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Deep-sea gravity measurements: GEOSTAR-2 mission results

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Abstract
A new concept gravity meter with sensitivity close to $10^{-8}\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ in the range of 10^{-5}–1 Hz intended for observation of the vertical component of the Earth gravity and teleseismic waves was implemented at the Istituto di Fisica dello Spazio Interplanetario (IFSI), CNR and successfully operated during the GEOSTAR-2 mission. The gravimeter has demonstrated a capability to operate for a long time in an autonomous regime and a good reliability for operation in extreme environments; at the same time the experimental measurements gave information for further gravimeter implementation. Results of observation and data analysis including the recording of seismic waves excited by global earthquakes and the evaluation of the low frequency modes of free oscillations of the Earth are reported.

Key words *seafloor gravimeter – teleseismic waves*

1. Introduction

The rarity of gravity observation in regions that are difficult to access still restricts our knowledge of the detailed gravity field of the Earth. A special interest from this point of view is the gravity measurement on the sea or ocean bottom. A gravity meter for deep-sea use was implemented at the Istituto di Fisica dello Spazio Interplanetario (IFSI), CNR on the basis of technology developed in the framework of the programs for design and realization of a space-borne high sensitive accelerometer (Iafolla *et al.*, 1997, 1998) with financial support of the Agenzia Spaziale Italiana (ASI). Such technology has also been used for the implementation of tiltmeters, one of them has successfully operated for several years in the INFN underground laboratory (Gran Sasso) (Iafolla *et al.*, 2001).

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The instrument, named «GeoGrav-1», is conceived for measuring the vertical component both the variation of gravitational field and seismic waves and is able to operate in extreme environments (deep-sea level) for a long period without remote control. The gravimeter, together with other scientific instruments, was installed on the autonomous deep-sea observatory named GEOSTAR intended for multidisciplinary, long-term monitoring. The GEOSTAR-2 Observatory was successfully deployed in September 2000 on the bottom of Tyrrhenian Sea at the depth of 2000 m, near Ustica Island (Italy), and was successfully recovered in March 2001. The full operation time of the observatory was 172 days (Favali *et al.*, 2002; Gasparoni *et al.*, 2002).

2. Seafloor gravimeter

The mechanical part of the gravimeter consists of a proof mass which is connected to an external frame by two torsion arms and represents an harmonic oscillator with resonance frequency equal to 15 Hz. The mechanical oscillator is obtained machining a single plate of aluminium AL 5060. Two external plates are faced in its opposite sides to realize a couple of capacitive detectors working in differential mode. This difference should be zero when the proof mass is under the action of the Earth gravity ($g = 9.8$ m/s^2). (The minimum detectable acceleration, 10^{-8} m/s^2, produces a displacement of 6.3×10^{-13}m).

The read-out system of the instrument is a capacitive bridge biased by a voltage $V_p = 100$ V at the frequency of 100 kHz. Two arms of the bridge are constituted by the two capacitor detectors in the differential configuration while the other two are external fixed capacitors. The displacement of the proof mass gives the variations of the two sensing capacitors, producing a bridge inbalance and a consequent modulation of the driven voltage at the signal frequency. The output signal due to the unbalancing bridge is amplified by a low noise amplifier, demodulated and sampled at a rate of 10 s. The digital signal is sent to the GEOSTAR Data Acquisition Control System (DACS), which also synchronizes the gravimeter acquisition system with the other instruments (Iafolla and Nozzoli, 2002). The total gravimeter power consumption is 190 mW.

The gravimeter is suspended inside special spherical deep-sea glass housing by means of gimbals and is installed on the GEOSTAR platform. During the mission there is no possibility for remote control of the gravimeter. The gimbals allow automatic recovery of the verticality of the gravimeter sensitive axis with a precision better than 1° (1.5×10^{-3} m/s^2 in gravity units) when the GEOSTAR platform is located at the sea bottom. The arrangement of the gravimeter inside the spherical glass housing is shown in fig. 1.

