Three years of high precision gravity measurements at the gravimetric station of Brasimone - Italy

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Abstract
From August 1995 up to now, at the Enea Research Center of Brasimone, in the Italian Apennines between Bologna and Florence (Italy: 44°07′N, 11°07′E, 890 m height), the superconducting gravimeter GWR model TT70 number T015 has been continuously recording the variation of the local gravity field, in the frame of the Global Geodynamics Project. The gravimetric laboratory, being a room of the disused nuclear power plant of Brasimone, is a very stable site, free from noise due to human activities. Data blocks of several months of continuous gravity records have been collected over a time span of three years, together with the meteorological data. The gravimeter has been calibrated at relative accuracy better than 0.3% with the aid of a mobile mass system, by imposed perturbations of the local gravity field and recording the gravimeter response. The results of this calibration technique were checked by two comparison experiments with absolute gravimeters performed during this period: the first, in May 1994 with the aid of the *symmetrical rise and fall* gravimeter of the Institute of Metrology Colonnetti of Turin, and the second in October 1997 involving an FG5 absolute gravimeter of the Institute de Physique du Globe of Strasbourg. The gravimeter signal was analysed to compute a high precision tidal model for Brasimone site. Starting from a set of gravimetric and atmospheric pressure data of high quality, relative to 46 months of observation, we performed the tidal analysis using Eterna 3.2 software to compute amplitudes, gravimetric factors and phases of the main waves of the Tamura catalogue. Finally a comparison experiment between two of the STS-1/VBB broadband seismometers of the MEDNET project network and the gravity records relative to the Balleny Islands earthquake (March 25, 1998) were analysed to look for evidence of normal modes due to the free oscillations of the Earth.

Key words *Earth tides – tidal analysis – seismic – spectral analysis*

1. Introduction

In a cryogenic gravimeter a niobium hollow sphere of 2.5 cm diameter and about 2 g mass is suspended by the inherently stable magnetic field generated by two superconducting coils, operating in a liquid helium bath at a temperature of about 4.3 °K.

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The gravimeter signal corresponds to the voltage variations induced on the terminals of a feedback coil which represents an active feedback system, keeping the sphere centred inside the electrodes of a capacitance bridge, used to hold the levitating sphere in a fixed position when the gravity changes. The sensitivity is of the order of 0.1 nm/s^2, but geophysical and environmental noises reduce the effective accuracy to 1 nm/s^2 or better (Goodkind, 1991).

In order to estimate the calibration constant which converts the output voltage in gravity variation, we adopted a moving mass technique: an annular stainless-steel ring is moved with respect to the gravimeter vertical axis by an automatic servo-controlled system, to produce a known perturbation of the gravity field (Baldi *et al.*, 1995).

Owing to the simple geometry adopted for the mass and to the symmetrical shape of the gravimeter sensor, it was easy to perform a simple analytical computation of the perturbing acceleration of the mass and to adjust it, in the least squares sense, to the response of the gravimeter, in order to get the calibration constant.

2. The Brasimone calibration experiments

A mass of simple geometry, a circular ring of 80 and 91 cm of internal and external radii respectively, with a square cross section of 11×11 cm^2, was placed around the superconducting gravimeter; this mass can be easily moved up and down in order to produce a gravity signal which is adjusted in the least square sense to the corresponding modelled analytical signal.

A second mass is placed about ten meters away from the gravimeter connected by means of steel cables and pulleys and used to balance the weight of the annular mass (273.40 ± 0.01 kg); an engine controlled by a personal computer produces a small force that is applied to the cables in order to move the calibrating mass in the frame of a planned calibration cycle. A wireless digitiser measures the ring position with an accuracy of 0.1-0.2 mm.

Owing to the symmetrical distribution of masses around the gravimeter sphere, the effect of an erroneous determination of the position of the sensitive sphere mounted inside a cryostat is estimated to be well below the precision of the method which is about 0.3% (Achilli *et al.*, 1995).

