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Tidal tilts observations in the Gran Sasso underground laboratory(*)

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Summary. — A new tiltmeter, based on the technology for building a space-borne high-sensitivity accelerometer and manufactured at IFSI/CNR, has been operating during several years in the INFN Gran Sasso underground laboratory. The results of the analysis of a three-year data set, processed with the program package ETERNA, to estimate earthtidal parameters are reported. For the best series of data (1998) tide measurement accuracies are: 0.5–1% for the M_2 (lunar principal) amplitude and 3–4% for the O_1 (lunar declination) amplitude. The tiltmeter installed at a depth of 1400 m shows no clear evidence of meteorological effects. Observed tidal parameters are compared with theoretical tidal parameters predicted for a non-hydrostatic inelastic Earth model and demonstrate good agreement for the M_2 component. Due to the high accuracy of the tidal components prediction (better than 1%) tidal measurements were used to estimate the long-term stability of the instrument response.

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PACS 93.85 – Instrumentation and techniques for geophysical research.

1. – Introduction

The spatially and time-varying Luni-Solar gravitational forces acting over the Earth produce ocean and solid Earth tides, manifested in deformations of the Earth surface (strains and tilts) and in variations of the gravitational field. Tide expansion models contain more than one thousand harmonic components with periods spanning from 6 hours to 18.6 years (the main waves are diurnal and semidiurnal) [1], whose amplitudes and phases are modified at the point of observation due to the elasticity and viscosity of

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the Earth. Amplification coefficients and phase shifts are called earthtides parameters and are evaluated with analysis of long-term run data. The observation of earthtides provides information on the elastic constants of the Earth. Tidal measurements might conceivably be useful in the research about great natural disasters, such as earthquakes and volcanic eruptions.

Tidal tilts have been measured for over 100 years. The present accuracy for the determination of the principal tidal tilt components is a few percent [2-4]. The measured tilts of the Earth are a complex function of the direct response of the Earth to the deforming forces combined with the instrument response, surface loading, effects of local crustal structure, and environmental conditions. Since the global driving forces and frequencies of tides can be predicted with an accuracy better than 1%, solid Earth tidal measurements can be used to investigate the effects of instrument response. This is used by the authors to test an accelerometer originally designed for space missions [5,6]. Such an instrument has operated during several years as a horizontal tiltmeter with the aim to estimate its sensitivity and long-term stability.

2. – Instrument location site

The one-axis tiltmeter, built at Istituto di Fisica dello Spazio Interplanetario CNR and named GS1, was installed in the INFN (Istituto Nazionale di Fisica Nucleare) underground laboratory, in the basement of the geophysical laser interferometer [7] at a depth of 1400 m under the free surface and at 800 m above the sea level. The INFN laboratory is located in a seismically active region of the Apennines, in the Gran Sasso Mountains of Central Italy, approximately 90 km from the Adriatic sea and 180 km from the Tyrrhenian sea. The tiltmeter co-ordinates are: latitude, $42°28'$ N; longitude, $13°34'$ E; and azimuth, $33°00'$.

3. – Instrument

The GS1 implementation is based on a technology pioneered at IFSI CNR for building a space-borne high-sensitivity accelerometer. The tiltmeter GS1 has operated in the Gran Sasso laboratory from 1994 to 1998. A detailed description of the instrument is given in [8, 9]. The tiltmeter consists of a mechanical part (a sensitive proof mass connected to the external rigid frame by a crank-shaped suspension), the active capacitive transducer and the data acquisition system. The mechanical structure has been obtained by machining a single plate of aluminium Al 5060. The mechanical part, electronic equipment, computer, thermometer and atmospheric pressure gauge were assembled inside a box with dimensions of $40 \times 30 \times 30$ cm.

The GS1 output voltage signal is converted into a tilt signal by calibrating the instrument with known inclinations. The instrument was calibrated in 1995 and again in 1999, showing no significant change of the calibration factor. The value of the calibration factor is 4764 ± 42 mas/volt (1), estimated in the dynamic range of ± 60000 mas. The instrumental response is linear within 0.4%. The experimental tiltmeter sensitivity is $0.2\,\mathrm{mas/Hz}^{-1/2}$.