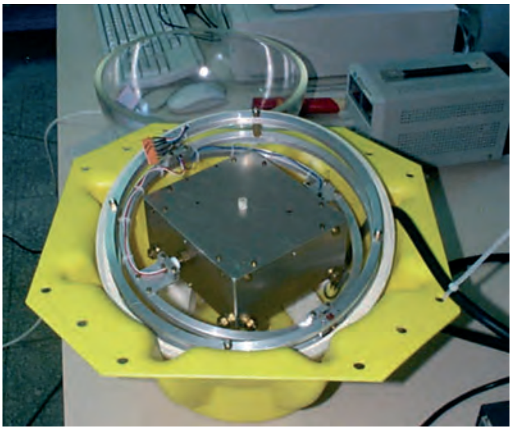

Fig. 1. General view of see-floor gravimeter mounted inside of spherical glass housing.

The pre-mission calibration of the gravimeter was done by the standard procedure – high precision inclination in a vertical plane. The value of the calibration factor is equal to $(0.98 \pm \pm 0.26)\times10^{-8}$ ms^{-2}/ADC_count, estimated in the dynamic range of 0.1 m/s^2. The instrumental response is linear within 0.5%.

3. Estimation of the instrument dynamic

During the operation time the gravimeter is underwent the action of the following signals: a variation of the vertical tidal gravity component, seismic waves from global earthquakes, local disturbances of the gravitational field. One can expect the largest signal variation at the level of $(2-3)\times10^{-6}$ m/s^2 caused mostly by tidal gravity.

The greatest instrumental effects are due to thermal variations and ageing of the gravimeter mechanical springs. The gravimeter thermal dependence, caused mainly by the thermal variation of the spring elastic constant, is estimated at the level of 10^{-3} ms^{-2}/°C. The daily temperature variation is expected to be less than 10^{-3} °C, while during the six months of the mission it could be approximately 1°C. The maximum signal variation related to this value is 10^{-3} m/s^2. Time dependence of the output signal is caused by ageing of the elastic springs and the consequent changing the proof mass equilibrium position. The preliminary experimental estimation indicates an upper limit of 5×10^{-4} ms^{-2}/day. During 180 days of the mission this exponential drift gave the signal variation of 9×10^{-2} m/s^2. This value determines the total signal variation during full mission time, and the necessary instrument dynamic range.

4. Data analysis

The gravimeter operated from September 25, 2000 up to March 16, 2001, almost 172 days. The original data consist of 21 uninter-

Table I. Time parameters of the GEOSTAR gravimeter data.

	Beginning		End		Duration
	date	time	date	time	hours
Run 1.	25/09/2000	11:00:00	27/09/2000	12:59:50	50
Run 2.	27/09/2000	13:57:40	30/09/2000	12:59:50	71
Run 3.	30/09/2000	14:57:30	03/10/2000	02:59:50	60
Run 4.	03/10/2000	04:57.30	08/10/2000	11:59:50	127
Run 5.	08/10/2000	03:57:30	09/10/2000	07:59:50	18
Run 6.	09/10/2000	08:57.30	20/10/2000	19:59:50	275
Run 7	20/10/2000	21:57:30	26/10/2000	04:59:50	127
Run 8.	26/10/2000	05:57:30	04/11/2000	06:59:50	217
Run 9.	04/11/2000	07:57:30	16/11/2000	01:59:50	282
Run 10.	16/11/2000	03:57:30	01/12/2000	23:59:50	380
Run 11.	02/12/2000	01:57:30	02/12/2000	19:59:50	18
Run 12.	02/12/2000	20:57:30	02/12/2000	20:57:30	3
Run 13.	03/12/2000	01:21:30	20/12/2000	21:59:50	429
Run 14.	20/12/2000	22:57:30	06/01/2001	00:59:50	386
Run 15.	06/01/2001	01:57:30	25/01/2001	05.59:40	470
Run 16.	25/01/2001	16:57:30	28/01/2001	15:59:50	71
Run 17.	28/01/2001	16:57:30	22/02/2001	08:59:50	592
Run 18.	22/02/2001	10:57:30	26/02/2001	04:59:50	90
Run 19.	26/02/2001	05:57:30	28/02/2001	12:59:50	55
Run 20.	28/02/2001	13:57:30	03/03/2001	00:59:50	59
Run 21.	03/03/2001	02:57:30	16/03/2001	00:59:50	310