As calibration procedure we adopted the so called *calibration signal scan* which consists in moving the calibration mass along the gravimeter vertical axis step by step in a period ranging from about 45 min to 2 or 3 h (fig. 1),

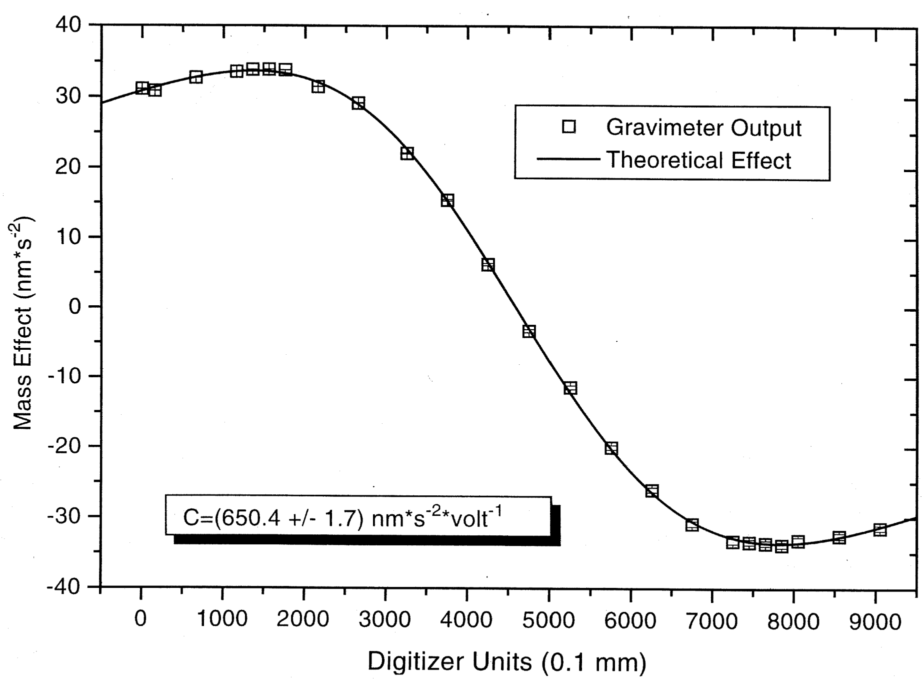

Fig. 1. Example of *calibration signal scan*: the response of the gravimeter to a step by step motion of the ring along its vertical axis is least-squares adjusted to the theoretical signal.

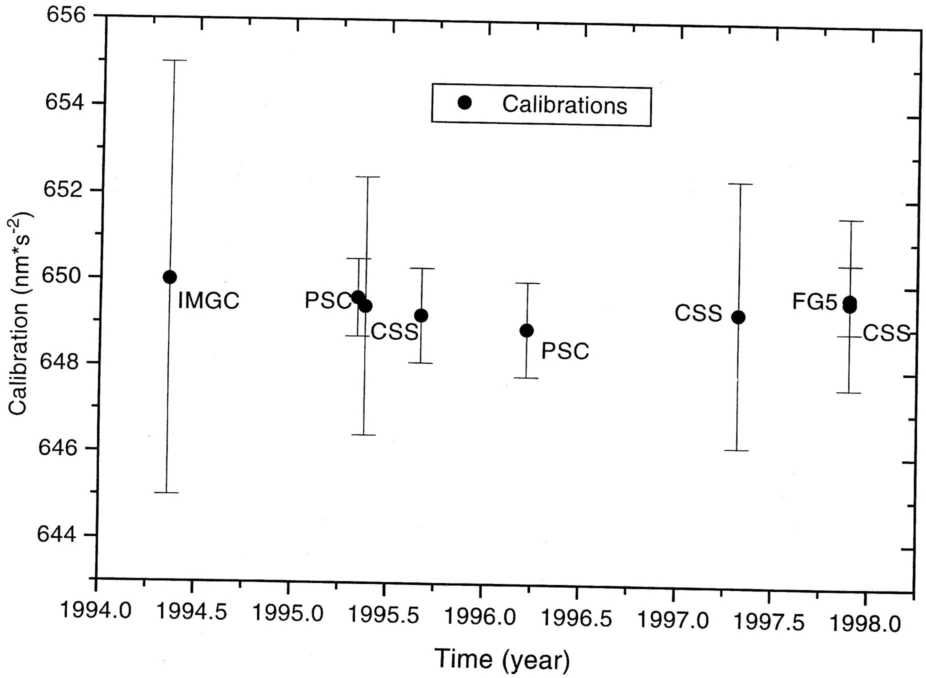

Fig. 2. Results of the calibration experiments performed at the Brasimone laboratory from 1995 up to now: the data labelled PSC and CSS represent mass system calibrations, the data with the IMGC label is a calibration factor obtained by the comparison experiment with the Colonnetti absolute gravimeter, the last calibration constant evidenced by the FG5 label, is relative to the comparison with the FG5 absolute gravimeter.

recording the time, the mass position and the response of the gravimeter.