(1) The tilt unit is milliarcsecond (mas). $1\,\mathrm{mas} = 4.8481 \times 10^{-9}$ rad.

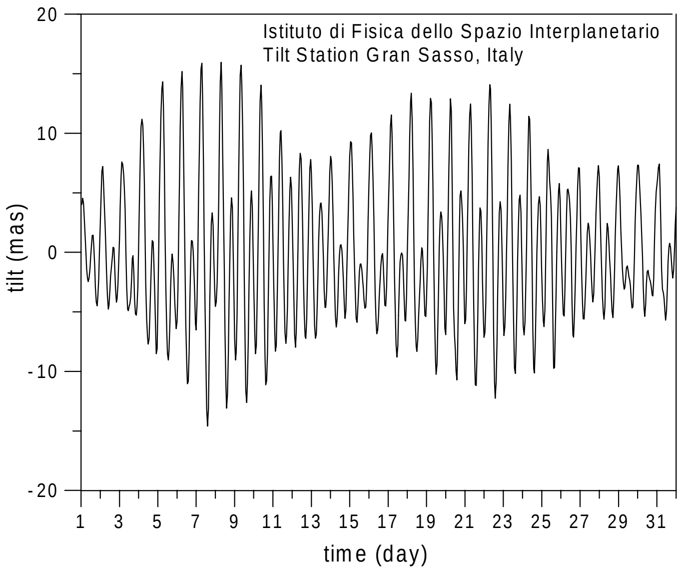

Fig. 1. – Typical monthly time series filtered with 49-hours-length filter. August 1998.

4. – Earth tide analysis

Three years data were analysed: from January 1996 to December 1998. The sampling time for 1996-1997 data was 1 min, and 10 seconds for the 1998 data. The program packages PRETERNA and ETERNA, which now are standard for Earth tide analysis, were used for data processing [10].

Monthly data rows were pre-processed by PRETERNA with the following procedures. The computed model tides (tidal potential development TAMURA 1987, 1200 waves) and the model air pressure contribution were removed from the records and a remaining signal was considered as the sensor drift. The remaining signal was cleaned aiming to remove steps, spikes and gaps and then the known signals were added back to the cleaned remained signal. Finally the edited data were filtered, firstly by a 2-hour-length low-pass numerical filter with 5 min sampling rate, then with one hour (a 14-hour-length filter).

Tidal parameters were analysed with the package ETERNA. The ETERNA input file contained three hourly sampled observation data streams: tilts, pressure and temperature. The values of tidal parameters were estimated for 12 standard wave groups, their main components are reported in table I [11]. The program performed the least-squares adjustment of tidal parameters and meteorological regression parameters from band-pass filtered observations. We have tested some of the filters, which are available in the program. Due to the relatively noisy and monthly divided data which were analysed, the Wentzel 49-hour-length filter was generally the most useful. Finally for the estimate of tidal parameters 12 monthly series were selected. A typical monthly raw data filtered with this filter are shown in fig. 1.

Since meteorological and other disturbing factors often contain periodicities of a solar day, the partial tide to be experimentally determined with the highest accuracy will be the one of the highest amplitude, which has the period most strongly deviating from the solar day or its fractions. These are the lunar principal wave M_2, for the semidiurnal

Table I. – *The harmonic constituents of Luni-Solar tidal potential used in the data analysis.*

Symbol	Frequency (degrees/h)	Period (hour)	Origin (L=lunar, S=solar)
		Semidiurnal components	
$2N_2$	27.968208	12.8717	L, elliptic wave M_2
N_2	28.439730	12.6583	L, large elliptic wave M_2
M_2	28.984104	12.4206	L, principal wave
L_2	29.528479	12.1916	L, small elliptic wave M_2
S_2	30.000000	12.0000	S, principal wave
K_2	30.082000	11.9666	L-S, declination wave
		Diurnal components	
Q_1	13.398661	26.8683	L, elliptic wave O_1
O_1	13.943036	25.8193	L, declination wave
M_1	14.496694	24.8332	L, elliptic wave K_1
P_1	14.958931	24.0659	S, principal wave
S_1	15.000002	24.0000	S, elliptic wave ${}^sK_1$
K_1	15.041069	23.9345	L-S, declination wave
J_1	15.585443	23.0985	L, elliptic wave ${}^mK_1$
OO_1	16.139102	22.3061	L, declination wave
		Tertiodiurnal component	
M_3	43.476115	8.2804	L, principle wave

waves group, and the lunar declination wave O_1, for diurnal harmonics.