rupted runs divided by gaps of the different time duration (table I). During the mission the signal changed in time at a rate of $\Delta g/\Delta t = 2.33\times10^{-4}$ ms^{-2}/day, that is twice less than the predicted value. The maximum signal variation is 4×10^{-2} m/s^2. Removing the time trend reduces the gravity variation from 4×10^{-2} m/s^2 to $0.16\times\times10^{-2}$ m/s^2. The variations of the gravity signal, the temperature and the pressure during the whole mission are shown in fig. 2, indicating the strong correlation between the gravity signal and the temperature.

The thermal constant of the gravimeter was estimated using the data of November 2000. The second order polynomial of the temperature data was fitted by the least squares method to the gravity data. To avoid the distortion of the gravity signal due to the high frequency temperature noise, the temperature data were filtered by a low pass filter with a cutoff frequency of 10^{-4} Hz. The estimated experimental value of the linear thermal constant of the gravimeter is $(\Delta g/\Delta T) = -5.478\times10^{-3}$ms^{-2}/°C. The temperature regression reduces the gravity signal variation to the level of $(20–30)\times10^{-6}$ m/s^2. The standard deviation (STD) of the residual gravity signal is 9.1×10^{-6} m/s^2, while STD of the detrend gravity signal is 179×10^{-6} m/s^2. Therefore regression to the temperature reduced the signal variation of almost 20 times.

To compare the gravity signal with theoretical tides, the residual signal was filtered with the pass-band filter in the tidal frequency domain (diurnal and semidiurnal waves). Theoretical gravity tides were calculated by means of the ETERNA package (Wenzel, 1996) for the same period (November 2000) and for the gravimeter location. The experimental gravity signal and the theoretical tides are shown in fig. 3. STD of residual gravity is 4.3×10^{-6} m/s^2,

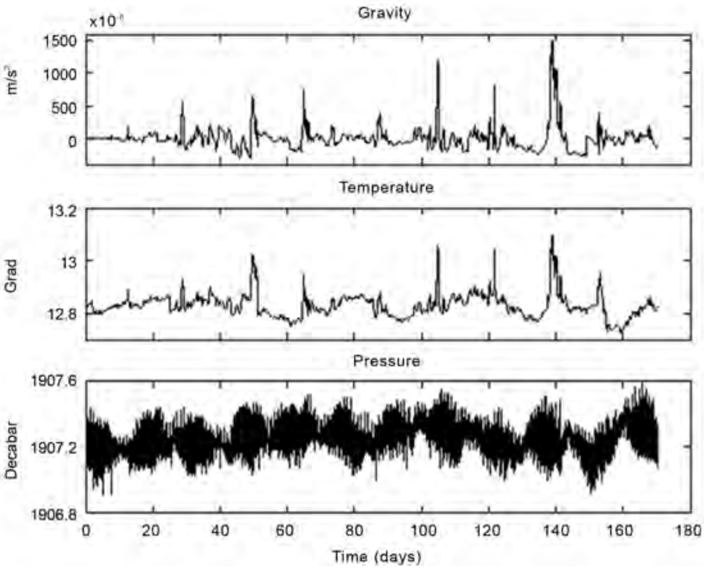

Fig. 2. Gravity, temperature and pressure observations in GEOSTAR-2 mission.