Following the formula

$$| a(z) - C \cdot g(z) |^2 = \min \tag{2.1}$$

where $a(z)$ represents the theoretical perturbing mass acceleration, $g(z)$ the response of the gravimeter and C the calibration constant, we minimise in the least square sense the residuals between the theoretical model and the records of the gravimeter for each epoch, taking as unknown the calibration constant.

The results of the calibration experiments performed from 1995 up to now are represented in (fig. 2) and in (table I).

A different way to calibrate the superconducting gravimeter is given by a direct comparison of the gravity signals due to the Earth

Table I. Results of the ring calibration experiments, and of the comparison with the IMGC and FG5 absolute gravimeters.

Time (year)	Value (nm/s^2)	Method
1994.36	650.0 ± 5.0	IMC
1995.34	649.6 ± 0.9	PSC
1995.38	649.4 ± 3.0	CSS
1995.67	649.2 ± 1.1	PSC
1996.22	648.9 ± 0.8	PSC
1997.32	649.3 ± 3.1	CSS
1997.92	649.6 ± 2.0	CSS
1997.92	649.7 ± 0.8	FG5
1998.32	650.4 ± 1.7	CSS

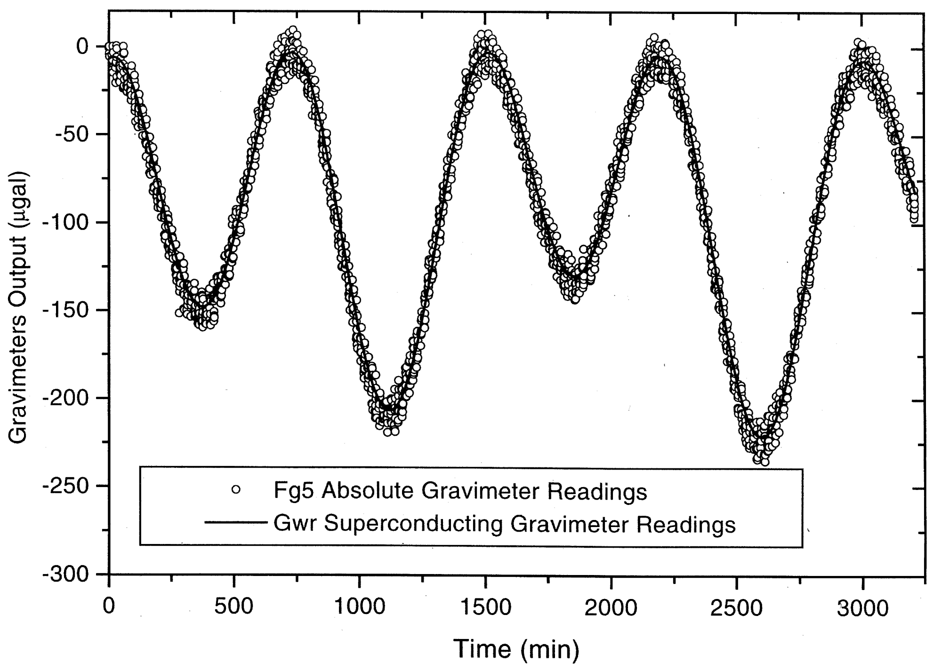

Fig. 3. Calibration for comparison with the FG5 absolute gravimeter, the readings of the superconducting GWR gravimeter (Volts, solid line in the figure) are adjusted in the least-squares sense to the corresponding ones of the absolute gravimeter (μgal, open circles).

tides measured simultaneously by an absolute and a superconducting gravimeter. The gravity change of about 250 μgal of the Earth tide signal can be recorded by the absolute gravity meter with an accuracy of about 1 μgal (Baldi *et al.*, 1995). The calibration is obtained by fitting the tidal curve observed by the superconducting gravimeter (in Volts) to the gravity curve measured by the absolute one (fig. 3). The accuracy of the final results depends on the length of the observation period.

In May 1994 we performed the first comparison between the superconducting gravimeter and the absolute *symmetrical rise and fall* IMGC gravimeter (Baldi *et al.*, 1995).

The result of this first experiment is in agreement with the mass calibration method at the level of 0.8% (see table I and fig. 2).