Table II shows various monthly values of the amplitudes and phases for M_2 and O_1 tidal components obtained with the GS1 tiltmeter. Values shown in parentheses are the uncertainties in the fit of data estimated by ETERNA. The best accuracy estimate for the mean monthly M_2 amplitude is 0.5%, in the same time the ratio of the extreme values for M_2 is $6.542/5.850 = 1.1$. Corresponding values for O_1 are 3.7% and $4.21/2.61 = 1.6$. Such scattering of values can be explained by the influence of local disturbances connected with human activity in the underground laboratory.

The observed values of the M_2 amplitude factor for three-year observations are summarised in fig. 2. The vertical bars are the standard deviations. The experimental values are close to the theoretical ones (the Wahr-Dehant inelastic amplitude factor for M_2 used in ETERNA is 0.69085). There are not considerable time variations of the amplitude factor. Fitting a linear regression shows that the variation is below 0.5% per year.

Nonetheless there are significant differences of standard deviations for the observed values. The instrument response to the solid Earth tides is complicated by the combination of ocean tidal loading [12], local geologic, topographic [13], and cavity effects. All of them introduce systematic errors in measured parameters but cannot affect too much the dispersion. The main influence seems to be connected with meteorological effects and local laboratory temperature variations. The meteorological periodic disturbances penetrate deep into the ground in the form of elastic stresses. They attenuate rapidly with depth [14]; however mean diurnal thermoelastic amplitudes of 1.5 mas have been observed at a depth of 800 feet (250 m) [15]. A deep underground location of the GS1 surely reduces these effects, while laboratory temperature variations remain significant.

TABLE II. – *Monthly means of the parameters of the Earth tide semidiurnal (M_2) and diurnal (O_1) harmonics. Values shown in parentheses are the standard deviations.*

Tide	M_2		O_1	
Time	amplitude (mas)	phase lead (degree)	amplitude (mas)	phase lead (degree)
		1996		
June	6.172 (0.583)	12.3 (5.4)	2.62 (1.12)	157 (24.6)
July	5.864 (0.120)	5.5 (1.1)	3.66 (0.17)	−50 (2.6)
August	6.168 (0.128)	13.0 (1.2)	3.23 (0.22)	5 (3.9)
		1997		
July	6.542 (0.220)	9.7 (1.9)	3.82 (0.53)	22 (8.2)
August	6.230 (0.083)	8.0 (0.7)	4.21 (0.10)	16 (1.4)
October	5.925 (0.202)	9.3 (2.0)	2.61 (0.37)	49 (8.2)
November	6.010 (0.092)	12.3 (0.8)	3.31 (0.40)	34 (7.0)
December	5.850 (0.247)	12.8 (2.4)	3.77 (0.50)	−6 (7.2)
		1998		
June	6.282 (0.087)	6.5 (0.8)	3.37 (0.23)	21 (4.0)
July	6.420 (0.076)	14.0 (0.7)	3.30 (0.13)	22 (2.2)
August	6.276 (0.041)	7.4 (0.4)	3.19 (0.12)	28 (2.2)
September	5.897 (0.059)	6.7 (0.8)	4.19 (0.16)	26 (2.1)