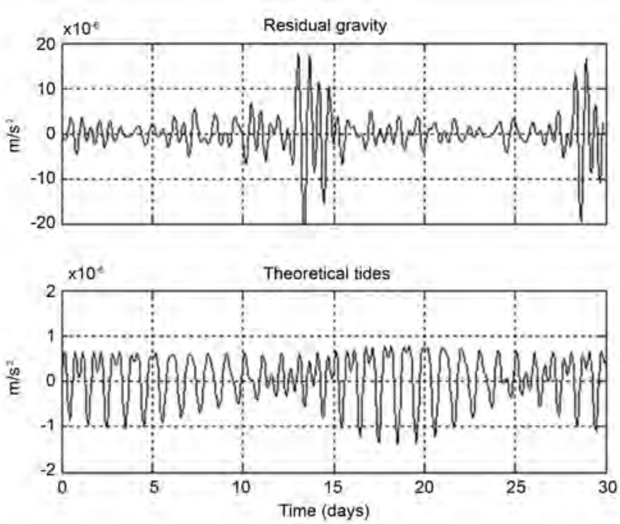

Fig. 3. Residual gravity signal after temperature regression (November 2000), and gravity tides calculated by ETERNA program for the same period of time. Signal variation is almost one order higher then tidal gravity.

while STD of tidal gravity is 0.54×10^{-6} m/s^2. It means that the signal variation in the tidal domain even after temperature reduction is still almost one order higher than tidal gravity.

The spectral densities of the gravitational signal, the temperature and pressure data were estimated for the entire set of the observation, from September 2000 to March 2001. The grav-

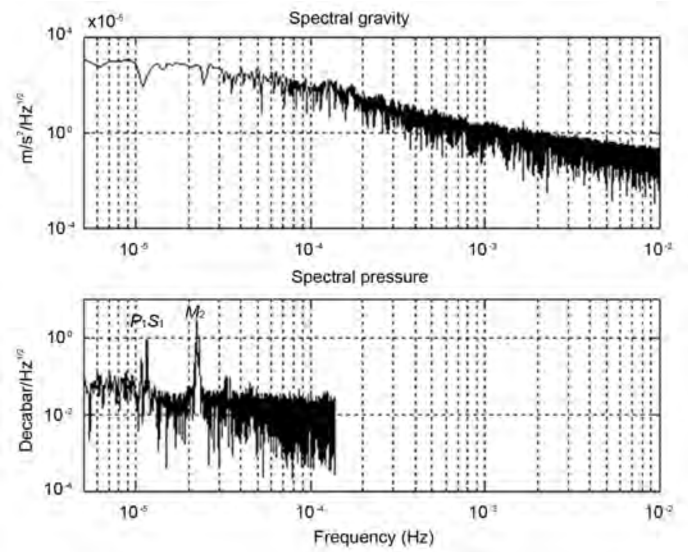

Fig. 4. Amplitude spectra for gravity and pressure signals for all observation data. Two peaks of the pressure spectrum are corresponding to diurnal P_1S_1 (P=24.0 h) and semidiurnal M_2 (P=12.41 h) tidal waves.

Table II. List of seismic events registered by the gravimeter in GEOSTAR mission. The magnitudes are given Moment Magnitude units, M_w. The last column is the values of the maximal amplitudes of the gravimeter response to the appropriate earthquake.

USGS National Earthquake Information Center							
Date	Origin time UTC h:min sec	Geographic coordinates Lat	Long	Depth	Magnitude	Region	Gravimeter max amplitude m/s^2
2000							$\times 10^{-6}$
1. 28/09	23:23 43	0.215S	80.582W	23	M_w 6.6	Near Coast of Ecuador	1.0
2. 02/10	02:25 31	7.977S	30.709E	34	M_w 6.5	Lake Tanganyika Region	4.0
3. 04/10	16:58 44	15.421S	166.910E	23	M_w 6.7	Vanuatu Islands	1.0
4. 06/10	04:30 19	35.456N	133.134E	10	M_w 6.5	Western Honshu, Japan	4.0
5. 25/10	09:32 24	6.507S	105.604E	38	M_w 6.8	Sunda Strait, Indonesia	0.5
6. 07/11	00:18 04	55.627S	29.876W	10	M_w 6.6	South Sandwich Islands	6.0
7. 10/11	20:10 53	36.601N	4.773E	10	M_w 5.7	Northern Algeria Region	4.0
8. 16/11	04:54 56	3.980S	152.169E	33	M_w 7.6	New Ireland Region	15.0
9. 16/11	07:42 16	5.233S	153.102E	30	M_w 7.4	New Ireland Region	8.0
10. 17/11	21:01 56	5.496S	151.781E	33	M_w 7.6	New Britain Region	0.5
11. 25/11	18:09 11	40.245N	49.946E	50	M_w 6.3	Eastern Caucasus	12.0
12. 06/12	17:11 06	39.566N	54.799E	30	M_w 7.0	Turkmenistan	7.0
13. 15/12	16:44 47	38.457N	31.351E	10	M_w 6.0	Turkey	1.5
14. 20/12	11:23 54	39.01S	74.66W	11	M_w 6.5	Southern America	1.5

Table II (*continued*).

