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Analysis of ground deformations time-series measured at Stromboli (THEODOROS System) from 2003 to 2005.

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Introduction

The surface of Stromboli, like all other active volcanoes, deforms when magma moves beneath it or rises into its conduits. Shallow cracks or deep faults, some tens to hundreds of meters long, may develop in hours or days. The ground can change shape by rising up, subsiding, tilting, or forming fractures that are clearly visible. A variety of methods can be considered to monitor ground deformation in active volcanic areas, such as EDM (Electronic Distance Measuring) or satellite based techniques such as the GPS (Global Positioning Systems) or SAR (Synthetic Aperture Radar). Despite the use of these modern technologies, measuring and evaluating ground deformation data is not a completely automatic process. Indeed, for instance, traditional EDM techniques require a considerable use of operators to reach the summit of a volcano in order to perform the measuring process. However, at present, remote control instrumentation is commercially available in order to make automatic measuring. Such kind of measuring systems consist of a remote control sensor that can be programmed to measure slope distances and angles between the sensor and appropriate reflectors positioned at ground level. Recorded information is then sent to a central recording centre (e.g. an observatory) using an appropriate communication link (e.g. radio or/and cable). The use of such kind of equipment is important in order to have real-time information on the state of ground deformation and represents the premise for reducing the risk to people living around active volcanic areas.
Despite the availability of information in real time, this is not enough to implement a system able to automatically evaluate the state of ground deformation and eventually issue alarm messages. To reach a similar goal, it is necessary to implement appropriate software procedures that can process and interpret ground deformation data. The main aim of this paper is to present a preliminary analysis of data obtained by a tool, currently being developed at the INGV, devised to process ground deformation data recorded on the Stromboli volcano (Aeolian island, Sicily) by an automatic measuring system, referred to here as THEODOROS.
The main features of this tool are: 1) spectral analysis; 2) harmonic analysis (detection of periodic signal component; 3) filter design; 4) statistical analysis: average, variance, standard deviation, correlation function, density probability function; 5) data interpolation.

The THEODOROS Measuring System

The set up of this new system was a real challenge, given the logistic and operative conditions existing on Stromboli during the volcanic crisis. The chosen instrument was the Leica TCA 2003 (Leica and Geodetics, 2002) Total Station (TS) equipped with GeoMos software (Leica proprietary software) that allows remote control of the sensor. The acronym of this system operating at Stromboli is THEODOROS (THEOdolite and Distance-meter Robot Observatory of Stromboli). To guarantee a continuous stream of data from the instrument, it requires a constant power supply and a continuous link with the PC that controls the Total Station’s activities, installed on the S. Vincenzo Observatory, where the National Department of Civil Protection (DPC) control room is located. These technical solutions were achieved by exploiting two facilities already installed by the DPC and the Istituto Nazionale di Geofisica e Vulcanologia (INGV). A reference system of 5 reflectors (Fig. 1), (400, CURV, BORD, SEMF, SPLB2) was installed around the TS, on sites considered stable from the geological point of view.

The reference system aims to guarantee the same orientation in space (both horizontally and vertically) through the measurements of appropriate reference baselines. At the very beginning THEODOROS carried out measurements on only four reflectors installed on the SdF (SDF5, SDF6, SDF7 and SDF8), that were the only remaining ones after the destruction due to the lava flows, and on three reflectors installed around the site belonging to the reference system (SEMF, 400, SPLB2). After the end of the eruption, the network was improved by setting up other reflectors in the SdF and redefining the reference network. The actual system aims to follow the post-eruptive movements of the recent lava flow field. At present, THEODOROS consists of 5 reflectors for the reference system (400, BORD, SEMF, SPLB2 plus ELIS), 10 reflectors for monitoring movements in the SdF (the four previously installed plus SDF9, SDF10, SDF11, SDF12, SDF14, SDF16) and 2 more reflectors to check the stability of the measurements both on short and very long distance measurements (CURV and CRV) (Fig. 1). The current measurement strategy assumes that the horizontal geometry and the relative distance of the reference system are fixed (by fixing the coordinates of the reference system benchmarks), while the TS adjusts its own vertical positions by using only the internal vertical compensators. This geometry is maintained fixed through each cycle of measurements during which the TS successively performs the measurements in the group of reference system points and monitoring targets. Each cycle last less than 30 min so we have 48 cycles per day. Each measurement for each target or reference point provides three relevant pieces of information: the slope distance (sd), the horizontal (hz) angle and the vertical angle (ve). Starting from this information, the GeoMos system is able to transform the TS measurement vectors (whose components are sd, hz, ve) into an equivalent vector whose components are expressed in terms of North (N), South(S) and Quota (Q) with respect to the assumed reference system. In this computation, GeoMos is able to take into account the constraints imposed by the assumption of the reference system.

