (1995). Here we concentrate on data from the 1995-96 period. Scenes from two frames (frame 747 from ascending passes and frame 2853 from descending passes) were selected. For differential interferometry, short perpendicular baselines (Bp) are required. Choosing a minimum Bp threshold of 200 m reduces the number of potential interferometric pairs to 137. We find that during the winter months (November - April) the summit of the volcano, which is covered in snow, has its phase coherence reduced to levels that are too low in interferograms with at least one winter image. In practice, therefore, we use the following criteria to select and prioritise the image pairs for processing:

1. Bp < 200 m

2. Selection only from summer month acquisitions

3. Prefer pairs with at least one image contemporaneous with a field survey

This reduces the number of pairs to about 20, essentially between summer 1995 and summer 1996.

Our processing uses the method that requires 2-pass data together with a DEM. The data shown here were produced using the UCL 3D Image Maker System for differential SAR interferometry (UCL-3DIM/dIfSAR) that is described by Upton et al. (1996). This employs a modified version of the IfSAR interferogram creation software from POLIMI (Feretti et al., 1996) together with a further set of programmes developed at UCL for converting the results to ground coordinates (WGS84 elipsoid is used throughout to allow easy comparison of GPS with IfSAR results).

### 3. DEMS

The quality of the DEM used to remove topography affects the quality of the interferogram. We have experimented with a number of different DEMs of Etna to assess this effect and early results are reported in Muller et al. (1996). Two of the DEMs we have used are :

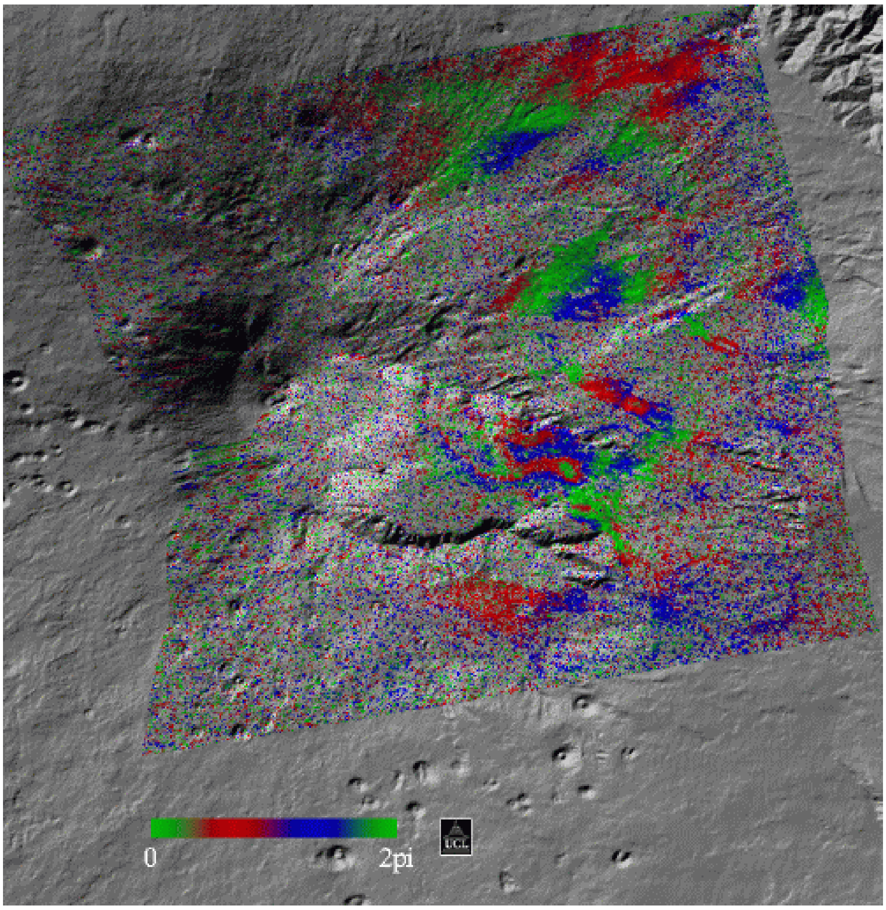



*Figure 1. Geocoded differential interferogram for ERS-1/ERS-2 ascending pass data (Bp = 5 m) from September 1996 to June 1996 superimposed on a shaded relief image (25 km E-W) of the CNR-DEM of the summit area of Etna. A threshold of > 0.13 for coherence has been used to display the phase data. The large valley feature in the centre of the scene is the Valle del Bove. © UCL 1997*