In October 1997 a second experiment involving the absolute FG5 gravimeter of the Institute de Physique du Globe of Strasbourg was performed in Brasimone and the preliminary results are in agreement with the Colonnetti experiment and with the mass calibration experiments at the level of 0.1% (see fig. 2).

3. Tidal analysis

The tidal signal recorded by the superconducting gravimeter at a rate of 10 s is interpolated, numerically decimated and converted into an international format by means of FORTRAN 77 programs suitably implemented.

The data pre-processing is carried out by means of the Preterna 3.2 program (Wenzel, 1994), using a remove-restore technique.

The procedure consists of removing all the known waves: approximated model tides and influences of barometric pressure and optionally other meteorological parameters. The remaining residual signal including the superconducting gravimeter drift is then cleaned, spikes, step and gaps are eliminated, and the known signals are subsequently added back to the cleaned residual (Wenzel, 1994).

By this procedure the errors in the model tide signal and meteorological parameters are corrected to a large extent. The corrected samples at the original sampling interval may finally be numerically filtered and decimated to 5 min and 1 h rates, respectively.

Thus an elaboration procedure carried out by means of the Eterna 3.2 program allows us to compute amplitudes, amplitude factors and phases of the main tidal waves of the selected catalogue (*i.e.* Tamura, 1987), together with a real barometric pressure admittance.

In particular, a least-squares adjustment procedure is applied, based on the following equation:

$$l(t) + v(t) = \sum_{i=1}^{n} \delta_i A_i (theor) \cdot \cos(\omega_i t + \Phi_i (theor) + \Delta\Phi_i) + \sum_{j=1}^{m} b_j F_j (t) + D(t), \quad (3.1)$$

where, $l(t)$ are the recorded values, $v(t)$ the residuals, $A_i(theor)$ are the theoretical amplitudes, and δ_i and $\Delta\Phi_i$ are the gravimetric factors and phase delays of the main tidal species of the Tamura 1987 tidal catalogue (Tamura, 1987).

The regression coefficients b_j describe the dependency between the state parameters F_j and the instrument readings and $D(t)$ represents the drift term (Torge, 1989). The final result of this elaboration step is shown in table II;

Table II. Improved tidal parameters computed using data recorded for several months at the Brasimone station.

Tidal model computed for the gravimetric station of Brasimone
Tamura 1987 Catalogue – 1214 waves

Wave	Amplitude (nm/s^2)	Amplitude factor δ	RMS	Phase $\Delta\phi$(°)	RMS
MF	33.45	1.1557	0.0118	– 0.61	0.38
Q1	68.11	1.1457	0.0013	– 0.33	0.07
O1	356.17	1.1471	0.0003	0.08	0.01
M1	28.04	1.1484	0.0025	0.16	0.14
P1	165.88	1.1482	0.0005	0.17	0.03
S1	4.89	1.4300	0.0276	10.59	1.59
K1	495.19	1.1340	0.0002	0.26	0.01
PSI1	4.22	1.2356	0.0196	3.21	1.12
PHI1	7.37	1.1855	0.0107	– 0.87	0.61
J1	28.23	1.1560	0.0032	0.04	0.18
OO	115.39	1.1521	0.0067	0.78	0.39
2N2	13.69	1.1567	0.0024	1.77	0.14
N2	87.02	1.1740	0.0005	1.76	0.03
M2	456.71	1.1797	0.0001	1.20	0.01
L2	12.84	1.1733	0.0023	0.47	0.13
S2	212.42	1.1793	0.0002	0.07	0.01
K2	57.79	1.1802	0.0009	0.33	0.05
M3	5.83	1.0660	0.0018	– 0.06	0.11

which represents the estimated amplitudes, gravimetric factors and phases of the main *diurnal*, *semi-diurnal* and *ter-diurnal* bands of Tamura catalogue. A mean real barometric pressure admittance of (-3.2 ± 0.1) nm/s$^2 \cdot$ Hpa is estimated and used to eliminate the larger amount of barometric noise from the data.

To verify the repeatability of the barometric admittance we performed on a monthly database blocks, covering the total observation period, the computation of the mean real barometric pressure admittance parameters (fig. 4). The computed monthly admittances for Brasimone range from -2.5 to -3.5 nm/s$^2 \cdot$ Hpa and the average is close to -3 nm/s$^2 \cdot$ Hpa, in good agreement with the theoretical models.

