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Monitoring Tidal and Non-tidal Tilt Variations in Lanzarote Island (Spain)

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Abstract

Analyses of tiltmeter data from the Geodynamics Observatory of Lanzarote (Canary Islands, Spain) are evaluated in order to investigate ground deformations. The tiltmeters are operating in two locations of the Island, with different sensitivity ranges depending on the site conditions. The results of tidal analysis show a clear influence of the ocean loading and also meteorological disturbances. Air pressure and temperature effects are different depending on type, location and orientation of the tiltmeter, with different magnitude of the effect in the high and low frequency bands.

1. Introduction

The role played by tiltmeter gauges is well known in crustal structure and ground deformation studies (Edge et al., 1981; Mentes et al., 1999). However, continuous observations with tiltmeters are strongly influenced by local and regional effects, especially the long period data (Agnew, 1986). Furthermore, continuous recording with tiltmeters is very sensitive to local atmospheric perturbations such as air pressure and temperature variations, as well as to the inverse barometric effect if the station is close to the ocean. In consequence, it is necessary to correct such disturbances in order to investigate ground deformations produced by other natural phenomena.

In our case, the tiltmeters are placed in Lanzarote (Canary Islands). The island is of volcanic origin and the last eruption took place at the beginning of Eighteen Century. The instruments are installed in two locations of the Geodynamics Laboratory of Lanzarote (Vieira et al., 1991; Arnoso et al., 2000) known as Cueva de los Verdes (CV) and Timanfaya National Park (T). The first one is located at the most north-eastern part of the island, in a lava tunnel (Bravo et al., 1964) and the second one is located at southwest part, inside a National Park, just above the largest geothermal anomaly in the zone (Araña et al., 1984). The tiltmeters considered in this study are operating thanks to cooperation between the Institute of Astronomy and Geodesy of Madrid (Spain) and the Institute of Seismology of Wuhan (P. R. of China) (see Cai Weixin et al., 1994; Cai Weixin et al., 1997; Arnoso et al., 1998; Vélez et al., 2001).

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2. Tiltmeters Installed in Cueva de los Verdes (CV)

Two long base-line tiltmeters are installed at the station CV. The instruments are a kind of water tube type and are placed in the two orthogonal directions of the lava tunnel. The tiltmeters were installed in May 1992 (WTCE92 is installed in the longitudinal direction of the tunnel, which has an azimuth of 135°.2 N) and December 1994 (WTCE94 is installed in the transversal direction of the tunnel, which has an azimuth of 45°.2 N). Both water tube tiltmeters are glass-assembled tubes of 1.5 m length, with two end pots with a diameter of 230 mm. The tubes are refilled with distilled water. The two pots are equipped with a special float, which detects the water level variations by means of a magnetic sensor (a more detailed description can be found in Cai Weixin, et al., 1997; Arnoso et al., 1998; Vélez et al., 2001). The WTCE92 has 38.2 m length, with a sensitivity of 0.21 mas (1 mas = 10^{-3} arc seconds) and a range of ±5000 mas. The WTCE94 has 8m length, with a sensitivity of 0.24 mas and a range of ±5000 mas. Both instruments are connected to a Meteodata-256 data logger, with a sample period of 2 seconds and acquisition period of 10 minutes.

2.1. Tidal Analysis and Meteorological Influences

Tiltmeters installed at the station CV are dedicated mainly to tidal research. Analyses of tidal records for WTCE92 and WTCE94 are listed in Table 1a and Table 1b, respectively.

Table 1. Results of the tidal analysis (observed amplitude A, tidal parameters γ, α and tidal residual vector B, β) evaluated by the least squares harmonic analysis method at station CV (ϕ: 29°09'36" N, λ: 13°26'28" W, H: 37m). The Earth response is according to Molodensky for body tides and the tidal potential used is Tamura (1987). Amplitudes are in mas, and phases, in degree, are local. (a) for the WTCE92 tiltmeter (from 15-05-1992 to 23-10-1999) and (b) for WTCE94 tiltmeter (from 03-12-1994 to 23-10-1999).