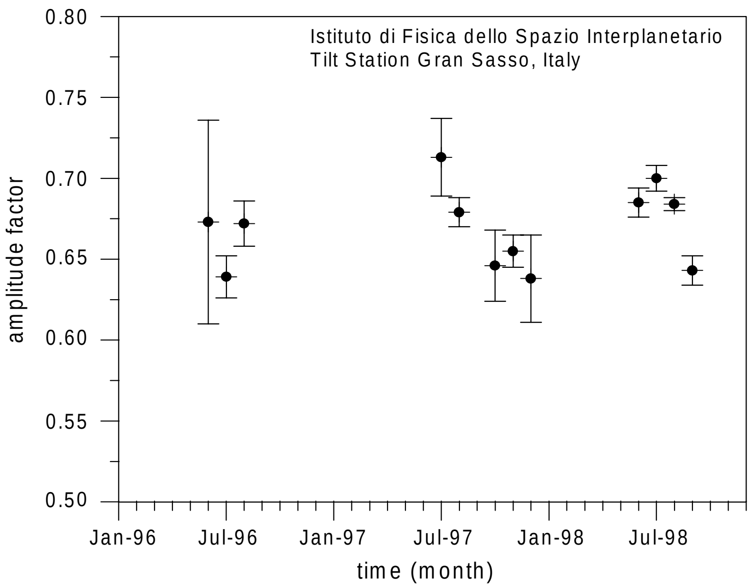

Fig. 2. – Mean monthly values of the amplitude factor for lunar principal wave M_2. The vertical bars are the values of standard deviation.

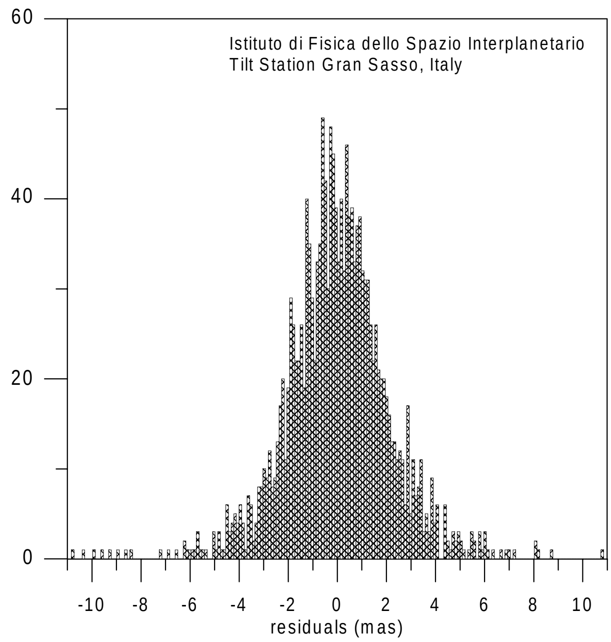

Fig. 3. – The histogram of residuals for data of August 1998.

An additional temperature shielding installed around the tiltmeter in 1998 improved somewhat the situation. It can be seen in the data of 1998 (fig. 2).

The less noisy data of 1998 allowed the use of the Wentzel 145-hour-length filter, which yielded the better signal-to-noise estimate without changing parameter values. The results of the analysis for the 41-day run are given in table III that is part of the output ETERNA file. The histogram of residuals demonstrates the Gaussian distribution with zero mean value (fig. 3). Besides the M_2 and O_1 parameters, which can be considered as always reliably, and stably estimated, the parameters for other wave groups are also determined. In terms of signal-to-noise ratio these are the semidiurnal lunar elliptical wave N_2 and the group of waves with periods close to 24 and 12 hours (P_1S_1 and S_2K_2). The uncertainty of the M_2 amplitude factor estimate is 0.5%. There is a good agreement between observations and the theory (the Wahr-Dehant amplitude factor); the difference is about 1%. It means that the measured amplitude of M_2 is practically free from systematic distortions. As a whole the parameters of semidiurnal components are estimated better than the diurnal ones. Although the estimated amplitude factors for diurnal components are different enough from theoretical values we cannot draw a conclusion about observed anomalies because the adjusting of the tidal parameters for ocean loading and local topography was not done.

ETERNA allows the simultaneous determination of tidal parameters and local meteorological admittance factors. There are no stable estimated values of meteorological admittance factors. Such a situation can reasonably be explained by the deep underground location of the instrument.