In a second step, a cross spectral analysis of the detided residuals and of the barometric pressure is carried out on the superconducting gravimeter pre-elaborated data and a complex frequency dependent barometric admittance may be computed (fig. 5); the function varies from -1.5 at the lower frequencies slowly approaching the value of -4 nm/s$^2 \cdot$ Hpa for higher frequencies.

In the final analysis step a high-pass filter, called *Pertsev number II*, is applied to the residuals to reduce the meteorological channel noise. An example of the result of this computation is shown in fig. 6; the final high-pass filtered residuals ranges within ± 2.5 nm/s^2.

The characteristic of our gravimeter has always been its large drift; a computation of a mean daily value of this drift can easily be performed by fitting a linear model to the low-pass filtered residuals of the Eterna program. This computation performed for the larger data block of continuous readings, 272 days long, gave the result $D(t) = -(18.8 \pm 0.1)$ nm/s$^2 \cdot$ day, the corresponding correlation coefficient of the fit: $R = 0.99942$, shows that the trend of the drift is linear in time (see fig. 7).

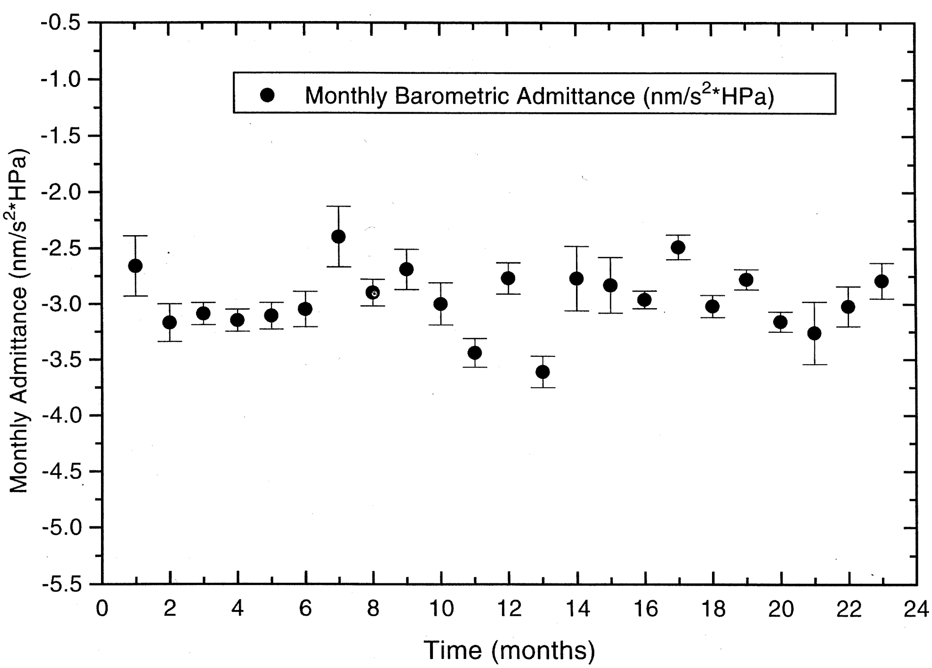

Fig. 4. Single real barometric pressure admittances computed for monthly data blocks from data of the gravimetric station of Brasimone.

