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Spectral analysis of the clinometric data at the Phlegraean Fields from 1992 to 1998

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Abstract
Ground deformation is one of the most important precursors for volcanic eruptions. In this respect, the surveillance of volcanoes has greatly benifited from the continuous recording of clinometric data, which represents an economical and reliable way to identify significant ground deformations. In this paper we analyze the clinometric data recorded at the Phlegraean Fields, Italy, in the period 1992-1998 through a classical time series analysis. We show that these techniques can be advantageously used to discriminate between the signals relative to the internal and external processes. In particular, we find that high-frequency fluctuations are mainly due to thermal and atmospheric pressure variations, while at lower frequencies we highlight a constant subsidence, without any evidence of volcanic reactivation.

Key words *spectral analysis – Phlegraean fields – clinometric data*

1. Introduction

The Phlegraean Fields are a restless caldera resulting from the Campanian Ignimbrite eruption, 37 ka before present, (*e.g.*, Rosi *et al.*, 1995) and the Neapolitan Yellow Tuff eruption, 12 ka before present (*e.g.*, Wohletz *et al.*, 1995), after which volcanic activity alternated with periods of quiescence (Di Vito *et al.*, 1999), until the last eruption in September 1538. Interest in this area has never ceased because of its intense geodynamic and geothermal activity, with strong ground uplift and subsidence episodes, earthquake swarms, and fumarolic emission.

In the past three decades, two major deformational events occurred, in 1969-1972 and in 1982-1984, with maximum ground uplifts of 170 cm and 180 cm respectively, accompanied by seismic activity (De Natale *et al.*, 1995), gravity changes (Berrino, 1994) and geochemical anomalies (Martini *et al.*, 1991).

At present, a very weak seismicity and ground subsidence are detected, while a strong fumarolic emission is present. The total output of CO_2 due to the deep degassing process has been estimated as about 1500 t d^{-1}, and a flux of vapour of 3300 t d^{-1} is measured. The associated thermal energy has been calculated to be 1.4×10^{20} erg d^{-1}, equivalent to a thermal flux of 260 W m^{2} (Chiodini *et al.*, 2000). In the last three years the values of the flux of CO_2 have been nearly constant, thus suggesting that the system should be in a steady state.

The behaviour in the past and the current state of the Phlegraean Fields caldera indicate that it is an active volcanic complex which may

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erupt again in the future. Because of the high hazard of the caldera and the urbanisation both inside and in the surrounding area, the volcanic risk is extremely high and the Phlegraean Fields deserve very careful surveillance. The Osservatorio Vesuviano manages the continuous monitoring of ground deformations, seismicity, and fumarole activity, as well as periodic campaigns to measure the gravimetric and electromagnetic field and to sample and analyse the thermal fluids (Osservatorio Vesuviano, 1999).

The main purpose in the surveillance of volcanoes is to detect signals coming from inside the earth. Unfortunately, most of the instruments designed for this task collect data that are also strongly influenced by external signals, and a filtering procedure would then be needed, with the main goal to distinguish between external and internal processes. Actually, we barely know the external processes that can influence the data, such as temperature, atmospheric pressure, earth tides and so on, but their relative importance and the law that links them to the data observed are almost unknown. This fact makes it very difficult to design an optimal filter to detect internal processes, such as a magmatic reactiviation, and, undoubtedly, the classical time series analysis (*cf.* Bath, 1974; Priestley, 1981) is the first step that should be performed to quantify the relevance of external parameters, and therefore to provide a first quantitative tool to remove them.

The power of the time series analysis in discriminating between internal and external signals is due to the fact that the main rough difference between them is their characteristic time period. External factors usually act on time scales of hours, days, and months, while the time periods that mark internal processes, such as the reactivation of a magmatic system, are significantly longer.

As regards the ground deformation, that is the main topic of this paper, the signals due to external processes are related to all the periodical processes, such as the thermal excursions, both diurnal and seasonal, the sea tidal loading, the solar-lunar tides, as well as to a number of recurrent natural phenomena, such as the rainfall and the atmospheric pressure variations, and to incidental events related to human impact (*e.g.*, water withdrawal). The internal causes producing ground deformation are rather long-term recurring phenomena, such as the bradiseisms typical of the Phlegraean area, which can be in turn related to underground fluid (water or magma) movements, and short-term incidental events, as indicated by the tilt anomalies measured before an earthquake (Rikitake, 1976).

The techniques which allow a continuous control of ground deformations are the GPS method, which is still very expensive, and clinometric monitoring, which is currently used for example at the Cascade Volcano Observatory (Dzurisin, 1992), Long Valley caldera (Hill *et al.*, 1991), and at the Phlegraean Fields. Very few works, in the past, were devoted to a quantitative analysis of the clinometric data (*e.g.*, Mortensen and Hopkins, 1987; Peters and Baumont, 1985). Nevertheless, the relatively low cost of the clinometric stations and their sensitivity in detecting very small deformations of the ground are the main advantages of this kind of instrument.