### CNR-DEM

This is derived from vector contour data supplied by CNR- Gruppo Nazionale per la Vulcanologia which was compiled from aerial photogrammetric data captured mainly in September 1985. It is a 1arc-second DEM in WGS84 ellipsoid co-ordinates gridded using a minimum curvature interpolator. Its use in this context suffers from errors introduced via the digitisation process and the patching together of sub-areas and from the fact that the topography over the areas that were subject to lava flows of 1986-7, 1989 and 1991-3 are now incorrect.

### ERS-IfSAR DEM

Tandem data (ascending pass) from 5/6 September 1995 were used to generate a 1 arc-second DEM using the UCL 3D Image Maker (IfSAR) system (Muller et al., 1996b) and PRC vectors from D-PAF to model the SAR geometry. The model is very noisy in places, especially over the forested lower slopes where there is low phase coherence between the two images. Much higher quality DEM results are possible using a multi-baseline approach (Ferretti et al., 1997). The estimates of height for each pixel can be compared to eliminate those pixels affected by local transients (e.g. atmospheric effects). This serves the dual purpose of providing a very high quality DEM for differential work and mapping areas affected by path-effect noise.

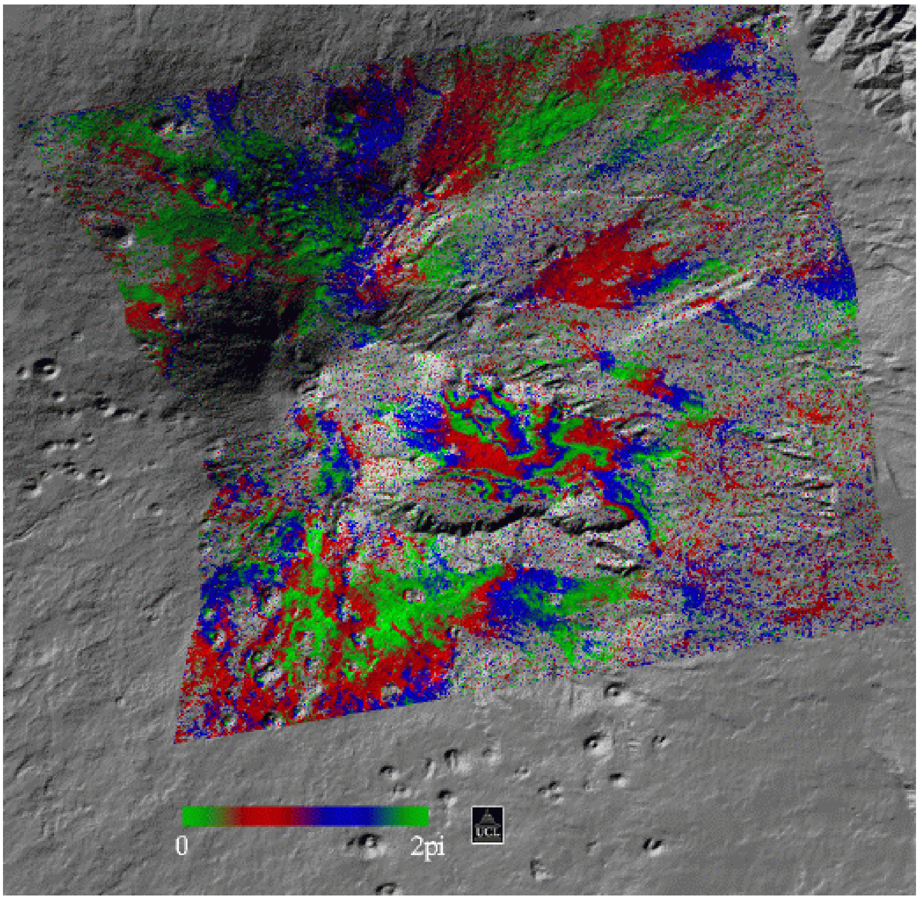



*Figure 2. Geocoded differential interferogram for ERS-2/ERS-2 ascending pass data (Bp = 112 m) for the same period as (a). A threshold of > 0.2 for coherence has been used to display the phase data. © UCL 1997*

The existence of DEMs before and after the emplacement of lava flows on a volcano can be put to use in calculating the volume and morphology of the flows. We have used the difference between the 1985 CNR-DEM and the 1995 ERS-IfSAR DEM to measure the 1991-93 lava flow-field in this way (we know from ground survey that this flow is up to 95 m thick in places, Stevens et al. (1997)). The principle difficulty with this approach in this case is the correct registration of the DEMs due to the unknown datum shifts between the CNR maps and WGS84 ellipsoid.

### 4. SAR-DERIVED SURFACE DISPLACEMENTS

Our analysis is in its preliminary stage. Here we discuss two pairs of differential interferograms created from ascending pass images from September 1995 and June 1996. The first pair is an ERS-1 /ERS-2 pair (orbits 21660 and 5995), the second an ERS-2 / ERS-2 pair (orbits 1987 and 5995). These geocoded interferograms are shown in figures 1 and 2. They should represent either (i) displacements of the surface of the volcano in the intervening 9 months, or (ii) effects due to changes in properties of the atmosphere. In the absence of some independent means of distinguishing these two effects, for any given pair, we can only rely on generalisations such as ionospheric anomalies should be of small (< 10 km) size and lower tropospheric effects will be related to weather or systematic change in moisture content with height. We can potentially avoid atmospheric problems using multi-image data as described previously, though this is not done here.

Assuming that the fringes seen in a differential interferogram are due to surface displacements, there are two main possible causes of such displacements on Etna: internal deformation and movements associated with lava flows. Internal deformation displacements should have the characteristic of being wide-scale (e.g. volcano-wide) except perhaps before and close to eruptive fissuring. The surfaces of lava flows can move due to thermal contraction, downslope creep or relaxation of the substrate. The spatial pattern of such displacements should be related to the shape of the flow. Recently emplaced flows (few years) may show such displacements, but older flows should be more stable. It is the historical lava flows on the flanks of the volcano that are the most coherent surfaces over periods of months to years. We see this effect clearly in figure 1 when a threshold minimum level of coherence is used. On the eastern flanks of Etna, north of the Valle del Bove the flows of 1865 and 1971 are distinct in figure 1 whilst south of the Valle del Bove the flow of 1766 is obvious. There are two problems associated with qualitative interpretation of these type of results. Firstly, it is difficult to see regional displacement patterns from isolated patches of information. Secondly, these individual patches (the lava flows) may have their own local displacement signal, superimposed on the regional one.

The clearest pattern evident from these, albeit limited extent, differential interferograms is in the northern Valle del Bove (Fig. 2). Here 2-3 fringes (5-8 cm) of displacement towards the satellite indicate uplift towards the west or summit of the volcano. Superimposed on these are the lava flow-related displacements of the 1989 and 1986-87 lava flows described by Briole et al. (1997) which are in the opposite sense (displaced away from the satellite). Interestingly, most of the 1991-93 flow in the southern part of the Valle remains incoherent over this 9 month period though the north central edges (in Fig. 2) are now coherent. There is some indication that the volcano-uplift pattern seen in the northern Valle del Bove also exists in the northeastern parts of figures 1 and 2 and southwestern part of figure 2 though only 1-2 fringes appear to be involved. The ERS-directed vector of motion detected by differential interferometry is largely a measure of the vertical component of displacement.

