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The Grotta Gigante horizontal pendulums - instrumentation and observations

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Abstract. The horizontal pendulums of the Grotta Gigante have a long history dating back to 1959. In the past the instruments have been revised several times. The main instrumental characteristics are exposed, including the noise spectrum calculated over about 30 years. A review on the main results obtained with the pendulums is made, results which cover the topics of Earth tides and loading effects, free oscillations of the earth, preseismic effects and regional deformations.

1. The instruments

The two horizontal pendulums installed in the Grotta Gigante near Trieste (Lat 45° 42' 30", Lon 13° 45' 48") are Zöllner type horizontal pendulums of extreme dimensions (Fig. 1). The Grotta Gigante cave (GG-cave) is a natural ellipsoidal shaped cave, formed in compact upper cretaceous limestones. It is approximately 140 m long, 80 m wide and 100 m high. The temperature of the cave at the bottom is about 11°C, with an annual temperature variation of 1°C. The instruments were designed and first installed by Prof. A. Marussi in 1959, on the occasion of the third International Earth Tides Symposium held in Trieste (Marussi, 1959). Subsequently, completely revised instruments were reinstalled in 1967 and 1997. Due to the enormous dimension of the natural cave they are housed in, the distance between the upper and lower attachment of the pendulums could be chosen to be in the order of 95 m. Both upper and lower attachments are fixed to the solid rock of the cave, thus ensuring great instrumental stability. The wires suspending the pendulums are made of steel, the upper wire meaning 0.8 mm, and the lower 0.6 mm in diameter. The pendulum mass (m), the total moment of inertia with respect to the axis of rotation (J_0), and the distance of the center of gravity from the axis of rotation (R), are given in Table 1. The axis of rotation lies on the line connecting the lower and upper attachment. The above quantities, together with the angle of inclination (i) of the axis of rotation with the

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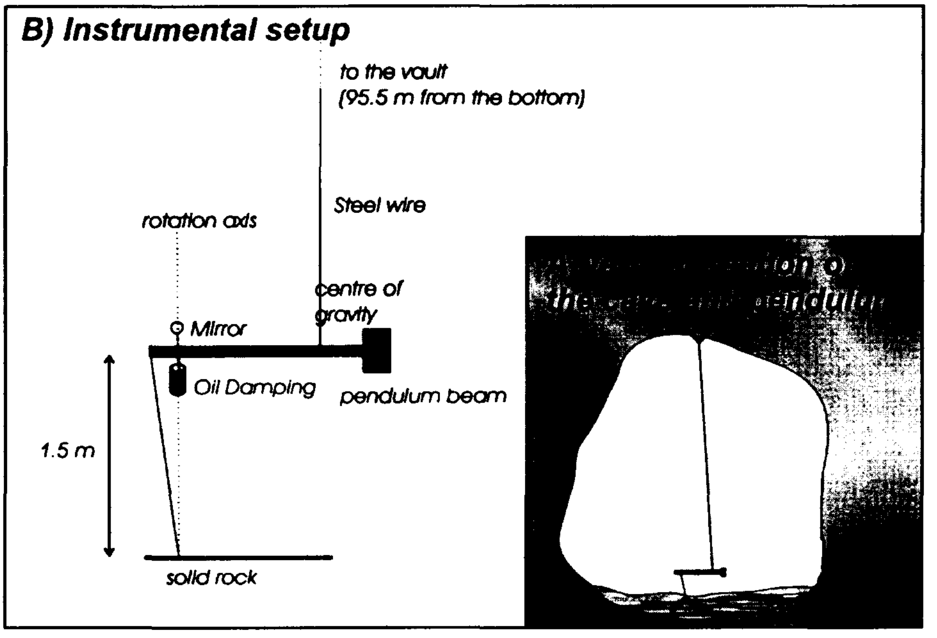

Fig. 1 – Scheme of the GG-pendulums: a) Schematic view of the pendulums in the cave b) Enlarged portion of the instrumental setup of the pendulums.

vertical, define the period of oscillation of the pendulums: $T_o = 2\pi\sqrt{\frac{J_o}{mgR\sin(i)}}$. The oscillation period of the pendulums is fixed to the value of 360 sec. The damping system is made of a metal frame equipped with adjustable narrow plates arranged like a venetian blind immersed into an oil-filled vessel. The system is adjusted so as to keep the instruments at critical damping.

The data recording is presently optical, with a light beam reflecting on a mirror mounted on the pendulum beam along the rotation axis, and recorded on photographic paper. The static amplification factor (A) is related to the inclination (i) of the rotation axis by the relation: A=1/sin(i), which in the present case amounts to a value of A=24 000. At present, the magnification on the photographic recording is of 0.9 msec/mm (4.4 nrad/mm), which leads to a

Table 1 – Technical description of Marussi horizontal pendulums.