USGS National Earthquake Information Center							
Date	Origin time UTC h:min sec	Geographic coordinates Lat	Long	Depth	Magnitude	Region	Gravimeter max amplitude m/s^2
2001							$\times10^{-6}$
15. 09/01	16:49 28	14.928S	167.170E	103	M_w 7.1	Vanuatu Islands	5.0
16. 10/01	16:02 44	57.078N	153.211W	33	M_w 7.0	Kodiak Island Region Alaska	4.0
17. 13/01	17:33 32	13.049N	88.660W	60	M_w 7.7	El Salvador	60.0
18. 26/01	03:16 40	23.419N	70.232E	16	M_w 7.7	Southern India	25.0
19. 13/02	14:22 05	13.671N	88.938W	10	M_w 6.6	El Salvador	3.0
20. 13/02	19:28 30	4.680S	102.562E	36	M_w 7.4	Southern Sumatera	3.0
21. 17/02	20:25 15	13.79N	89.11W	10	M_w 4.9	El Salvador	0.8
22. 24/02	07:23 48	1.127N	126.249E	35	M_w 7.1	Nothern Molucca Sea	3.0

ity and temperature spectra look like a flicker-noise having no outstanding peaks while the pressure spectrum clearly demonstrates two well-pronounced maxima, corresponding to the diurnal P_1S_1 and semidiurnal M_2 tidal waves (the corresponding frequencies are 1.16×10^{-5} Hz and 2.24×10^{-5} Hz). Figure 4 shows the gravity and pressure spectra.

During the GEOSTAR-2 mission the gravimeter working like a vertical seismometer recorded several global earthquakes. The total number of detected events during the six months of the mission is 22, the majority of them with magnitudes of M_w 6.5-7.5 (hereafter magnitudes are given in the moment magnitude units, M_w). The minimal detected magnitude is M_w 4.9 (El Salvador, 17/02/2001). The recorded earthquakes are listed in table II (the earthquake parameters are taken from the National Earthquake Information Center, Denver; U.S.A.). The seismograms for some of them obtained from our data are shown in fig. 5.

Estimate of the gravimeter response to seismic waves – The response of the gravimeter to seismic waves excited by earthquakes differed in amplitude (the maximum amplitudes recorded by the gravimeter are shown in the last column of table II). According to the Gutenberg and Richter formula, the empirical relationship between the energy E radiated as seismic waves and the moment magnitude M_w is the following: $\log E = 11.8 + 1.5\, M_w$. One can estimate the relationship between the energy of seismic waves and the maximum amplitude response of the gravimeter (fig. 6). Even if some of the important earthquake parameters were not taken into account (such, for example, as distance and depth), the rough estimate demonstrates the linear relation between the logarithm of the amplitude and the released energy, which is described by an empirical formula:

$$\log A_{\max}(\mathrm{ms}^{-2}) = -5.4 + 0.33\times10^{-23}E(\mathrm{erg}).$$

Spheroidal oscillations of the Earth – Free oscillations of the Earth were observed and evaluated for the first time after the historical great earthquakes with magnitudes of M_w 8.5 and greater (Kamchatka, 1952, M_w 9.0; Chili, 1960, M_w 9.5; the Kurile Islands, 1963, M_w 8.5; and Alaska, 1964, M_w 9.2). Due to evolution of both the instrumentation and analytical methods it becomes possible to observe the eigenfrequencies of many free oscillations of the Earth excited by earthquakes also with magnitudes of M_w 7-8. Nevertheless the lowest order modes with frequencies below 0.8 mHz can very rarely be observed with good signal-to-noise ratio. Due to the rather quiet condition the GEOSTAR mission provides a