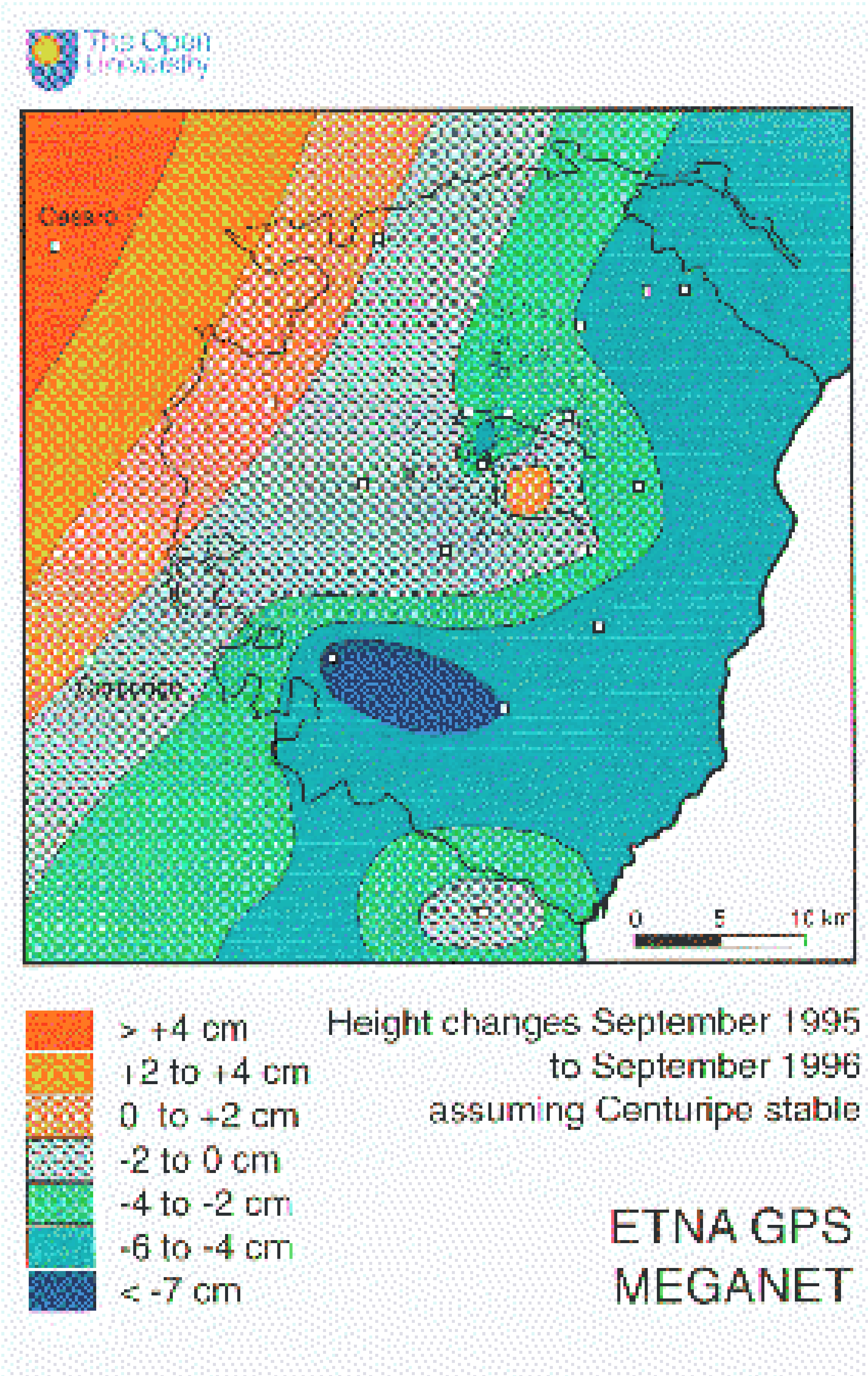



*Figure 3. Contour map of the vertical component of relative displacements measured by the MEGANET GPS network between September 1995 and September 1996. White squares are station positions.*