The Phlegraean Field clinometric net, which records the tilt variations with respect to the equi-potential gravity field, was installed by the Osservatorio Vesuviano in 1987, and has been active since then.

In this paper a spectral analysis of the data collected from 1992 to 1998 is performed, and the tilt variations and their causes are recognised. Our aim is to build a very well defined picture of the present, almost quiescent state, in order to be able to recognise any anomalous tilt variation which could be ascribed to an endogenous process, such as a restart of the volcanic dynamics.

2. The Phlegraean Fields clinometric net

The automatic net for clinometric monitoring at the Phlegraean Fields provides a continuous recording of the ground tilt variations and the tele-transmission of the digitised signals to the surveillance centre of the Osservatorio Vesuviano.

Four tiltmetric stations are working (fig. 1): three, called DMA, DMB, and DMC, are locat-

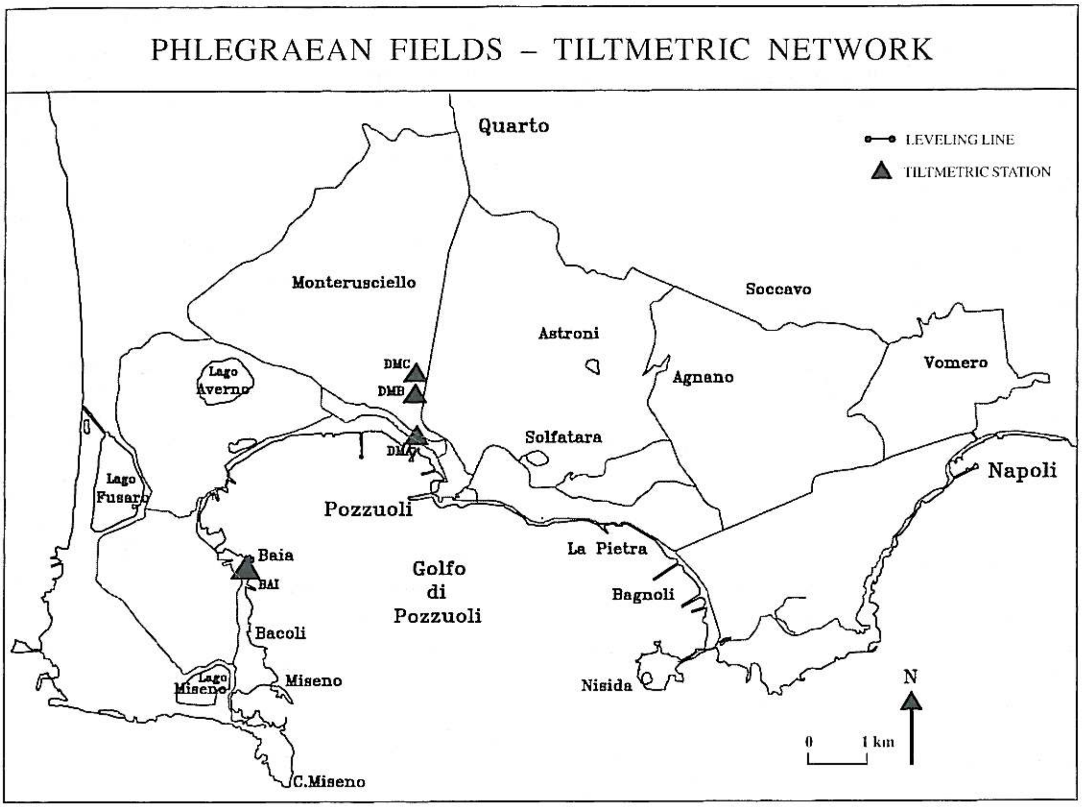

Fig. 1. Map of the clinometric net at the Phlegraean Fields.

ed in the via Campana underground gallery, and are aligned along the north-south direction; the fourth, denoted BAI, is placed in a cave in the Baia castle. The first three stations are about 2 km away from the area affected by the maximum uplift, while the BAI station is about 4 km away.

All the stations use a two component (*X*-axis and *Y*-axis) transducer (Applied Geomechanics, mod . 702) equipped with temperature sensors. The tilt transducers have a calibrated angular range of ± 800 μ radians, a resolution of 0.1 μ radian, a measurement repeatability of 1 μ radiant, and the possibility of sensitivity setting in high gain (0.1 μ radians/mV) or in low gain (1 μ radians/mV); the scale factors reported in brackets are determined by the linear regression of *X*-axis and *Y*-axis outputs in mV over the calibrated angular range. The linearity, that represents the greatest deviation (%) of tiltmeter output from the regression line to full-range calibration curve, is 3%. The tiltmeters are also equipped with temperature sensors with a sensitivity of at least 0.1°C/mV. The sampling frequency is set at a 0.5 h rate.

Every sensor is connected to an automatic record station which carries out the conversion of the signal into digital mode, its storage and enables the telematic connection with the Surveillance Center of the Osservatorio Vesuviano, in order to allow the continuous control of the recorded tiltmetric variations.