TABLE III. – *The estimated values and standard deviations for tidal and meteorological parameters. August-September 1998.*

```
Program ETERNA, version 3.0 930801 FORTRAN 77,    file: Aug-Sep98

####################################################################
# Tilt station Gran Sasso, Italy                                   #
#                                                                  #
# Istituto di Fisica dello Spazio Interplanetario  CNR             #
# Lat= 42.35 N, Lon= 13.40 E, H= 800 m, Horizontal tilt component  #
# Tiltmeter  GS1                                                   #
#                                                                  #
# 1998.08.01 - 1998.09.10   41 days                                #
# Installation and maintenance:     V.Iafolla, S. Nozzoli          #
# Data processing :                 V. Milyukov                    #
# Calibrated absolutely from inclination at 20.01.1999             #
####################################################################
```

Summary of observation data :

19980801 60000...19980910 160000

Initial epoch for tidal force : 1998. 1. 1. 0

Number of recorded days in total : 40.46
TAMURA 1987 tidal potential used.
HANN window used for least squares adjustment.
Numerical filter is WENZEL 145 with 145 coefficients.

Estimation of noise by FOURIER-spectrum of residuals

0.1 cpd band	9999.9999 mas	1.0 cpd band	0.1616 mas
2.0 cpd band	0.0346 mas	3.0 cpd band	0.0985 mas
4.0 cpd band	0.0967 mas		

adjusted tidal parameters :

from	to	wave	ampl. mas	signal/ noise	ampl.fac.	stdv.	phase lead [deg]	stdv. [deg]
286	428	Q1	0.673	4.2	1.43741	0.34482	-1.0943	13.7449
429	**488**	**O1**	**3.075**	**19.0**	**1.25639**	**0.06602**	**24.9407**	**3.0108**
489	537	M1	0.345	2.1	1.79043	0.83947	56.0778	26.8639
538	**592**	**P1S1**	**3.799**	**23.5**	**1.10393**	**0.04694**	**15.9581**	**2.4365**
593	634	J1	0.294	1.8	1.52793	0.83949	-167.8102	31.4801
635	736	OO1	0.234	1.4	2.21879	1.53427	-65.5252	39.6195
737	839	2N2	0.432	12.5	1.53971	0.12346	-8.5106	4.5942
840	**890**	**N2**	**1.271**	**36.7**	**0.72415**	**0.01972**	**8.0372**	**1.5600**
891	**947**	**M2**	**6.324**	**182.7**	**0.68968**	**0.00377**	**8.4551**	**0.3136**
948	987	L2	0.269	7.8	1.03729	0.13355	-8.3197	7.3768
988	**1121**	**S2K2**	**2.338**	**67.5**	**0.54805**	**0.00811**	**9.2658**	**0.8482**
1122	1194	M3	0.104	1.1	0.77793	0.73901	40.3688	54.4297

Standard deviation of weight unit: 1.030
degree of freedom: 801
Standard deviation : 1.030 mas

Adjusted meteorological or hydrological parameters:

no.	regr.coeff.	stdv.	parameter	unit	
1	-0.22982	0.08736	Airpres.	mas	/hPa
2	-1.77357	7.07681	Temperat	mas	/Grad

5. – Conclusions

The one-axis tiltmeter with associated hardware and software has been designed and used to measure tidal tilts in the Gran Sasso, Central Italy. The tiltmeter has a dynamic range of ± 60000 mas ($\pm 300\,\mu$rad), and a sensitivity of $0.2\,\text{mas/Hz}^{1/2}$. The linearity of the instrument response is within 0.4% in the dynamic range. The long-term stability of the calibration factor is better than 99.5% per year.

The analysis of three-year observation tilt data shows a good agreement between the observations and the theory for the M_2 tide component. It proves that this component is practically free from ocean loading and local topographic effects. There is no change in time for the M_2 amplitude factor. The tiltmeter installed at a depth of 1400 m shows no stable evidence of meteorological effects, at that time the local underground disturbances, mainly connected to human activity, distorted the observation signal. For the best series of data (1998) tide measurement accuracies are: 0.5–1% for the M_2 amplitude and 3–4% for the O_1 amplitude, which are comparable with those of the best modern tiltmeters.

The above analysis demonstrates a good capability of the designed instrument to precise tilt measurements, which are accurate enough to be of general geophysical interest. A new two-axis tiltmeter instrument designed with the same technique and with some improvements is now operating in the Gran Sasso site. Such an instrument was operating during several months in the Grotta Gigante (North Italy). In the light of the relative simplicity and good reliability of the instrument, the development of an Italian network of tilt observation stations equipped with such instruments can be proposed.

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