### 5. GROUND SURVEY DISPLACEMENTS

There are a large number of ground surveying measurements made on Etna. We report on the preliminary findings of two such sets of GPS measurements made with Wild GPS system 200 receivers in September 1995 and September 1996 (Murray and Sargent, 1997), a period that includes the SAR data acquisition. This Etna MEGANET GPS network consisted of 52 stations and error ellipsoid dimensions for changes between the two occupations average 10 mm horizontally and 16 mm vertically. Horizontal displacements show a radial pattern of movement away from the volcano by up to 10 cm. Vertical movements show a pattern of depression of the flanks of the volcano relative to the summit by 4-6 cm superimposed on an apparent NW-SE gradient (Fig. 3). The pattern of relative outward and downward movement of the flanks of the volcano is qualitatively compatible with the weakly-defined SAR-derived displacements from the September 1995 - June 1996 period.

### 6. 3D MODELLING

Apparent agreement of the SAR- and ground survey-derived displacements suggests that the volcano's magma storage system may be re-pressurising after the 1991-93 eruption, which was very voluminous. To properly test this type of hypothesis the observations must be compared to a realistic model of internal behaviour. We are developing such a model using 3D finite elements (Williams et al., 1997). The model incorporates the major structural surfaces and appropriate material property constants of the volcano and the crust