3. Results

The East-West and North-South components of the tilt variations measured by the station DMB and N in the period August-December 1995 at the Phlegraean Fields are displayed in fig. 2a,b , and can be considered as a sample of the typical tilt variation recorded in this area. The collected data clearly show that the two normal components are not independent, but rather, in this case, an anticorrelation is evident.

The first analysis performed on the data (decimating the data at a 2 h rate) aimed to ascertain if the value of the tilt variation at time t is influenced by its previous value at time $t-\tau$. This task is achieved calculating the autocorrelation function

$$C(\tau) = \int f(t)\, f(t-\tau)\, dt \qquad (3.1)$$

where $f(t)$ is the temporal series to be analysed.

The autocorrelation function was evaluated up to a delay τ of 30 days for both the E-W and the N-S tilt component recorded by the four stations. For all the data set no autocorrelation longer than a few hours is evident, while 1 day periodicity can be identified, particularly evident in the E-W data recorded by DMA and DMB and in the N-S data recorded by DMC, as shown in fig. 3a-f.

The periodicity of the data series were then further investigated by means of spectral analysis, performed for each tilt component and for each station, with a sampling frequency of 1/(2 h), and using a Hamming window (Priestley, 1981).

In order to reduce the noise in the measurement series, we calculated for each station the average Welch spectrum obtained for periods of 4 months each year. Figura 4 shows the Welch spectra of each tilt component, and fig. 5 shows the Welch spectra calculated in the same way for the temperature data measured at DMB and BAI. In addition to the diurnal periodicity, already evidenced by the autocorrelation function analysis, a semi-diurnal periodicity and low frequency components are clearly shown.

The diurnal periodicity $(K_1 - P_1)$ is also present in the temperture data spectra, and can be ascribed to the diurnal thermal effect.

The two semi-diurnal periodicities have a different origin. One is present in all the spectra with a period of 12 h 00 min, and is likely due to the concomitant contribution of the lunar-solar tide S_2 and the atmospheric pressure. Figure 6 shows, for example, the atmospheric pressure recorded in 1993 as a function of time, and its Welch spectrum which also exhibits the strongest periodicity at 12 h 00 min.

The other semi-diurnal periodicity of 12 h 25 min is related to the main lunar tide component M_2. It is interesting to note, however, that this periodicity is not always present, but rather is very evident at BAI station, which is the closest to the sea, while it is lacking at DMC, which is the furthest from the coast. This seems to suggest that the measured ground deformations are not due in a significant manner to the lunar attraction, but mostly the sea loading, that obviously has the same periodicities.

Therefore, the simplest way to highlight possible internal signals and to remove the external contribution is to apply a low-pass filter.

Here, we removed all the periodicities with a period shorter than 1 month applying a moving average filter. The results of this filtering for the DMB station are reported in fig. 7. It is evident from this figure that the main ground deformation is a subsidence recorded on the N-S component, while the E-W level variations are strongly correlated to the long-term temperature variations.

The reliability of this result was checked comparing the ground level variations recorded at two altimetric benchmarks in the same area. In figure 8, the tilt variations calculated from the two benchmarks appear quite similar to those measured by the tiltmetric stations.

4. Conclusions

In summary, the time series analysis of the tiltmetric variations recorded by the Phlegraean Fields stations in the period 1992-1998 leads to general and more specific considerations.

In general, we have demonstrated the reliability of the clinometric data for surveillance purposes, showing that the time series analysis is a preliminary, but fundamental tool to dis-