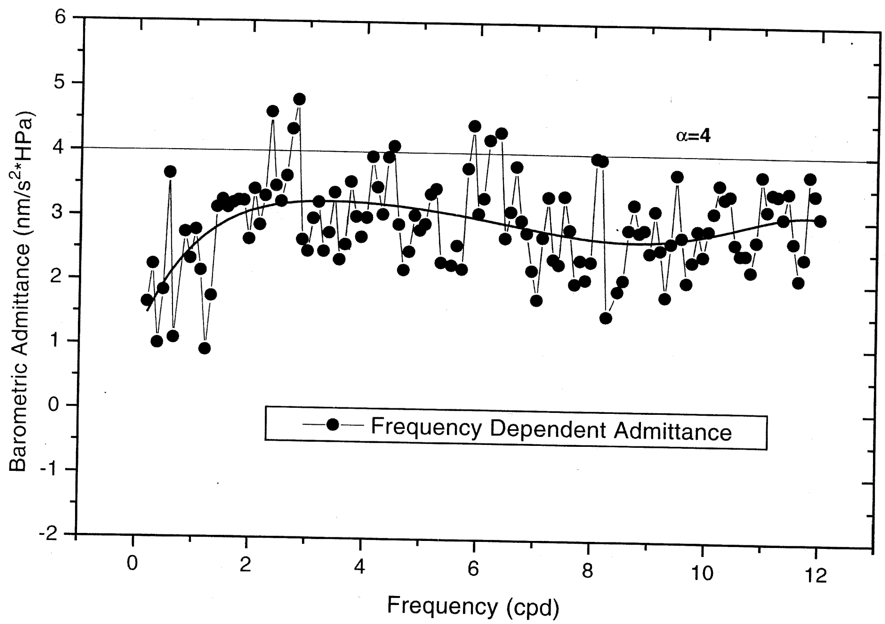

Fig. 5. Real part of the complex barometric pressure admittance of Brasimone site as a function of the frequency.

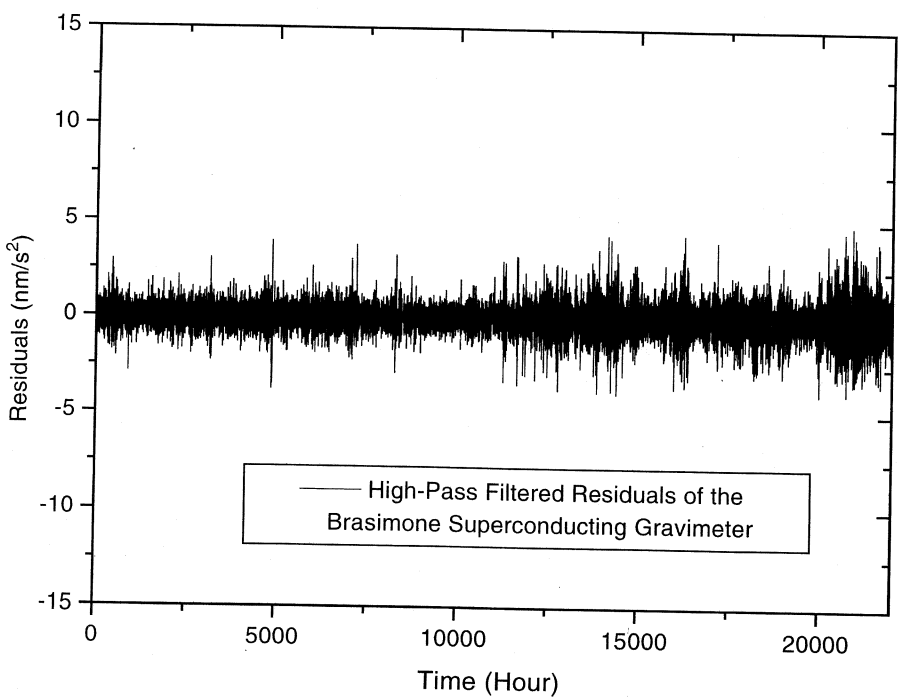

Fig. 6. *Pertsev number II* high-pass filtered residuals of data analysed with the Eterna program.