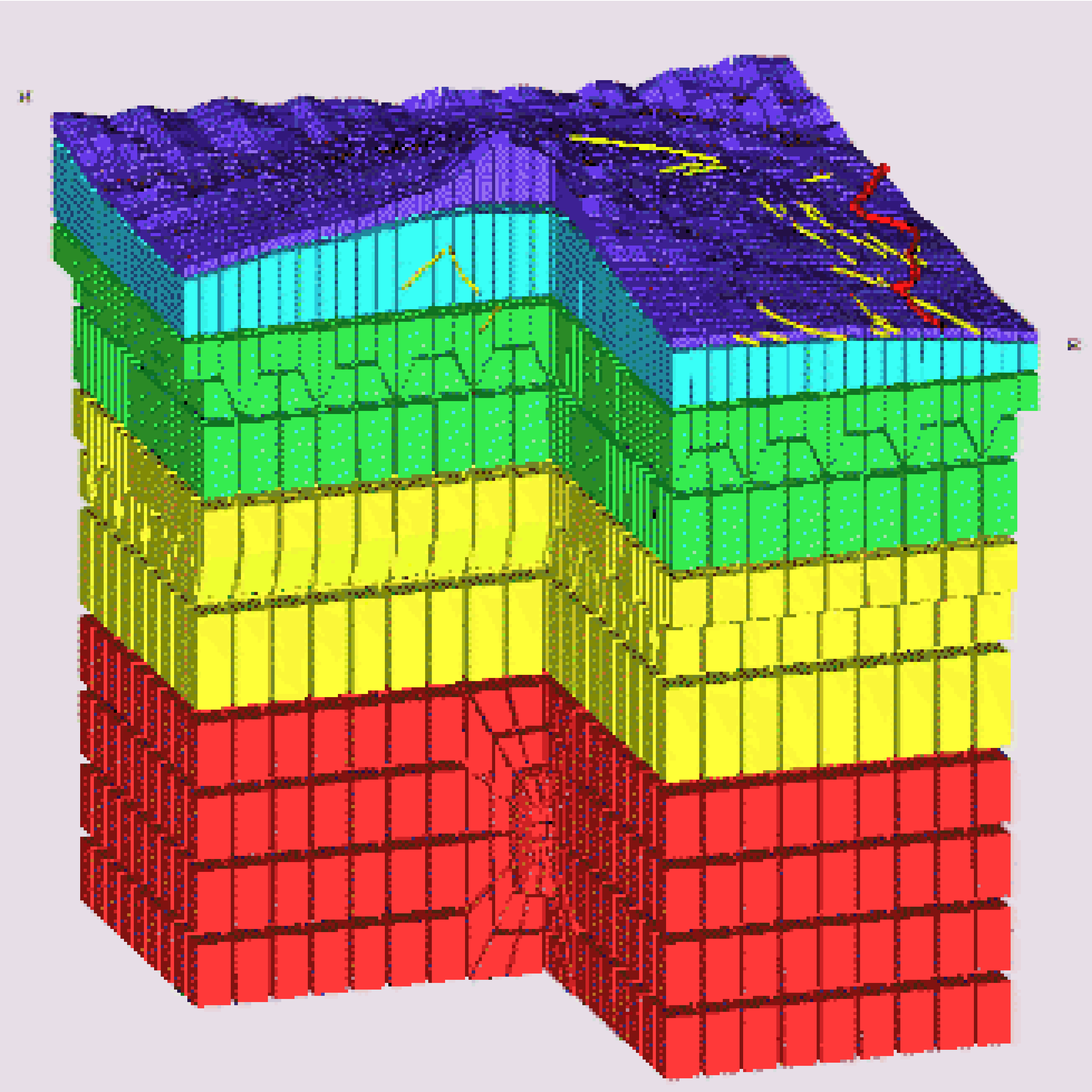
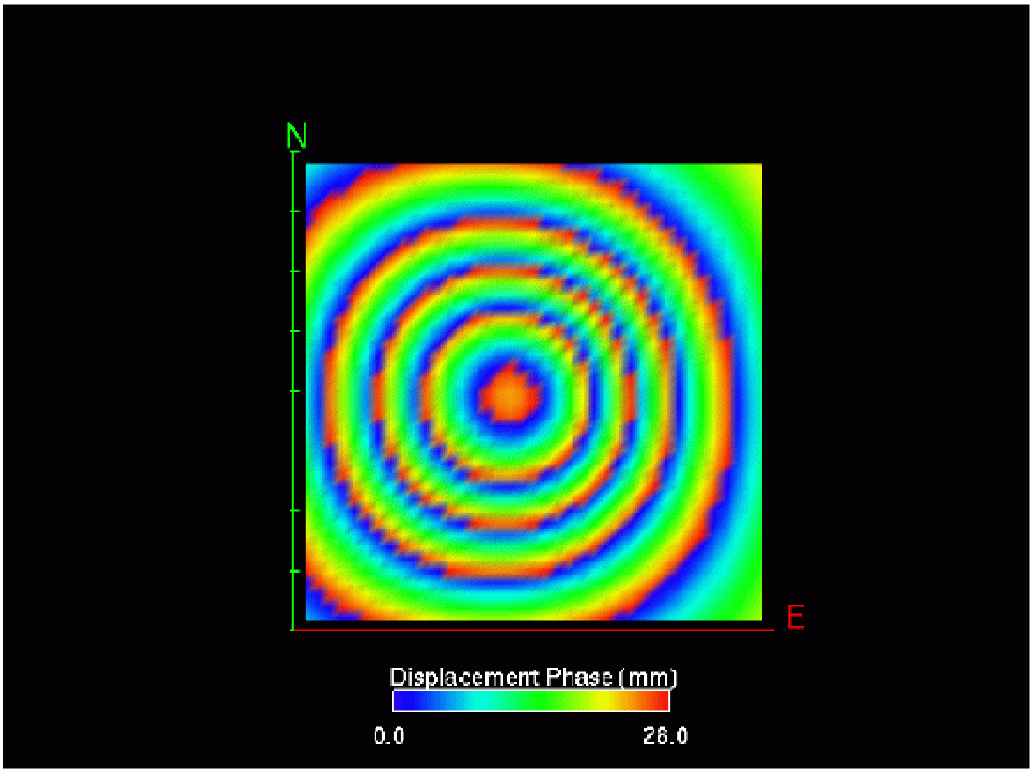