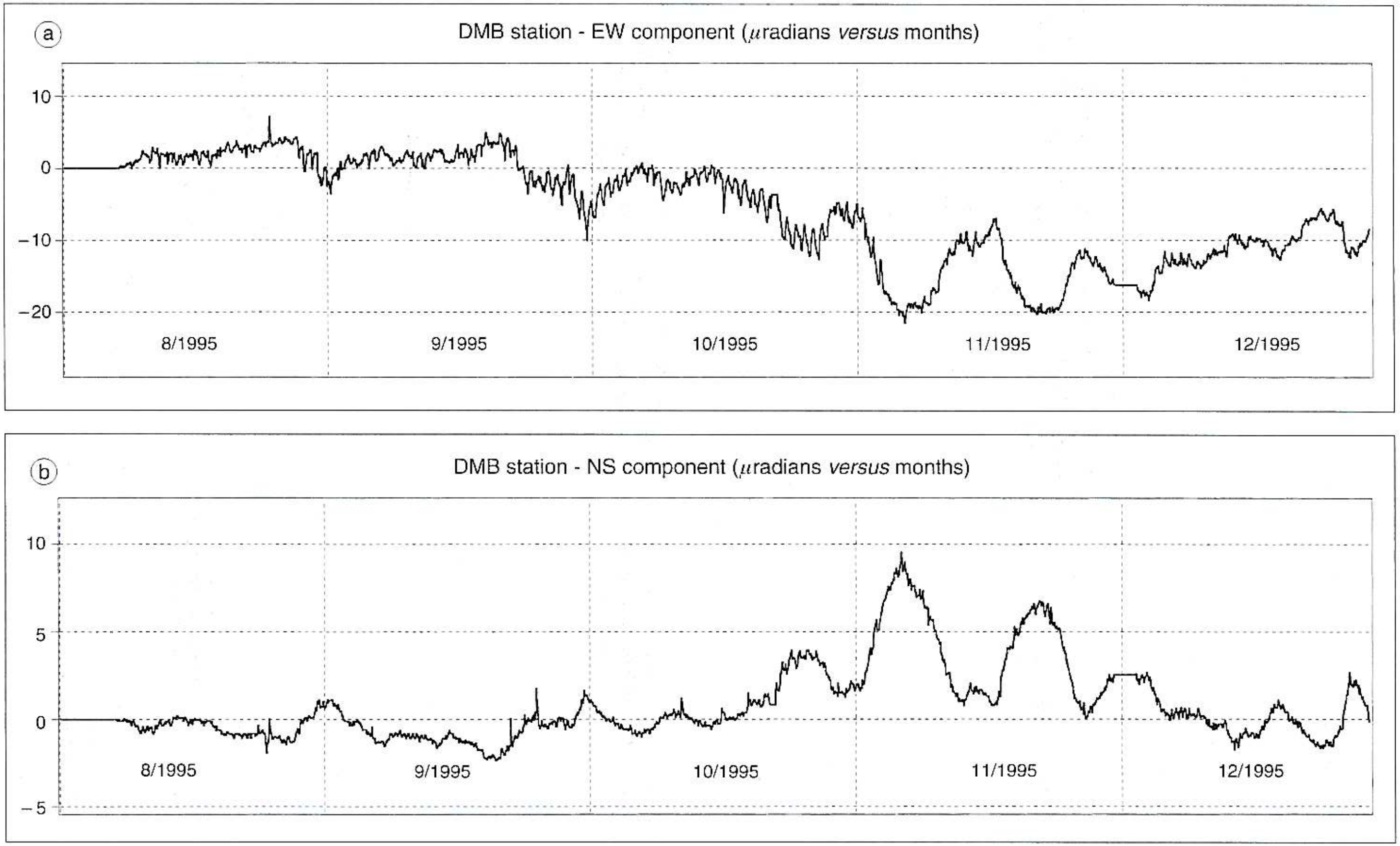

Fig. 2a,b. a) East-West and (b) North-South tilt component recorded at the station DMB in the period from August-December 1995.

