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Working Group on HIGH PRECISION TIDAL DATA PROCESSING
Bonn meeting October 10 - 12, 1990

4. Tidal residuals

5. Drift representation and other non-tidal signals

Continuation in next BIM 111

Preface

During the 11th International Symposium on Earth Tides in Helsinki, August 1989, the working group on

'High Precision Tidal Data Processing'

were continued until the next meeting of the Permanent Commission on Earth Tides (PCET). Thus, the tasks of this working group were to examine the introduction of new advances in computing technology and instrumentation into tidal data processing and to report back to the next meeting of the PCET.

Therefore, the group met again in October 1989 in Bonn. The results of this meeting are now being published in this volume and the following of the Bulletin d'Information Mareés Terrestres.

During this meeting the previous discussions of the progess made with the superconducting gravimeter were further amphesized. Now a proposal was presented by D.J. Crossley from Montreal (written by K. Aldridge, D.J. Crossley, L. Mansinha and D.E. Smylie) to establish **'The Global Geodynamics Project'**. In the frame of this project all operating gravimeters of this type should be tied together to record in parallel over about five years under conditions as equivalent as possible. This means, that the data collection (gravity variations and environmental conditions) should be done at the same sampling rates and similar dynamical resolutions, and that for data treatment and analysis the same software should be available. For the participating groups access to all the data should be possible.

Since our working group already recommended similar standards we strongly support this proposal.

The meeting again took place at the Institute for Theoretic Geodesy, University of Bonn, October 10 - 12, 1990. Again Prof. M. Bonatz was our host and provided good conditions for the meeting of the members of the group and other interested scientists. In all more than 33 scientists from 13 countries were present.

In the following the contributions to the topics of the meeting are presented. The conclusions drawn are printed at first place. They allow an overview over the following papers.

As the chairman of the working group I wish to thank all participants for their contributions and Prof. Bonatz for his hospitality. We all acknowledge the support from the 'Deutsche Forschungsgemeinschaft'. I thank Prof. Melchior for publishing all the material in the Bulletin of the International Center of Earth Tides.

Gerhard Jentzsch

Conclusions
drawn during the meeting of the Working Group
on
'High Precision Tidal Data Processing'
Bonn, October 10 - 12, 1990

In continuation of the tasks of the Working Group we passed the following conclusions. In general we would like to note that these conclusions are based on the recommendations of the former meetings. We recommend applying them in order to achieve a more general standard.

1. Instrumentation (general)

For absolute calibration of gravimeters in-situ the use of an inertial method is highly recommended.

For phase determination better than 0.1° the step response method should be used applying an electrostatic voltage directly to the beam of the gravimeter.

2. Superconducting Gravimeter

Regarding the progress made with the application of the SCG it is recommended to achieve a standard in data acqusition systems and monitoring environmental parameters among the respective groups.

The site noise should be examined in advance by all means possible, for example, with broad band seismographs, and spring gravimeters.

We encourage working out terms of reference for the Global Geodynamics Project (GGP) to be submitted to the IUGG-meeting in Vienna, August 1991.

3. Tidal potential

For high precision data we recommend the use of potentials which include the 4th order terms.

We realize that at present it is not possible to decide which of the new potentials (Y. Tamura and Q.W. Xi) is better. According to the comparison to high precision data they look equivalent, although they apply different constants and different approaches of the problem.

4. Tidal analysis

For the model of the Love numbers and the factors δ and v we recommend the adoption the conclusion of the WG on Theoretical Tidal Model, which will be submitted to the IAG in Vienna, August 1991.

In order to give boundaries for the determination of the quality of the record the noise level should be examined also at high frequencies.

We recommend the analysis of long time series regarding possible modulation effects. But one should be aware of different Love numbers for the 2nd, 3rd, and 4th order terms of the potential.

5. Tidal residuals

An inventory of the existing ocean tidal models should be provided by ICET esp. for shelf areas.

6. Non-tidal signals

Stochastic models for the reduction of air pressure should be replaced by physical models.

7. Data bank

Regarding the characterization of the recorded time series we extend earlier conclusions recommending the provision of a full description of the station as well as all available information about the instrument used.

If available also data on the environmantal conditions should be provided (e.g. air pressure, etc.).

SOME IMPROVEMENTS TO THE CONSTRUCTION OF THE LONG WATER TUBE TILTMETER OF THE FGI

by

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Introduction.

Two water tube tiltmeters are recording in the underground mine in Lohja. The lengths of the instruments are 177 m in E–W direction and 62 m in N–S direction. The value of the efficiency, however, has been rather small especially in the longer instrument (KÄÄRIAINEN and RUOTSALAINEN 1989). This was the reason to look at the subjects to improve the stability of the instrument. During the first half of the year 1990 modifications on the E–W instrument have been made by adapting the new design of the endvessels and their better attachment to the ground. Also the conductivity of the water used is now more inferior.

New design of the endvessels.

The already mentioned low efficiency is due to many interruptions in the recording. It was found that very often the frequently adjusted interference pattern was lost and it was thought this was due to the undesirable movements of the endvessels. Up to these days the pots were fastened with one screw through the bottom. It was found that this screw made of stainless steel was damaged by the electrochemical corrosion and consequently no longer functioned properly. Therefore, this one–screw attachment was replaced by making a collar around the bottom part of the pot and using three screws through this collar then fix the pot to the bedrock (Fig.1.). These screws are of brass, i.e. the same material as the endvessels themselves. This construction also makes it unnecessary to have any hole through the bottom.

Another improvement in the design is the adjustable support for the reference lens. This cylindrical ring has now threads and thus can be easily adjusted to the most proper height with regard to the water surface. The interference pattern namely appears in the range of millimeters but has an optimum image quality in a certain position.

Water used in the tube.

The fluid used in the tubes has been that obtained in the main. It was expected to be pure fluid but has revealed to contain a certain amount of calcium. As a consequence it was found some settling on the tube walls when opening the instrument. Therefore, when filling the tube again, water with small conductivity of 0.1 μS/cm was used. This water came from the ionex-changer of the metals laboratory of Technical Research Centre of Finland.

Remarks

After completion the renovation work right before the total solar eclipse in July the instruments have worked properly. To investigate the possible non–newtonian effect of the eclipse, the film speed was accelerated to be about 300 cm/hour for the time of the eclipse. Soon after the phenomenon the usual speed of 5cm/hour was brought in again.

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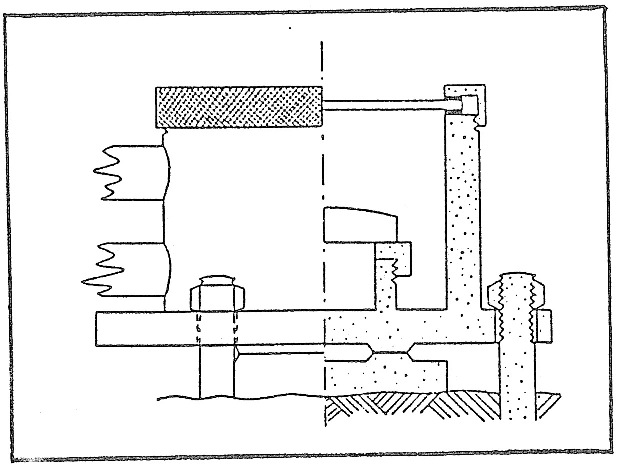

Figure 1. The renovated endvessel.

New design for water-tube tiltmeters

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Summary :

New prototypes of water-tube tiltmeter has been installed in a lava tunnel at Lanzarote (Canary islands). This VRD instrument is an easy to install instrument with a noise level of a few mseca. It is adapted to ground motion monitoring in seismic or volcanic areas. We compare its characteristics with the FSQ water-tube tiltmeter installed in Walferdange which has a noise level of 0.15 mseca only.

1. Introduction :

The water-tube tiltmeters are the most precise and reliable instruments used for Earth tides registration at the level of 0.1 mseca of resolution (Van Ruymbeke & alii, 1990). The FSQ water-tube tiltmeters (Cai & alii, 1990) is a typical example of such sophisticated instruments. It is widely used by the Chinese State Seismological Bureau for the monitoring of ground deformations in seismic areas. Such an instrument has been installed by Ing. Cai Wei Xin in the Underground Laboratory for Geodynamics at Walferdange where it is recording tidal tilt for more than four years. However the instrument is made up from glass pipes and the two end vessels are also in glass. It has to be very carefully levelled and aligned so that its installation is very delicate and time consuming. Our aim was thus to design an easy to install instrument with, for the first prototypes, lower sensitivity.

2. The water-tube tiltmeters at the Cueva de Los Verdes (Lanzarote)

The prototypes of 24.3 and 8.2 meters length have been installed in the E-W and N-S component inside of a lava tube located at the "Cueva de los Verdes" in the North of Lanzarote one of the Canary islands.

The principle of these instruments is the following :

a polyethylene tube with a 2 cm section is connecting together to aluminium end vessels of a 17 cm inner diameter.

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The position of a 9 cm diameter aluminium float immersed in each pot is monitored by means of a capacitive transducer (fig. 1). Suited electronics (National Semiconductor, 1988) are giving a signal either directly in frequency modulation (FM) or after integration (see § 3).

The end vessels are fixed on pillars anchored to the lava floor of the gallery and levelled within one millimeter.

The two pots are hermetically sealed and atmospheric pressure compensation is obtained by means of an auxiliary polyethylene tube with a 2 cm diameter (fig. 1).

The floats are centered by means of a horizontal leaf spring. It is important to adjust the water level in such a way that the leaf spring is effectively working close to its rest position (unbended) i.e. horizontally.

The choice of polyethylene is not accidental. This material has the enormous advantage to oppose practically no resistance to the water flow as the menisque angle is nearly ninety degree. This property is shortening considerably the response time of the system and is reducing the number of air bubbles in the water. The air bubbles are opposing to the flow of the liquid on one side and by degassing at the end vessels they will produce jumps in the measurements. The distilled water is poured very carefully in the tubes in such a way that only microbubbles are sticking on the wall. They are too small with respect to the diameter of the tube to impede the flow and if they could, very unlikely, move to the end vessels their influence would be perfectly negligeable.

3. The capacitive transducers

We are measuring the capacities between the wall of the floats and two concentric cylindrical electrodes fixed to the cover of the pots. The correct centering is insured by the leaf spring. The electronics transform the value of the capacitance in a frequency modulated signal. The two frequencies are sent to an electronic counter where one frequency f_1 is counted during a time which is modulated by the second frequency f_2. The integration time is taken close to one minute in order to insure an efficient filtering of the resulting signal. For a typical input frequency of 35 khz, one minute corresponds to 2^{21} cycles.

The total number of counts n of the frequency f_1 is thus

$$n = f_1 \times (2^{21}/f_2)$$

Initially the two oscillators are tuned on the same nominal frequency f_o so that $n_o = 2^{21}$

As long as the two input frequency are close to the nominal frequency f_o, the system is linear.

A tilt will rise the water level at one end and lower it at the other and the total count will become

$$n = n_o + \Delta n$$

$$= f_1 \times 2^{21}/f_2$$

$$= 2^{21} \times (f_o + \Delta f)/(f_o - \Delta f)$$

$$= 2^{21} \times \left(1 + \frac{\Delta f}{f_o}\right) \times \left(1 + \frac{\Delta f}{f_o} + 2\left(\frac{\Delta f}{f_o}\right)^2 + \ldots\right)$$

$$= 2^{21} \times \left(1 + \frac{2\Delta f}{f_o} + 3\left(\frac{\Delta f}{f_o}\right)^2 + \ldots\right)$$

In our example at the nominal frequency f_0 = 35 kHz the sensitivity is 120 counts per Hz. In table 1 we evaluate the effect of non linearity with increasing offsets of the two frequencies.

Table 1

Linearity of Electronics

Δf (hz)	n	Δn	Δn_o	$(\Delta n - \Delta n_o)/n$	Tilt EW	NS
-	2 097152	-	-	-	-	-
10	2 098357	1198.7	1198.4	$2.5 10^{-4}$	0.1"	0.3"
100	2 109170	1201.8	1198.4	$2.8 10^{-3}$	1"	3"
1000	2 220514	123362	119837	$2.9 10^{-2}$	10"	30"

At the installation special attention had to be paid to the grounding of the electronics including the analog and digital recording devices. It was necessary to place a metal plate in a small lake nearby.

4. Calibration

To calibrate the water tubes we decided to take out or in a given volume of water. We used a 4 cl syringe. We take out successively 4 syringe at one end and carefully reinjected them later on at the other end. During the operation we monitored the frequency at each end vessel to follow the change of the water level. After few seconds the water level equalized in each pot.

However oscillations were triggered and a two minutes delay was necessary to reach a stable equilibrium. At each step the values agree

Table 2

Calibration of EW water-tube

displaced valu	time (minutes)	(KHz) East	West
0	0	0.0	0.0
- 4 cm^3	3	0.15	0.15
- 8 cm^3	5	0.32	0.31
- 12 cm^3	7	0.48	0.47
- 16 cm^3	9	0.645	0.625
- 12 cm^3	11	0.48	0.48
- 8 cm^3	13	0.32	0.31
- 4 cm^3	15	0.16	0.15
0	18	0.0	-0.01
final position	19	0.0	-0.01

within 10 Hz as well in the way down as in the way up.

As the extraction of one centiliter of liquid corresponds to a change of level of 22 μm in each pot the total calibration corresponds to a level change of 352.5 μm

The corresponding measured frequencies are for the EW component :

initial position : f_E = 36.740 khz
f_W = 36.080 khz
final position : f'_E = 37.385 khz
f'_W = 35.455 khz

The corresponding counts at the integrator output are

$$n = 36740 * (2^{21}/36080) = 2135514.5 \text{ counts}$$
$$n' = 37385 * (2^{21}/35455) = 2211310.9 \text{ counts}$$

As one arc second of tilt corresponds to a level change of 58.90 μm for the EW component we get

$$\Delta n = (75796 \times 58.90)/352.5 = 12665 \text{ counts per arc second}$$

The counter as a full scale of 2^{21} counts (4096 points) corresponding to 0."323. The resolution of the system is 0.08 mseca.

The analog and digital recording systems have respectively a full scale of 0.66 V and 2 V. Their sensitivities are thus 2.0 mV $mseca^{-1}$ and 6.2 mV $mseca^{-1}$.

We found similarly for the shorter NS water-tube tiltmeter

initial position : f_N = 36.780 khz
: f_S = 33.930 khz
final position : f'_N = 37.470 khz
f'_S = 33.280 khz

and at the integrator output

$$n = 36780 * (2^{21}/33930) = 2273305.4 \text{ counts}$$
$$n' = 37470 * (2^{21}/33280) = 2361186.5 \text{ counts}$$

As one arc second of tilt corresponds to a level change of 19.88 μm for the NS component we get

$$\Delta n = (87881 * 19.88)/352.5 = 4956 \text{ counts per arc second}$$

The resolution of this water-tube is thus only 0.20 mseca.

As the full scale of the integrator is 2^{21} counts (4096 points) and as the analog and digital recording systems have a corresponding range of 0.66 V and 2 V respectively, their sensitivities are 0.8 mV $mseca^{-1}$ and 2.4 mV $mseca^{-1}$.

5. Preliminary results

Typical records of the digital system displayed in figures 2 and 3.

For the EW component the observed tidal amplitude reaches 400 mV corresponding to 0.065 arc second. This is larger than the normal clinometric tide but the indirect oceanic effects are very large in Lanzarote.

The short period noise with frequencies larger than 1 mhz is of the order of 10 mV corresponding to 1.6 mseca.

For the NS component the tidal signal reaches 100 mV corresponding to 0.041 arc second. The noise level is similar to what is observed for the EW component, 10 m V corresponding this time to 4,1 mseca.

It is thus clear that this noise find his source in the electronics as it is independent from the length of the tiltmeter 10 mV corresponds to less than 0.2 hz fluctuations on a nominal frequency of 35 khz. The stability of the oscillators is thus $5 10^{-6}$. This effect is probably due to short term thermal perturbation affecting the stability in frequency of the oscillators. It must be pointed out that the lava tunnel is opened at both ends and air currents are slowly flowing in it.

6. The FSQ water-tube tiltmeter

This instrument installed in the Underground Laboratory for Geodynamics at Walferdange (Grand Duchy of Luxemburg) is comparable to the EW component of Lanzarote as its length is 26 m. The position of the float is monitored with a LVDT transducer designed by SONY working on a principle similar to a magnetic tape recorder (variable induction). This transducer is widely used and very reliable. Its sensitivity is very stable as long as the moving part has no lateral displacements. The centering of the float is thus very important.

The water-tube is calibrated by immersing the tip of a micrometric screw at the middle point. The displaced volume is thus very accurately known and the water rise measured at each end vessel.

It is installed in very stable conditions at a depth of 100 m underground and at 800 m from the entrance of the gallery. It is buried in a trench covered by a styrofoam cover in order to keep its temperature as close as possible to the rock temperature which is stable all the year round at the millikelvin level.

This instrument is recording the tidal tilt in an azimut close to NS since more than four years. The stability of the results is impressive (Helsinki) e.g. the tidal factor for M_2 (amplitude 5 msea) for successive annual analysis is stable within 0.5 per cent.

Since this year a digital data acquisition system has been installed in the laboratory (fig. 4) reducing the noise level of 25 per cent in the tidal bands.

For periods of a few minutes the noise level is down to 0.15 mseca (table 3).

Table 3

Noise Level of FSQ tiltmeter

frequency band	diurnal	semidiurnal	terdiurnal	short period
noise (mseca)	1.01	0.4	0.2	0.15

7. Conclusions

It is clear that the FSQ water-tube tiltmeter installed at Walferdange has an precision ten times better than the VRD tiltmeter installed in Lanzarote. The question is : Is it possible to improve the VRD instrument in such a way that it will be able to record earth tidal phenomena? For that purpose the noise level should be reduced by a factor of five.

It is clear that the thermal stability is the key point and that the local conditions are the most important factor.

It is the reason why a VRD instrument will be installed in the Walferdange laboratory.

The other points to improve are :

- the stability of the oscillators
- the accuracy of the calibration

A weak point of the system is the non linearity of the capacitive readout system which is limiting the mechanical sensitivity. To insure a linearity better than 0.1 per cent on a 0.1 arc second range it is necessary to limit the length of the water-tube to 100 m.

8. Acknowledgments

The authors wishes to thank the "Calbildo Insular" of Lanzarote and the "Institute de Astronomica y Geodesia, Universidad Complutense de Madrid" for their participation to the installation of the VRD water-tube tiltmeters in the Cueva de los Verdes Laboratory. The European Center for Geodynamics and Seismology did sponsor the scientists participating to that installation.

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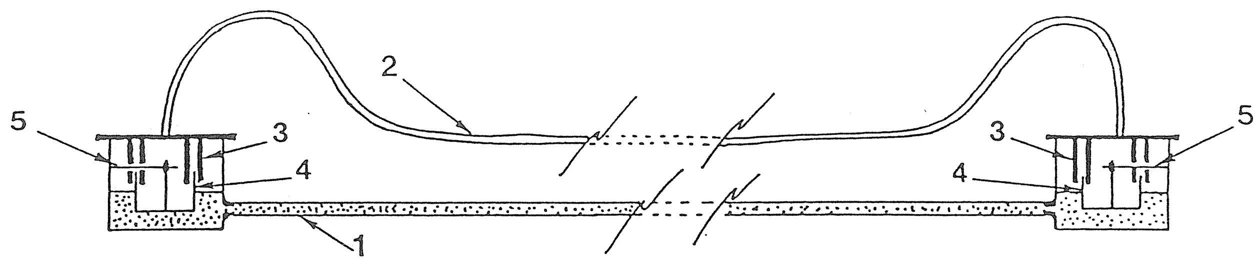

Figure 1 : Schematic diagram of the VRD water-tube tiltmeter.
1 water
2 tube for pressure compensation
3 fixed electrodes of the capacitive transducer
4 float
5 leaf spring

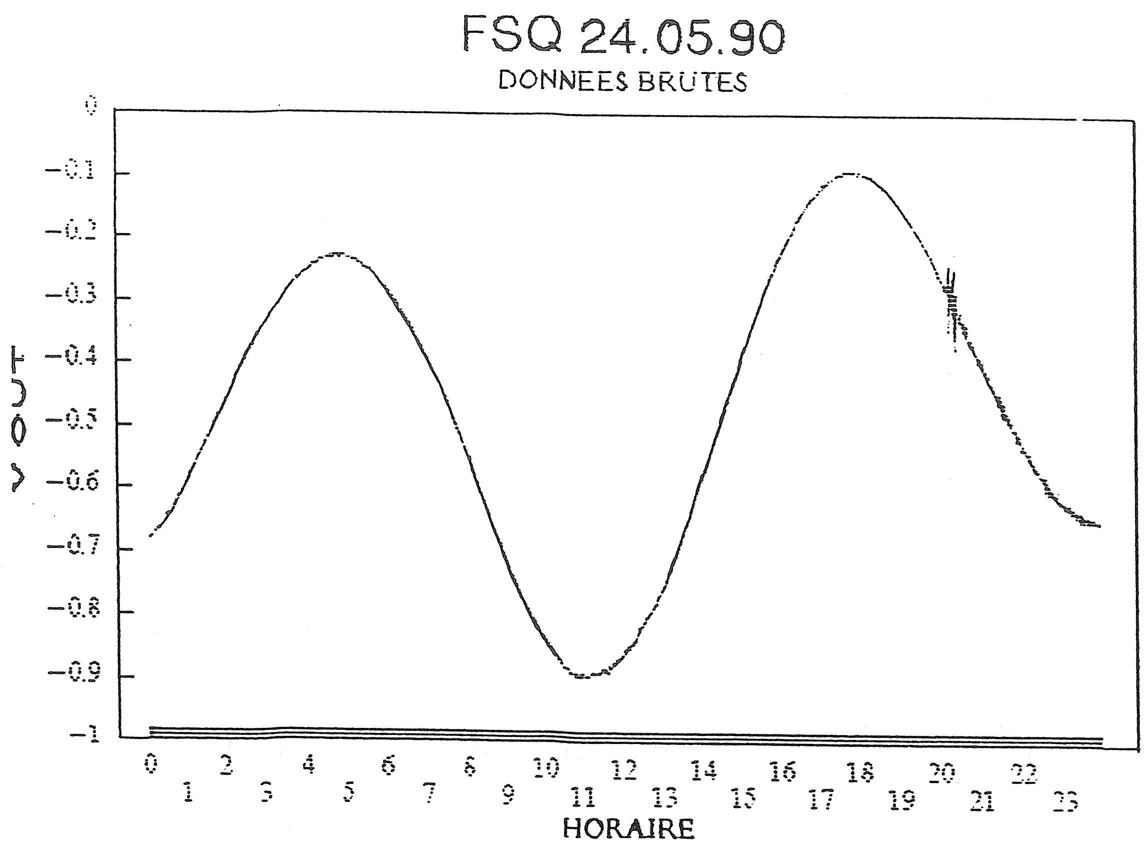

Figure 4 : drawing of the digital data obtained with the FSQ tiltmeter (26 m)