	A	mse	γ	mse	α	mse	B	β
(a) Q1	1.05	0.04	1.6476	0.0601	-2.54	2.09	0.61	-4.4
O1	3.51	0.04	1.0541	0.0112	-29.79	0.61	1.90	-66.6
P1	0.55	0.03	0.3532	0.0208	-49.82	3.38	0.84	-150.2
K1	1.33	0.03	0.2846	0.0075	-51.49	1.51	2.80	-158.1
N2	7.04	0.06	3.4629	0.0287	-48.72	0.48	6.21	-58.4
NU2	1.32	0.06	3.4048	0.1506	-55.69	2.53	1.19	-66.3
M2	32.95	0.06	3.1027	0.0053	-62.34	0.10	30.27	-74.7
S2	11.23	0.06	2.2720	0.0117	-83.19	0.29	11.34	-100.5
K2	3.22	0.07	2.3956	0.0511	-80.33	1.22	3.20	-96.9
(b) Q1	0.80	0.08	1.2634	0.1267	10.42	5.75	0.38	22.4
O1	3.53	0.08	1.0640	0.0241	5.92	1.30	1.28	16.5
P1	1.27	0.07	0.8249	0.0424	-14.29	2.94	0.35	-63.9
K1	3.92	0.07	0.8417	0.0158	-19.30	1.07	1.33	-77.5
N2	4.23	0.05	2.0315	0.0227	74.09	0.64	4.08	93.8
NU2	0.74	0.05	1.8646	0.1213	73.71	3.73	0.71	95.2
M2	18.59	0.05	1.7086	0.0043	58.57	0.14	16.02	82.0
S2	4.97	0.05	0.9824	0.0094	43.52	0.54	3.43	87.8
K2	1.54	0.06	1.1199	0.0443	36.61	2.27	0.96	72.3

Furthermore, data from these water tubes are also used to study ground deformations. As we stated above, meteorological perturbations are clearly present on the observed data (see Figure 1). Thus, air temperature induced tilt and ground deformation produced by variations of local atmospheric pressure are the main perturbations. By using the DAD program (Arnoso, et al., 1997) we have computed a single linear regression coefficient for long term and diurnal tidal bands (see Table 2) to quantify these effects. The program divides the data into intervals without overlapping, where the drift is represented by a polynomial of power k. At the first stage, k is one and the same for all intervals (k=0 or k=1). Thus, the method of least squares is applied directly on the hourly data (without any pre-filtration) and a zero iteration result is obtained. Next, k is varied individually for every interval until we get a value of k with lowest mean square deviation of the tidal parameters. In the final approach, the drift is represented by polynomials of different power k in every interval. If we deal with more than one non-tidal channel (air-pressure and temperature), our model is namely a multi-variate approach, i.e. the regression coefficients are estimated all together.

Concerning the LP (periods larger or equal than 15 days) tidal band, as we can see from Table 2, the temperature effect in WTCE94 is 8 times larger than that on WTCE92. The air pressure effect is almost 2 times larger for the same water tube. With respect to D tidal band (periods less or equal than 1 day), the air pressure effect for WTCE92 is negligible whereas for WTCE94 is obviously significant. On the other side, the air temperature effect is rather similar for both water tubes.

Due to the closeness to the sea from the station (about 1.3 km) we have an air pressure effect on the tilt through the ocean loading, which is affected by air pressure variations. The pressure

Table 2. Regression coefficients computed for both diurnal (D) and long period (LP) tidal bands at station CV. Numerical values are given in mas/0.1 degree Celsius and mas/mbar for air temperature and air pressure, respectively.

	air temperature		air pressure	
	D	LP	D	LP
WTCE92	1.72 ±0. 19	0.36 ±0. 03	----	0.63 ±0. 01
WTCE94	1.42 ±0. 47	2.99 ±0. 08	1.13 ±0. 11	1.24 ±0. 02