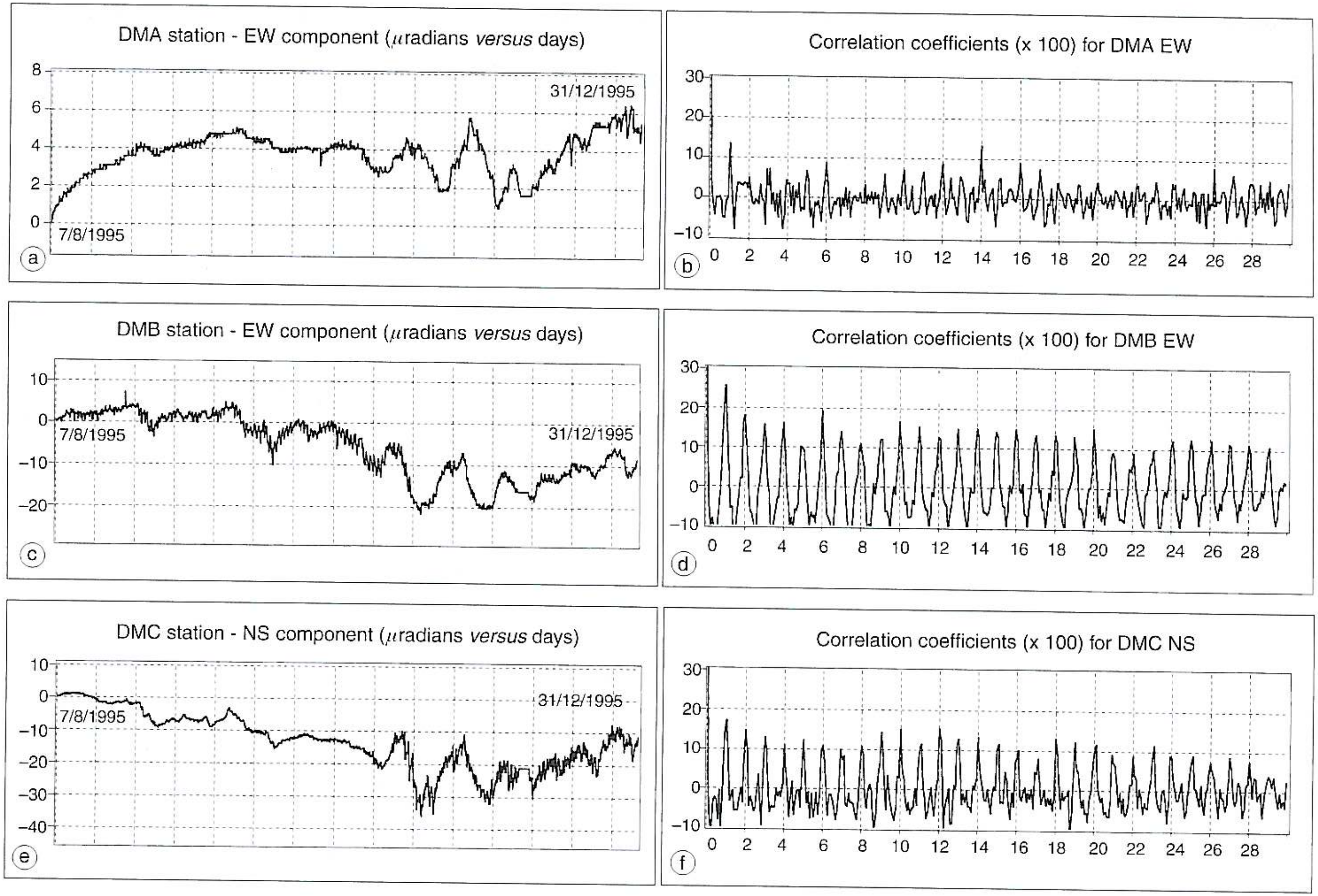

Fig. 3a-f. a) East-West tilt component at DMA, and (b) its autocorrelation function for a delay $\tau = 30$ d; c) and d) the same for the East-West tilt component at DMB; e) and f) the same for the North-South tilt component at DMC.