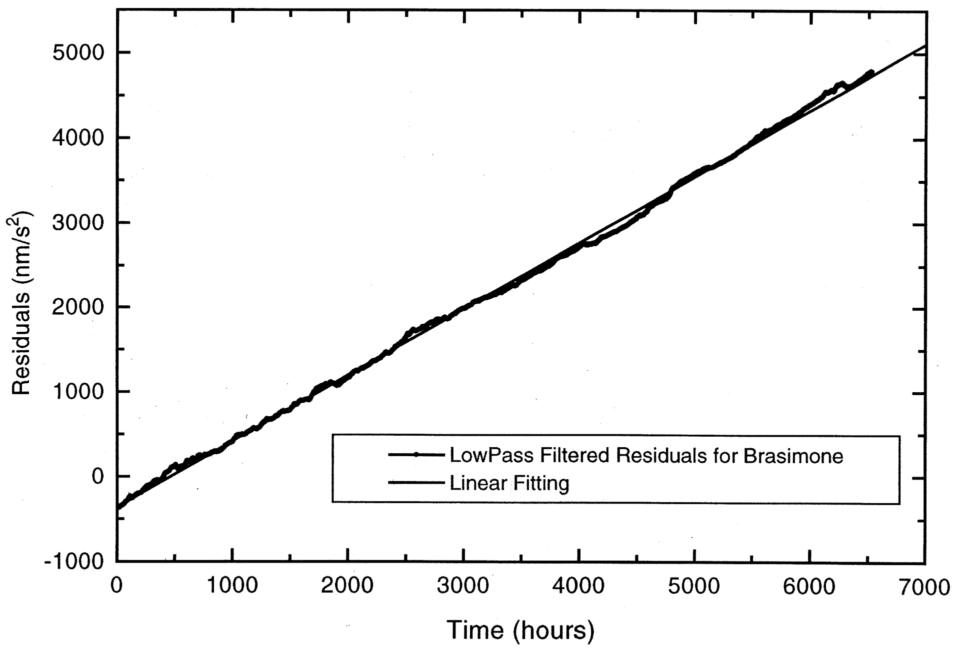

Fig. 7. Low-pass filtered final analysis residuals the longest period, term is the linear drift of the gravimeter and is fitted with a linear model.

This high drift level, in general anomalous for the more recent models of superconducting gravimeters, is a common characteristic of all the sensors built by GWR before the year 1992.

Unfortunately the large amount of drift prevented us estimating precisely the long period tidal species like the *monthly lunar* and the *solar annual* and *semi-annual* and also the gravimetric effect of the *polar motion*, these environmental effects being largely hidden by the drift trend.

4. Analysis in the seismic frequency band

We compared three instruments in the frequency band ranging from 0.2 to 1.7 mHz (*i.e.* 1/10-1/83 min), to look for evidence of the eigenfrequencies due to the free oscillation of the Earth generated by the big earthquake of the Balleny Islands region (Antarctica, 25th March 1998, $M_s = 7.9$).

We used 3 data sets, 24 h long, at 10 s sampling rate starting at the time of the seismic event and recorded by 3 different sensors: the *vhz* (vertical component) channel of the STS-1/VBB broadband seismometers of the MEDNET network (Boschi *et al.*, 1991) sited in Trieste Italy (45.709 N, 13.764 E, 161 m height), and Vitosha Bulgaria (42.618 N, 23.235 E, 1490 m height), respectively, and the *tide* channel of the superconducting gravimeter GWR T015 of Brasimone.

A precise tidal model was computed for the three sites and was subtracted from the original data; the resulting residual signals were analysed performing a Discrete Fourier Transform after multiplication by a Hanning Window. In fig. 8 we show the resulting amplitude spectra together with the theoretical eigenfrequencies of the observed modes calcu-