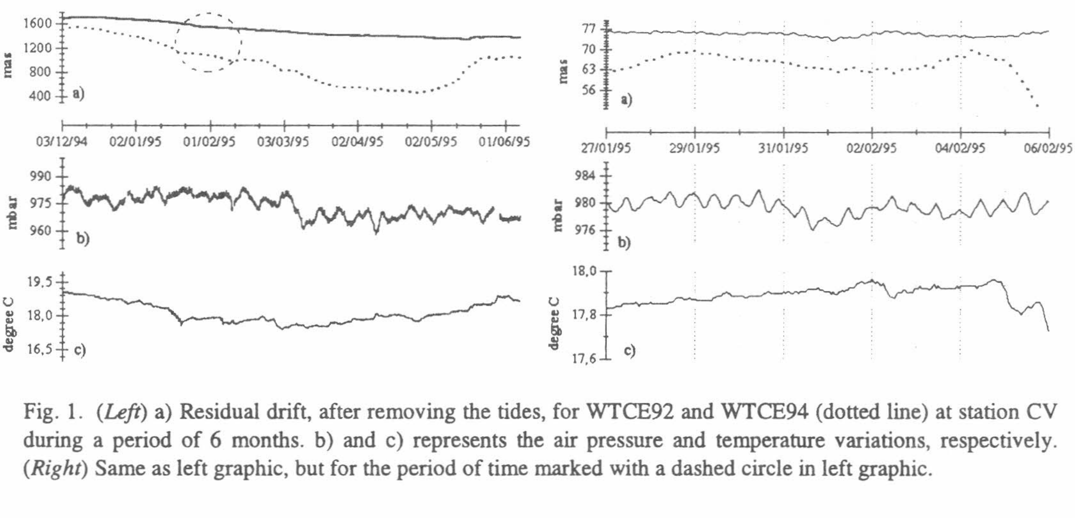

Fig. 1. (*Left*) a) Residual drift, after removing the tides, for WTCE92 and WTCE94 (dotted line) at station CV during a period of 6 months. b) and c) represents the air pressure and temperature variations, respectively. (*Right*) Same as left graphic, but for the period of time marked with a dashed circle in left graphic.

effect is related with the inverse barometric effect. It causes an elastic deformation of the Earth's surface, which in case of tilt is larger than the attraction effect. For WTCE94 this effect is clearly larger than for WTCE92, for D and LP tidal bands.

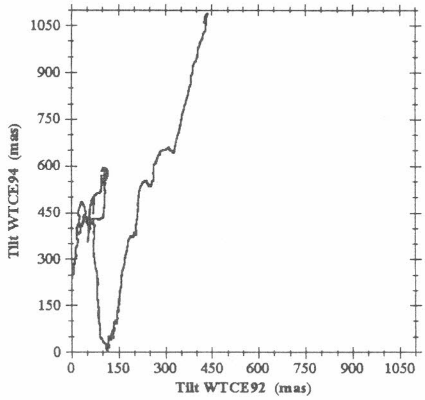

Fig. 2. Tracer plot showing the predominant direction of two water tube tiltmeters installed at station CV (Tidal signal was removed).

If we compute the tilt trace (Figure 2), we observe that the main direction is closest to WTCE94 (azimuth: 45°.2 N). This direction is also very close to the coast-line in this area. However, the effect should be larger in the direction perpendicular to the coast-line (Rabbel and Zschau, 1985). The reason could be related with the base-line direction of WTCE94, perpendicular to the tunnel axis. Thus, other effects could affect tilt measurements from WTCE94 as cavity, which are expected to be larger in the direction perpendicular to the tunnel axis (Harrison, 1976). Although cavity effect is not yet evaluated, further studies are necessary to answer this question.

3. Tiltmeters Installed in Timanfaya National Park

Timanfaya National Park is the area of Lanzarote where the last eruptions took place. The station is located near the geothermal anomalies field, inside a special cave named Casa de los Camelleros, about 3 meters below the surface. In this station we have installed a set of water tube tiltmeters (in two orthogonal directions of the cave) and two vertical pendulums. Site conditions at this station are different from Station CV. Thus, the initial sensitivity of the instruments installed has been diminished by a factor of 10 due to out of scale problems.