78**** 1433 -8888 WT(E-W) 33

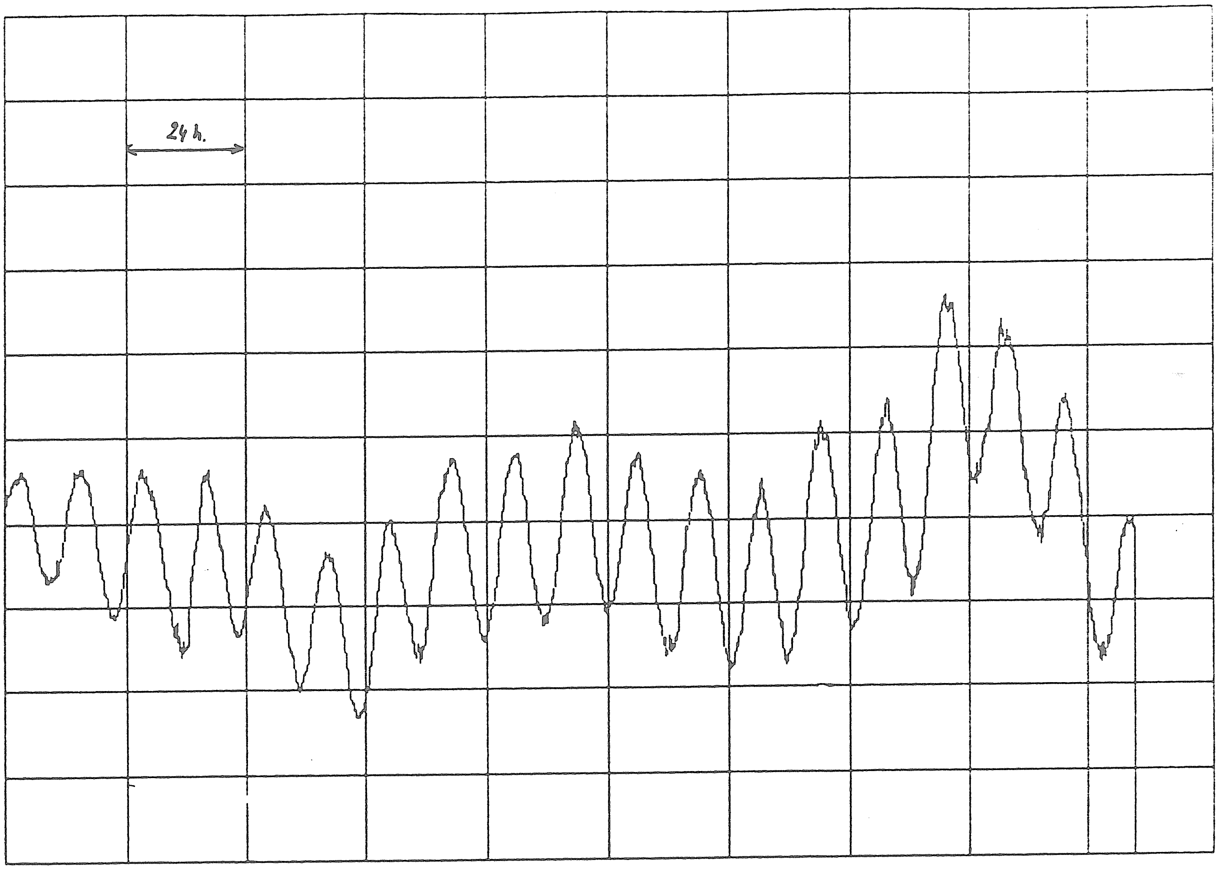

Figure 2 : drawing of the digital data obtained with the EW tiltmeter (24.3 m)

900502 1440 11099 WT(N-S)? _ 23

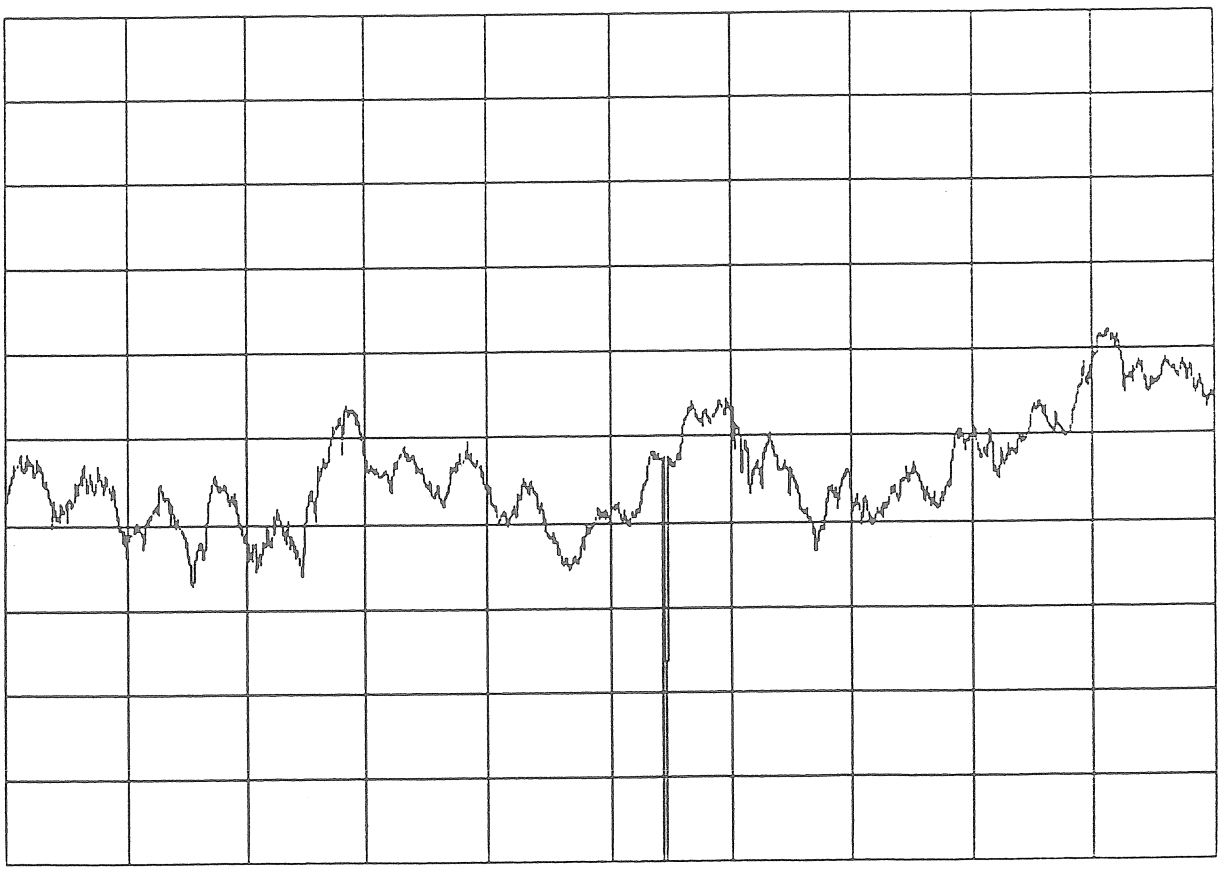

Figure 3 : drawing of the digital data obtained with the NS tiltmeter (8.2 m)

Installation of a quartz tube extensometer at the Sopron Observatory

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Summary

The paper describes a quartz tube extensometer which was developed in the frame of the Hungarian - Soviet scientific cooperation. The extensometer has been working at the Sopron Geodynamical Observatory of the Hungarian Academy of Sciences since May 1990. This paper describes the construction of the extensometer and gives a short overview of the first results.

Introduction

Since 1989 a quartz tube extensometer has been developed in the frame of a Hungarian - Soviet scientific cooperation. The extensometer was installed at the Sopron Geodynamical Observatory in May 1990. The quartz tube body, the calibration unit and a photorecorder were designed by L. A. Latinina. The capacitive transducer and the automatic controller of the calibration unit were developed by Gy. Mentes. The Sopron horizontal quartz tube extensometer is drawn together with Soviet and Slovakian extensometers - besides of Earth tide recording - into the investigation of the movements of the Carpath - Balkan Region.

The construction of the extensometer

Figure 1 shows the ground-plan of the Sopron Geodynamical Observatory and the placement of the horizontal quartz tube extensometer. As it can be seen in Fig.1 it was not possible to place the extensometer in N-S or E-W direction exactly. There is overlay rock of 60 m above the gallery. The distance of the extensometer from the entrance is about 30 m. The extensometer is separated from the gallery by a thermal insulating wall to ensure a good thermal stability.

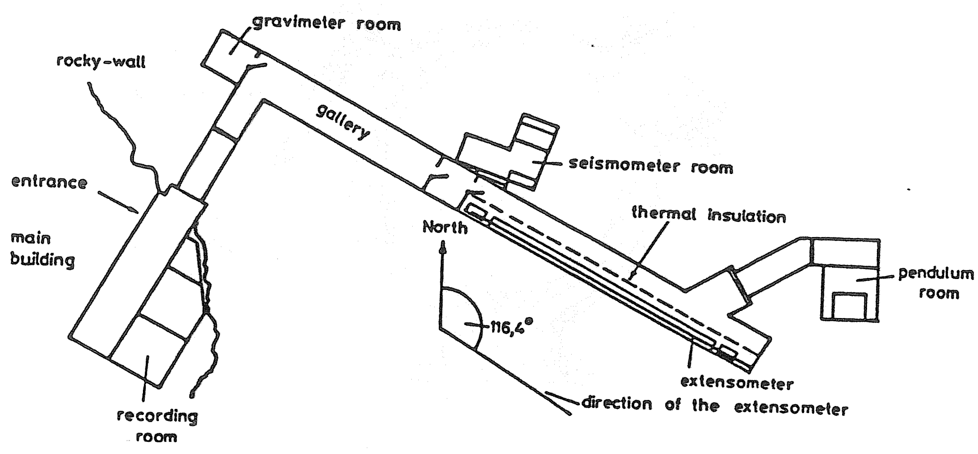

Fig.1. The ground-plan of the Sopron Geodynamical Observatory. The construction principle of the extensometer is shown in Fig.2.

The length of the quartz body is 20 m. The fixed end of the extensometer is attached to the rock by means of a steel rod fixed into the rock by concrete. The magnetostrictive calibration coil is jointed to the steel rod and is followed by quartz tubes of 2 m length each. The quartz tubes are attached together by means of three invar plates in the way shown in Fig.3. There is an adhesive between the invar plates and the touching quartz tube ends. The adhesive consists of cement, quartz sand and a two-component adhesive to accelerate the setting of concrete. The capacitive transducer is at the free end of the extensometer. The electronics of the capacitive transducer is the same which was developed to horizontal pendulums earlier (Mentes 1981, 1983). For testing the transducer and for continuous controlling the work of the extensometer in the first working period an optical recorder was installed besides of the electric recorder.

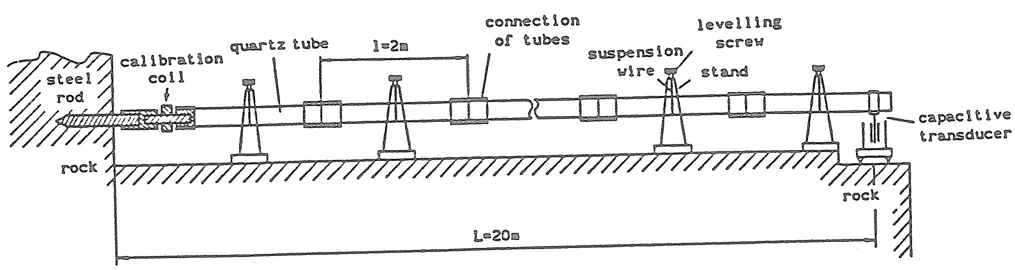

Fig.2. The construction principle of the extensometer.

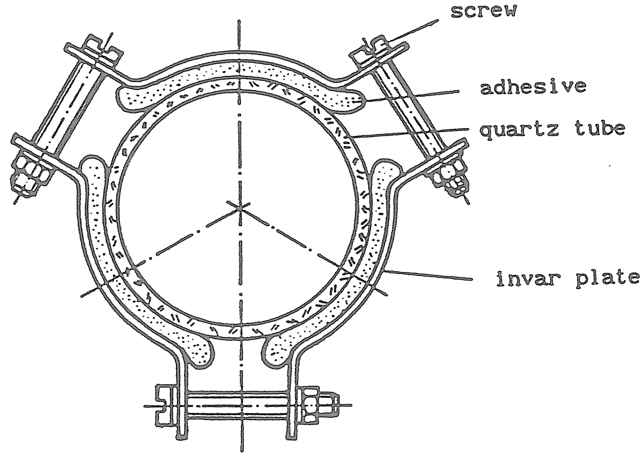

Fig.3. Sectional drawing of the attachment of the tubes.

Test of the extensometer

The test of the extensometer was made as follows: Different currents were led to the coil of the magnetostrictive transducer giving different strains to the quartz tube body. The displacements of the free end of the extensometer was recorded by means of optical and electric recorders simultaneously. The results are given in Fig.4.
From the measurements the following main parameters of the extensometer were obtained:

- electrical sensitivity: 0.5865 mV/nm
- optical magnifying: 9628
- calibration coefficient:
  - . measured electrically: 1.447 mV/mA
  - . measured optically: 2.467 nm/mA

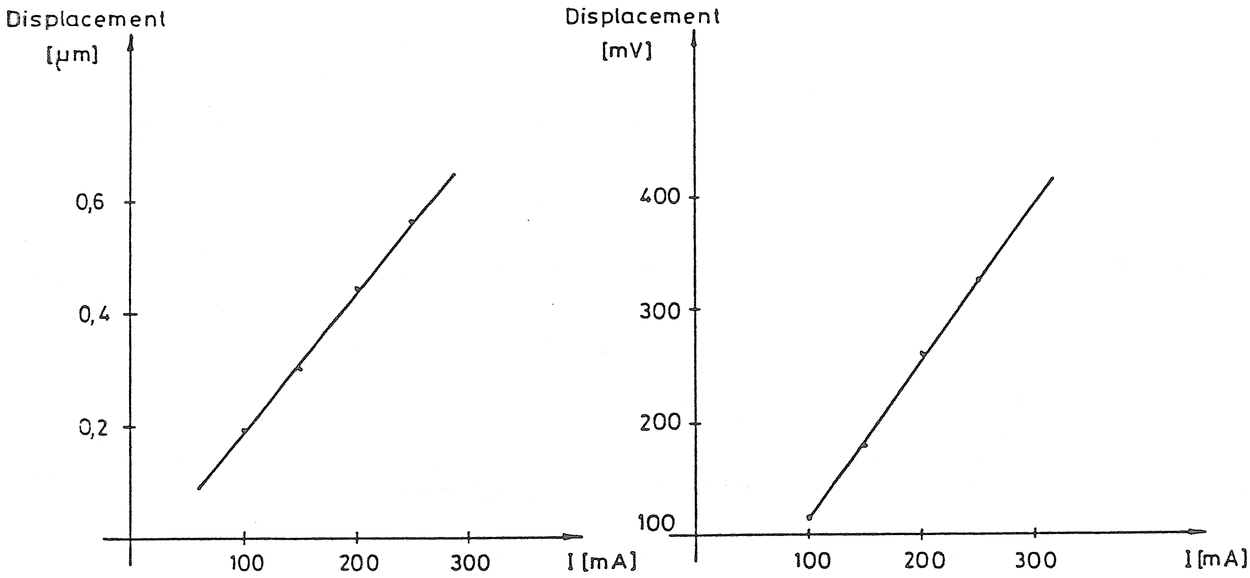

Fig.4. Calibration curves of the extensometer.

Observational data

The working period of the extensometer was very short to make a harmonic analysis up to the present. Fig.5 shows two typical parts of the recorded data. The upper curves were recorded optically, the middle ones electrically. The bottom curves are the theoretical ones calculated at the Sopron station. The electrically and optically recorded curves coincide very well, which all goes to show that the capacitive transducer works properly.

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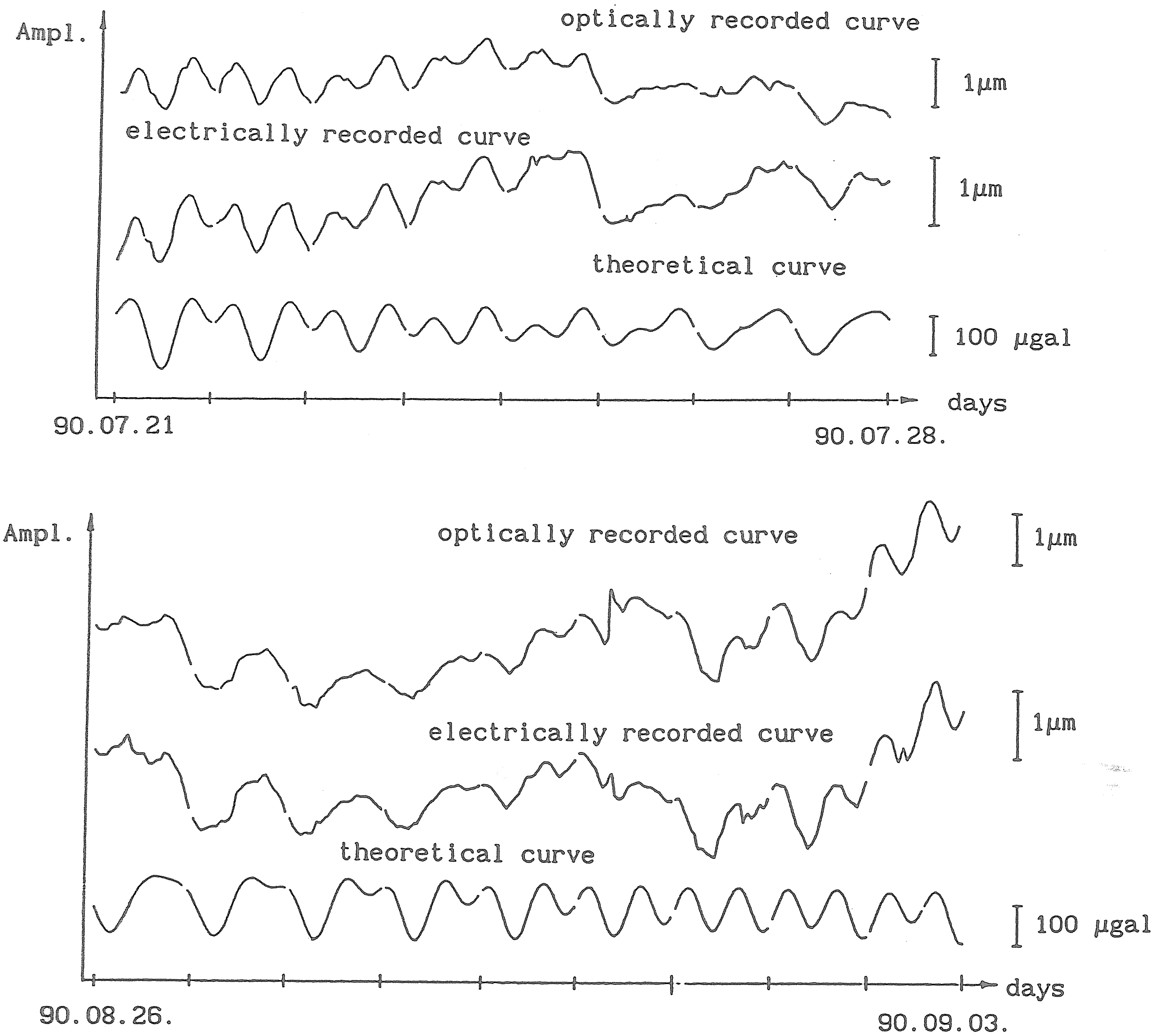

Fig. 5. Recorded data by the extensometer

High Quality Data from LaCoste-Romberg Gravimeters with Electrostatic Feedback: A Challenge for Superconducting Gravimeters

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Abstract

It is shown, that LaCoste-Romberg gravimeters with electrostatic feedback can achieve noise levels which are comparable to the ones obtained by the superconducting devices (so far) in a wide period range. This is certainly not the case at periods longer than 1 month, but at shorter periods it is not clear whether superconducting gravimeters can provide superior data.

1 Introduction

With the advent and increasing number of installations of superconducting gravimeters (SCG) clearly a new frequency band opened for studies of gravity variations on the surface of the earth (e.g. RICHTER and ZÜRN,1988), which cannot be reached even by the best spring gravimeters. The stable "magnetic" spring is far superior to the metal springs in the long term. However, at present it is not really clear, at what frequency the superconducting devices become superior to good spring instruments (with no noise sources being installed by man inadvertently) at low noise sites. The purpose of this paper is to remind the gravimetric community to the high quality of gravity data which were obtained in a rather broad band of frequencies by spring gravimeters (under favorable conditions and extreme carefulness) and to provide a challenge for superconducting gravimeters to be met. It is well known that the atmosphere and the oceans provide a large contribution to gravity noise at long periods, therefore the average power in the local pressure variations provides some measure of "earth" noise at a given station. There is not much one can do about this problem, if for scientific, logistic or political reasons one cannot move the instrument to another site. AGNEW and BERGER (1978) have demonstrated convincingly that sites near the coasts (a few kilometers) and on small islands have larger noise due to edge waves. Seismologists have established a so-called low noise model from observations with seismographs at many sites, including one SCG, which can be used to judge the quality of a given station on average (e.g. AGNEW et al. 1986, WIELANDT and STEIM, 1986).Obviously, in order to detect all observable signals, the total installation has to be able to resolve the minimum earth noise. This includes meteorological and hydrological sources other than direct influences on the instruments and its connection to the earth at that station (Newtonian attraction of the sensor mass by atmosphere and oceans is excluded from the latter). If a given (inferior) instrument resolves this noise by a sufficient margin, no other sensor can provide better data.

Here we will show, that at least some spring gravimeters as well as modern long period seismometers (under favorable conditions and extreme carefulness) have provided high quality data in different frequency bands of interest, with which the data from SCGs must compete. The IDA network (AGNEW et al., 1986) of spring gravimeters has been extremely successful in providing new information about the earth's free modes (see below) and thus about the earth, especially due to deployment of instruments in a global network of about 20 stations. Clearly SCGs may be equally successful in obtaining such information at much longer periods if used in a global network also. The search for Slichter and core modes (e.g. CUMMINS et al., 1991), the verification of the properties of the Nearly Diurnal Free Wobble (e.g. NEUBERG et al. 1987) and the measurement of the amplitude and phase of the Chandler wobble deformation (e.g. RICHTER and ZÜRN, 1988) are important geophysical tasks, which can be tackled with such a network. Another problem is the study of global atmospheric phenomena and their influence on gravity, especially the annual and semiannual waves.

The examples we show in the following from spring gravimeters are from the LaCoste-Romberg ET 19 equipped with electrostatic feedback and installed at Schiltach (BFO, see WENZEL and Zürn, 1990). The other high quality data referred to are from an identical instrument at the South Pole (SPA, SLICHTER et al., 1979) and from the very similar devices of the IDA network (AGNEW et al., 1986), besides the SCGs in Brussels (BR, DUCARME et al., 1986) and Bad Homburg (BH, RICHTER, 1987). All these instruments mentioned provide two output channels usually labelled the tide and mode channels, respectively and data were recorded digitally at rates much higher than 1 cycle per hour (cph).

2 Long Period Tides

The longest period phenomena measured with some confidence by the spring gravimeters are the fortnightly and monthly tides Mf and Mm. RYDELEK and KNOPOFF (1982) determined the amplitude and phase of these tidal constituents at the South Pole from 6 years of data recorded with the Lacoste and Romberg gravimeters. The results are compared in Table 1 with the results of RICHTER (1987) from 3 years of data obtained with the SCG at Bad Homburg. Both data sets were corrected for the barometric pressure effects using linear regression with one coefficient. Comparison of signal-to-noise ratios at different stations and with records of different lengths can of course not be used to compare the instrumental noise levels without additional information. It is possible, that the "earth noise" at these periods is not lower than about 0.025 μgals and that this may define the noise for the Mf tides at both stations, while for Mm the superiority of the SCG comes into play. On the other hand SPA could have a higher noise level than Bad Homburg at monthly periods, after all that station is located on ice 3 km thick. Of course, SPA is favored by the maximum amplitudes of the zonal tides. We do not try to show here that the ET - meter at SPA is better than the SCG at Bad Homburg, this cannot be concluded for the reasons given above. The point is to demonstrate the high quality of the gravity data from South Pole at these long periods obtained with a spring gravimeter. These results could only be obtained after several years of gaining experience and by reducing effects of local disturbances at this unique and austere site. One example is the installation of an anti - tilt frame in order to counteract the slow tilts due to the motion of the ice with a speed of about 10 m per year.

Table 1: Observed long period tidal amplitudes and standard deviations at the South Pole and Bad Homburg in μgal. Signal-to-noise ratio is defined as observed amplitude divided by 1 standard deviation. (1 μgal = 10 nm/s/s)

	SPA (South Pole)	BH (Bad Homburg)
	-	-
Mf		
$obs.signal$	17.20	5.667
$1st.dev.$	0.0252	0.0277
$signal-to-noise$	681.8	204.7
Mm		
$obs.signal$	9.239	2.944
$1st.dev.$	0.0689	0.0272
$signal-to-noise$	134.2	108.4

3 Daily Tides and Core Modes

The SPA records also provided information about the residual daily tides (KNOPOFF et al., 1989). The largest amplitude constituents observed in the diurnal and semidiurnal bands are K1 and M2 with amplitudes of 0.604 and 0.356 μgals, respectively. The corresponding signal-to-noise ratios are 86.3 and 118.7, indicating noise levels of 7 and 3 ngals, respectively. Again a pressure correction with one coefficient was applied to the data.