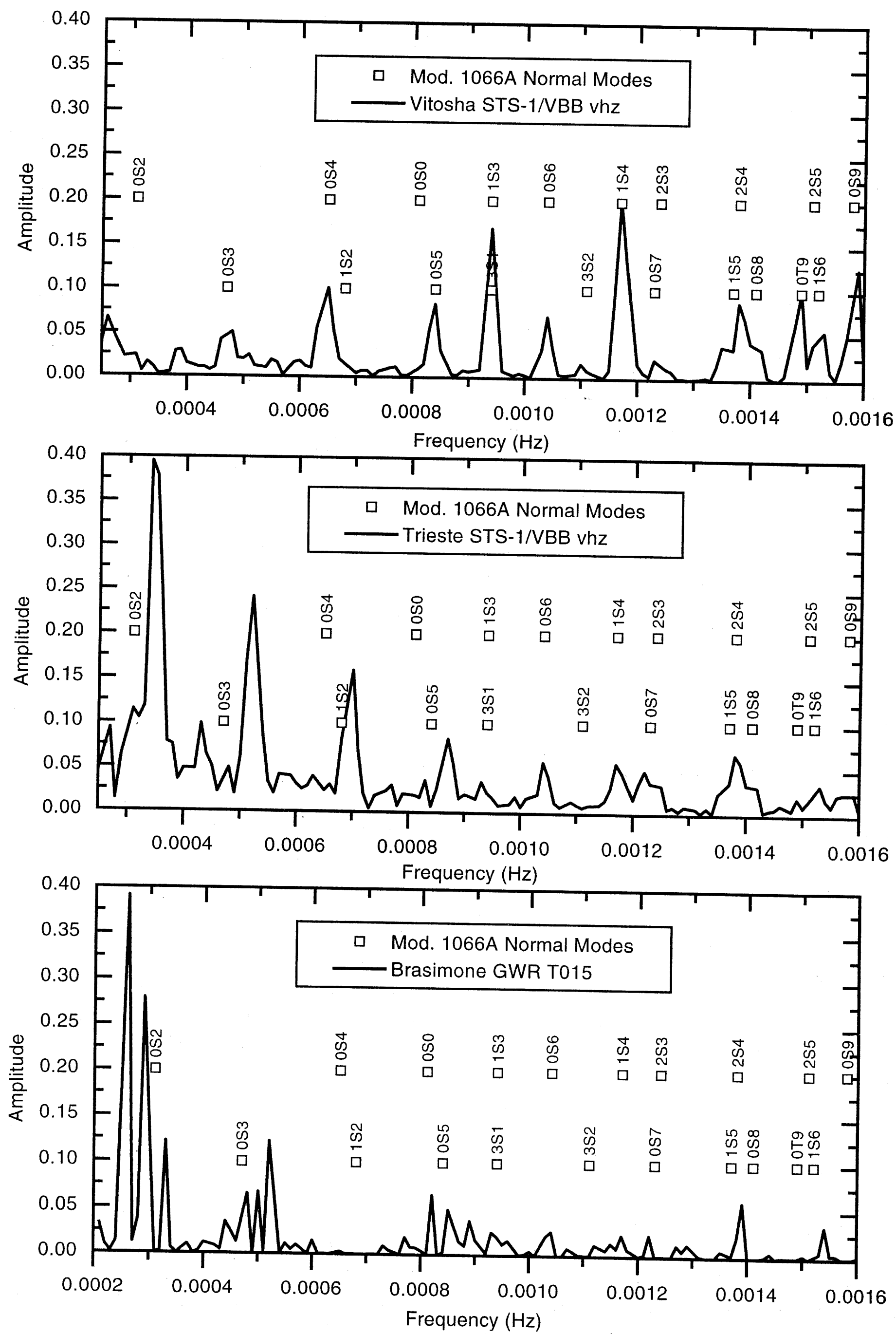

Fig. 8. Comparison between spectra of the vertical components of Trieste and Vitosha broadband seismometric stations and of the gravimetric station of Brasimone in the period of the Balleny Islands earthquake.

lated for Earth Model 1066A (Gilbert and Dziewonski, 1975). The amplitudes cannot be directly compared because the effects of the different anti-aliasing filters applied to the various records have not been removed (Freybourger *et al.*, 1997).

As expected there are similarities in the three spectra; the Vitosha station spectrum has the greatest Signal to Noise Ratio (SNR) and the peaks 1S3 and 1S4 have the largest amplitudes. The Trieste spectrum shows a smaller SNR than Vitosha and the largest peaks are in the frequency band 0.2-0.6 mHz as in the Brasimone one, and are probably due to thermal effects related to the sites.

The amplitude spectrum of the superconducting gravimeter of Brasimone shows a lower SNR than the two spectra of the STS-1/VBB broadband seismometers; for short period acceleration, (*i.e.* free oscillation of the Earth), this undesirable effect is also observed by other authors (Freybourger *et al.*, 1997; Richter *et al.*, 1995) and is probably due to site effects rather than to the instrument itselfs. Similar noise levels are present in other broadband seismometers of the MEDNET network whose spectra are not shown in the comparative fig. 8. A possible explanation can be found in the fact that in this frequency band a bedrock installation is needed to shelter from meteorological effects that can produce high level noise.

5. Conclusions

A GWR superconducting gravimeter was installed in a laboratory inside a disused nuclear power plant in the Research Centre of ENEA of Brasimone in 1991; starting from August 1995 it was involved in the final part of the Global Geodynamics Project and it is recording as one of the tidal stations of the global network.

The gravimeter is periodically calibrated at an accuracy level of 0.3% using a moving mass calibration system; furthermore it has also been calibrate by a comparison with non automatic *symmetrical rise and fall* and automatic *free-fall* absolute gravimeters. The results of all the calibration experiments performed are in agreement.

Tidal analysis was performed using Wenzel Eterna-Preterna software on different data blocks covering a time span of about three years of observations, obtaining an improved solution for the amplitudes, gravimetric factors and phases of several *diurnal*, *semi-diurnal* and *ter-diurnal* tidal species of the Tamura 1987 development and a precise estimation of the mean real air pressure admittance. A preliminary computation for the complex admittance as a function of frequency was also performed.

The comparison on the seismic band of the free oscillations of the Earth of two of the broadband seismometers of the MEDNET network and the superconducting gravimeter was performed on data of the recent Balleny Islands earthquake. In this frequency band the gravimeter data shows a lower SNR level than the seismometers. As pointed out by other authors, this effect is caused probably by site effects rather than the gravimeter itself.

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