The water tubes are of the same kind as installed at the station CV. The tiltmeter installed in 1996 (WTCE96) has 4.6m length and has an azimuth of 42°.8 N. At the end of 1999 was installed a new tiltmeter (WTCE99) with a base line of 11.6m and an azimuth of 132°.8 N. In both cases the resolution is of 4.5 mas and the range is of ±100 as. The instruments are placed inside a special gallery, 60 cm below the surface, where several pillars are fixed in order to support the tubes.

Two vertical pendulums GK-10 were installed in 1996 (Cai Weixin et al., 1997). Both instruments are placed in two respective pillars at some 60 cm depth and with the same orientations as the two water tubes. The dimensions of the pendulums are 170×110×220 mm. The pendulums have a resolution of 57 mas, a period of 0.665 seconds and the range is of ±5 degrees.

All the instruments are connected to a Meteodata-1256 data logger, with a sample period of 2 seconds and acquisition period of 10 minutes (or 1 minute eventually).

3.1. Temperature Induced Tilt

Near the station (about 100 m) are installed several thermometers for high temperature measurements, placed inside a borehole at different depths (Vélez et al., 2001). Figure 3 is an example of tilt records with WTCE96 and the vertical pendulum GK-10 set in the azimuth 132°.2 from North (hereafter denoted as VPGK-10) at station T, together with the air temperature variation inside the station (external temperature and gallery temperature) and the temperature variations recorded inside the borehole at 10m (denoted as HTT3) and 20m (denoted as HTT2) depth.

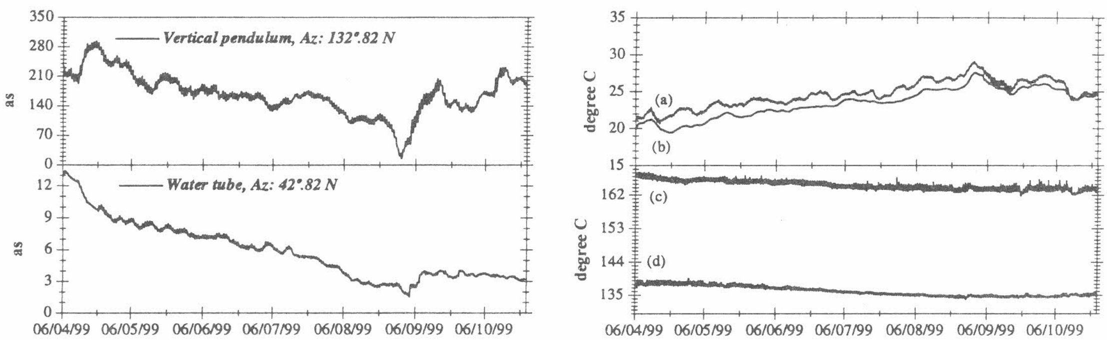

Fig. 3. (*Left*) Raw data observed at station T with WTCE96 and VPGK-10 tiltmeters. (*Right*) (a) Air temperature variation inside station T; (b) air temperature variation inside the gallery; (c) temperature recorded inside the borehole, at 20 m depth; (d) temperature recorded inside the borehole, at 10 m depth.

Figure 4 shows the spectral amplitude of the tiltmeters data as well as the spectral amplitude of the high temperature observations, for diurnal frequencies. From this figure, the solar components are clearly present for both tiltmeters, which coincide with the peaks found in the spectral amplitude of the thermometers. Note that amplitudes of the deepest thermometer HTT2 are twice as high as for the shallowest HTT3. At present, we cannot conclude any explanation but investigations related with the response of the upper crust due to tidal strain as well as instrumental effects on the electronics (not yet evaluated) will be considered for further studies.