In the next comparison we again only attempt to demonstrate that good spring gravimeters can compete with SCGs. Comparison of data from different stations at different times cannot be used to compare the gravity sensors themselves and to draw conclusions about lower or higher sensitivity of those sensors. Of course, it is very easy to make the resolution of a very good sensor low by putting it at a noisy site, employing noisy amplifiers, filters, recorders and by bad data reduction techniques. It is well known, that shielding from environmental conditions is extremely important at long periods. Fig. 1 shows spectra obtained from gravity residuals for the SCGs at Brussels and Bad Homburg and for the LaCoste - Romberg ET 19 at BFO. The residuals were obtained by analyzing three data sets of identical lengths (90 days) with the same least squares-program (ETERNA), using the Tamura potential (TAMURA, 1987), and fitting local pressure simultaneously with the tides with one regression coefficient (WENZEL and ZÜRN, 1990). Note that two of the records were simultaneous in time. Modestly one can say that the noise level of the spring gravimeter is between those of the two SCGs; less modestly one could claim that the noise level for the BFO record is as low as that for the Bad Homburg data. Anyway, the noise level of the spring gravimeter compares well with the two others. No conclusion is drawn except that high quality records can be obtained with spring instruments in the daily tidal band.

While there is slightly more residual tidal energy in the BFO data than in the Bad Homburg

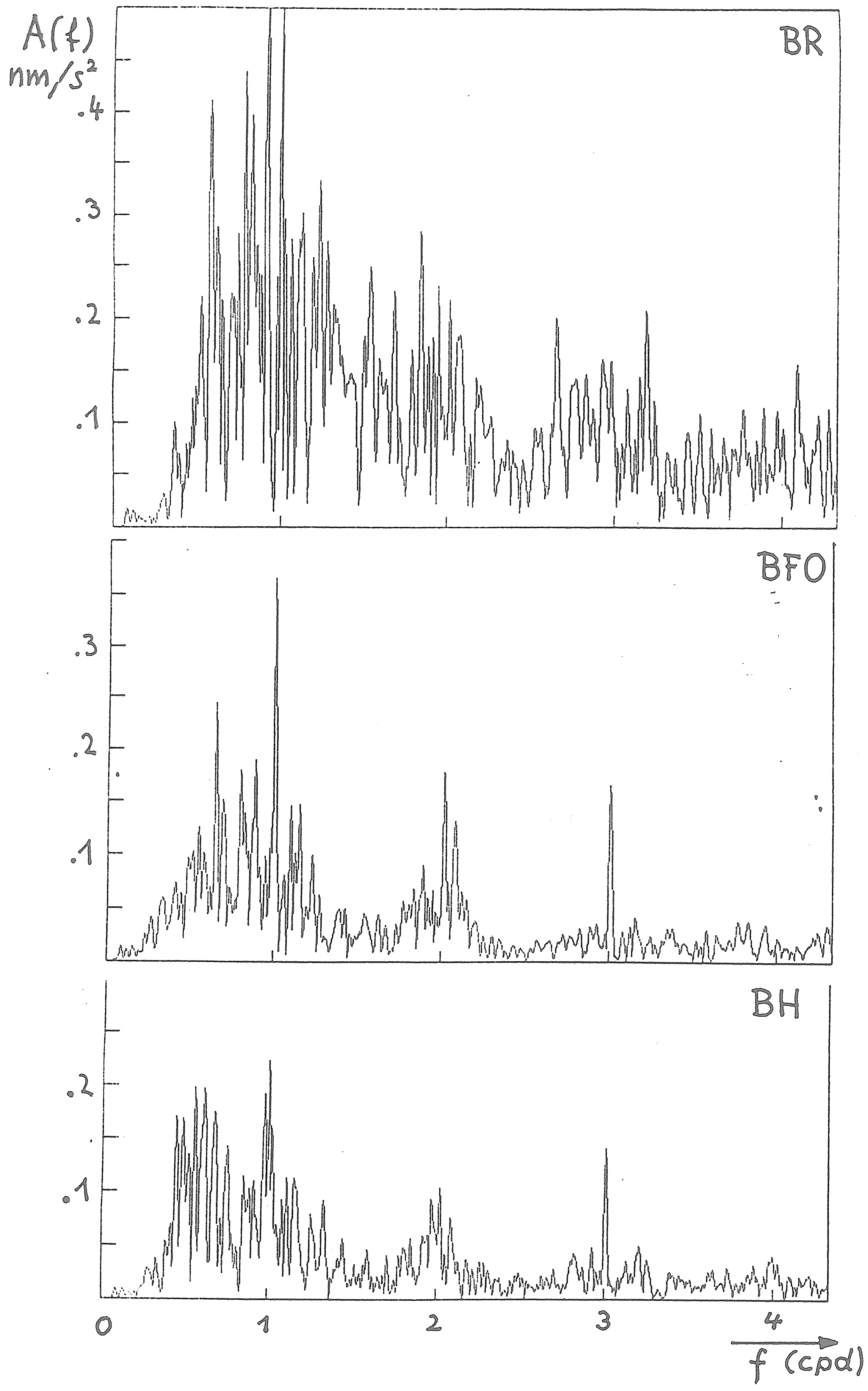

Figure 1: Spectra of gravity residuals after tidal analysis with ETERNA using the TAMURA (1987) potential and including local barometric pressure. Records of 90 days were selected from the SCG at Brussels (Jan - Apr 1989, top), the ET 19 at BFO (Jan - Apr 1989, middle) and the SCG at Bad Homburg (Jan - Apr 1982, bottom).

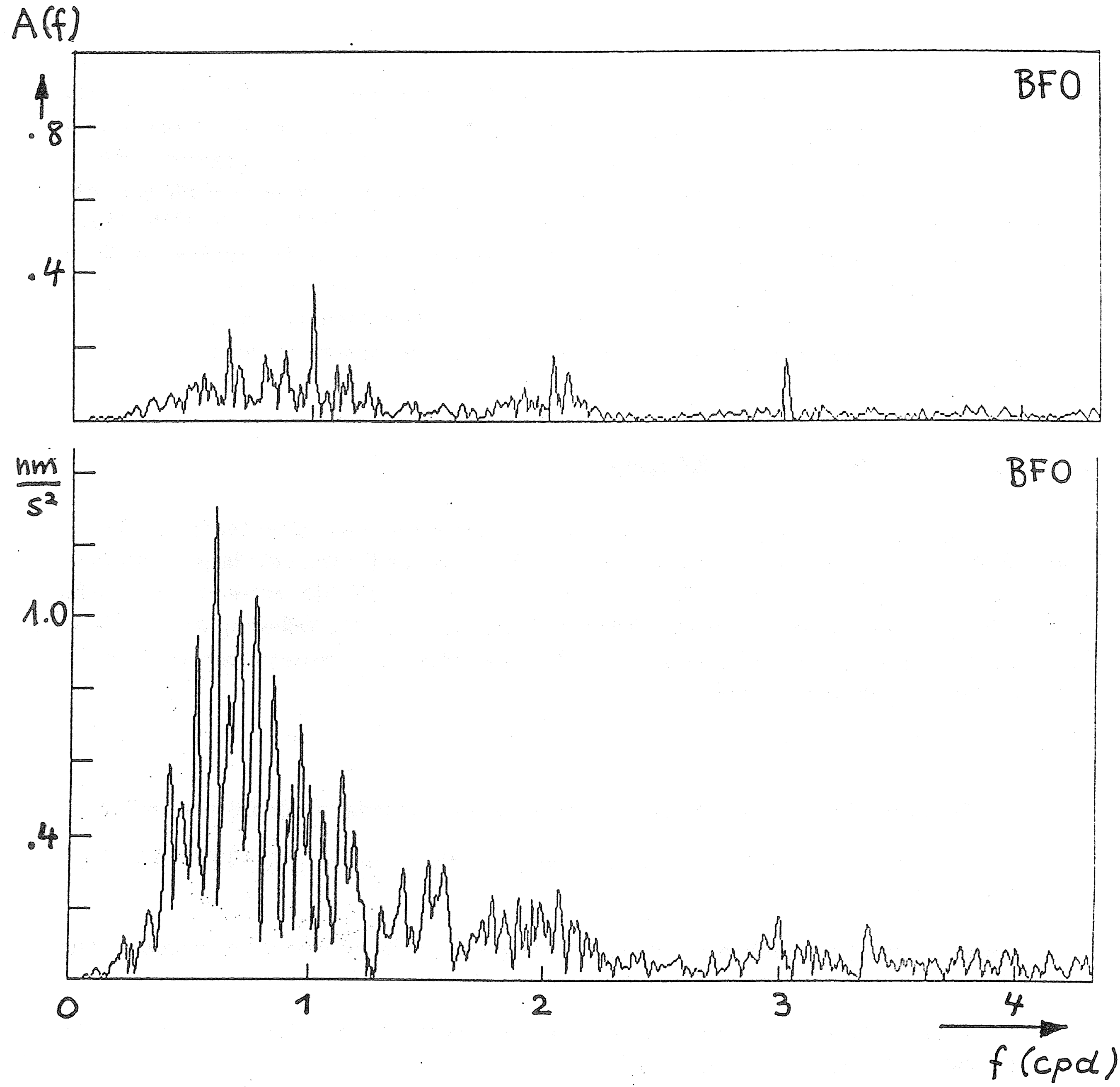

Figure 2: The top panel shows the spectrum of gravimeter ET 19 at BFO from Fig. 1 at a different scale. The bottom panel shows the residual spectrum after analysis without the local barometric pressure.

data, the noise energy between the tidal bands is very similar. These are the frequency ranges where the searches for core and Slichter modes have to be carried out. CUMMINS et al. (1991) have conducted such a search with the IDA network data and present a review of recent observational activities. Since the amplitudes of these modes are functions of position on the surface of the earth, these (best) spring gravimeters can help the SCGs in the search. This is especially important, because the logistical efforts in operating a SCG is an order of magnitude larger than for even the best spring devices.

Fig. 2 shows again the residual spectrum of the BFO data, once with local barometric pressure effects included in the analysis and once without this correction. The effect on the noise levels in the residuals is quite dramatic, despite the fact that the mathematical model used (a simple linear relationship between gravity and local barometric pressure without time- or frequency dependence) is hardly adequate to describe the complicated physics (e.g. MÜLLER and ZÜRN, 1983; RABBEL and ZSCHAU, 1985; VAN DAM and WAHR, 1987). Models describing the physics better could lead to further reduction of the residual variance. The subtraction of imperfect models of atmospherically caused gravity variations can, of course, introduce energy into the residuals which is not of gravitational origin. This has to be kept in mind, when detection of new phenomena like core modes is the purpose of the data analysis.

4 Seismic Normal Modes

The IDA - network of spring gravimeters was established a few years after the large Chilean (1960) and Alaskan (1964) earthquakes in order to be prepared for the next large excitations of the earth's seismic free modes. This network has been scientifically extremely successful (see AGNEW et al. (1986) or DAVIS (1989) for reviews). In the following only a few of the achievements are listed and only a few of the large number of research papers are given (with apologies to those not cited).

- Identification of more than thousand spheroidal and toroidal mode frequencies
- Measurement of the quality factors Q of many of those modes (MASTERS and GILBERT, 1983)
- Measurement of the multiplet splitting of some spheroidal modes of low angular order (BULAND et al., 1979; RITZWOLLER et al., 1986)
- Derivation of large - scale heterogeneity in the mantle (MASTERS et al., 1982) from the global distribution of peak - shifts
- The identification of Coriolis coupling between spheroidal and toroidal modes as an important effect in a certain frequency band (MASTERS et al., 1983)
- Tentative detection of 'silent' earthquakes (BEROZA and JORDAN, 1990)

- Measurement of the frequency of the breathing mode ${}_0S_0$ with an accuracy of 4 ppm (RIEDESEL et al., 1980) and its extremely high Q

Meanwhile very-broad-band seismographs have been developped (e.g. WIELANDT and STEIM, 1986), which are capable of recording the free oscillations of the earth with comparable quality, for example GEOSCOPE (ROMANOWICZ et al., 1984). Some years ago an international Federation of Digital broad-band seismic Networks was established to coordinate different efforts to achieve global coverage with such instruments. In the very near future about hundred stations globally distributed will be able to record the earth's free modes with high quality.
Here we will show a few examples of free mode spectra obtained from the mode channel of the spring gravimeter at BFO. The quality of this data is similar to the ones from the IDA and other modern long period seismic stations. In passing we point out that the variance reduction in the noise attained by fitting local barometric pressure to the time series is not as large as for the longer periods, because the dynamics of the atmosphere becomes important (MÜLLER and ZÜRN, 1983). The data examples shown have not been treated in any way with barometric pressure.
Fig. 3 shows the spectrum of a record 9 days long starting 6 days after the 1985 Chilean quake (March 3, 1985, Magnitude 7.8). The time series was bandpass filtered to remove the residual tides in the mode channel and to avoid aliassing in the resampling process. The sampling rate was reduced from 1/4 Hz to 1/60 Hz. Before spectral analysis a Hanning window was applied to the data. The only mode above the noise is ${}_0S_0$ (the 'breathing' mode), which due to its large Q of about 5000 to 6000 decays very slowly, while all the other spheroidal modes have decayed into the noise after about three days. The average amplitude of this mode in this record is 2.7 ngals.
The disastrous Mexican earthquake of September 19, 1985 also excited low angular order free modes to observable amplitudes. The low frequency part of the spectrum of a time series with a length of 33 hours (Hanning window) starting a few hours after the first arrivals is shown in Fig. 4. The saturation of the instrument due to the arrival of the first train of Rayleigh waves and a very large aftershock 36 hours after the main shock limit the length of the usable time series. Nevertheless all the fundamental spheroidal modes, including the rarely seen ${}_0S_2$ with 54 min period, and a few overtones are identified. In this figure the squared amplitude is plotted, in contrast to all the others. For this quake a record from the tide channel of the SCG TT40 at Bad Homburg was made available to us. In Fig. 5 the spectrum of this data is compared to the mode channel data from BFO. The noise level in the SCG data is slightly higher, thus ${}_0S_2$ is inside the noise, while ${}_0S_3$ is already visible. But the higher noise level can be seen below the higher frequency modes also. The amplitudes of the modes below 8 cph are comparable in both spectra, while at higher frequencies the patterns are quite different. At BFO there is a distinct high-low variation around 12.5 cph, which is not present at Bad Homburg. At these higher frequencies the station separation starts to have an influence on the shape of the spectral envelope, while at lower angular orders there is no difference between the two stations 200 km apart. The slightly higher noise level in the SCG data is either due to slightly higher noise at the station or, more likely, due to filter, amplifier or data acquisition noise in the tide channel, which is not designed to be used for free oscillation recording. Unfortunately the mode channel was not recorded digitally at that time.
The great earthquake on the Macquarie Ridge on May 23, 1989 (magnitude 8.3) provided a new opportunity to record with high signal-to-noise ratio the free oscillations. Figures 6

and 7 show spectra of records from the BFO mode channel starting a few hours after the quake (Hanning window). Fig. 6 shows the low frequency end using a record of 86 hours. The mode ${}_0S_2$ is hidden in the noise, while ${}_0S_3$ clearly stands out. One misses ${}_0S_0$ supposed to be visible just to the left of ${}_0S_5$, the reason is that this quake excited radial modes very poorly, because of an almost pure strike-slip focal mechanism. However, PARK (1990) could show the radial modes in stacks of some IDA records, thus obtaining new information on the source process. Fig. 7 shows the spectral range between ${}_0S_{11}$ and ${}_0S_{21}$, where spheroidal-toroidal fundamental mode coupling is known to be strong. The toroidal mode ${}_0T_{12}$ shows up clearly next to ${}_0S_{11}$, while coupling is less strong at the higher order modes and consequently the amplitudes of the toroidal modes in the gravity record decrease.The length of this time series was 128 hrs.

5 Conclusions

We have demonstrated that some of the best spring gravimeters under favorable conditions and with extreme care could provide signal-to-noise ratios comparable to the ones achieved with superconducting gravimeters for periods of 14 days and shorter. The gravimeters are LaCoste - Romberg gravimeters equipped with electrostatic feedback and data were recorded digitally. It is not really clear at present at which periods the instrumentally caused noise becomes larger than the earth noise (including unavoidable gravity signals from the atmosphere and hydrosphere) at quiet sites, although AGNEW et al. (1986, Fig. 5) suggest that this is the case already at the low frequency end of the seismic normal mode spectrum. Since the magnetic spring of the SCGs is more stable than the metal alloy spring of the LaCoste-Romberg meters, it is expected that better signal-to-noise ratios can be obtained with the SCGs. This has not really been demonstrated at present except for periods of the order of one month and longer.

6 Acknowledgements

The records from the SCGs at Bad Homburg and Brussels were kindly provided by B. Richter and the International Center for Earth Tides (P. Melchior and B. Ducarme), respectively. W. Kaminski, M. Baumann, U. Beck, M. Flinspach and G. Polzer helped with the data processing of the BFO and Bad Homburg data. Discussions with P. A. Rydelek, B. Richter and H. Wilmes were very helpful and they also critically read the manuscript. Part of this work has been supported by the Deutsche Forschungsgemeinschaft grants for SFB - 108 / D9 at Karlsruhe University. All this help is gratefully acknowledged.

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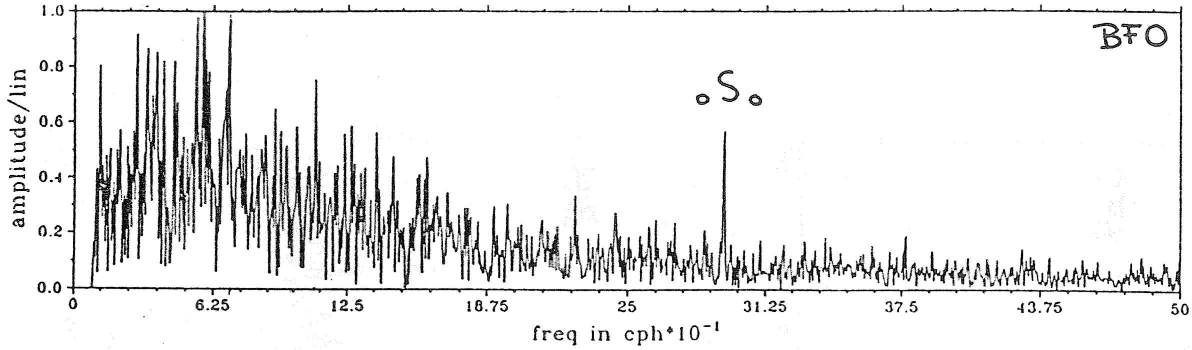

Figure 3: Spectrum from gravimeter ET 19 at BFO after the Chilean quake 1985. Time series 9 days long starting 6 days after the quake. Amplitude of $_0S_0$ is 2.7 ngals.

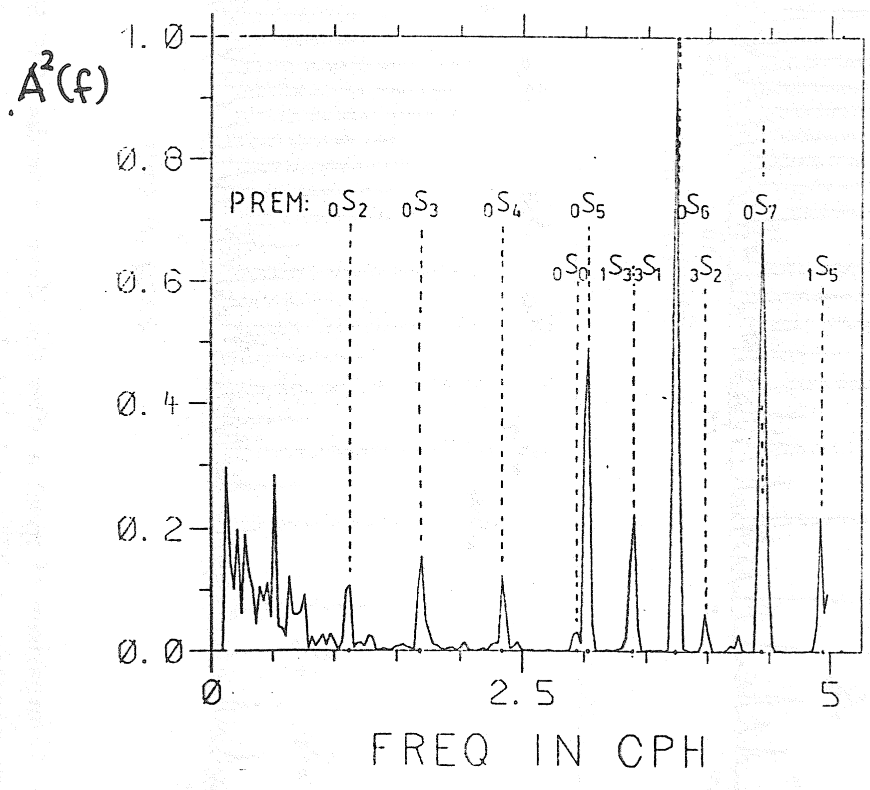

Figure 4: Spectrum from gravimeter ET 19 at BFO after Mexican quake 1985. Time series of 33 hours starting 3 hours after the quake. All fundamental spheroidal modes above the noise. Squared amplitudes, normalized to $_0S_6$, Hanning window.

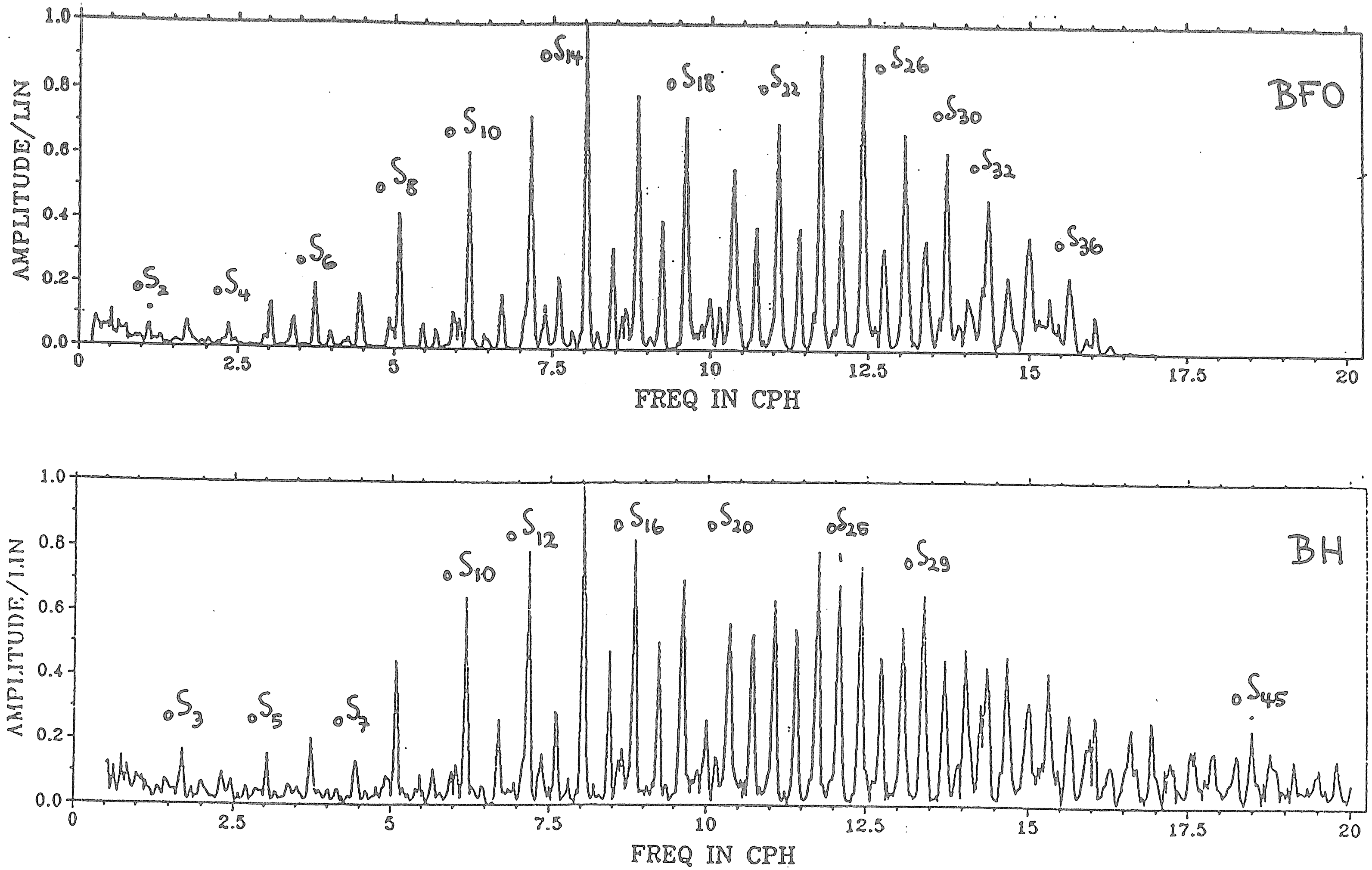

Figure 5: Comparison of spectra after the Mexican quake 1985 from spring and superconducting gravimeters at BFO and Bad Homburg, respectively. Amplitudes normalized to ${}_0S_{14}$.