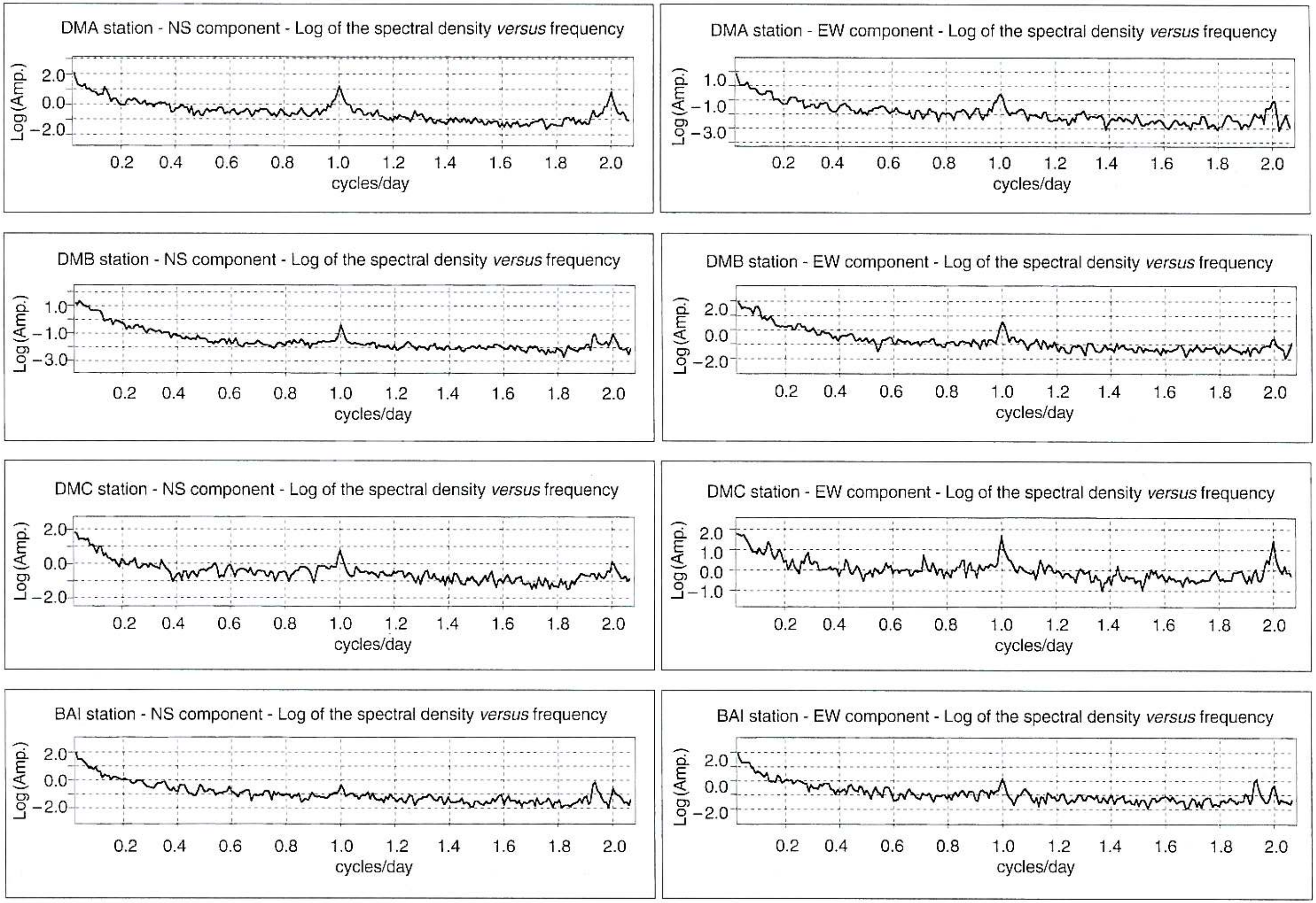

Fig. 4. Welch spectrum of the North-South (left panels) and East-West (right panels) tilt components recorded at the four Phlegraean stations.

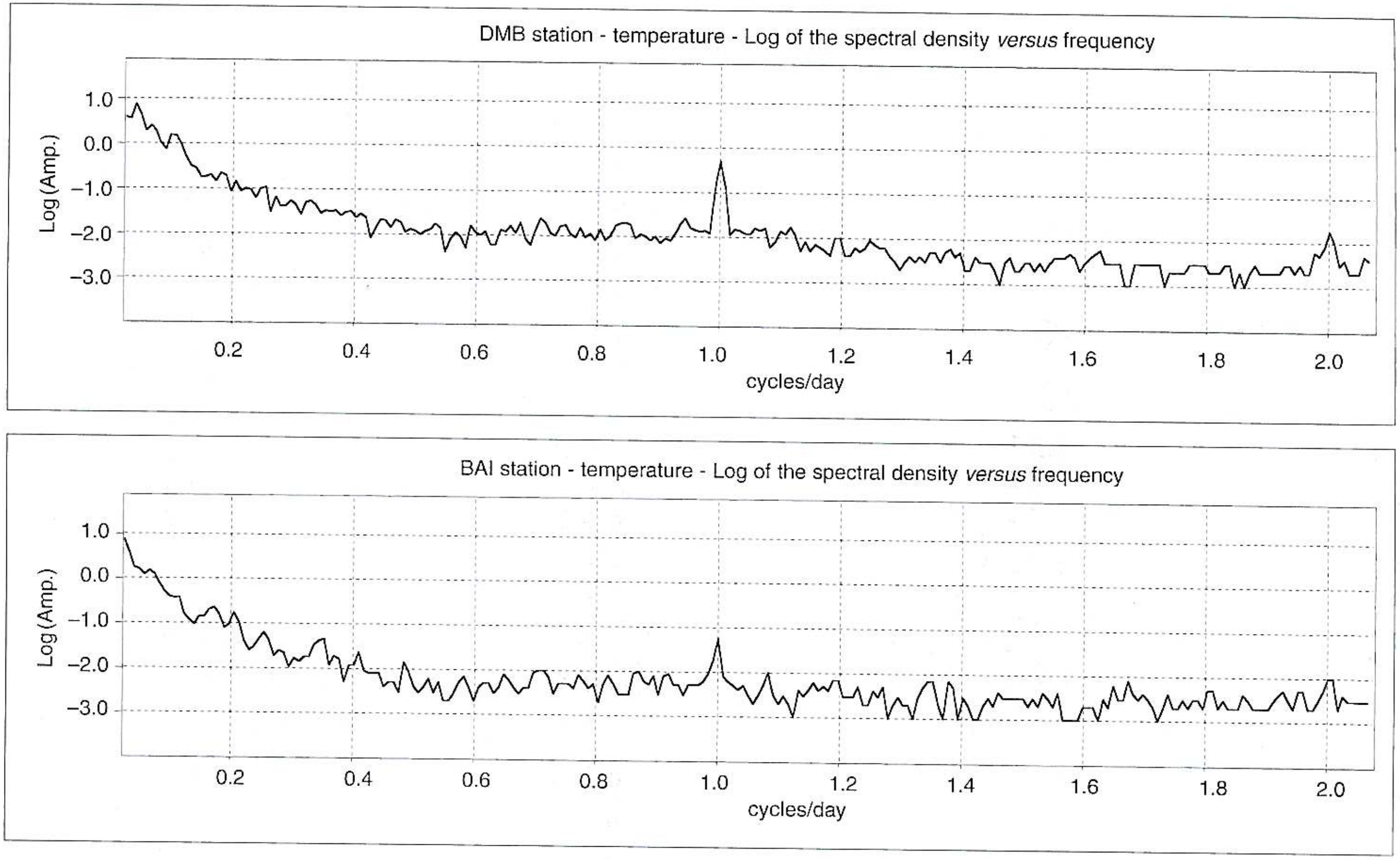

Fig. 5. Welch spectrum of the temperature data recorded at the DMB (top) and BAI (bottom) stations.