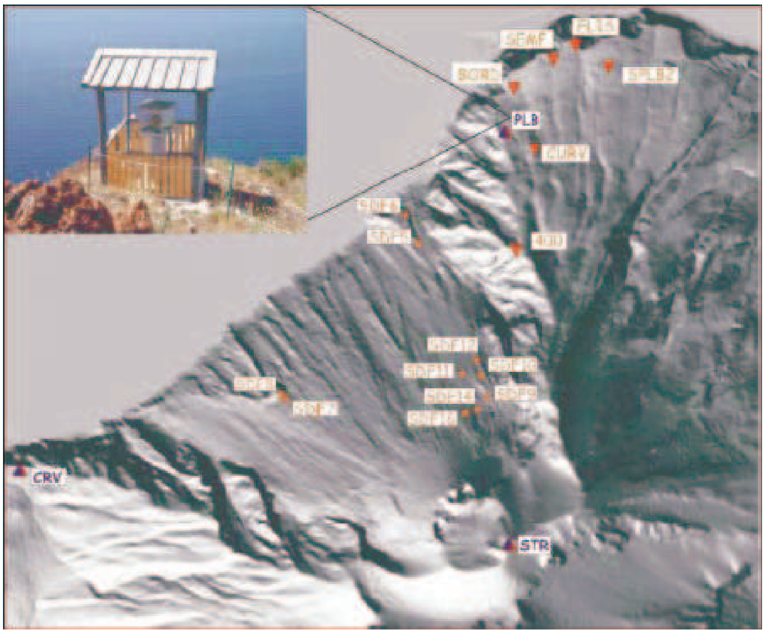

Fig. 1. The position of the reflectors and the total station.

Harmonic analysis

In this section we describe some analyses with the purpose of characterizing features that could be useful to describe normal activity, i.e. quiescent time period of the volcano.

The purpose of harmonic analysis is the detection of periodic signal components in a time series in the presence of noise. A general overview on this topic can be found in Percival and Walden (1993, ch. 10). We have implemented two tests to verify the presence of periodic signal components. These methods are built on the assumption that the noise is white, and are based on a periodogram $P(f_k)$ calculated by using the Fast Fourier Transform (FFT) algorithm.

The first test, developed by Fisher (1929), allows assessing if a single periodicity exists in a time series. The test statistic is

$$g = \frac{\max_{1 \le k \le K} P(f_k)}{\sum_{i=1}^{K} P(f_k)}$$

where K is the number of Fourier components. Critical values for Fisher's test, g_f, can be approximated by

$$g_f = 1 - (\alpha / K)^{1/(K-1)}$$

If $g > g_f$ for some α, the null hypothesis (signal is pure white noise) is rejected, and it can be stated with a $(1-\alpha)$ confidence level that a periodic signal is present at the frequency where the periodogram has its maximum. The major disadvantage of Fisher's test is that it only tests the presence of a single periodic component. Siegel (1980) extended Fisher's test for cases in which up to three periodic components are present in a time series. Starting from a normalized periodogram

$$P_N(f_k) = \frac{P(f_k)}{\sum_{i=1}^{K} P(f_i)}$$

the test is based on all values of $P_N(f_k)$ that exceed some level g_s instead of only their maximum as in the Fisher's test. g_s is related to g_f by a parameter λ with $0 < \lambda \le 1$. The test statistic is

$$T_\lambda = \sum_{k=1}^{K} [P_N(f_k) - \lambda g_f]_+$$

where $[a]_+ = \max(a, 0)$. For $20 < K < 2000$ critical values of $t_{\lambda;x}$ for this test can be computed according $t_{\lambda;x} = aK^b$ (Percival and Walden,1993). Empirical coefficients a and b are given in Table 1 for different values of α and λ. Similar to Fisher's test, the null hypothesis is rejected if $T_\lambda > t_{\lambda;x}$. In this situation, one or more periodic components are present in the time series at the frequencies where the largest $P_N(f_k)$ values occur.