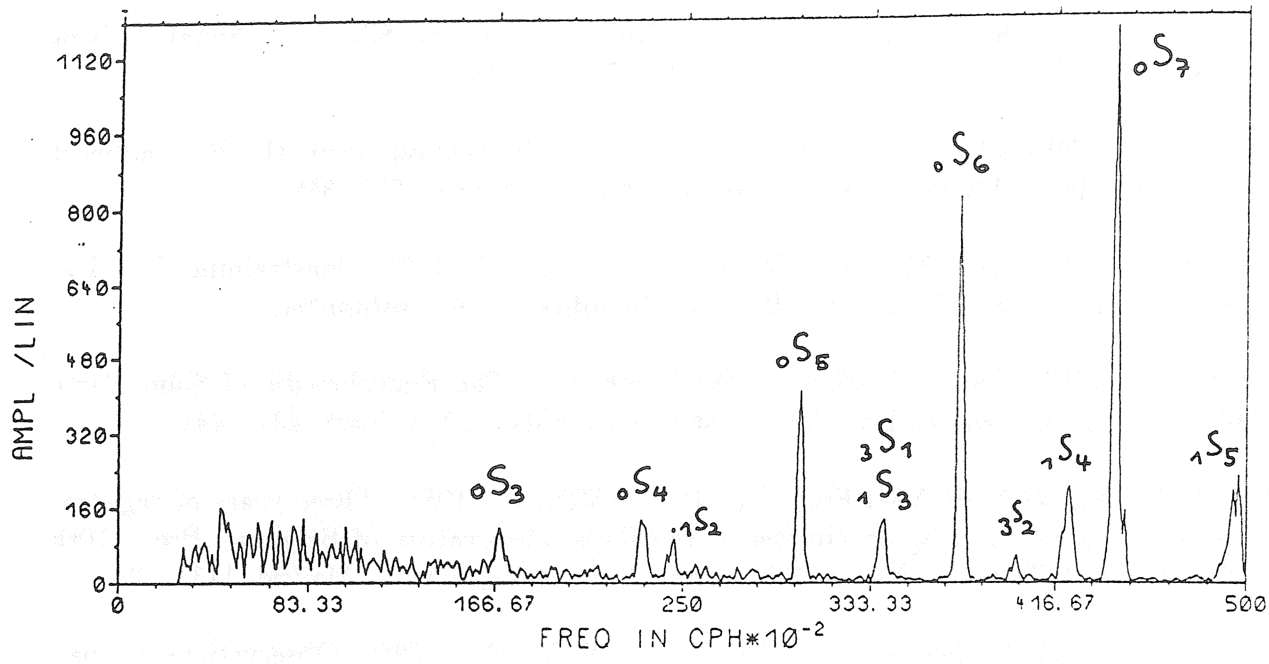

Figure 6: Spectrum from ET 19 mode channel at BFO after Macquarie Ridge quake 1989. Low frequency portion of spectrum. Amplitude in arbitrary units. Length of time series 86 hours, Hanning window.

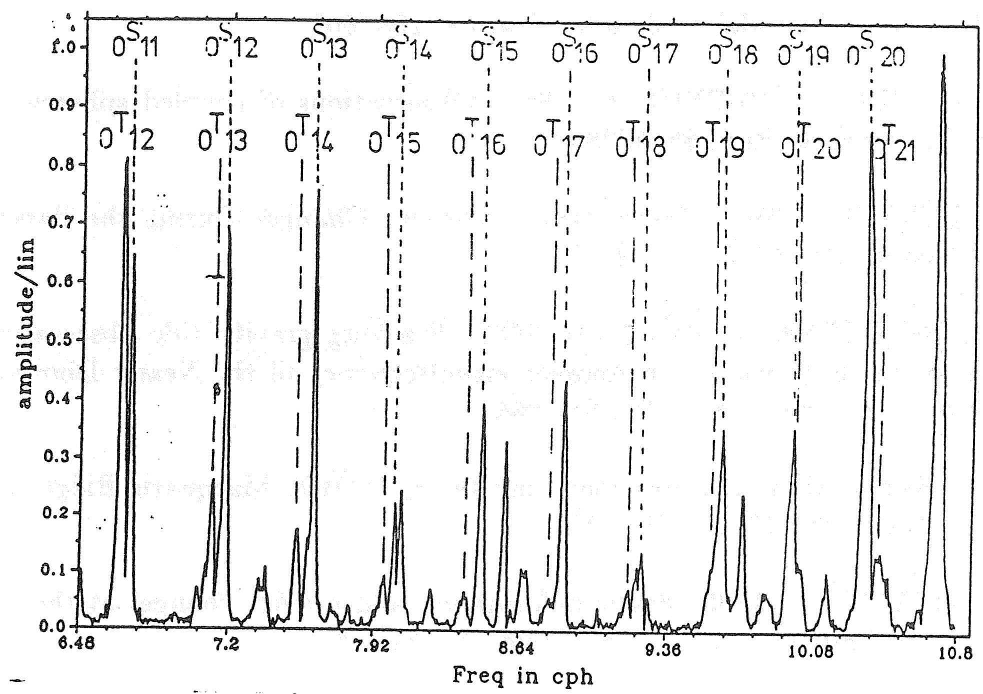

Figure 7: Spectrum from ET 19 mode channel at BFO after Macquarie Ridge quake 1989. Portion of spectrum showing toroidal-spheroidal mode coupling. Amplitudes normalized to $_0S_{21}$, length of time series 128 hours, Hanning window.

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SOME PROBLEMS OF TIDAL RECORDING WITH ASKANIA GRAVIMETERS

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Introduction

A gravimetric tidal recording may be described by a known formula which is valid for a linear dynamic system:

$$y(t) = S\int_{-\infty}^{\infty} x(\tau)\, w(t-\tau)\, d\tau + y_0 , \qquad (1)$$

where is

$x(\tau)$ - input function (changes of gravity),
$y(t)$ - output function (recorded ordinates),
S - record sensitivity,
y_0 - constant value,
$w(t-\tau)$ - weighting function, dimensionless, equal to zero for $\tau > t$.

The main charakteristics of the tidal apparatus S and $w(t-\tau)$ must be accurately controlled to obtain real values of tidal waves parameters. The record scale value $k = S^{-1}$ affects the values of gravimetric factors δ and is determined by record calibration. The Fourier transform $W(\omega)$ of the weighting function $w(t-\tau)$ represents the instrumental damping effect, for which the phase lags $\varkappa$ of the tidal waves must be corrected. The unit step method is used mostly for its determination.

Further we shortly describe the methods used for the determination of both these instrumental characteristics at the Pecný station, where Askania gravimeters are being used.

Record calibration

The electromagnetic calibration cannot give the absolute record scale values. Therefore, for basic calibrations the measuring screw is being used. Its scale must be controlled by the micrometer for linearity and calibrated on a gravimetric base line. There is no problem to achieve an accuracy better than 0.1% in this calibration if we use a sufficient great gravity difference.

The problem lies in the linear subdivision of the calibrated scale with recpect to the small range of the record. We have found that the micrometer of the Askania gravimeters does not work linearly, its nonlinearity may achieve up to 3%.

For the control of the micrometer nonlinearity a small value must be measured by the micrometer on different parts of its scale. The simpliest way would be to make an additional line on the gravimeter measuring scale for this reason near one of its lines, see Fig. 1.

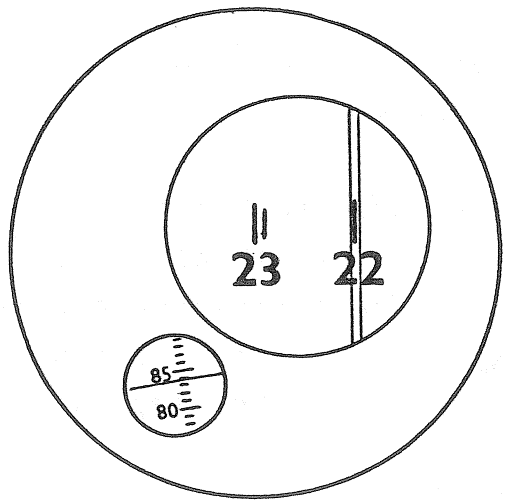

Fig. 1.

Instead of them one of the numbers on the scale may be used. Yet it is not the same, as another part of the micrometer double line is used during the calibration. Therefore, we measure an unit of the output signal by multiply record calibration on different parts of the micrometer scale, i.e. at different settings of the measuring screw. In this case the output signal must be compensated to save it in the recording device range. Moreover, the nonlinearity of the transducer of the lever arm movement must be eliminated.

In evaluating the record calibration, each micrometer reading must be separately corrected for the micrometer nonlinearity. The same holds for the micrometer run error.

It was found at some gravimeters that the micrometer nonlinearity changes with time. In such a case it is better to calibrate the record without using the micrometer. The measuring screw is shifted by a whole measuring scale value (~5mGal). Also here the output signal must be compensated and the transducer nonlinearity eliminated.

Detailed description of the mentioned methods of record calibration has been published in (Brož et al. 1983), (Brož 1986), (Brož et al. 1989), (Volkov et al. 1990) and (Dittfeld et al., in print).

At some gravimeters the transition process after a step change on the input lasts very long and we are not sure, during the record calibration, that the chosen time interval between the shifts is sufficient and that we have obtained correct results. In this case we use two kinds of record calibration.

The first one is the usual method of calibration "from inside", see Fig. 2. Here we have three shifts between the end positions y_{max}, y_{min} . The transition curves are A,B,C, their ordinates $y_A(t_r), y_B(t_r), y_C(t_r)$; t_r is the time measured at each curve from the moment of the step. We can calculate a series of differences

$$\Delta y(t_r) = \frac{1}{2}\left[y_A(t_r)+y_C(t_r)\right] - y_B(t_r) \, , \qquad (2)$$

from which the linear part of the drift and tides are eliminated. It convergates to the value $\Delta y = y_{max} - y_{min}$. Using the rests

$$z(t_r) = y_{max} - y_A(t_r) = y_{max} - y_C(t_r) = y_B(t_r) - y_{min} \qquad (3)$$

we can write

$$\Delta y_1(t_r) = \Delta y - 2\, z(t_r). \qquad (4)$$

Corresponding series of "record scale values" is

$$k_1(t_r) = \Delta g/\Delta y_1(t_r) = \Delta g/[\Delta y - 2z(t_r)] = \frac{\Delta g}{\Delta y}\left\{1 + \frac{2z(t_r)}{\Delta y} + \left[\frac{2z(t_r)}{\Delta y}\right]^2 + \ldots\right\}. \qquad (5)$$

Usually it is a sinking series convergating to the correct scale value k . In Eq. (5) Δg is the shift in microgal given by the measuring screw.

The second kind of calibration "from outside" is on Fig.3.

The amplitudes of the curves B and D are twice greater than that of curves A,C,E . For calculation we use the ordinates $y_A(t_r)$, $y_C(t_r)$, $y_E(t_r)$. We have a series of differences

$$y_2(t_r) = \Delta y + 2z(t_r) \tag{6}$$

free from linear drift and tides and a corresponding series

$$k_2(t_r) = \Delta g/\Delta y_2(t_r) = \Delta g/[\Delta y + 2z(t_r)] = \frac{\Delta g}{\Delta y}\left\{1 - \frac{2z(t_r)}{\Delta y} + \left[\frac{2z(t_r)}{\Delta y}\right]^2 - \dots\right\} . \tag{7}$$

From Eq. (4) and (6) it is

$$\Delta y = \frac{1}{2}[\Delta y_1(t_r) + \Delta y_2(t_r)] . \tag{8}$$

It means that we receive a correct shift value Δy for all t_r with exception of the initial ones, which may be affected by the not finished response to the previous step. For greater t_r we have from Eq. (5) and (7) a correct scale value

$$k = \frac{1}{2}[k_1(t_r) + k_2(t_r)] . \tag{9}$$

As the result we can take the mean of several last k values.

Instrumental damping corrections

Usually we use the unit step method for determination of these corrections. The ordinates of the registrated response curve must be freed from the drift before evaluation, which is always difficult.

But we have the possibility to obtain a corrected response curve from the results of the first kind of record calibration. By adding the value Δy to the Eq. (4) we have

$$\Delta y_1(t_r) + \Delta y = 2\Delta y - 2z(t_r) , \tag{11}$$

which is a response curve with a double amplitude. It is free from the linear change in y during the whole interval $3\Delta t$ of calibration, i.e. from linear drift and tides. Further, by multiplication by $100/\Delta y$ we receive a response curve normalised to the amplitude 200 on output:

$$\Delta Y(t_r) = \frac{100}{\Delta y}\Delta y_1(t_r) + 100 = \frac{200}{\Delta y}[\Delta y - z(t_r)] . \tag{12}$$

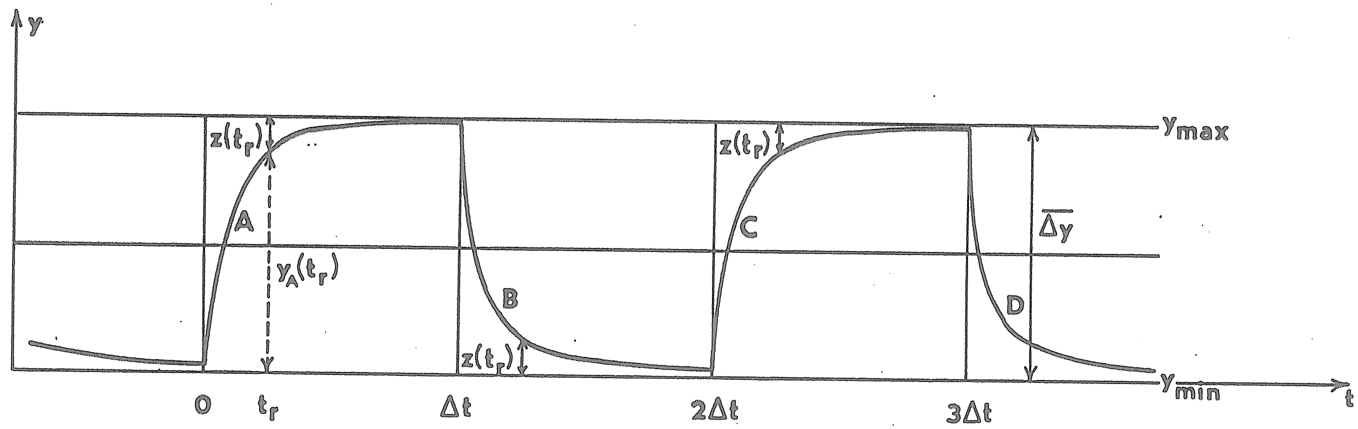

Fig. 2. 1st kind of calibration.

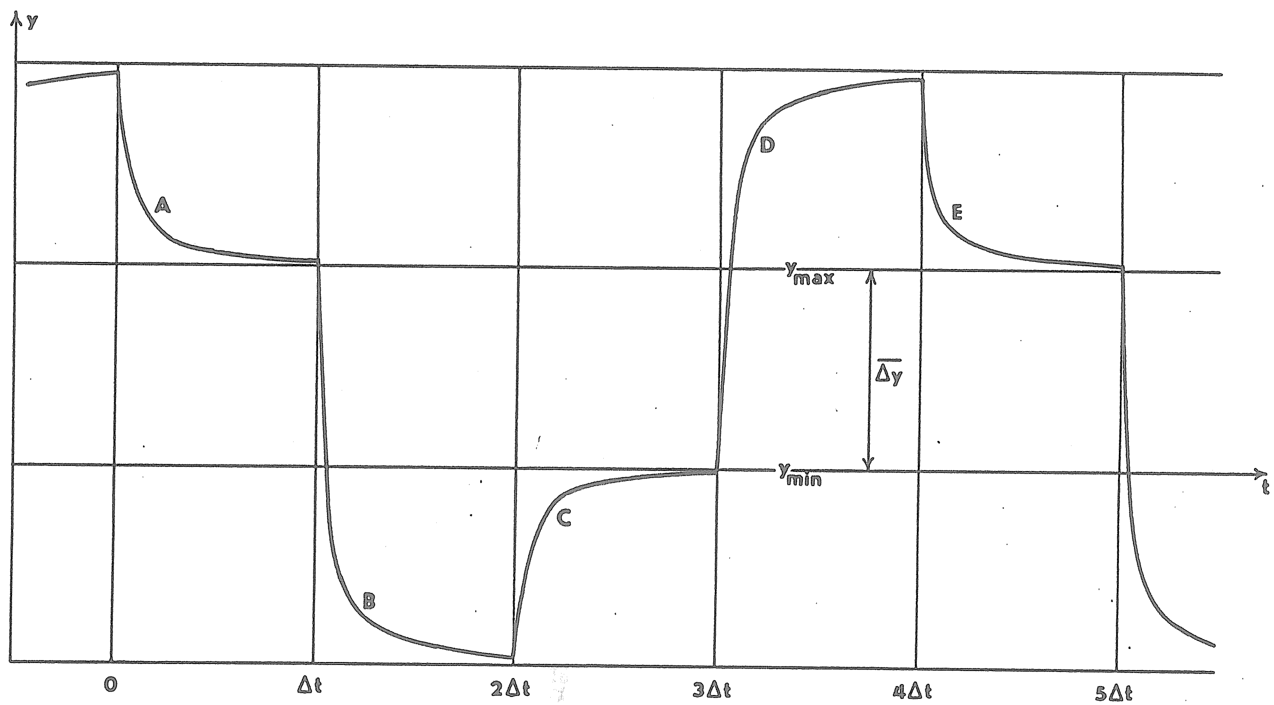

Fig. 3. 2nd kind of calibration.

This normalisation enables us a common evaluation of many experiments in which the shifts Δy are not exactly equal.

From Eq. (5) it is

$$\Delta y - z(t_r) = \frac{1}{2}[\Delta y + \Delta g / k_1(t_r)]$$

and because $\Delta g = k \Delta y$

$$\Delta y - z(t_r) = \frac{\Delta y}{2} [1 + k / k_1(t_r)] .$$

After substituting this in Eq. (12) we obtaine also

$$\Delta Y(t_r) = 100 [1 + k / k_1(t_r)] . \qquad (13)$$

So, using the series of sinking values $k_1(t_r)$ and its limiting value k we are able to construct the response curve which is free from the linear drift. Because of the normalisation to the amplitude 200 we can evaluate a mean curve from all experiment (shifts), which may be used to evaluate the corrections of the measured phase shifts.

Conclusion

The mentioned methods of record calibration enabled us to reach at our station a good agreement beween the δ factors resulting from measurements with different gravimeters (to 1×10^{-3} with the main waves). They are in full agreement with the theoretical Earth Tide model Wahr-Dehant (Šimon, Zeman 1989).

The described method of drift elimination from the response curve will be used for future determinations of damping corrections. The question of real values of the phase shifts $\varkappa$ is very actual now (Melchior, Ducarme 1989).

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SOME PROBLEMS OF THE CALIBRATION OF RECORDING GRAVIMETERS

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The study of the earth tides needs a real improvement of the calibration methods. It was mentioned by many authors (see for example Molodensky and Kramer, 1980) that gravimetric body tide anomalies in principle can be used for the study of lateral heterogeneities of the earth's structure. For a better understanding of the gravity earth tidal parameter (δ and κ) obtained from the tidal records we need an absolute calibration accuracy better than 0.1%. For the study of temporal variations of the gravity we must be sure that the time stability of the record scale is good enough. Recently a difference has been observed between constants of gravity obtained from laboratory measurements with torsion balances and those obtained from large scale determinations using different geological units. The first attempt of gravity constant measurements on a scale much larger than the laboratory determinations was done by G.B. Airy in the middle of the last century. Similar work was done slightly later on by Sterneck in Pribram (1883). The principle of these large scales, so called geophysical, gravity constant (G) determinations is simple. Measurements of the gravity at different surface levels are compared. A collection of recent geophysical G determinations was published by Stacey et al. in 1987. These values differ significantly from those obtained in laboratories (table 1). It can be concluded that G values of two different types show a systematic difference of the order of 1%. It seems to us that this difference, which is of great importance if it is a real one, can be investigated by means of calibrating gravimeters in different ways.

In our study, which aims at investigating the above problems, we need both relative and absolute calibrations.

Table 1: Laboratory and large scale G determinations

G laboratory		George scale (Stacey et al.1987)		
author	$G \times 10^{11}$	author	depth (m)	$G \times 10^{11}$
Facey, Pontikis (1972)	6.6714 ± 0.0006	Mc'Culloh	0 –648.8	6.733
			57.3–2085	6.793
Sapitov et al.(1981)	6.6744 ± 0.0008		223.0–3890	6.724
			418.0–648.8	6.726
Luther,Towler (1983)	6.6726 ± 0.0005	Hinz et al.	371.2–396.3	6.746
		Hussian et al.	251 –590	6.810
"Mean"	6.673 ± 0.0045	"Mean"		6.740±0.1%

The relative calibration is necessary for the study of the record scale and (or) for the investigation of the temporal variations of the gravity. This type of calibration can be carried out in different ways. We used, for example, an electrostatic calibration device. On the plates of the calibration unit we used (15.000± 0.001) V every day. The results which have been obtained from 1988 until the middle of 1990 show that the record scale has been stable during this time interval within an error limit of 0.05%.

The absolute calibration of the gravimeters is a more complicated problem. As was mentioned above we need an accuracy for this type of measurement better than 1/10 % for solving the problems in gravity earth tide research. The comparison of instrumental intercalibration results (Gerstenecker, Varga, 1986) shows that the typical deviation between instruments is of the order 0.4% in δ and 0.3° - 0.4° in κ. The unknown with the required accuracy calibration is the most important source of errors in earth tide gravity. The same error limits have been found in our practice during parallel recording at the Budapest Geodynamic Observatory (Meurers et al., 1990, Broz et al., 1990) (Table 2).

Table 2

	LCR D-9* 1987-88, 236 days		GS-11 190** 1988, 201 days		GS-15 228*** 1984	
1	δ	$\kappa[°]$	δ	$\kappa[°]$	δ	$\kappa[°]$
O_1	1.1475	− 0.118	1.1515	0.134	1.1496	0.064
K_1	1.1307	0.035	1.1378	− 0.071	1.1362	0.031
M_2	1.1763	− 0.843	1.1813	− 0.366	1.1823	− 0.769
S_2	1.1514	− 0.122	1.1764	− 0.451	1.1855	− 0.490

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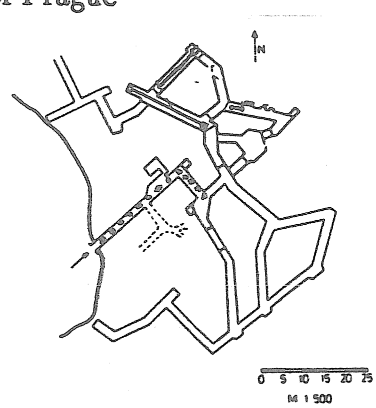

Fig.1: Plan of the Geodynamic Observatory
... — the calibration line, o o o — recording gravimeters, |——□ — extensometers

to solve the problem of absolute calibration with an accuracy better than 0.1% we are developing two different techniques at the Budapest Geodynamic Observatory (Fig.1). The observatory is situated in the Matyas-hegy cave.
In this place an underground gravity calibration line was installed which has a range of Δg = 1300 microgal and consists of 14 points (stations). The gravity difference between the points is 100 microgal. Our calibration line is almost perfectly horizontal. The height difference of neighbouring stations lies between 1 - 12 mm, and the maximal difference is 60 mm. On every measuring point the LCR type gravimeters can be installed with an accuracy of 1 mm. These features of our line

- allow to avoid the influence of barometric influences due to height differences
- the temperature variations are small (in the course of one day less than 0.1°C and the annual variations are of the order 1°C).
- on every point the measurements can be carried out in the identical azimuths with an orientation accuracy better than 5°.

The most important fact was that due to the horizontality we could calibrate our line in an absolute scale and independently of the gravimeters. To do so it was necessary to reconstruct an old Eötvös torsion balance and to complete it with a computer regulation. Then the gravity differences of the measuring points were determined by using torsion balance. At every station the horizontal gravity gradients have been determined in five directions (three recording series in each). Considering the smallness of the distances separating the measuring points and the level differences we can neglect the non-linearity of the gravity field variations and can determine the gravity differences based upon the gradients, which have been obtained at neighbouring stations directed along the calibration line and measured in both directions as $\Delta g = (G_1 + G_2 / 2).s$ (where G_1 and G_2 are the corresponding gradient values and s is the distance between neighbouring stations). In doing so we managed to determine the gravity differences with an accuracy of 0.1 microgal at a level of 54 cm above the floor of the cave on an absolute scale and without using any gravimeters. Due to the unknown but existing vertical gradients of gravity a special tripod was constructed which allows measurements on this level with LCR type equipment. It is worth mentioning that at the station a recording gravimeter is always in operation. This is important for the calibration procedure because the recorded temporal variations allow one to obtain some necessary additional information (e.g. strong microseismic activity). The temporal variation of the air pressure and the temperature in and around the station are also permanently recorded.
At the same time there is another calibration device in the construction which has been described in a former paper (Varga, 1988). This equipment can generate gravity variations of different magnitudes up to 200 microgals (Fig.2) with the use of a vertically moved heavy and homogeneous circular ring.