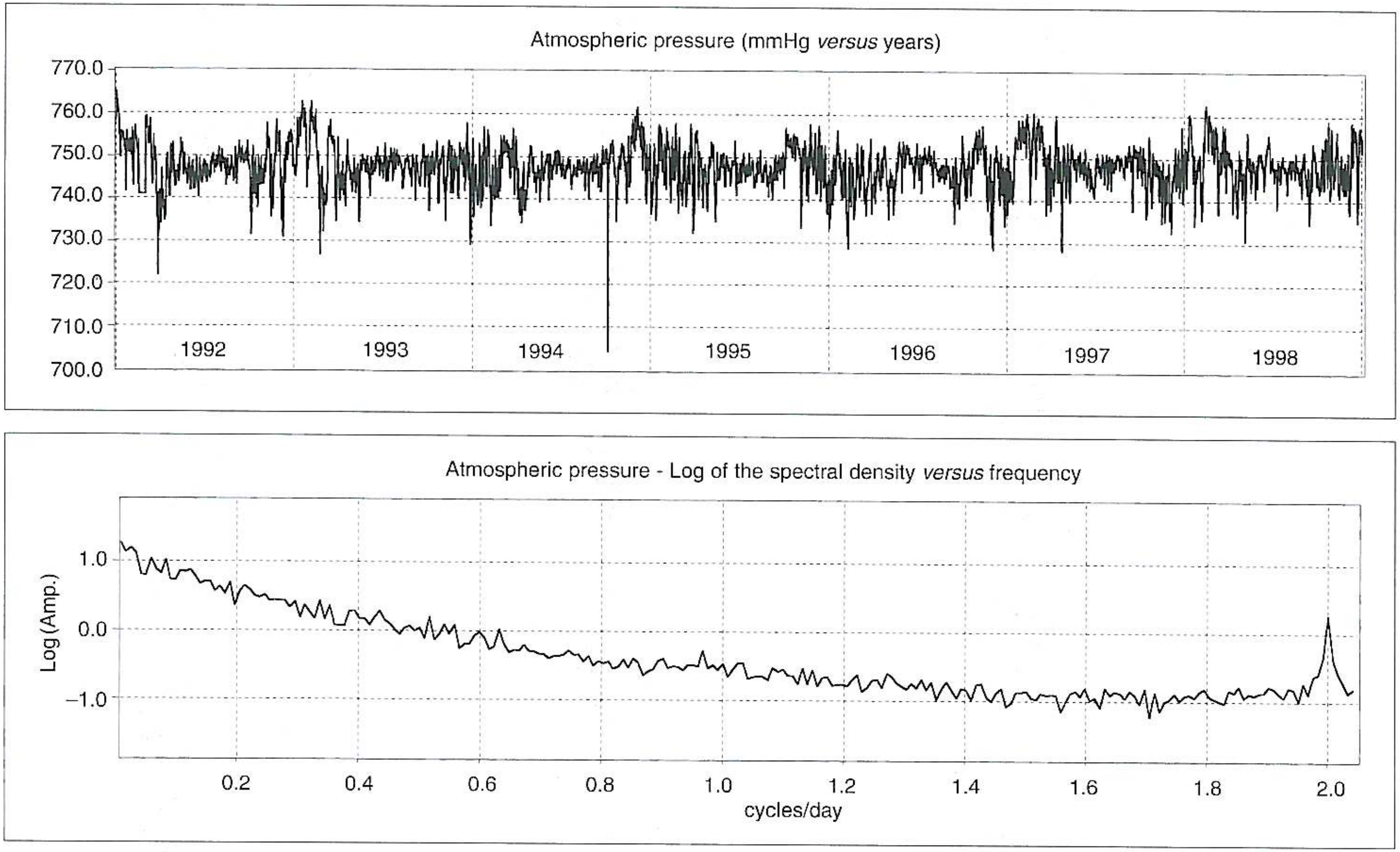

Fig. 6. Atmospheric pressure as a function of time in the period 1992-1998 (top) and its Welch spectrum (bottom).