	$\lambda = 0.4$	$\lambda = 0.6$
$\alpha = 0.05$	$a = 0.9842$ $b = -0.51697$	$a = 1.033$ $b = -0.72356$
$\alpha = 0.01$	$a = 1.3128$ $b = -0.59518$	$a = 1.4987$ $b = -0.79695$

Table 1. Coefficients for computing critical values $t_{\lambda;x}$ for Siegel's test.

Since the Fisher test gives information on an individual component alone, here the Siegel test, which extends the former one, is considered. Now we will investigate how Siegel's test performs on the considered data set showing its usefulness for data interpretation. As an example, we process the time series referring the point SDF5 (North). The power spectrum of this series is shown in figure 3. Since $T_\lambda > t_{\lambda;x}$ ($T_\lambda = 0.179$, $t_{\lambda;x} = 0.018$)

the null hypothesis is rejected and hence harmonic components are present. In particular, the presence of 24h and 12h components is evident. The 24h harmonic component is well known as the daily component that is due to thermo-elastic effects, while the 12h harmonic component might be interpreted as due to mareale force.

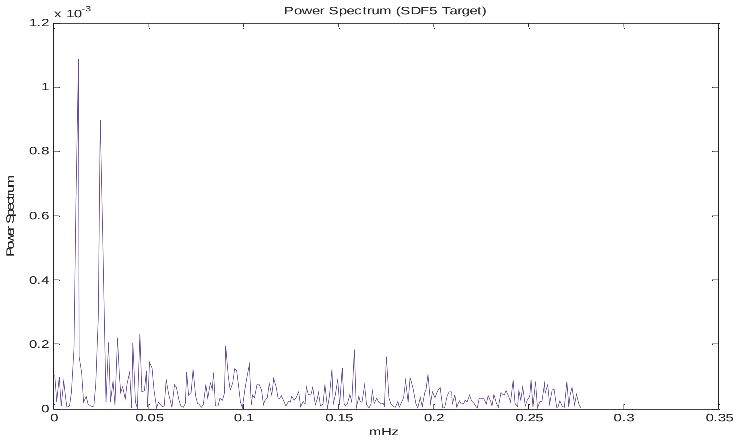

Figure 3. Power Spectrum of SDF5 (North)

To better characterize both 24h and 12h effects the tool provides filter design and statistical analysis. We use bandpass filters to isolate the single component in order to perform statistical analysis in the time domain.
Figure 4 shows periodic components of SDF5 (North) target, while table 2 and 3 gives statistical properties of periodic components of several targets. The 24h and 12h components shown in figure 4 are not perfectly sinusoidal due to the finite band of the considered bandpass filters. However, these components allow to characterize some useful information on daily and 12h ground deformation such as: minimum, maximum, mean and standard deviation.

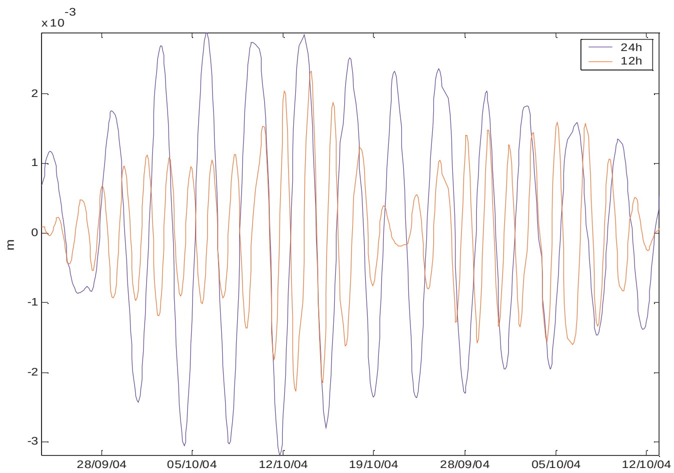

Figure 4. 24h and 12h periodic components of SDF5 (North)

Target	**Min.**	**Max.**	**Mean**	**StdDev**
SDF5	-3.1853	2.8804	-0.0011	1.6140
SDF6	-3.3489	3.2589	-0.0019	1.8216
SDF9	-4.1453	4.6260	-0.0009	1.4779