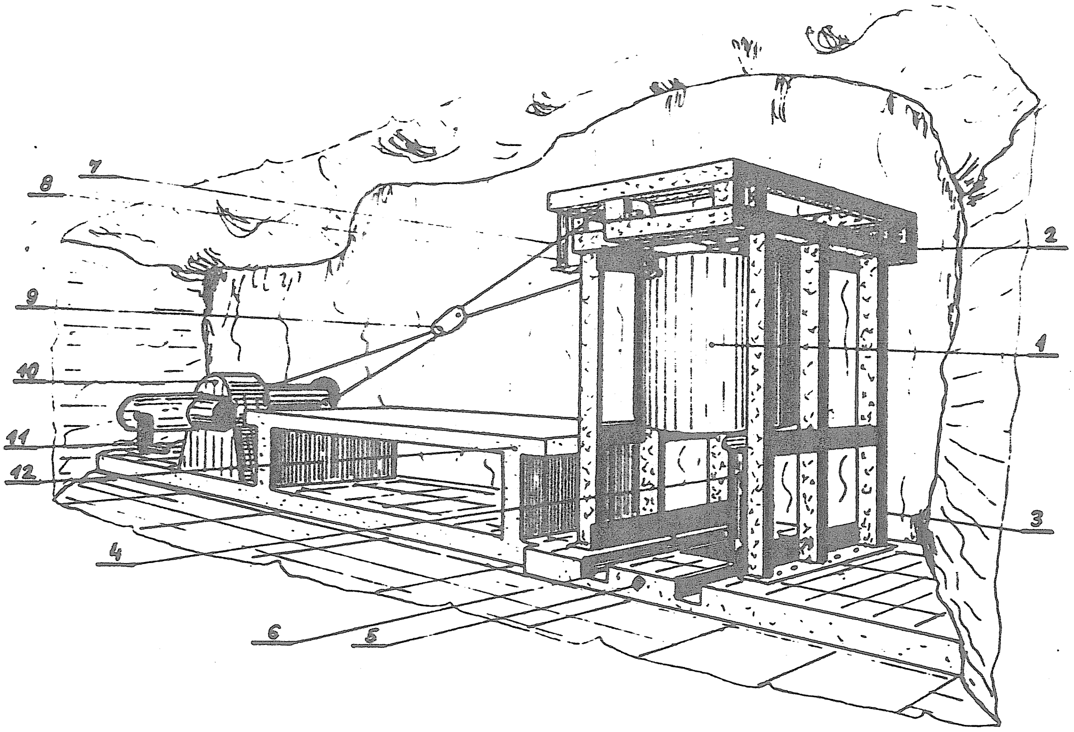

Fig.2. Calibration device based on gravity effect produced by a vertically moved heavy circular ring.

The positive features of such a gravity scale determination are:

1. the homogeneity of the field at the extremes of the generated gravity effect
2. the raised and lowered ring around the instrument does not load the ground around the meter
3. the gravimeter remains stationary during the procedure
4. due to technical reasons the gravity change caused by the ring is greater than the one caused by other geometrically regular bodies (e.g. a sphere)

It was found out earlier that in this way we are able to calibrate with an accuracy of 0.1% which is convenient to solve the problems connected with the earth tide measurements on the one hand and the problem of different G values valid in macro- and laboratory ranges on the other hand. In this last case the solution is the comparison of calibration results obtained with the suspended and vertically moved heavy circular ring and along our calibration line.

It is remarkable that in the case of calibration with the circular ring the gravimeter to be investigated is installed in the same direction and on the same level as in the case of the measurements in the gravity calibration line. The mass of the suspended ring may vary from 0.5 to 3 tons.

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The high frequency signals in high rate tidal data: Noise spectra from different tidal observations

by
G. JENTZSCH [1] and J. MELZER [2]

1. Introduction

The investigation of the high frequency spectrum (50-5000 seconds) of tidal observations is important for the estimation of the noise level at different stations and the resolution of the instruments.
We show a comparison of four digital datasets according to different configurations (instrument/recording system) at 3 stations: Berlin/Germany, Metsähovi/Finland and Wuhan/China.
The aim of this work is to examine the quality of the records regarding the instrument and the station according to high frequency signals especially for the analysis of the earth's free oscillations.

2. Instrumentation and digital recording systems

From 1978 to 1980 we used the LaCoste-Romberg ET18 with mechanical feedback - as delivered by the manufacturer - at the former tidal observatory in Berlin. The signal was recorded with a resolution of 14 bit (11 bit for the tides) at a sample rate of 60 seconds on data cassettes (Tab. 1 and Tab. 2).
In 1983 the instrument was transformed to electrostatic feedback by Larson and started recording again from 1984-1985 at Berlin. The signal was recorded at a sample rate of 30 seconds and 12 bit resolution, still allowing 11 bit for the tides like from 1978 to 1980.

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Since April 1987 the gravimeter is recording at Metsähovi/Finland making use of the new 22 bit multi-channel recording system developed by Dr. Asch (*ASCH,* 1988; *ALMS* et al., 1989).
This recording system combines a digital voltmeter (6 1/2 digits) averaging over 10 seconds and over-sampling to provide the data with a resolution of 22 bit every 20 seconds. This system is also used in Wuhan/China since 1988 with the Superconducting Gravimeter GWR-TT70 (*JAHR* et al., 1990, same issue).

3. Noise spectra

In the range of 50 to 5000 seconds we mostly have stochastic data with continuous spectrum. In a usual Fourier spectrum we therefore have a random distribution of each Fourier coefficient and varying density of coefficients over period - decreasing with increasing periods.
To solve both problems a Power Spectral Density (PSD) which is the normalization of the coefficients over a constant bandwidth must be calculated (*GADE* & *HERLUFSEN,* 1987) - leading to a quadratic spectrum.
The noise investigation follows the basic ideas of *WIELANDT* & *STRECKEISEN* (1982), *WIELANDT* & *STEIM* (1986), *ZÜRN* (pers. comm. 1986) and *ASCH* (1988): Calculation of Fourier spectrum using a Hanning window and determination of PSD by normalizing over 1/6 decade. For comparison with other works a reduction to sqrt(PSD) is done, resulting in the dimension ngal/sqrt(Hz).
According to *ASCH* (1988) who got consistent results by using 4096 20-second-samples (22h 45m 20s) which is nearly one day we used 2048 values (17h 04m 00s) sampled at 30 seconds and 1024 values (17h 04m 00s) sampled at 60 seconds, respectively (see Tab. 1 and Tab. 2). Thus, we have 57, 84 and 123 seconds for the shortest periods in the PSD depending on the sample rates 20, 30 and 60 seconds; as longest period for all data sets we choose 39000 seconds due to the presence of deterministic signals at longer periods. This results in 18, 17 and 16 values in the PSD for the sample rates of 20, 30 and 60 seconds, respectively.
We had to correct the data recorded with the ET18 in mechanical feedback version for the instrumental function given by the manufacturer (Fig. 1); for the other data sets this as well as the correction for the transferfunction of the recording system could be neglected because of no significant influence.

4. Results and comparison

A comparison of noise spectra from the LCR ET18 at the station Berlin with mechanical and electrostatic feedback, respectively, is given in Fig. 2. The lower level of the mechanical feedback in the interval $2*10^2$ to $4*10^3$ seconds is due to instrumental effects which artificially damp all signals with periods less than 5 minutes (see Tab. 2). This could not be reasonably explained with the instrumental function given in Fig. 1. The noise level of the electrostatic feedback system within a range of 10 to 40 ngal/sqrt(Hz) is therefore nearly one decade higher. This demonstrates the possibility to detect high frequency signals with the converted system. However high frequency signals at this station are mainly due to man-made noise.

The noise spectra from the station Metsähovi presented in Fig. 3 show the high quality of the sensor, the recording system and the station: With a few ngal/sqrt(Hz) the noise level is clearly below that at the station Berlin especially at periods of the free oscillations.

The noise spectra in Fig. 4 are typical for data of the years 1988, 1989 and 1990 at the station Wuhan. Obviously the noise level is at least more than half a decade higher compared to Metsähovi even in the important interval of 200 to 3600 seconds and thus reducing the signal to noise ratio for the analysis of free oscillations significantly. The curve with a very high level ranging from some 10 to some 100 ngal/sqrt(Hz) is due to an earthquake south of Alaska on September 4th 1989 (m_b=6.9).

For comparison typical noise bands for the 4 different configurations are shown in Fig. 5 and additionally that received at Zürich/Switzerland with the long-period leaf-spring seismometers (*WIELANDT & STRECKEISEN*, 1982).

5. Conclusion

As demonstrated by Fig. 2 the conversion of the LCR ET18 to electrostatic feedback made the sensor sensitive for high frequency signals. The comparison of the four investigated configurations with the results from the long-period seismometers at Zürich (Fig. 5) demonstrates the quality of the configuration LCR ET18 and the recording system at the station Metsähovi to monitor high frequency signals especially in the period of the free oscillations of the earth. Compared to Metsähovi the location Wuhan with the Superconducting Gravimeter GWR-TT70 is not ideal situated. This is also

represented by the results of the tidal analysis (*JAHR* et al., *1990,* same issue). The responsible Chinese staff prepares a new observatory outside the city, right now (Prof. H. *HSU*, pers.comm.).
We consider a suitable location at least as important as the choice for the type of instrument and therefore in future we suggest to have a detailed seismic pre-investigation for the determination of the station site.

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Tab. 1: Summary of digital recording periods, geographical coordinates and station conditions

Period	Station	subsoil condition	remarks
1978-1980 & 1984-1985	Berlin 65.7091°N 15.2631°E	cellar in observatory on artificial hill	noise from city mainly man-made
since 1987	Metsähovi 60.2179°N 24.3954°E	solid block on bedrock	great distance to traffic
since 1988	Wuhan 30.5333°N 114.3500°E	solid block in sediment	high noise from traffic and industry

Tab. 2: Stations, instruments and recording systems

Station	Instrument	cutoff-period for instrument and record. syst.	dynamic range and sample rate
Berlin 1978-1980	LCR-ET18 (mechanical feedback)	> 5 min	14 bit 11 bit for tides 60s-samples
Berlin 1984-1985	LCR-ET18 (electrostatic feedback)	≈20s 40s	12 bit 11 bit for tides 30s-samples
Metsähovi since 1987	LCR-ET18 (electrostatic feedback)	≈20s ~1 min	22 bit 18 bit for tides 20s-samples
Wuhan since 1988	GWR-TT70	≈ 1s 40s	22 bit 16 bit for tides 20s-samples

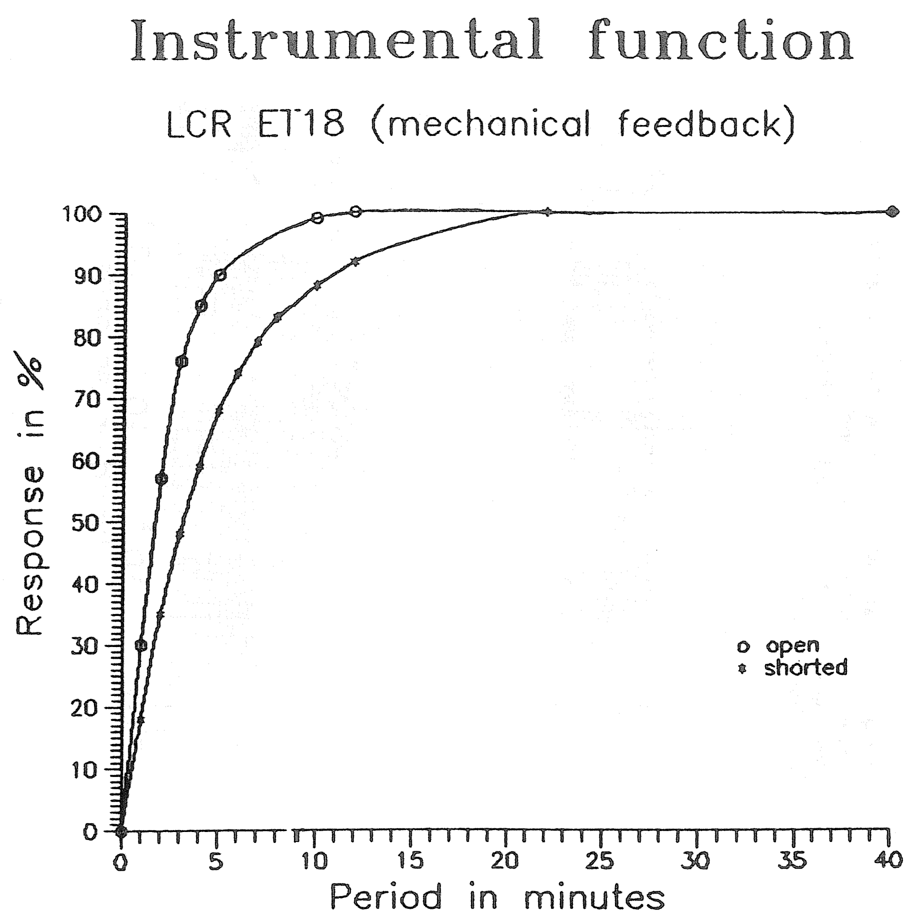

Fig. 1: **Transferfunctions for ET18 with mechanical feedback as given by the manufacturer.**

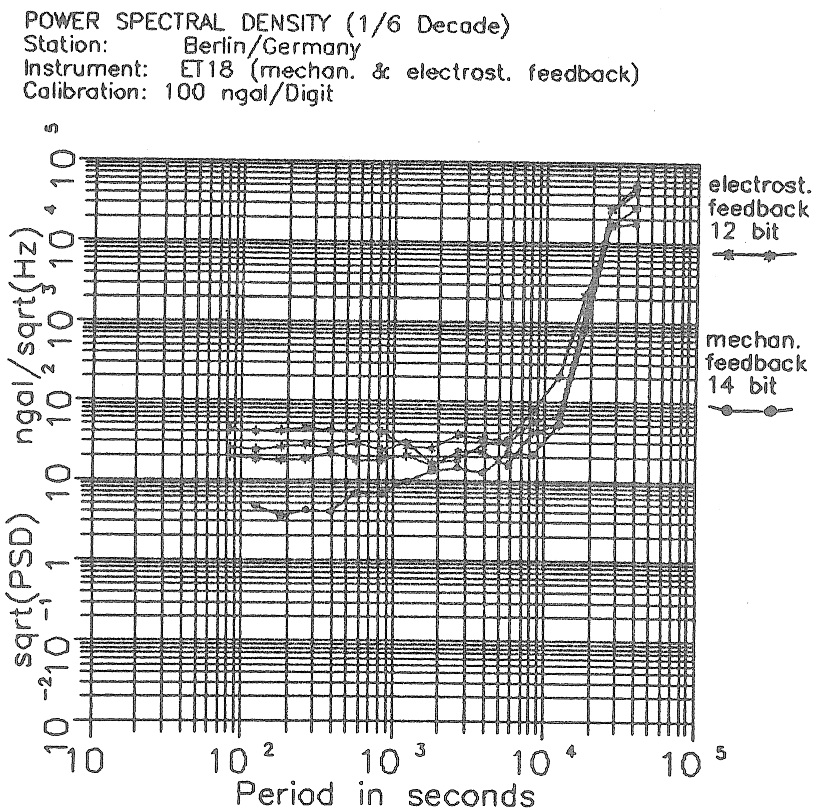

Fig. 2: Power Spectral Density for the ET18 with mechan. and electrost. feedback at the station Berlin/Germany.

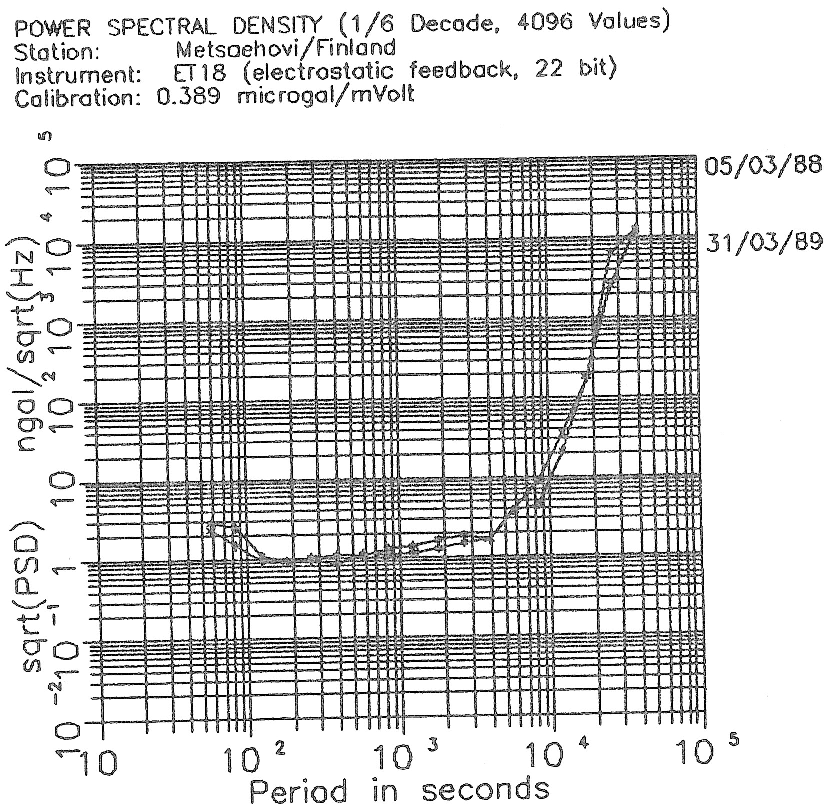

Fig. 3: Power Spectral Density for the ET18 with electrost. feedback at the station Metsaehovi/Finland.

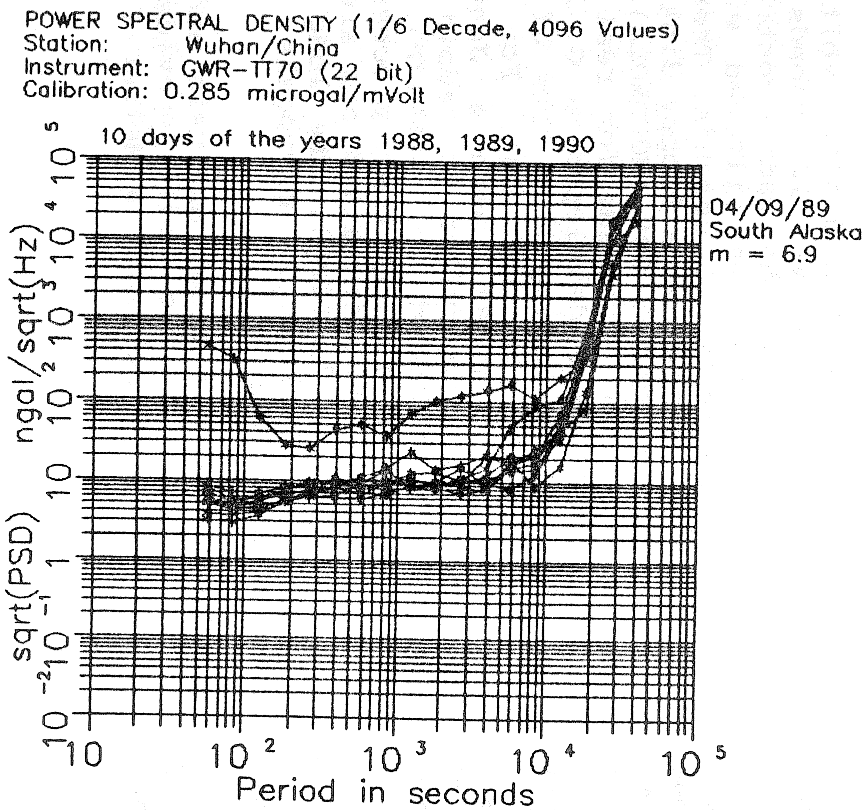

Fig. 4: **Power Spectral Density for the GWR TT70 at Wuhan/China**
- **10 characteristic days of 1988, 1989 and 1990**
- **high level is due to an earthquake of 04/09/1989 South Alaska (m=6.9).**

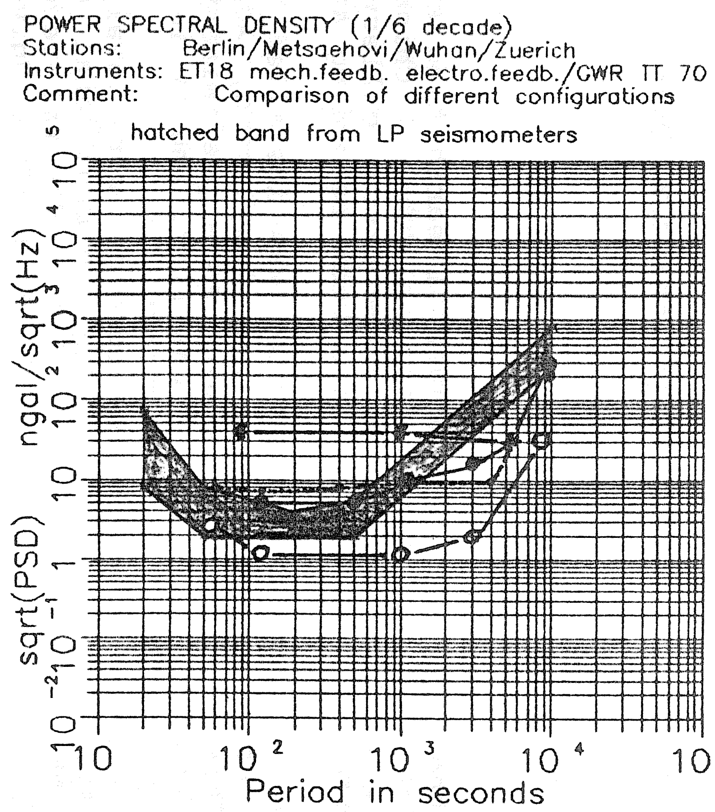

Fig. 5: **Comparison of Power Spectral Density for all four configurations with the noise-band of long-period (LP) seismometers at the location Zürich/Switzerland (*WIELANDT & STRECKEISEN*, 1982).**

ET18 Berlin (mech. feedb.)
ET18 Berlin (elec. feedb.)
ET18 Metsähovi (elec. feedback)
GWR TT70 Wuhan

Some results from SCG in Wuhan/China

by

H.T. Hsu[1], T. Jahr[2], G. Jentzsch[2], and G.X. Tao[1]

1. Introduction

Beginning in the year 1979 a fundamental earth tide station for the continent of Asia was established in Wuhan / China. The tidal observatory was built up in an underground gallery, and since that time different gravimeters have been recording at this site.

Six years later a second tidal station was installed in the building of the Institute of Geodesy and Geophysics, Academia Sinica, in Wuhan. This place was to be used as a preliminary test site for the superconducting gravimeter GWR-TT70, and it is about 1.2 kilometers away from the first observatory.

Until November 1988 only analog records were available, applying a chart stepper provided by the International Center (ICET) to increase the dynamical range. Then a digital recording system was attached in cooperation with G. Asch (Free University of Berlin).

2. Digital data acquisition and recorded data

The digital recording system consists of a digital voltmeter (PREMA 4000) covering 6½ digits by averaging over 10 seconds. The data is read out every second making use of the radio controlled time base of the computer. There, the data is filtered with a sharp low-pass filter of a cut-off period of 40 seconds. Then the filtered data are stored at 20 second samples on a floppy disk.

The computer used is basing on the CPU 68 000 (MOTOROLA). The recording program is written in a special language for real time applications. In 1984, when this system was developed by G. Asch, it was a very reasonable solution for recording this type of data covering a dynamic range of 22 bit (or 132 dB). For more information on this system see Asch (1988), Asch & Jentzsch (1986). We also use this type of recording system to record tilt and gravity variations in Fennoscandia (Alms et al., 1989a/b).

The floppy disks were sent to us for further processing. Fig. 1 shows the filtered hourly values. The interruptions are due to power fails (enlarged by numerical filtering). The long term drift signal has an amplitude of less than 20 microgals. This signal is subject to further considerations.