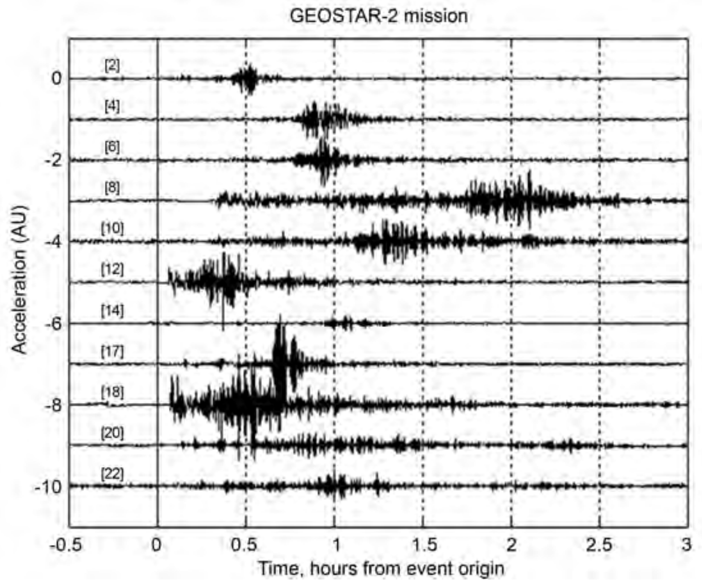

Fig. 5. Seismograms of some of the earthquakes registered by gravimeter. Number of seismogram is corresponding to number of the earthquake in table II. Acceleration is given in Arbitrary Units (AU). «Zero line» is original time of event.

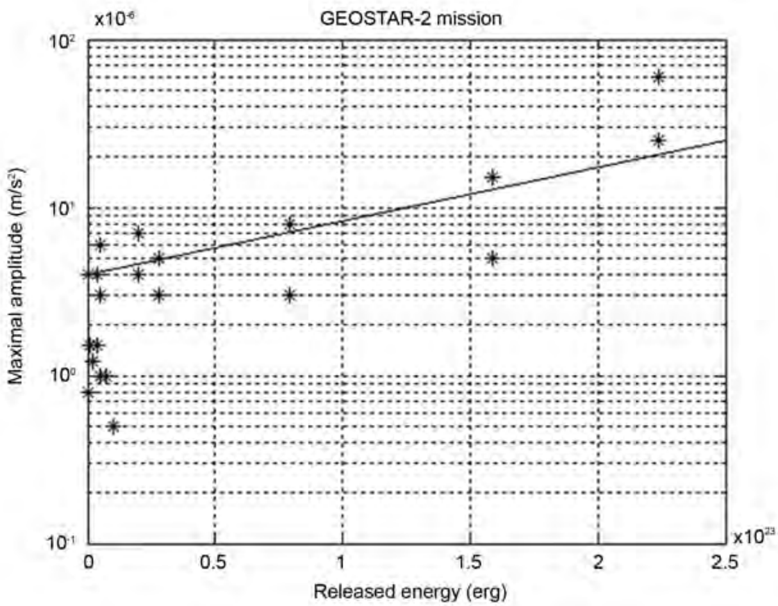

Fig. 6. Relationship between gravimeter response and energy of seismic waves excited by earthquakes. Linear polynomial is fitted to experimental values denoted as (*).