SDF11	-2.0689	2.1892	-0.0008	0.9042
SDF13	-4.8645	5.3128	-0.0006	1.5691
SDF14	-2.3458	2.2125	0.0010	1.0017

Table 2. Statistical properties of 24h periodic component (mm)

Target	**Min.**	**Max.**	**Mean**	**StdDev**
SDF5	-4.2935	4.3895	0.0001	1.8080
SDF6	-4.5283	4.7341	0.0000	1.9253
SDF9	-3.3850	3.3950	-0.0023	1.1374
SDF11	-2.9336	2.6603	0.0014	0.9316
SDF13	-3.4051	3.4443	-0.0023	1.0607
SDF14	-2.9125	2.8634	0.0002	1.0110

Table 3. Statistical properties of 12h periodic component (mm)

These tables show the "normal" North ground deformation components for each benchmark whose data set allows to calculate them. Similar analyses have been performed on the East and Quota components but numerical results are not given here for their lack of simplicity.
Both diurnal and semi-diurnal periodic components act simultaneously on the process of ground deformation, therefore useful information can be extracted from their combined behaviour. For this purpose, a bandpass filter is used to isolate both periodic components in order to perform an analysis in the time domain. This operation is shown in figure 4.

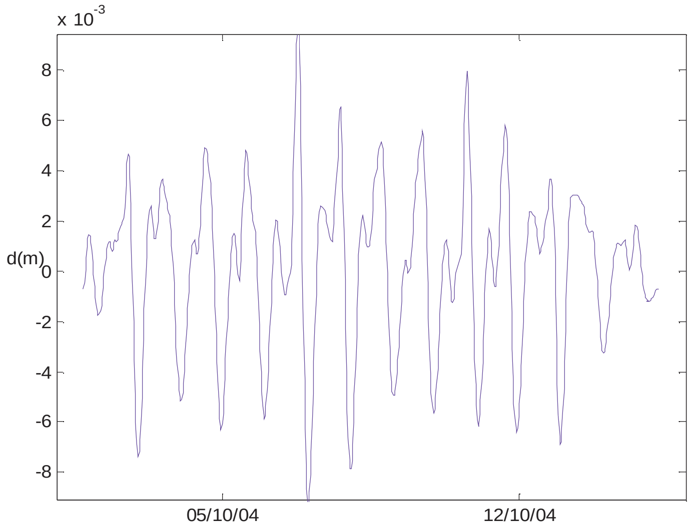

Figure 4. Contribution of 24h and 12h periodic components.

The arranged action of the two periodic components involves an increase in the range of variation of the observed data with respect to the action of the single component. Statistical analysis on this data has been useful in order to define and optimize a simple analytical model able to give us an approximation of average behaviour of observed components. The model is

$$f(t) = A\cos(2\pi ft + \theta_1) + B\cos(2\pi 2 ft + \theta_2)$$

where $A = 0.00231,\ B = -0.00136,\ \theta_1 = 1.8776,\ \theta_2 = 4.35601,\ f = 1/86400Hz$.

Parameter A and B (amplitudes), θ_1 and θ_2 (phases) have been computed by using an appropriate optimisation algorithm. The result is shown in figure 5.

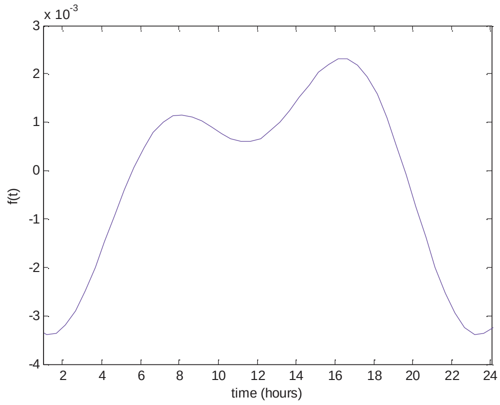

Figure 5. Average behaviour of periodic component

Conclusions

In this paper, some results obtained with the aim of characterizing the *normal* ground deformation pattern in the area of Sciara del Fuoco at Stromboli have been presented. Spectral analysis of a generic time series, performed by using the Fast Fourier Transform (FFT) algorithm and Siegel test, highlighted that the signal is affected by two marked periodic components: 24h and 12h. Statistical analysis on both components has been performed and an analytical model has been defined in order to characterize their contribution to the normal activity of ground deformation at Stromboli volcano. The result will be useful for implementing a warning system that is currently being developed.

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