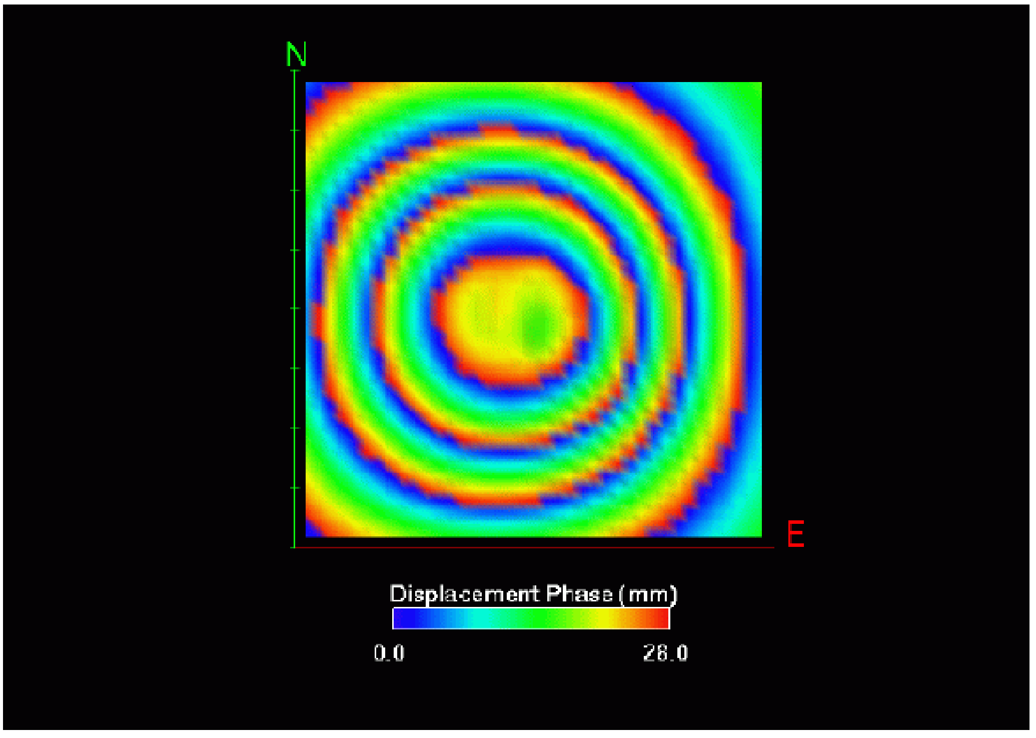