Quantify described	symbol	Pendulum A (EW)	Pendulum B (NS)
Distance between upper and lower mountings		94.9 m	95.5 m
Total weight of the pendulum, including the wires	m	18.374 kg	18.340 kg
Distance of the center of gravity from the actual axis of rotation	R	124.5 cm	124.2 cm
Moment of inertia with respect to the actual axis of rotation (gr cm^2)	J_o	307.2 10^6	305.5 10^6
Period of oscillation in the horizontal plane	T_o	360 sec	360 sec

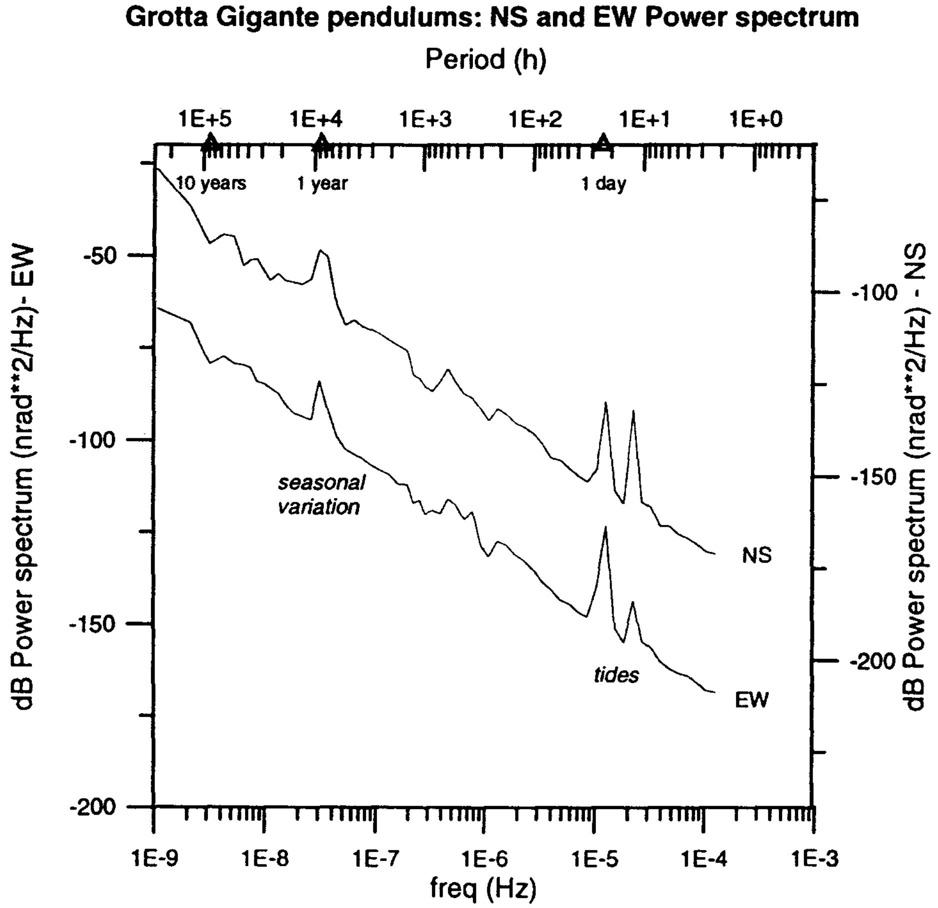

Fig. 2 – Mean spectra for the NS and EW components of the GG-pendulums.

digital readout resolution of about 0.5 msec (2 nrad). The data are digitized manually at a sampling rate of 1 sample/hour. Presently, a new data acquisition system is being developed in collaboration with the Istituto Nazionale di Geofisica (ING; Dr. G. Romeo, Dr. Q. Taccetti), with the aim of replacing the photographic paper with a CCD-recording. The digital recording system has the advantage of an increase in tilt-resolution and in a greatly enhanced temporal resolution, allowing the instruments to be used in the study of free oscillations and long period seismic waves.

The analysis of the noise spectrum reveals the low noise level of the instruments compared to conventional short-base tilt stations. For this purpose the Fourier spectrum was calculated on 5 decades in frequency. Two different data sets with daily, and respectively, hourly sampling were used for the low and high frequency band. The spectrum of the high frequency band ($2.\ 10^{-7}$ – 10^{-4}) Hz was calculated on hourly data for the period 1991-1996, whereas the low frequency spectrum is calculated as mean spectrum over the period (1967-1996). The complete spectra are shown in Fig. 2 for both the EW and NS components. The linear approximation of the spectrum for the GG-pendulums is (-8.5±0.4 dB/log (frequency)) and is equivalent to a decay