During this period, no noticeable changes in the drift have been found for these tiltmeters. The small changes are mostly related with temperature variations. To quantify the temperature effect on tilt observations, we have computed a single linear regression coefficient (see Table 3) by using the DAD program (Arnoso et al., 1997). The results show, for diurnal frequencies, a large influence of temperature in the data from vertical pendulum, whereas for water tube only a slight significant coefficient has been found with external temperature variation. It is important

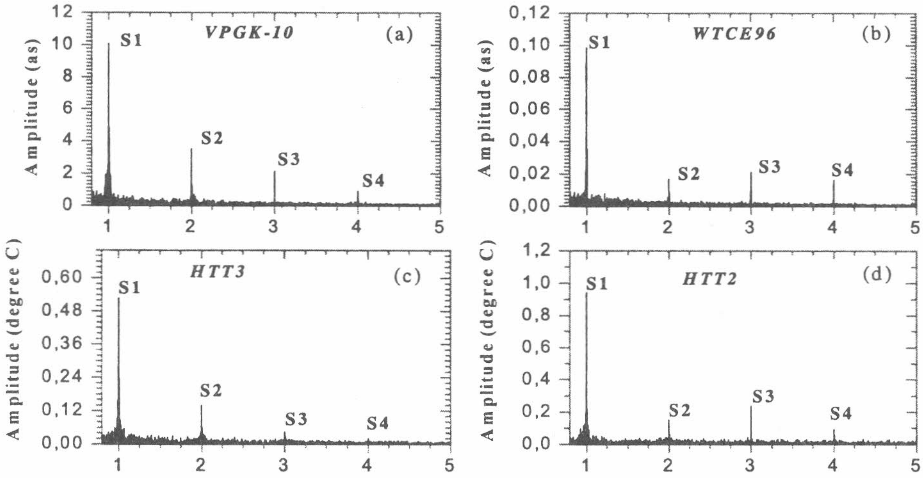

Fig. 4. Spectral amplitude of (a) vertical pendulum, (b) water tube, (c) thermometer HTT3 (10 m depth) and (d) thermometer HTT2 (20 m depth) at station T. The abscissa axis shows the frequency in cycles per day.

to note that VPGK-10 exhibits an important direct correlation with HTT3 thermometer, which is inversely correlated with air temperature variations (the regression coefficient obtained is –0.2 ±0.07 degree Celsius/degree Celsius) for diurnal frequencies. This is not the case with HTT2, installed 10 m deeper than HTT3, which is less influenced by external temperature variations.

Table 3. Regression coefficients computed for diurnal and long period frequencies for tiltmeters WTCE96 and VPGK-10 at station T. Numerical values are given in as/degree Celsius.

	Station Temperature	Gallery Temperature	HTT3	HTT2
diurnal				
VPGK-10	-16.86 ±0.421	-34.25 ±0.903	1.66 ±0.248	---
WTCE96	-0.05 ±0.012	---	---	---
long period				
VPGK-10	-27.40 ±0.849	-50.05 ±1.984	8.61 ±0.306	-1.06 ±0.146
WTCE96	0.23 ±0.016	0.36 ±0.042	-0.09 ±0.007	---

In case of long period frequencies, the values found for the linear regression coefficients are much higher than for diurnal frequencies. Even, for VPGK-10 a significant coefficient is found with the borehole thermometer HTT2, but opposite in sign that for HTT3. For WTCE96 the coefficients are clearer defined for long period frequencies than for diurnal frequencies. Thus, long period tilt is clearly correlated with seasonal variations of temperature, which are less noticeable for deepest thermometer. Also, the vertical pendulum is more sensitive to such variations than the water tube tiltmeter.

4. Conclusions

We show in this paper results from tiltmeter observations at two different locations of the Geodynamics Laboratory of Lanzarote. Data from tiltmeters, installed with different sensitivity and ranges according to the local conditions of observations, are useful to study ocean and meteorological perturbations. The ground deformations are mainly related with temperature-induced tilt at both locations. In case of station CV, the tilt meters show an important tilt change related with the orientation of the lava tunnel. In case of station T, the largest perturbations correspond to the short baseline tiltmeter. A preliminary study of the correlation with high temperature measurements shows larger regression coefficients for long period than for diurnal frequencies. This correlation is lower for the deepest thermometer. Also, a temperature effect on the vertical profile of the borehole is reported and will be investigated in further studies.

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