Scientific report for loan 825 - "Long-term far-field deformation of Etna as an indicator of eruptive control"

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Abstract
An 88 station dual-frequency GPS network on Mt Etna was occupied between 10th September and 10th October 2006, to measure for deformation in association with the current series of eruptions. 17 stations that had been measured by trilateration and levelling in 1981 and 1983 were re-located with hand-held GPS and included in the network. The timing of the trip was perfect, in that new flank fissures opened up on 12th October and lava began flowing from them on October 13th, so that we have a complete picture of the volcano immediately preceding the 2006 flank eruption. Accuracy achieved was excellent, and the results show that Etna had resumed its characteristic spreading after a temporary reversal following the 2004-5 eruption.

Background
This study forms part of a series of inter-related investigations into the deformation and eruptive activity of frequently-erupting volcanoes, particularly Mt Etna, Sicily. The aim is to apply analogue and numerical models to the observed horizontal and vertical deformation, in order to detect changes in the volcano’s magmatic plumbing system and thereby to elucidate its eruptive mechanism, with the ultimate aim of facilitating the prediction of eruptions. The P.I. began ground deformation measurements (precise levelling and Dry Tilt) in 1975, and three-dimensional measurements in the 1980s (trilateration with total stations, and later the first rudimentary GPS survey in 1989). The present whole-volcano GPS network measures 37 km E-W by 34 km N-S, and was set up in 1995, since when it has been totally or partially occupied 15 times. The location of the network is shown in Fig. 1. 42 papers have been published on this work so far. The project has clear relevance to the NERC mission in terms of long-term environmental monitoring, and post-graduate training in earth sciences. It specifically addresses the second of the environmental and natural resource issues: Environmental Risks and Hazards.

Figure 1.
Location of Mt Etna GPS survey network
Survey procedure
Where travel time and distance allowed, the 7 Leica 530 kits were simultaneously deployed to 7 stations in the network for periods of up to 12 hours, enabling 21 lines to be measured at one time. In the summit region, where stations were close together and shorter occupation times possible, one or two kits were carried to successive stations (up to 7 in one day). More than half the lines were repeat measured, and principal lines in the network were measured more than this: up to 8 times in the case of 4 lines. A list of times occupied and length of occupation is shown in fig. 2.

Data quality
There were very few problems encountered, and overall the data quality is excellent. Some of the stations down the Valle del Bove, where both the summit and the caldera walls obstruct low satellites, had higher GDOPs than is desirable (up to 5.6). It was intended to re-measure these, but poor weather at the end of the trip precluded re-measurement of the lower four. There are no paths or vehicle tracks in the Valle del
Bove, and the measurement of these stations requires a 10 hour hike over difficult and at times dangerous ground, and can only be attempted in good conditions. Elsewhere, 7 witness stations were occupied for less than 20 minutes, sufficient to tie them in to principal stations nearby.

**Processing & modelling**

Processing was carried out using Leica GeoOffice software. The data were post-processed using data recorded at permanent GPS stations at Noto (southern Sicily), Cagliari (Sardinia) and Matera (southern Italy) from the internet. The data quality of the fully adjusted network is shown in Fig. 3 in the form of histograms of the station residuals after network adjustment.

*Figure 3. Histograms of residuals to network adjustment. N = number of stations with residual value in mm.*
There is considerable difference (>4 cm) between the vertical displacements of the off-volcano stations at Centuripe and Cesaro, and the use of the normal reference station at the former yields overall upward motion of the volcano, whereas holding the station in the town stationary gives a slight rise of the upper flanks bordering a central N-S subsidence of the summit and northeast rift. The volcano itself may have been inflating during the finite time of the survey, which could have contributed to the scatter of vertical measurements.

**Figure 4. Horizontal movements 2005-2006, with confidence ellipses.**

**Preliminary findings**
A map of changes since 2005 is shown in fig. 4, with arrows denoting amount and direction of horizontal displacement compared to one of the three stations at Centuripe, off the volcano to the southwest. In the vast majority of cases the uncertainty in vector direction is small. The movements clearly show that the contraction 2004-5 has ceased, and radial outward movement, which was uninterrupted since 1995, has resumed. On the eastern side, this outward movement continues almost undiminished to the seashore, where a movement of 7 cm was measured at Santa Maria la Scala. However, there seems to be a dichotomy between the east side, where most of the radial movement (up to 10 cm) is occurring, and the west side, where movements are much smaller and the radial component not so much in evidence. A further point is that most of the stations lie in the eastern mobile sector. To improve coverage, 11 further stations have been added in the more stable western and northern sides of the volcano, to further constrain movements here. The
outward radial movement 2005-6 exceeds the inward contraction 2004-5, by a factor of about 3 on average. Comparing outward movement 2003-4 with 2005-6, the two patterns are very similar in terms of vector direction and amount. The most notable difference is that the western stations appear to have moved less in 2005-6 than in 2003-4, whereas in the lower northeastern flanks the opposite is the case.

**Interpretation to date**

It seems likely that a combination of both inflation of a magma storage area and outward gravitational spreading are responsible for the movement 2005-6. In view of the flank eruption that began 3 days after the survey was completed, it is probable that the volcano was inflated, but on the other hand, the similarity in flank vectors 2003-4 and 2005-6 suggests that this inflation is superimposed upon a fairly constant rate of spreading.

**Conclusions and recommendations**

The ground deformation of large volcanoes with steep slopes and large topographic differences can only really be studied by the use of dual-frequency GPS and other precise ground surveying techniques. The method of satellite radar interferometry, which showed such promise in the 1990s, and is still an extremely useful tool for volcanoes of low relief (such as some Hawaiian and Icelandic volcanoes), is subject to systematic topographic and unknown atmospheric errors. In addition, vegetation causes incoherence so that many areas of the volcano are inaccessible to this technique, which in any case can only yield movement in the ground-satellite vector, so that horizontal and vertical movement is indistinguishable. Whilst rapid kinematic GPS surveys are useful during an eruption or when large movements are taking place in small areas, the small movements shown over a long period within such a large network as this require a well-coordinated campaign of multiple static observations.

**Publications**

Murray, J.B. & Pitty, A.R. Intrinsic and extrinsic influences on deformation and eruptive activity at Mt Etna volcano, Sicily. *Bull. Volc.* In preparation. This paper lays out the evidence for 3 different influences: magmatic, gravitational and regional, on the recent eruptions at Etna.