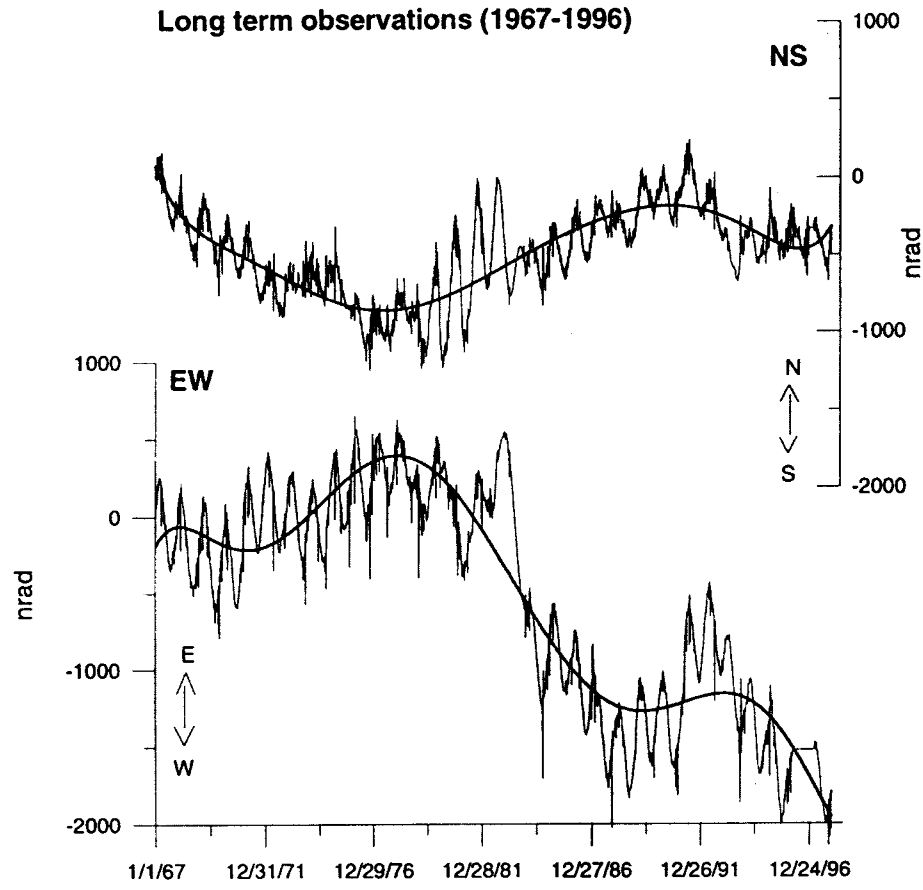

Fig. 3 – Long term records of the GG-pendulums for the period 1967-1996. The data have been reduced from hourly to daily sampling. The long term trend has been interpolated by a polynomial of order 6.

of $1/f^{0.8}$. The most evident features in the spectral curves are the tidal signals (diurnal and semidiurnal band), and the yearly cycle. A comparison of the spectra of the GG-pendulums to those of a couple of conventional tiltmeters installed in a station about 80 km N of Trieste at 60 m below the surface shows that the noise level of the GG-pendulums is much lower than the latter (Braitenberg, 1999; Zadro and Braitenberg, 1999).

2. The observations

The GG-station was originally built as an Earth tides observatory. A series of studies were carried out concerned with the earth tides and the loading effects of the Adriatic Sea (Bozzi Zadro (1972) and references therein). The instruments though, proved useful in subsequent years for the detection of Earth signals at increasingly shorter periods, down to those typical of surface waves. The Chilean earthquake of May 22, 1960 activated free oscillations which were recorded by the pendulums on both components for 82 hours. In the frequency range between 0.02 cycle/min and 0.2 cycle/min a complete sequence of torsional eigenfrequencies ($2 \le l \le 22$) could be identified for the first time and also the lowest fundamental spheroidal modes were recorded (Bolt and Marussi, 1962; Bozzi Zadro and Caputo, 1968). A subsequent spectral analysis of the same data showed the presence of some low frequency components, not belonging to the set of free oscillations, but equal to the sums, or differences of frequencies of the normal modes. These could be explained with departures from linearity of the elasticity of the Earth's body (Bozzi Zadro, 1971).

Starting from 1973 a new kind of observation was made, which initiated with a sudden permanent deflection of some msec in both components. After this deflection the pendulums started to record perturbations which lasted for several hours. The number and duration of the perturbations increased between 1973 and 1976, when they suddenly disappeared with the M=6.4 May 6, 1976 Friuli earthquake (Zadro, 1978). The observations were interpreted as very long period elastic preseismic waves generated by aseismic slip on a fault neighbouring the main fault of the 1976 event (Bonafede et al., 1983).

In subsequent years and up to the present the GG-station was kept as a reference station to the tilt-strainmeter network installed in Friuli in 1977. The instruments have shown long term stability over the several decades of their functioning. Fig. 3 shows the tilt records for the time span from 1967- 1996. In order to better evidence the long term behaviour of the records, the data have been interpolated with a polynomial of order 6. The long period continuous tilt records of two Friuli stations and the GG-station were jointly studied, revealing that the tilt signals are correlated at pluriannual periods (Rossi and Zadro, 1996). The correlation has been interpreted in terms of a deformation of the Northern Adriatic plate with principal directionalities aligned with the alpine (EW) and dinaric (NW-SE) orientations.

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