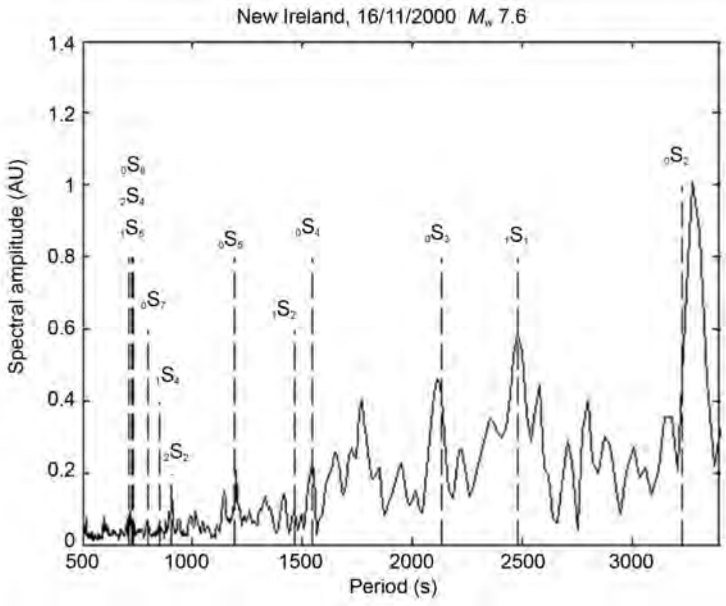

Fig. 7. Amplitude spectrum of 182-h-long record of New Ireland earthquake. The vertical dashed lines show the degenerate frequencies of selected spheroidal modes as predicted for Earth model 1066A.

Table III. Periods (P_{exp}) of the low frequency main tones and overtones of free oscillation of the Earth observed in the New Ireland earthquake. P_{th} is spheroidal modes as predicted for Earth model 1066A.

	Fundamental tones						Overtones					
$_nS_l$	$_0S_2$	$_0S_3$	$_0S_4$	$_0S_5$	$_0S_7$	$_0S_8$	$_1S_1$	$_1S_2$	$_1S_4$	$_1S_5$	$_2S_2$	$_2S_4$
P_{exp}, s	3277	2114	1546	1200	801	708	2482	1463	849	733	905	720
P_{th}, s	3230	2136	1547	1191	813	709	2466	1468	853	730	904	722
$P_{exp}-P_{th}$, s	47	−22	−1	9	−12	−1	16	−5	−4	3	1	−2

good opportunity to estimate and study the low frequency modes of the Earth.

For our analysis we selected three earthquakes which followed each other during two days in November 2000: New Ireland (November 16, 04:54); New Ireland (November 16, 07:42); and New Britain (November 17, 21:01). These earthquakes were closely located (coordinates, depth) and had very similar magnitudes: *Mw* 7.6, 7.4 and 7.6. For such a case the energy of seismic waves is expected to be accumulated during following quakes and «lifetime» of excited modes is increased.

The length of the record used for the analysis is 182 h after the first quake. The data were filtered by the high pass filter with the cut frequency of 1.8×10^{-4} Hz and then the Fast Fourier Transformation with application of the Hanning window of 91 h was performed. Figure 7 presents the evaluation of the low-degree spheroidal modes of the free oscillation of the Earth. The spectrum peaks can be identified with the most of the fundamental spheroidal modes of degree from 0 till 8. The some overtones of first and second degrees are pronounced too. The estimated periods in comparison with theoretical

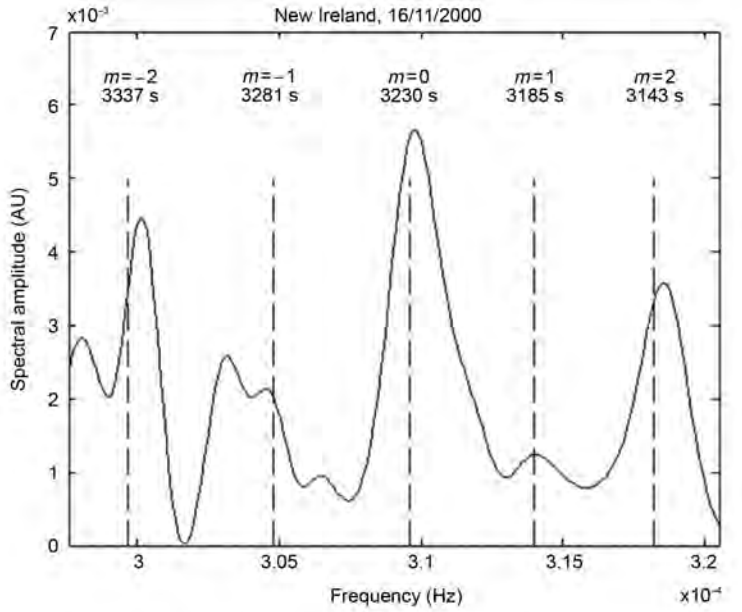

Fig. 8. Fine resolution of fundamental spheroidal mode $_0S_2$ evaluated from 273-h-long record of New Ireland earthquake. Sampling time is 1 min. The vertical lines represent theoretical periods for $_0S_2$ quintet.