*Figure 4. Cut-away view of a simplified 3D finite element model of the structure of Etna. Some of the surface faults (yellow) and the coastline (red) are shown and the putative location of a magma chamber at 16 km. The model dimensions are 40 km horizontally and 20 km vertically with twofold vertical exaggeration.*




a)




b)

*Figure 5 (a) Synthetic differential SAR interferometric fringes (from an ascending pass pair) due to pressurisation at a 16 km deep magma chamber as seen on a flat surface (c.f. same numerical result as the analytical one shown by Massonnet et al., 1995). (b) Equivalent result taking into account the surface topography of the volcano. Both results created using the finite element model approach of figure 4. Models are 40 x 40 km.*

beneath. These surfaces include: surface topography, sedimentary basement, shallow decollement surface, acoustic basement, plutonic body beneath the Valle del Bove, deep decollement surface, crustal magmatic reservoir and the Moho (Fig. 4).

The benefits of this approach compared to that which seeks a best-fit solution to an analytical model for an elastic half-space (e.g. Massonnet et al., 1996) can be seen in figure 5. This shows the difference that ignoring the substantial (> 3 km) surface relief of Etna makes in the pattern of surface displacements, expressed as a synthetic interferogram, due to a buried pressure source at 16 km. Because the summit of the volcano is further from the pressure source than the flanks nearly a whole fringe of displacement is, correctly, removed from the flat surface model version near the summit region of Etna.

## 7. ACKNOWLEDGEMENTS

We thank ESA for the ERS SAR data supplied under ERS AO2.UK117 and for the CNR - Gruppo Nazionale di Vulcanologia for DEM data. We are also grateful to our colleagues in the EC-funded MADVIEWS project whose work overlaps with that reported here. GW, JPM and PF thank the UK NERC for funding under grant GR3/09745 and GW thanks the UK NERC for general support to ESSC under grant F60/G6/12.

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