In the following, the results of the tidal analysis and the tidal residuals are discussed. Regarding the noise provided in that station we refer to the article of Jentzsch & Melzer (1991, this issue).

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2. Tidal analysis

Gaps less than two hours were interpolated in the raw data (20 second samples). Longer gaps are increased by the numerical low-pass filter for data reduction to one hour samples. This time series was calibrated according to the results of a 10 months record of the gravimeter LCR ET-15 from the Bidston group operating in parallel in Wuhan (Baker et al., 1990).

The tidal analysis carried out covered 573 days of filtered data applying Wenzel's analysis program which allows for the option of two different potentials: Cartwright-Tayler-Edden (CTE) and Tamura (Wenzel, 1990). The international system is used (1 μGal is equivalent to 10 nm/s^2). Tab. 1 containes the results for both potentials.

The noise levels in the different tidal bands are fairly small: only about 54 nGal for the diurnal band and less than 25 nGal for the semi-diurnal and ter-diurnal tidal bands. Corresponding to the expectation the errors are slightly smaller for the results applying Tamura's potential. This leads to increased signal-to-noise ratios esp. for the waves O1, K1 and M2. We even expected a greater improvement, but regarding the high mean square error of 0.8 μGal the advantages of Tamura's potential seem to be covered by noise.

Up to now the results of the analysis of the digital record fit very well to the tidal parameters obtained with other gravimeters at this site (compare Baker et al., 1990). On the other hand, there is no air-pressure correction yet.

3. Discussion of tidal residuals

In fig. 2 the tidal residuals (observed record minus analysed tides) are presented: There are several spikes which are due to noise or earthquakes, but also, most important, there are three small steps. The reason of these steps is not yet known, but they were observed already in the analog record (with chart stepper) earlier.

The lower curve in fig. 2 shows the residuals after correction of these steps. Fig. 3 containes the long-term signals seperated as well as the remaining short-period residuals.

The long-period behaviour seems to be related to the polar motion. We hope to add the prior recorded analog data in order to enlarge the record length to analyse the whole period later.

Regarding the short-period part of the residuals we see typical signals related to air pressure (compare Goodkind, 1986). Here the next step is to apply air pressure corrections, too.

4. Future plans

The site is situated in the city with many ongoing building activities and operating work shops. Therefore the noise level is much too high to allow to get all the profit of this high sensitive gravimeter. We just mention here that this can be realized especially by distinguishing working hours during the day from breaks or low activity periods during the nights.

After having now recorded digitally a more than two years period we are reanalysing all the data now including the analog records. That means, that based on the already achieved results we will correct for the steps and spikes in the raw data (not hourly data as done now). After filtering we will analyse the digitally recorded data as well as the former analog data separately as well as in one total record.

In this way we hope not only to get all the information contained in the data but also to achive informations about the instrument and recording systems themselves. This information could be used for the future recordings in the new observatory.

After several considerations the site of this new observatory was choosen outside the city in an area with some bed rock and low noise level. The building already has started to provide a underground room for the gravimeter and a house for data acquisition and maintenance including a complete meteorological station. It is intended to finish this building during the first half of 1991.

5. Acknowledgements

By this study a fine cooperation between the Chinese and the German groups was established and scientific exchange was possible through many personal contacts in China as well as in Germany. This work is still suported both by the Chinese Academy of Sciences and the Volkswagen Foundation, which made the digital recording system available for the superconducting gravimeter. All this is greatfully acknowledged.

G. Asch adapted his recording program to this instrument and helped to install it in Wuhan. Although being involved in other duties he is still available for dicussions regarding his recording system.

H.G. Wenzel kindly provided us with the new version of his analysis program ETERNA which allows to use different potentials.

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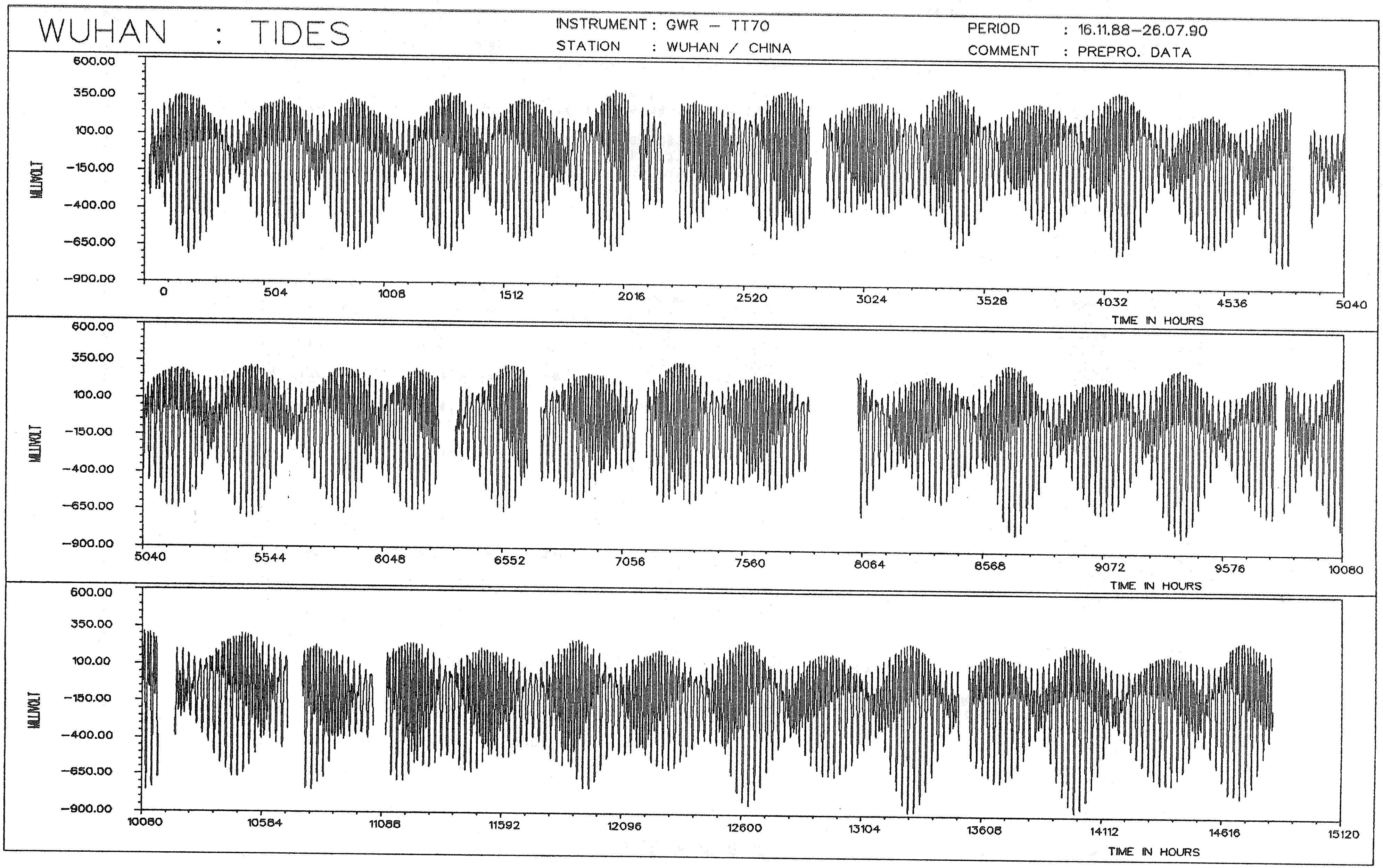


Fig. 1: Filtered hourly data of the superconducting gravimeter in Wuhan; 1 mV corresponds to 0.2855174 μGal; period Nov. 16, 1988 until July 26, 1990.

Tab. 1: Results of the tidal analyses according to the potentials of Tamura and CTE. Note the fairly small improvements to the signal-to-noise ratios after applying Tamura's potential.

T A M U R A

FOURIER-SPECT.OF RESIDUALS
- DAILY WAVES 0.5199 NM/S**2 (= 0.052 µGAL)
- HALF-DAILY WAVES 0.2255 NM/S**2
- THIRD-DAILY WAVES 0.2107 NM/S**2

ADJUSTED TIDAL PARAMETERS; NUMBER OF DAYS 573.0

C T E

- DAILY WAVES 0.5219 NM/S**2
- HALF-DAILY WAVES 0.2278 NM/S**2
- THIRD-DAILY WAVES 0.2063 NM/S**2

ADJUSTED TIDAL PARAMETERS

NR.	FROM	TO	WAVE	TAMURA AMPL. NM/S**2	TAMURA SIGNAL/ NOISE	TAMURA AMPL.FAC.	TAMURA PHASE LAG DEG	CTE AMPL. NM/S**2	CTE SIGNAL/ NOISE	CTE AMPL.FAC.	CTE PHASE LAG DEG
6	425	462	O1	319.5135	614.5	1.1762	-0.6084	319.5995	612.4	1.1766	-0.6183
						0.0019	0.0932			0.0019	0.0936
11	537	547	P1	149.0621	286.7	1.1794	-0.4916	149.1192	285.7	1.1797	-0.4793
						0.0041	0.1999			0.0041	0.2005
12	548	551	S1	2.5872	5.0	0.8654	26.3295	2.5696	4.9	0.8609	26.1060
						0.1810	11.5148			0.1748	11.6367
13	552	568	K1	439.7615	845.8	1.1511	-0.8455	439.8587	842.8	1.1514	-0.8461
						0.0014	0.0677			0.0014	0.0680
14	569	573	PSI1	4.2558	8.2	1.4237	2.9734	4.3204	8.3	1.4268	2.9089
						0.1739	7.0000			0.1723	6.9210
15	574	587	FI1	6.1832	11.9	1.1365	1.4201	6.1897	11.9	1.1402	1.1052
						0.0956	4.8180			0.0961	4.8309
16	588	600	THE1	4.9643	9.5	1.2152	0.0164	4.9022	9.4	1.1990	-0.2657
						0.1273	6.0010			0.1276	6.0997
25	832	863	N2	124.8729	553.7	1.1712	-0.8051	124.8682	548.1	1.1711	-0.8158
						0.0021	0.1035			0.0021	0.1045
26	864	876	NI2	24.0384	106.6	1.1870	-0.1221	24.0338	105.5	1.1866	-0.1639
						0.0111	0.5375			0.0112	0.5431
27	877	936	M2	653.7318	2898.9	1.1739	-0.5807	653.6922	2869.2	1.1738	-0.5924
						0.0004	0.0198			0.0004	0.0200
28	937	947	LMB2	4.8996	21.7	1.1931	-0.0106	4.9363	21.7	1.2015	0.2583
						0.0549	2.6371			0.0555	2.6445
29	948	975	L2	18.6743	82.8	1.1864	-2.5749	18.7515	82.3	1.1913	-2.7685
						0.0143	0.6919			0.0145	0.6961
30	976	984	T2	17.7789	78.8	1.1735	0.0169	17.7620	78.0	1.1725	-0.0198
						0.0149	0.7268			0.0150	0.7349
31	985	991	S2	303.7290	1346.8	1.1723	-0.4862	303.7266	1333.1	1.1723	-0.4804
						0.0009	0.0425			0.0009	0.0430
32	992	997	R2	2.5678	11.4	1.1839	1.4495	2.5890	11.4	1.1943	1.2377
						0.1040	5.0319			0.1051	5.0420
33	998	1020	K2	82.2548	364.7	1.1677	-0.5525	82.2459	361.0	1.1675	-0.5852
						0.0032	0.1571			0.0032	0.1587
37	1145	1169	M3	10.2056	48.4	1.0821	1.5526	10.2276	49.6	1.0854	1.4386
						0.0223	1.1830			0.0219	1.1557

TAMURA: MEAN SQUARE ERROR 7.769 NM/S**2 = 0.777 µGAL DEGREE OF FREEDOM 12909

CTE: MEAN SQUARE ERROR 7.787 NM/S**2 = 0.779 µGAL

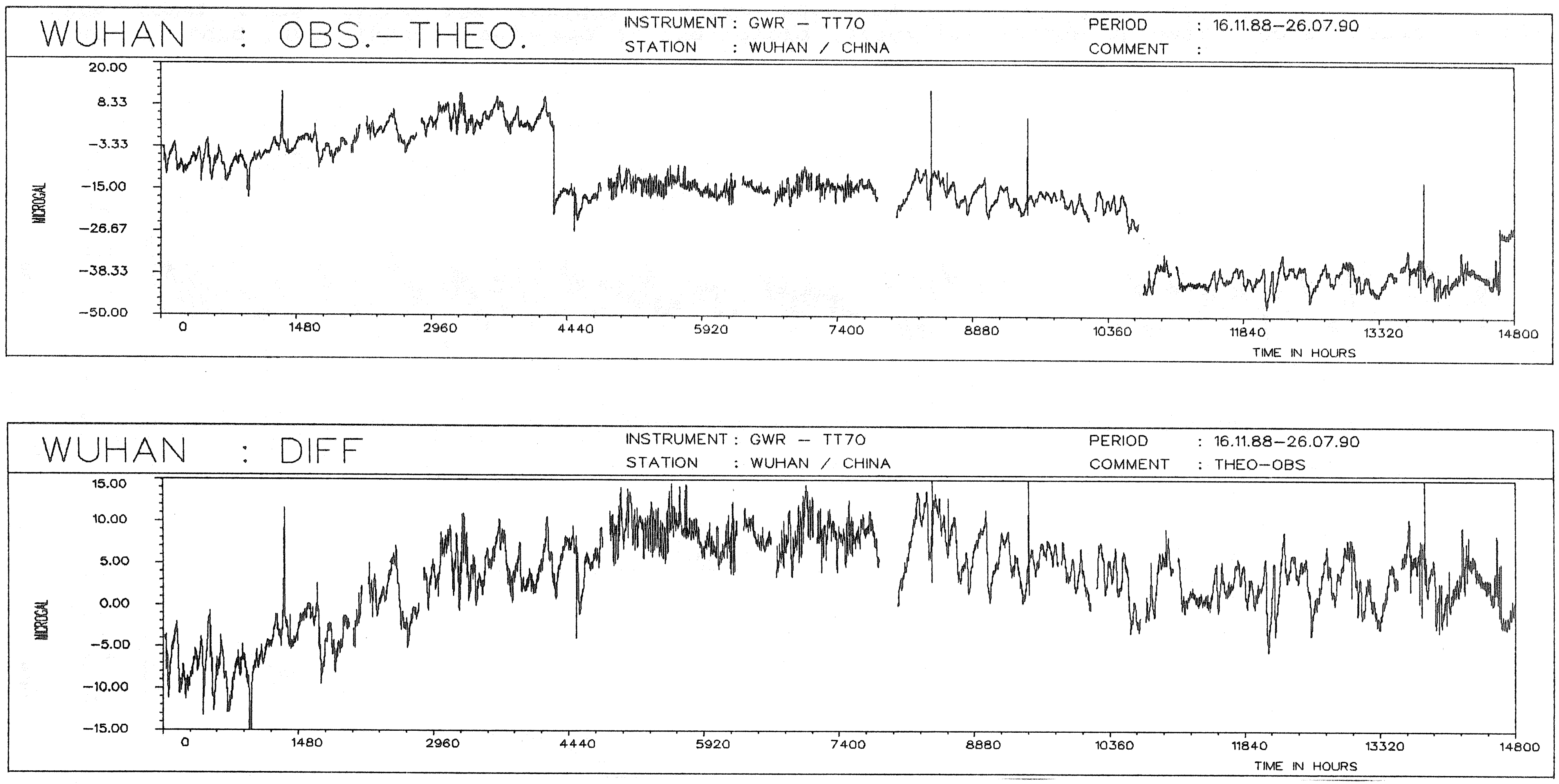
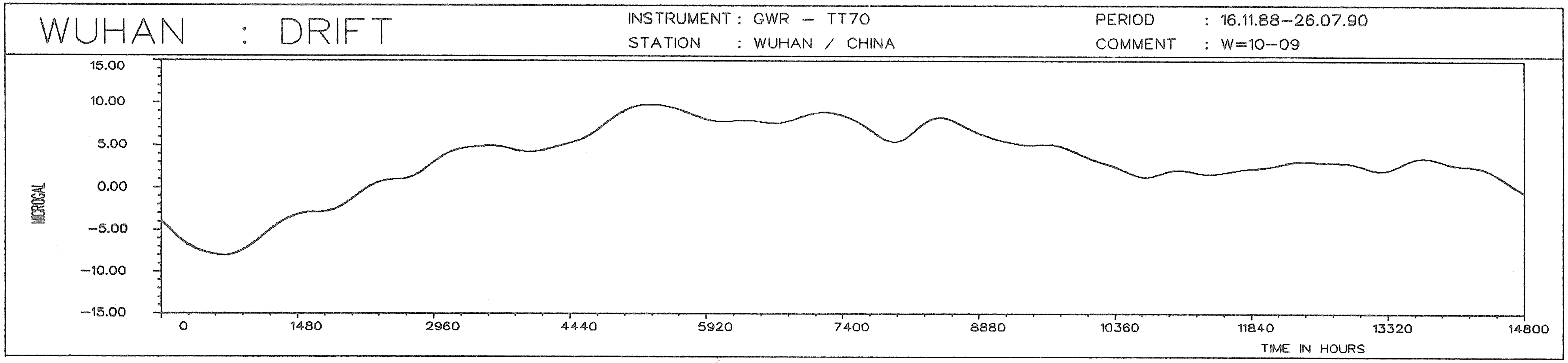


Fig. 2: Tidal residuals (upper curve) containing three small steps around 4000, 10500 and close to 14700 hours; below after correction (spikes are mainly due to noise or earthquakes).



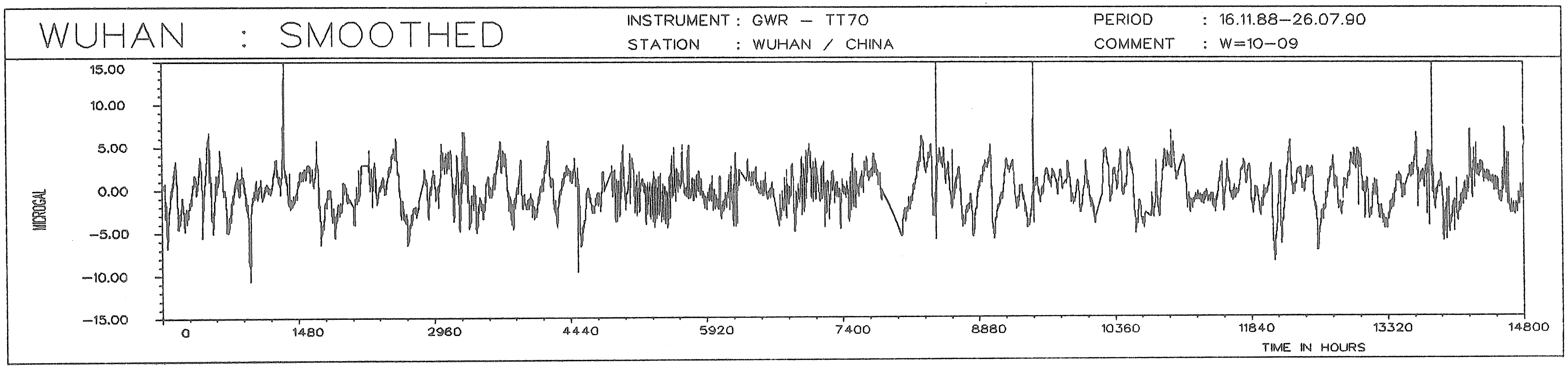


Fig. 3: Long-term signals contained in the record (after correction of small steps, upper curve); the lower curve shows the residuals after removing the long-term signals (short gaps are interpolated).

MODELISATION OF THE NON TIDAL GRAVITY VARIATIONS AT BRUSSELS

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A superconducting gravimeter GWR-TT30 is recording at the Royal Observatory of Belgium (Brussels) since April 1982. Its long term behaviour is difficult to model due to instrumental problems. However, when a reliable drift model is built, periodical gravity changes show up at the annual and Chandler (430 days) periods. Unfortunately a one month gap in october 1986 prevent doing a global analysis.

The main instrumental problem results from a slight leak of helium gas into the vacuum chamber insulating the gravimeter from the liquid helium bath. This helium is accumulating and had to be removed every six months by means of a getter. The installation of a permanent getter in 1987 has drastically improved the situation. The instrumental drift was completely modified from a large exponential decay. (A = 200 μgal, T = 900 days) to a relatively small exponential increase (A = 25 μgal, T = 200 days).

In 1987 also a new digital data acquisition system reduced the noise of the data.

To try a numerical evaluation of the annual term it is still necessary to fix the amplitude factor of the Chandler term (δ = 1.16)

This annual term has an amplitude of 5 μgal with a maximum in february. It is clearly found before and after the permanent getter installation.

A STANDARD DATA SET FOR EVALUATION OF HIGH PRECISE TIDES

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Abstract

In order to evaluate the precision of high precise tidal generating potential, a standard data set of gravity tides were established. In this paper the formulas for computation a standard data set are given. Moreover, the problems on the local true hour angle as well as the ephemerides for the true position of the sun and the moon are discussed. Those ephemerides adopted in our work were strictly computed by use of the same method as is used for compiling an astronomical ephemeris. They have the highest precision at present. Using the ephemerides we may establish a standard data set for other tidal observations.

Key words Precise tidal generating potential, Standard data set, Ephemeris, Hour angle, Zenith distance.

In order to evaluate the precision of tidal observations, especially the tidal generating potential, it is necessary to establish a standard data set. This is not only related to practical, but also theoretical problems. For practical purpose this standard data set has to independently compute directly from an ephemeris of the sun and the moon. Concerning to the tidal gravity, it seems that only Wenzel's data set for 1971 at Hannover is useful at present. It has the precision of $0.01^{\mu gal}$ order. However, the evaluation of precision for high precise tidal potential requires that the precision of the standard data set should come up to $0.001^{\mu gal}$ order, even smaller than that. Therefore, Either the formulas and the constants or the adopted ephemerides are a worth discussible problem.

1. The collection of the formulas for computation of the theoretical values for tidal gravity.

In order to establish the standard data set for tidal gravity, following formulas for computation of theoretical values are adopted. They include the potential up to fourth order for the moon and third order for the sun.

$$\Delta g = -165.1631\frac{\rho}{a}(\frac{c}{R})^3(cos^2\theta-\frac{1}{3})$$
$$-1.3702(\frac{\rho}{a})^2(\frac{c}{R})^4(5cos^3\theta-3cos\theta)$$
$$-0.007579(\frac{\rho}{a})^3(\frac{c}{R})^5(35cos^4\theta-30cos^2\theta+3)$$
$$-75.8491\frac{\rho}{a}(\frac{c}{R})_s^3(cos^2\theta_s-\frac{1}{3})$$
$$-0.001617(\frac{\rho}{a})^2(\frac{c}{R})_s^4(5cos^3\theta_s-3cos\theta_s) \quad (1)$$

where θ is a zenith, and

$$cos\theta = sin\psi sin\delta + cos\psi cos\delta cos\tau \quad (2)$$

ψ is geocentric latitude

$$\psi = \varphi - 0.192424° \, sin2\varphi \quad (3)$$
$$\frac{\rho}{a} = 1 - 0.00332479\, sin^2\varphi + \frac{H}{a} \quad (4)$$

In formula (2), τ is local true hour angle. We processed τ using a method out of the ordinary. Here τ is corresponding to the true position of a celestial body. According to

$$\tau_s + \alpha_s = t + \lambda - 180° + \bar{\alpha}_s \quad (5)$$
$$\tau_m + \alpha_m = \tau_s + \alpha_s \quad (6)$$

we got

$$\tau_s = t + \lambda - 180° + \bar{\alpha}_s - \alpha_s \quad (7)$$
$$\tau_m = \tau_s + \alpha_s - \alpha_m \quad (8)$$

where t is the universal time; λ, the local longitude ; α_s, α_m are corresponding to the true right ascension of the sun and the moon; $\bar{\alpha}_s$ is the longitude of the equatorial mean sun for the universal time.

$$\bar{\alpha}_s = 18.6973746^h + 2400.0513369^h T_u + 0.0000258622^h T_u^2$$
$$-1.7222^h \times 10^{-9} T_u^3 \quad (9)$$

where T_u is the Julian century measured from Jan. 1. 2000. 12^h. UT1 (JD=2451545.0).

The purpose to collect above formulas as everyone knows is not for showing them, but only for making clear that a series of new precise constants have been adopted. So that it may uniform all tidal computation. These constants are the same as [1][2] .

2. On the ephemeris of the sun and the moon (true position)

Tidal computation should adopt the true position of the celestial, but a common ephemeris only have the apparent position for the sun and the moon. The difference between the true and apparent position is derived from the aberration. The aberration of the moon is not so striking, but it may not be neglected for the sun.