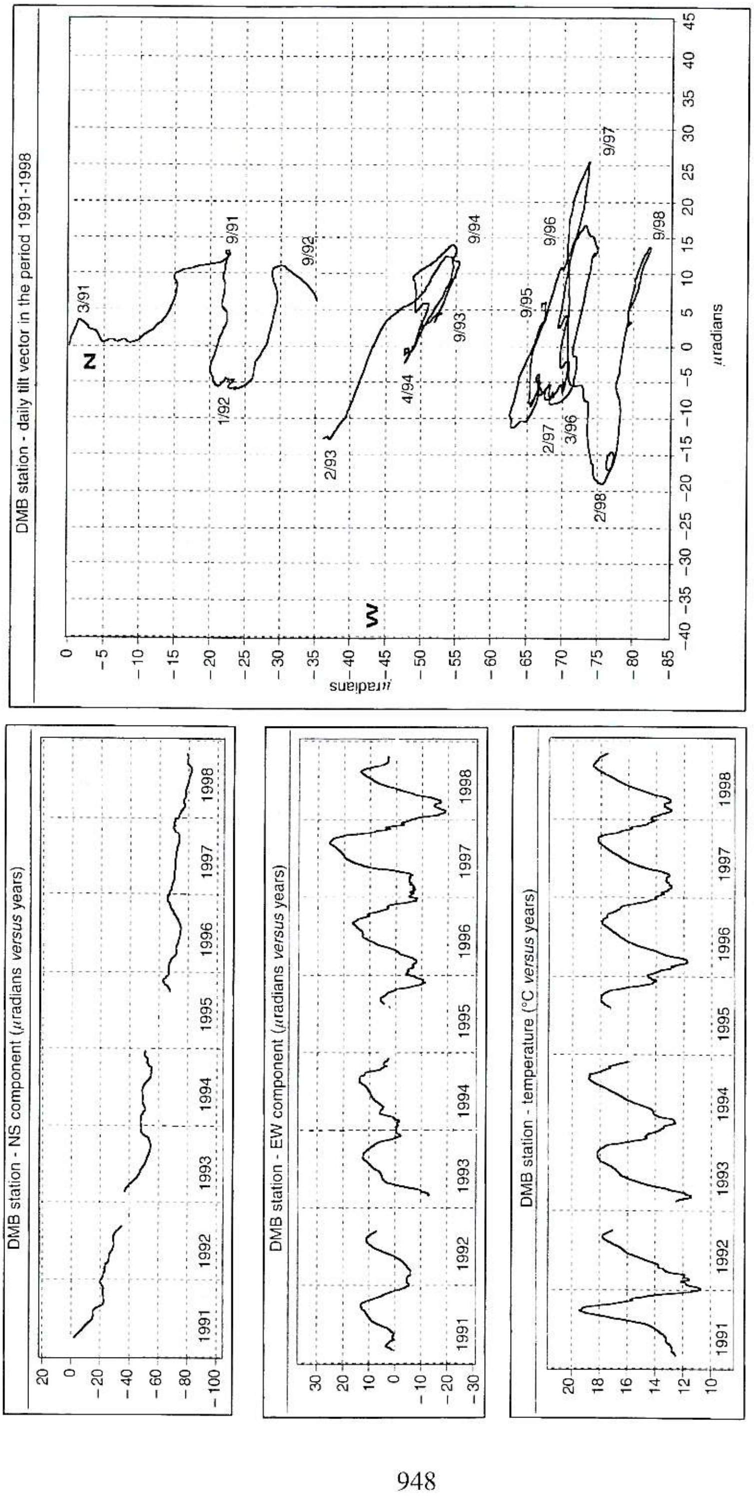

Fig. 7. Results for the DMB station in the period 1991-1998. The panels on the left report the filtered (see text) NS and EW components and the temperature. The panel on the right report the daily tilt vector in the same period.

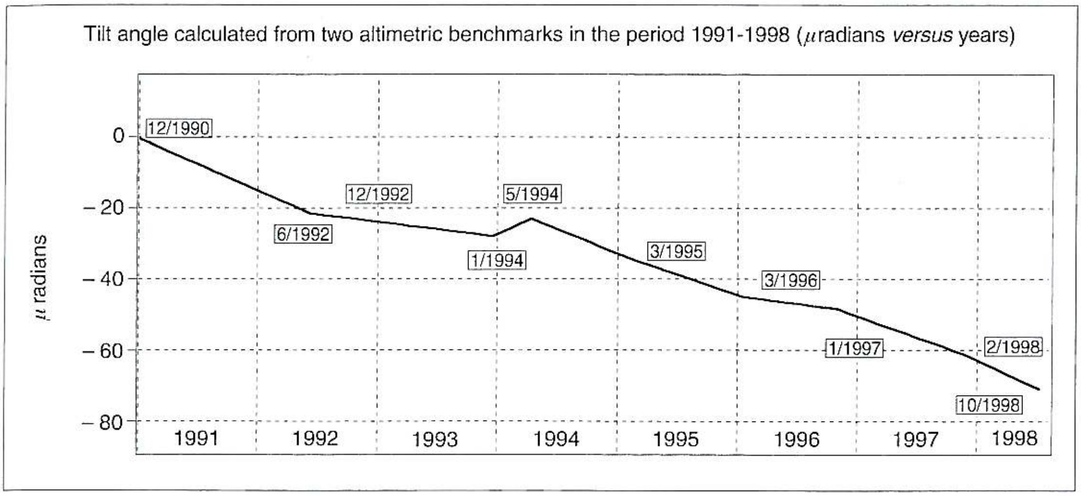

Fig. 8. Tilt angle calculated from two altimetric benchmarks close to the DMB station in the period 1991-1998.

criminate between the signals related to internal and external processes.

As regards the more specific considerations, we have found that at high frequency, the temperature and the atmospheric pressure play a major role in the ground deformation in comparison with the luni-solar tides, which are less significant and do not act directly but rather through the sea loading.

At lower frequencies, we found that, in the period 1992-1998 the Phlegraean Fields were affected by a constant ground subsidence.

Acknowledgements

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