ones are summarized in table III. The experimental values demonstrate a good agreement with the theoretical ones. It should be mentioned that, since the barometric pressure corrections were not made, some of the peaks could be misidentified. Due to this reason the non identified spectrum peaks could be related to possible pressure influence.

Fine resolution of the spheroidal mode $_0S_2$ – The spinning of the Earth produces the Coriolis force, which is spherically asymmetric. This effect as well as the ellipticity of the Earth lead to a breakdown of the degeneracy of the eigenfrequencies for $2l+1$ values for each spherical harmonic of l degree. The result is called splitting, with the split eigenfrequencies being close together. So, the spheroidal mode $_0S_2$, the longest-period fundamental ($n=0$) mode of the Earth, is split to five components.

The degenerated mode $_0S_2$ is clearly exposed in the spectrum of fig. 7. To resolve the fine structure of this mode the record data of the length of 273 h were resampled with sampling time of 1 min, and filtered with a narrow band-pass filter. Figure 8 shows the result obtained for the fine resolution of the quintet $_0S_2$. The vertical lines represent the theoretical values of quintet periods. The three highest peaks can, with reasonable certainty, be identified as, from left to right, $m=-2$, $m=0$, and $m=2$. Two others peaks of the quintet corresponded to $m=-1$, and $m=1$, are not completely resolved. The partial resolution of the quintet and the non symmetrical shapes of the resolved peakes can be explained by the fact that the data is rather contaminated by noise.

6. Conclusions

The new concept gravity meter for a deep-sea measurement with sensitivity close to $10^{-8}\,\mathrm{ms^{-2}}/\sqrt{\mathrm{Hz}}$ in the frequency range of 10^{-5}+–1 Hz was developed with the financial support of the Istituto Nazionale di Geofisica e Vulcanologia (INGV). The gravimeter was installed on the autonomous deep-see observatory GEOSTAR-2 intended for multidisciplinary, long-term monitoring, and has successfully operated from September 25, 2000 to March 16, 2001, almost 172 days with efficiency of 99%.

The large dynamic of the instrument permitted it to operate throughout the mission in an autonomous regime. The trend of the gravimeter output due to the spring aging had a value of 2.33×10^{-2} ms^{-2}/day and is easily removable. The temperature dependence of the output signal is mainly caused by the thermal effects of the mechanical springs. The experimentally estimated linear thermal constant of the gravimeter is -5.478×10^{-3} ms^{-2}/°C. Regression to the temperature reduces the signal variation almost 20 times in the low frequency region; nevertheless it is still one order higher than the expected tidal variation.

During the mission 22 global earthquakes with the magnitudes between M_w 4.9 and M_w 7.5 were recorded. The response of the gravimeter to the seismic waves exited by earthquakes differed in amplitude varying from 0.5×10^{-6} m/s^2 to 60×10^{-6} m/s^2. The logarithm of the response amplitude of the gravimeter and the energy of seismic waves released in the earthquakes demonstrate the linear relationship between them.

The high sensitivity of the gravimeter and quite environment disclosed some of the low-order spheroidal tones and overtones of free oscillations of the Earth below 0.8 mHz. The evaluation was done for the record of the New Ireland earthquake (16/11/2000, M_w 7.6). The experimental values demonstrate a good agreement with theoretical ones. For the same record the fine structure of the quintet ${}_0S_2$ was resolved and some of the constituents were estimated.

On the whole the gravimeter demonstrated a good capability to perform precise geophysical measurements in extreme environments and provides a good opportunity to record and study the phenomena such as teleseismic waves and free oscillations of the Earth.

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