In a common ephemeris dynamic time(TDT) is used as an independent variable, However, for our purpose we should use the universal time(UT) as an independent variable.

We have computed the true positions (α,δ) of the sun and the moon as well as the true geocentric distances Λ_s of the sun (the unit distance is of an astronomical length) and Λ_m of the moon (the unit distance is of the earth radius).

Obviously, corresponding to the symbols in (1), we have

$$(\frac{c}{R}) = \frac{1}{\frac{a}{c}\Lambda_m} = \frac{1}{0.01659251\Lambda_m} \quad (10)$$

$$(\frac{c}{R})_s = \frac{1}{\Lambda_s} \quad (11)$$

According to the resolution of IAU, since 1984 for the positions of the sun and the moon one start to adopt the results of new numerical integrations for the equations of the celestial motion in the solar system. The fundamental ephemeris is computed and compiled by JPL and N–OBS according to the new data of observations and adopting the new astronomical constants system. The table for the sun is called DE200 and that for the moon is called LE200. The figures in Chinese Astronomical Ephemeris are the same as Japanese Ephemeris [3] [4].

As an example, we take a passage from the ephemeris of the sun and the moon computed by us. It shows the true positions of the sun and the moon on Jan.1.1987.

h	α_s	δ_s	α_m	β_m	Λ_s	Λ_m
0	18 43 37.776	−23 3 51.83	19 40 38.175	−26 28 44.69	0.9833335	56.0808772
1	18 43 48.827	−23 3 40.29	19 43 25.350	−26 21 51.76	0.9833328	56.0946422
2	18 43 59.878	−23 3 28.71	19 46 12.100	−26 14 46.92	0.9833322	56.1089279
3	18 44 10.929	−23 3 17.08	19 48 58.415	−26 7 30.29	0.9833315	56.1237315
4	18 44 21.979	−23 3 5.39	19 51 44.286	−26 0 2.00	0.9833309	56.1390500

5	18 44 33.028	−23 2 53.67	19 54 29.702	−25 52 22.15	0.9833303	56.1548805
6	18 44 44.077	−23 2 41.89	19 57 14.655	−25 44 30.87	0.9833296	56.1712198
7	18 44 55.125	−23 2 30.06	19 59 59.137	−25 36 28.28	0.9833290	56.1880645
8	18 45 6.173	−23 2 18.19	20 2 43.139	−25 28 14.52	0.9833284	56.2054115
9	18 45 17.220	−23 2 6.27	20 5 26.654	−25 19 49.71	0.9833278	56.2232571
10	18 45 28.266	−23 1 54.30	20 8 9.674	−25 11 13.97	0.9833272	56.2415980
11	18 45 39.312	−23 1 42.28	20 10 52.192	−25 2 27.45	0.9833266	56.2604304
12	18 45 50.358	−23 1 30.22	20 13 34.201	−24 53 30.26	0.9833261	56.2797506
13	18 46 1.403	−23 1 18.11	20 16 15.695	−24 44 22.56	0.9833255	56.2995549
14	18 46 12.447	−23 1 5.95	20 18 56.668	−24 35 4.48	0.9833249	56.3198392
15	18 46 23.491	−23 0 53.74	20 21 37.114	−24 25 36.14	0.9833243	56.3405997
16	18 46 34.534	−23 0 41.48	20 24 17.028	−24 15 57.70	0.9833238	56.3618322
17	18 46 45.576	−23 0 29.18	20 26 56.404	−24 6 9.29	0.9833232	56.3835325
18	18 46 56.618	−23 0 16.83	20 29 35.238	−23 56 11.05	0.9833227	56.4056964
19	18 47 7.660	−23 0 4.43	20 32 13.525	−23 46 3.13	0.9833221	56.4283196
20	18 47 18.701	−22 59 51.98	20 34 51.262	−23 35 45.67	0.9833216	56.4513976
21	18 47 29.741	−22 59 39.48	20 37 28.445	−23 25 18.81	0.9833211	56.4749260
22	18 47 40.781	−22 59 26.94	20 40 5.071	−23 14 42.69	0.9833206	56.4989002
23	18 47 51.820	−22 59 14.35	20 42 41.136	−23 3 57.47	0.9833201	56.5233155
0	18 43 37.777	−23 3 51.77	19 40 38.139	−26 28 44.67	0.9833334	56.0808779

Table 1. The true position of the sun and the moon

In order to check the accuracy of the table above, here we give another numerical result at the bottom line in table 1 for 0^h.Jan. 1. 1987. These figures are of deducted aberration using the insert method. So it can be compare with the top line. Obviously the ephemerides for true position of the sun and the moon adopted by us are highly precise, and it also have the highest precision at present.

As mentioned above, in table (1) the universal time is used as an independent variable, but the dynamic time is used as an independent variable in an ephemeris. The difference ($\Delta T = TDT - UT1$) between them is adopted 56^s in 1987. Using the ephemeris adopted by us one may establish tidal standard data set besides the gravity tides.

3. Some additional notice for precise tidal generating potential.

As we know, the tables of the precise tidal generating potential provided by us include 3070 tidal waves. Moreover, we have divided the potential into 4 construct types according to the nomerical values of the amplitudes. The numbers of tidal waves and the accuracy in each construct type are as follows [5] .

	Amplitude H	Numbers of waves	Accuracy
I	>100	382	$\pm 0.048^{\mu gal}$
II	>50	530	$\pm 0.031^{\mu gal}$
III	>10	1054	$\pm 0.009^{\mu gal}$
IV	>1	3070	$\pm 0.005^{\mu gal}$

Table 2. The numbers of tidal waves and the accuracy in each construct type.

The accuracies of the 4 construct types are incremental with the numbers of tidal waves in each type. Obviously, the small waves have made its contributes to the increment of the accuracies.

In fact we have provided 4 tidal potentials with different accuracies. According to the request in use we may decide to adopt an appropriate tidal potential.

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ANALYSIS OF RESIDUAL GRAVITY SIGNALS USING DIFFERENT TIDAL POTENTIALS

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1 Introduction

The typical precision requirement of the lunisolar tidal potential development is of the order of 0.1 μgal for performing a classical Earth tide analysis of spring gravimeter records. With the achievement of superconducting gravimeters, the required precision must be better at least by a factor 10. The lunisolar gravitational potential which is the most currently used in Earth tides is that due to Cartwright, Tayler and Edden (CTE), having 505 waves coming from degree and order 2 and 3 (Cartwright and Tayler 1971, Cartwright and Edden 1973). More recently, new potentials with increased accuracy taking into account the 4th order and degree coefficients were introduced by Büllesfeld (1985) with 656 waves, Tamura (1987) (TAM) with 1200 waves and Xi Qinwen (1987, 1989) (XI), the latest with more than 3000 waves.

There are several methods of checking the accuracy of a given theoretical tidal potential. First, one can directly compare at a given station the theoretically predicted tide to the Ephemeris tide (ET) (from the known positions of the Sun and Moon). One obtains the gravity differences either as a function of time or as a function of frequency after Fourier transforming them.

This kind of study was first done by Ducarme (1989) using the ET computed by Wenzel (1978) for the year 1971 at the station Hannover (FRG). The upper limit for the standard deviation of gravity differences of TAM and XI (with only 2920 waves) with respect to ET was found to be about 11 nanogal for both models. However, because the accuracy of the ET was itself limited to the same amount (10 nanogal), the real precision is probably better.

A similar approach is described in Wenzel and Zürn (1990) where these authors compared the CTE and TAM tidal developments to the ET computed from a program by Broucke et al. (1972) for the station Schiltach (FRG) and the year 1989. The standard deviation of the gravity differences between TAM and ET was found to be also about 10 nanogal; moreover ±5 nanogal could be due to errors in the ET. Notice that the use of different fundamental geodetic and astronomical parameters may be an additional source of error.

A second possibility is to fit gravity tidal observations (at a given station) to different theoretical tidal developments. The resulting gravity residuals can then be analyzed either in the time or in the frequency domain. This was done by Wenzel and Zürn (1990) who investigated the residuals of a tidal fit with respect to CTE and TAM using a 3 month data set from two Lacoste-Romberg meters in Schiltach. One of their conclusions was the reduction in the gravity residuals when using TAM instead of CTE. However, some errors in CTE, which appear in the direct comparison with respect to TAM, have been partly absorbed in the fitted tidal parameters.

In this paper, we investigate two different aspects. On one hand, we compare the latest tidal XI (with 3070 waves) development to a very accurate and recent ET (based on the improved lunar Ephemeris). On the other hand, we perform a tidal least squares adjustment of XI with respect to CTE and TAM using two different standard programs.

2 Tidal gravity differences between GTIDE and GWAVE

In this section, we directly compare a precise Ephemeris Tide (GTIDE) and a recent theoretical tidal development (GWAVE), both of which written recently by J. Merriam (personal communication). The programs work completely differently, and share only the geometric mean orbital parameters of the Sun and Moon as common input. GTIDE computes positions for the Sun and Moon, and from these directly the tidal gravity. GWAVE sums a maximum of 3070 tidal constituents based on the last Xi Qinwen (1989) development to produce a tidal prediction. It should be realized that in order to compute the amplitude and phase of each tidal constituent, XI Qinwen had first to generate a tidal prediction based on an ephemeris just as GTIDE does. the derivation of the constituents being 'algebraic' (or analytical) as opposed to filtering and Fourier transforming (see Ducarme 1989).

This comparison is done for the station J9 near Strasbourg (North latitude 48.6222 °, East longitude 7.6850 °, elevation 180 m) and calculated for the year 1989 at 8760 hourly values. The calculations assume a rigid Earth model with no FCN (Free Core nutation) correction. From Figure 1a showing the time evolution of the tidal differences between GTIDE and GWAVE, we found a mean difference of about - 1.6 nanogal and a standard deviation of 6 nanogal. Due to phase enhancement, the discrepancy in real time can reach 40 nanogal. The histogram of the same differences is given by Figure 1b. The median of the distribution is close to zero though the distribution is slightly skewed towards negative values. Figure 1c shows the amplitude spectrum of the differences. The maximum discrepancy in tidal amplitudes is less than 1 nanogal in the low-frequency band, 2-3 nanogal in the diurnal band, 1-2 nanogal in the semi-diurnal band. The differences in the terdiurnal and quartdiurnal bands are of course much smaller.

3 Tidal gravity residuals

The GWAVE series was subjected to a tidal analysis using two different least squares adjustment programs, HYCON (Schüller 1976) and ETERNA (Wenzel 1976) as well as two different tidal developments (CTE and TAM). These programs produce a residual time series after subtraction of all the fitted tides (one amplitude and one phase for each tidal group which can be separated according to the length of the data set). Once again, these computations are done for the Strasbourg J9 station and for the year 1989. In Figure 2a are plotted the tide residuals of GWAVE using HYCON with the CTE tidal development. The maximum discrepancy can reach 0.2 microgal and is most of the time less than 50 nanogal. The corresponding histogram is shown in Figure 2b; the symmetric distribution has a standard deviation of 40 nanogal. From the spectrum (Figure 2c), we see that the residual amplitudes are similar, with a maximum of about 10 nanogal in the diurnal, semi-diurnal and ter-diurnal bands, and a maximum of about 5 nanogal in the low-frequency and quartdiurnal bands.

We also applied the ETERNA program which enables both CTE and TAM potentials to be used. ETERNA uses fewer tidal groups of the CTE potential than HYCON. The effect of some omitted long-period waves can be seen in the residuals (with respect to CTE) from GWAVE in Figure 3a, with significant deviations around the zero line. The standard deviation of the residuals (Figure 3b), about 58 nanogal, is slightly higher than with HYCON (for the reason given above). Discrepancies in the tidal residual amplitudes (Figure 3c) are, as for HYCON, about 10 nanogal. There is a significant disagreement in the long-period components with a 24 nanogal error in the tide at 143 day period (near the origin in this plot). The results of the same analysis using ETERNA with TAM are shown in Figures 4a, 4b, 4c. We see that the Tamura tidal potential with its 1200 waves is much more accurate than that of CTE and leads to time residuals always smaller than 40 nanogal and, in the mean, in the range +/- 10 nanogal. Figure 4b shows the symmetric histogram with a standard deviation of 7 nanogal; this is only slightly higher than the error between GTIDE and GWAVE (see Figure 1b). The reduction in the standard deviation is better by a factor 8 as compared to the residuals obtained from CTE (see Figure 3b). The amplitude spectrum shows tidal waves with residuals of only 2-3 nanogal with TAM, similar to the GTIDE - GWAVE differences.

4 Conclusion

The Ephemeris tide GTIDE and the theoretical tide GWAVE, which is based on the development of Xi Qinwen with more than 3000 waves, are in agreement to a few nanogal (the standard deviation is 6 nanogal) and it is evidently difficult to recommend the better programme. Due to phase enhancement, in real time the amplitudes can vary by more than 40 nanogal.
Using either version of the CTE potential (HYCON or ETERNA), the gravity residuals are unacceptably high for precise tidal and non-tidal work. In real time, the errors can reach several tenths of microgal. The Tamura potential (with ETERNA) significantly reduces the residuals to almost the error between GTIDE and GWAVE. It is therefore difficult to distinguish between GTIDE (ephemeris), GWAVE (Xi Qinwen potential) and the Tamura tidal potential in this analysis. More sensitive tests are required before further recommendations can be made.

Acknowledgements

We thank Jim Merriam for having made available to us the programs GTIDE and GWAVE. Walter Zürn helped us in using HYCON and Hans-Georg Wenzel kindly provided ETERNA. D.C. received funding through Canadian NSERC Operating Grant A2420. This study has also been supported by CNRS-INSU (DBT Dynamique Globale).

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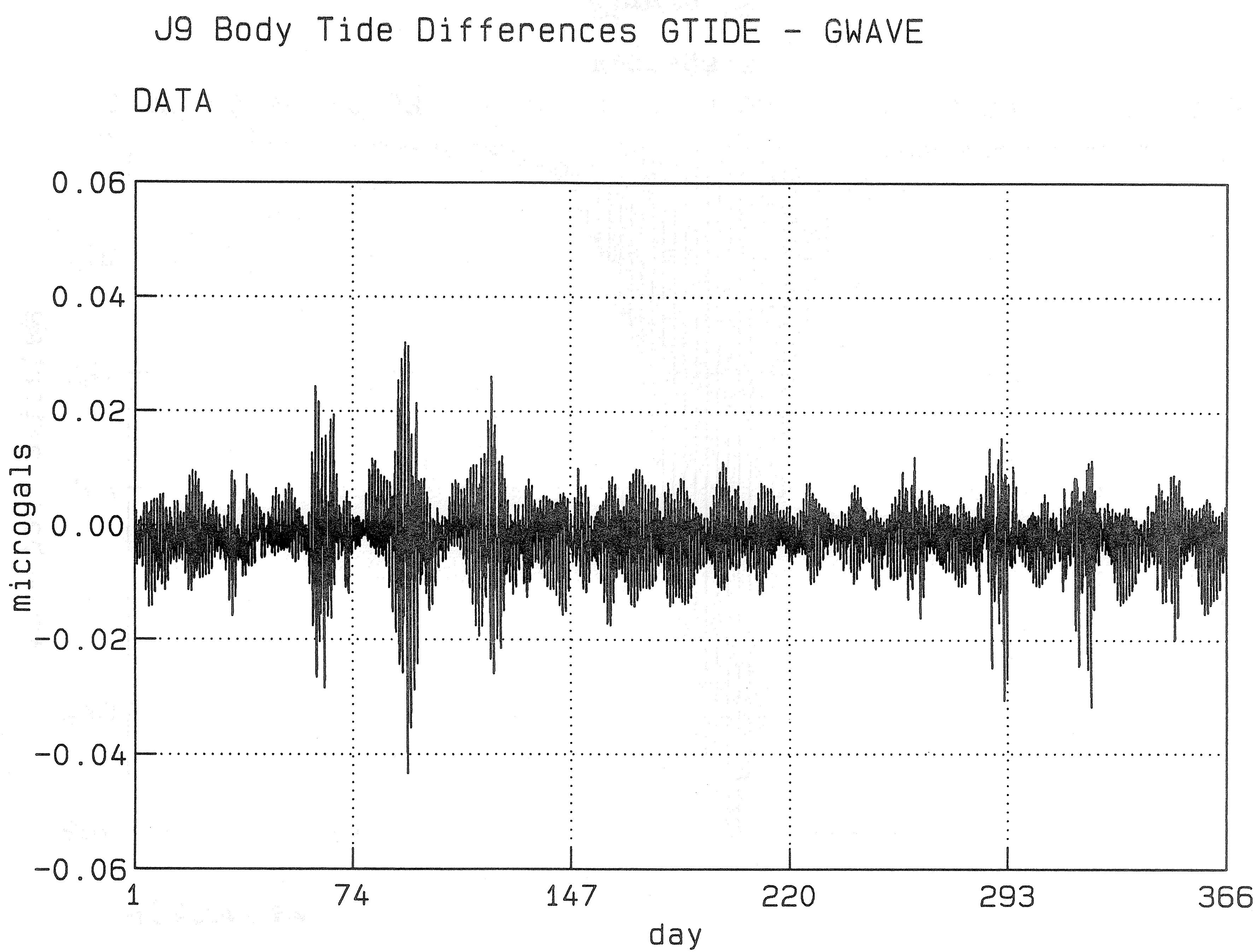

J9 Body Tide Differences GTIDE - GWAVE
DATA
microgals
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
1
74
147
220
293
366
day

Figure 1a

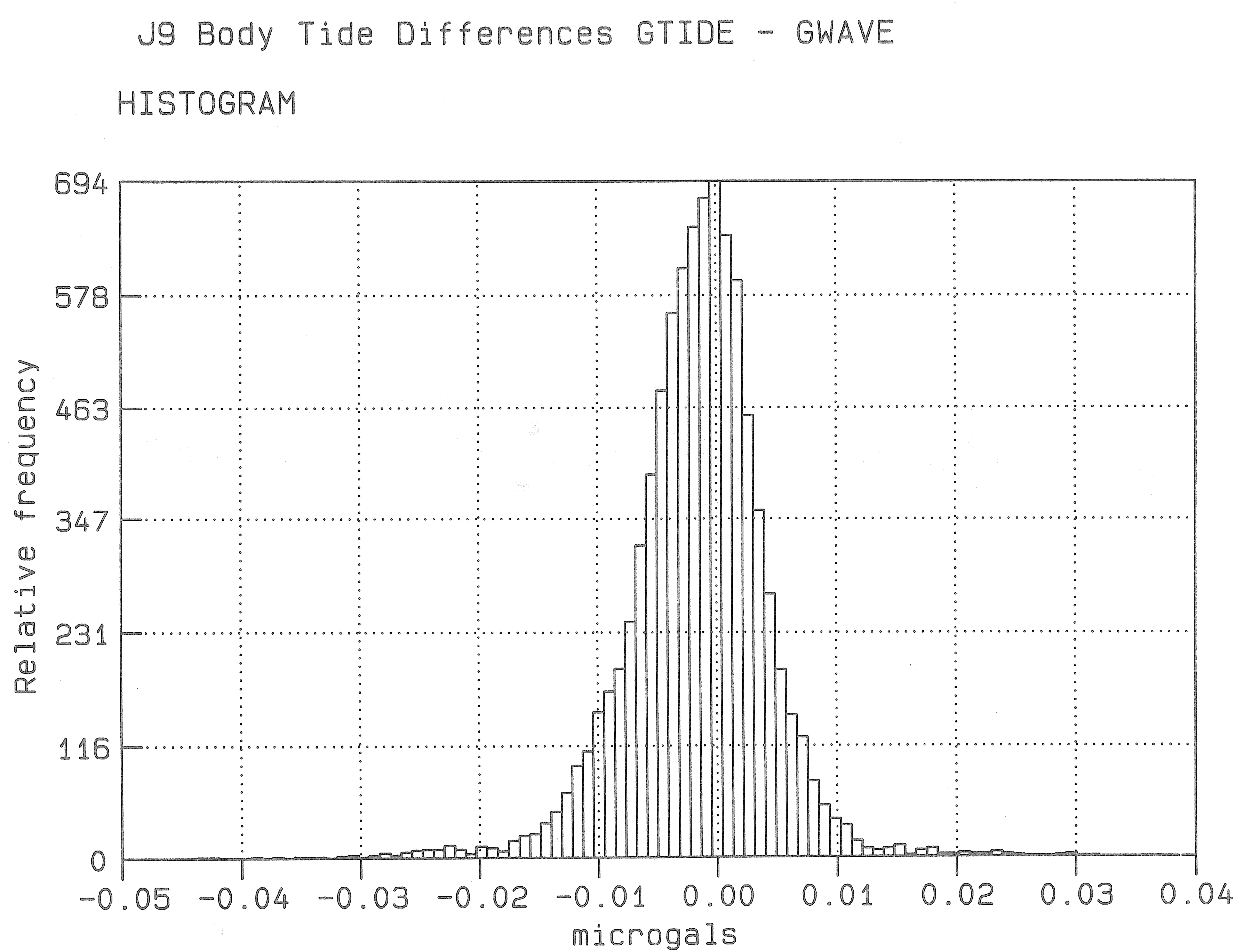

J9 Body Tide Differences GTIDE - GWAVE
HISTOGRAM
694
578
463
347
231
116
0
Relative frequency
-0.05
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
micrograls

Figure 1b

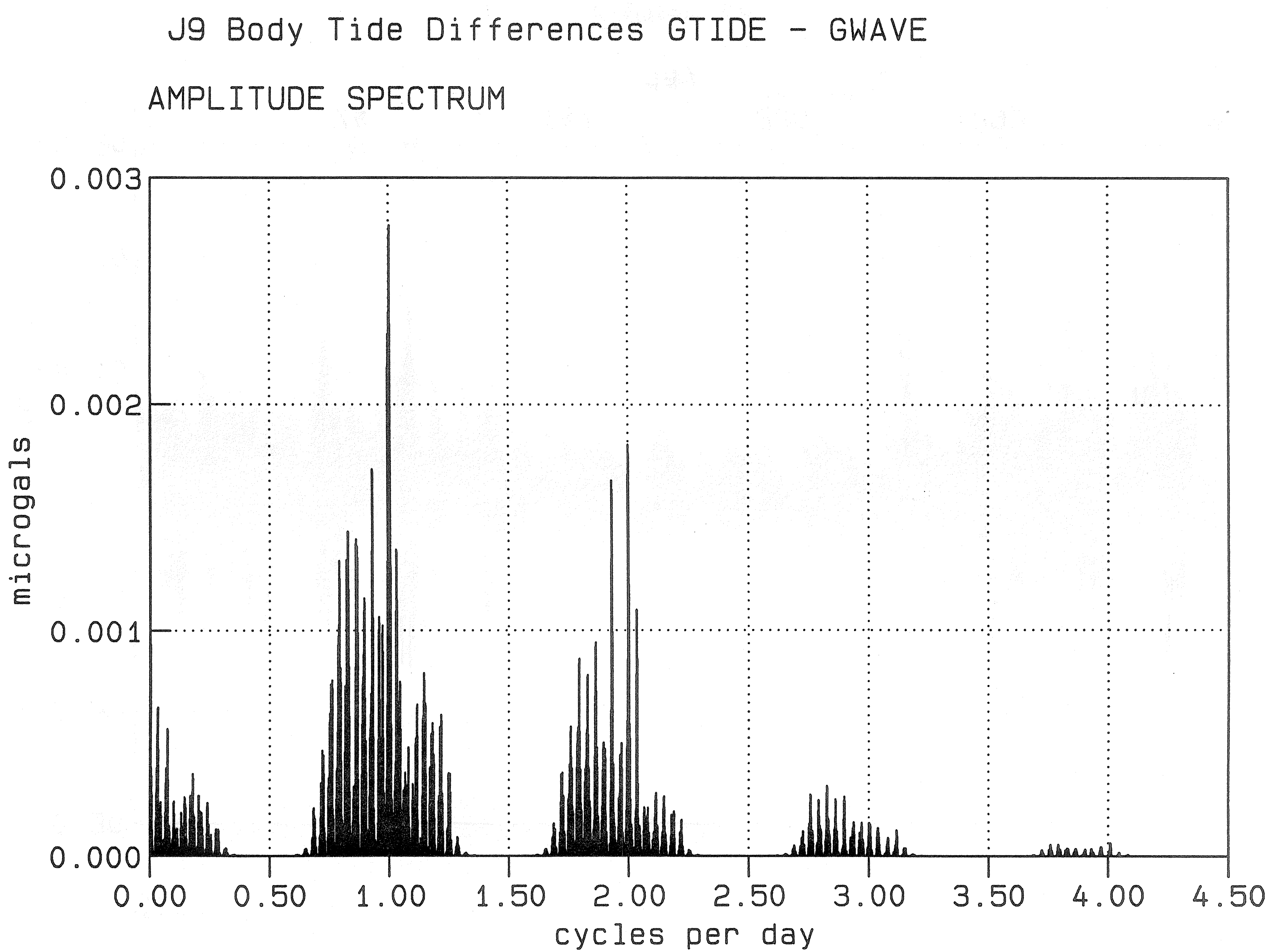

J9 Body Tide Differences GTIDE - GWAVE
AMPLITUDE SPECTRUM
microgals
0.003
0.002
0.001
0.000
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
cycles per day

Figure 1c

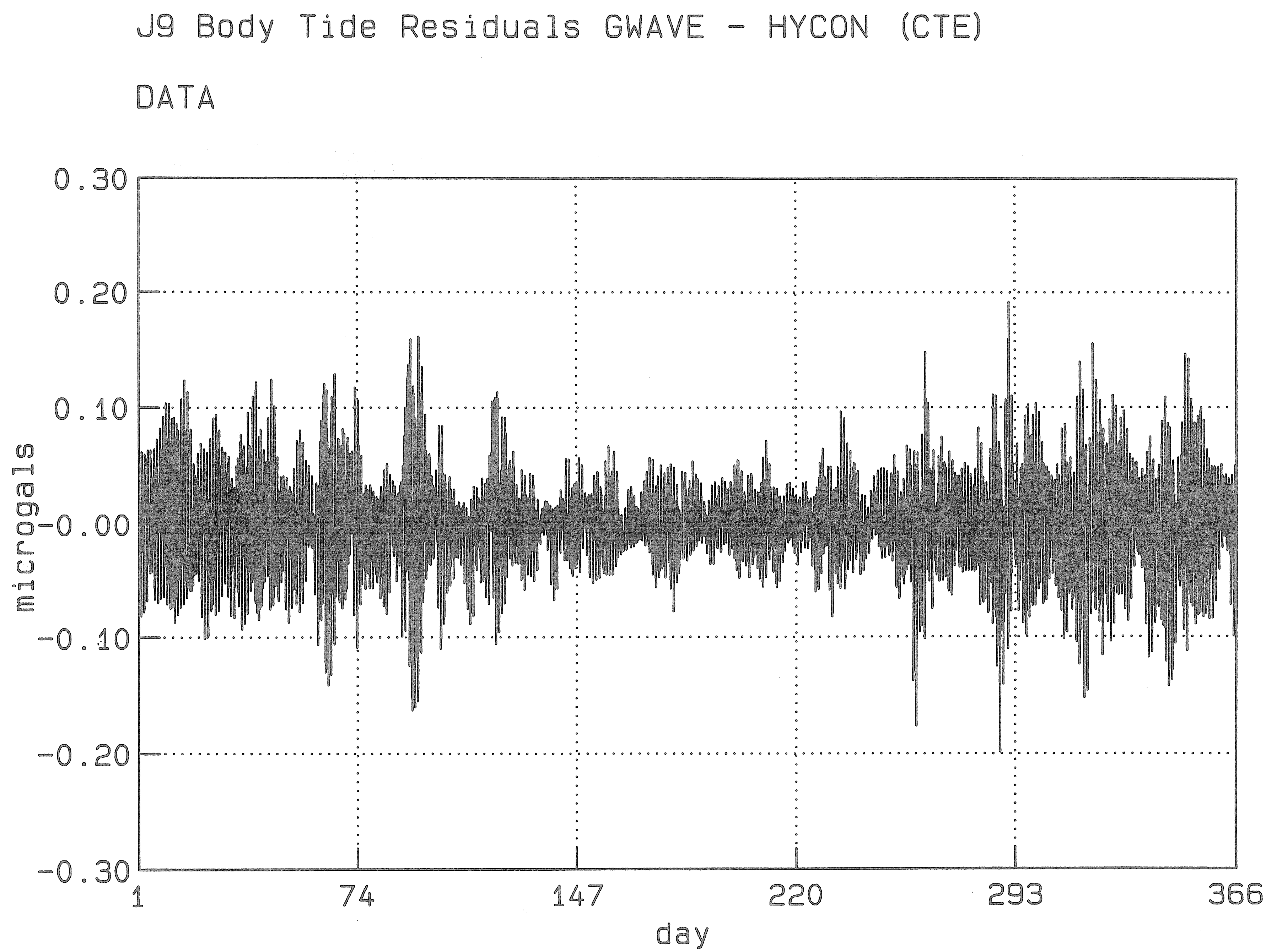
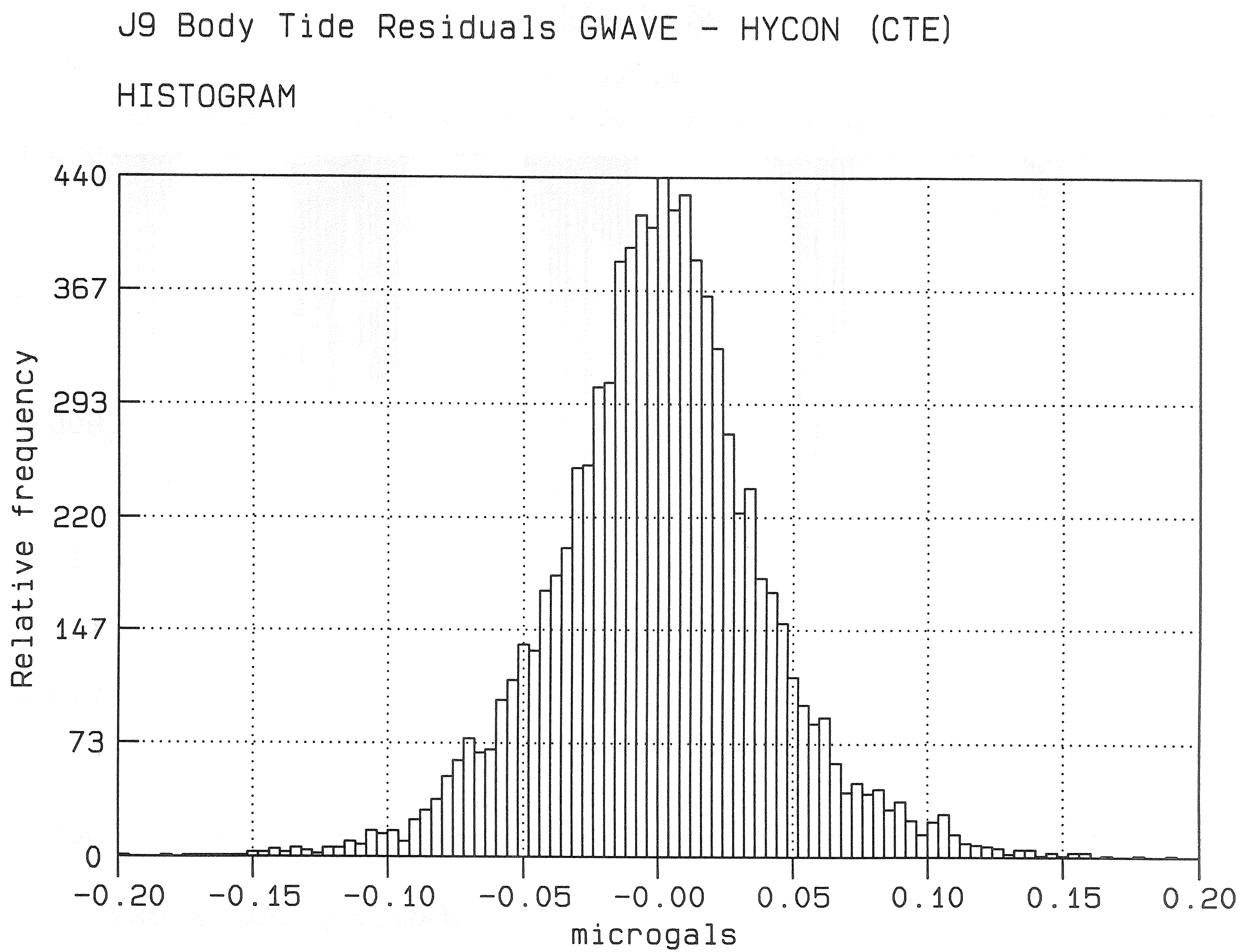

J9 Body Tide Residuals GWAVE - HYCON (CTE)
DATA
0.30
0.20
0.10
-0.00
-0.10
-0.20
-0.30
microgals
1
74
147
220
293
366
day

Figure 2a


J9 Body Tide Residuals GWAVE - HYCON (CTE)
HISTOGRAM
Relative frequency
440
367
293
220
147
73
0
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-0.15
-0.10
-0.05
-0.00
0.05
0.10
0.15
0.20
microgals

Figure 2b

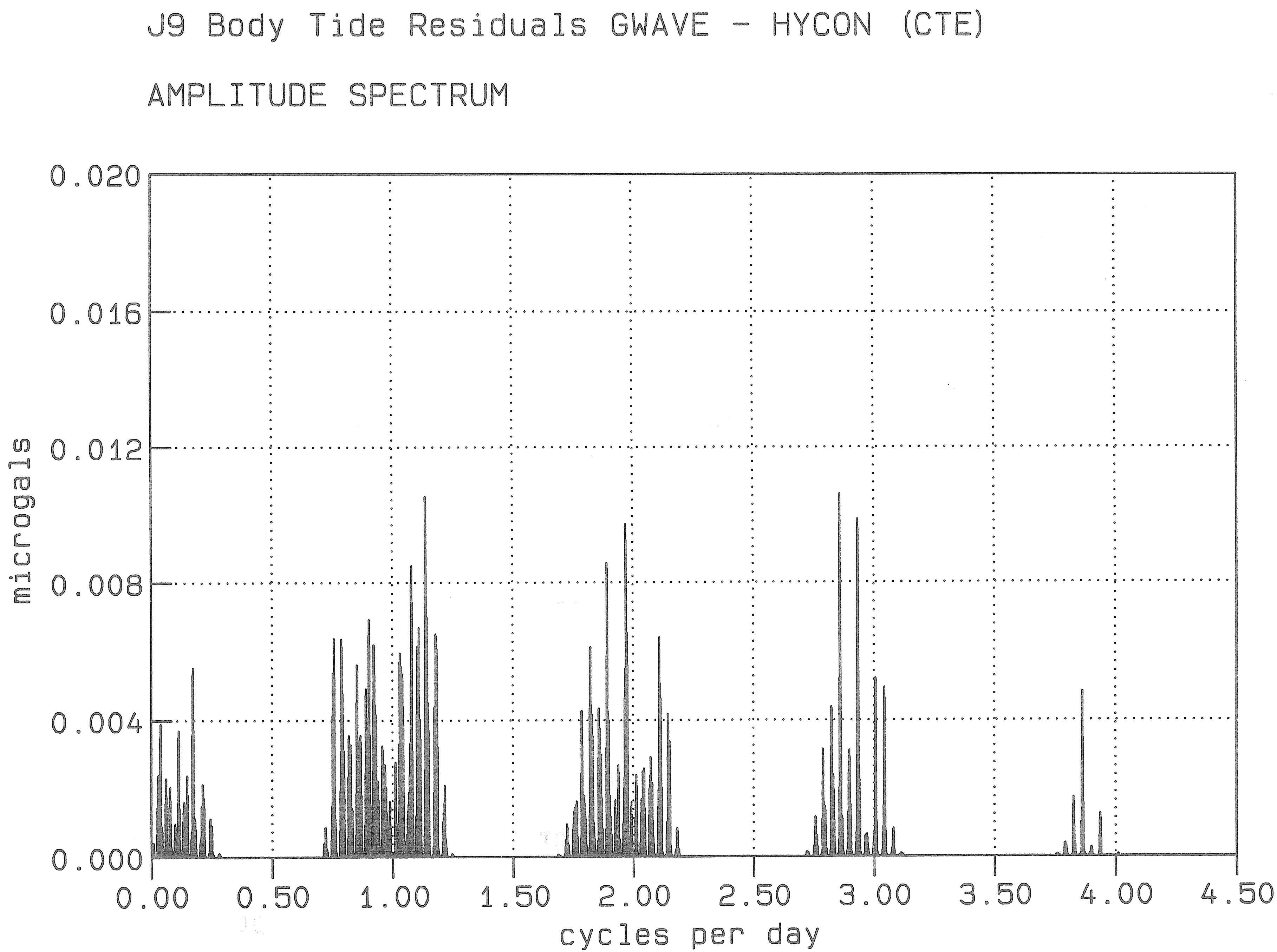
J9 Body Tide Residuals GWAVE - HYCON (CTE)
AMPLITUDE SPECTRUM
microgals
0.020
0.016
0.012
0.008
0.004
0.000
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
cycles per day

Figure 2c

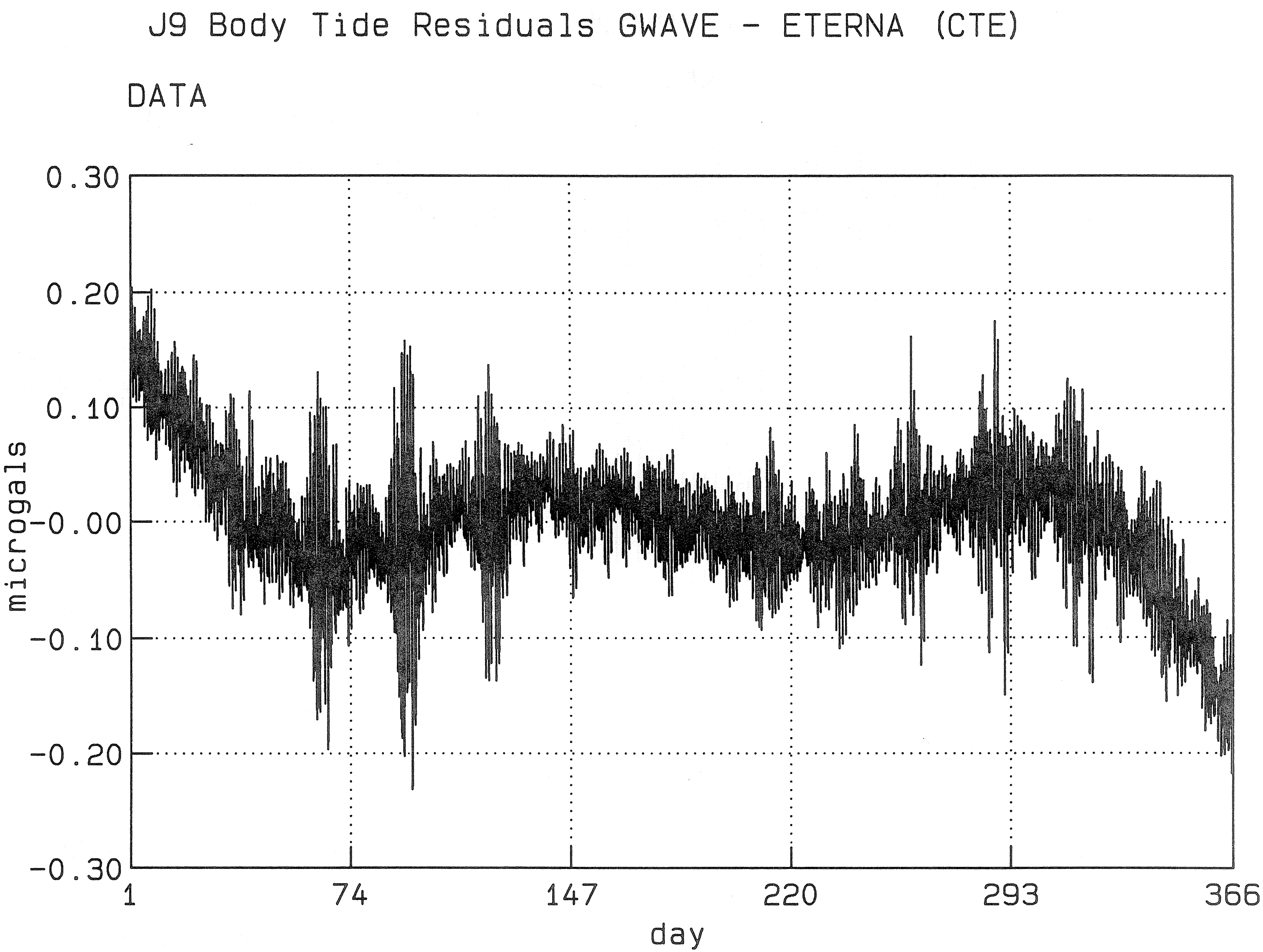
J9 Body Tide Residuals GWAVE - ETERNA (CTE)
DATA
0.30
0.20
0.10
-0.00
-0.10
-0.20
-0.30
microgals
1
74
147
220
293
366
day

Figure 3a

J9 Body Tide Residuals GWAVE - ETERNA (CTE)

HISTOGRAM

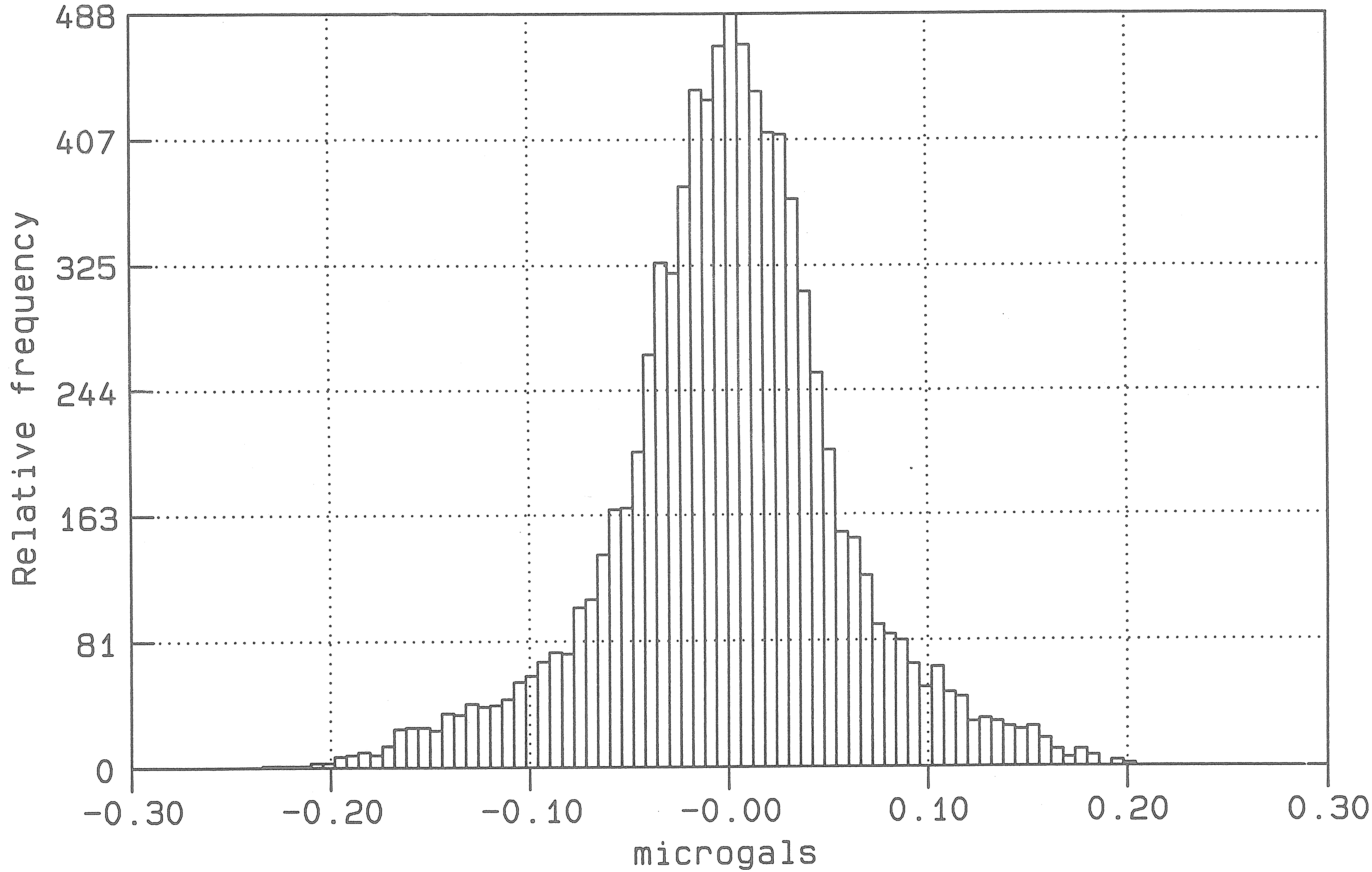

Figure 3b

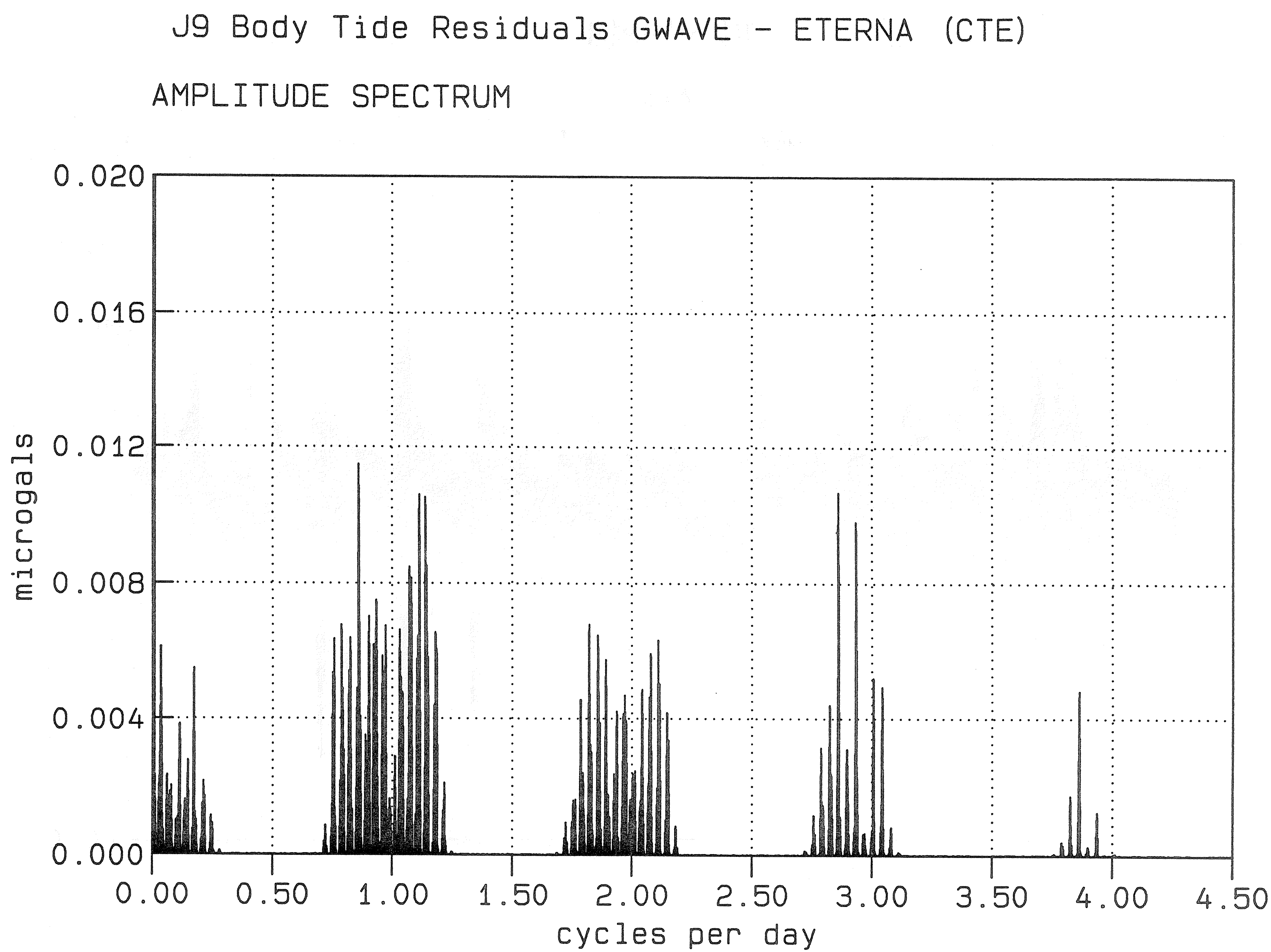
J9 Body Tide Residuals GWAVE - ETERNA (CTE)
AMPLITUDE SPECTRUM
microgals
0.020
0.016
0.012
0.008
0.004
0.000
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
cycles per day

Figure 3c

J9 Body Tide Residuals GWAVE - ETERNA (Tamura)

DATA

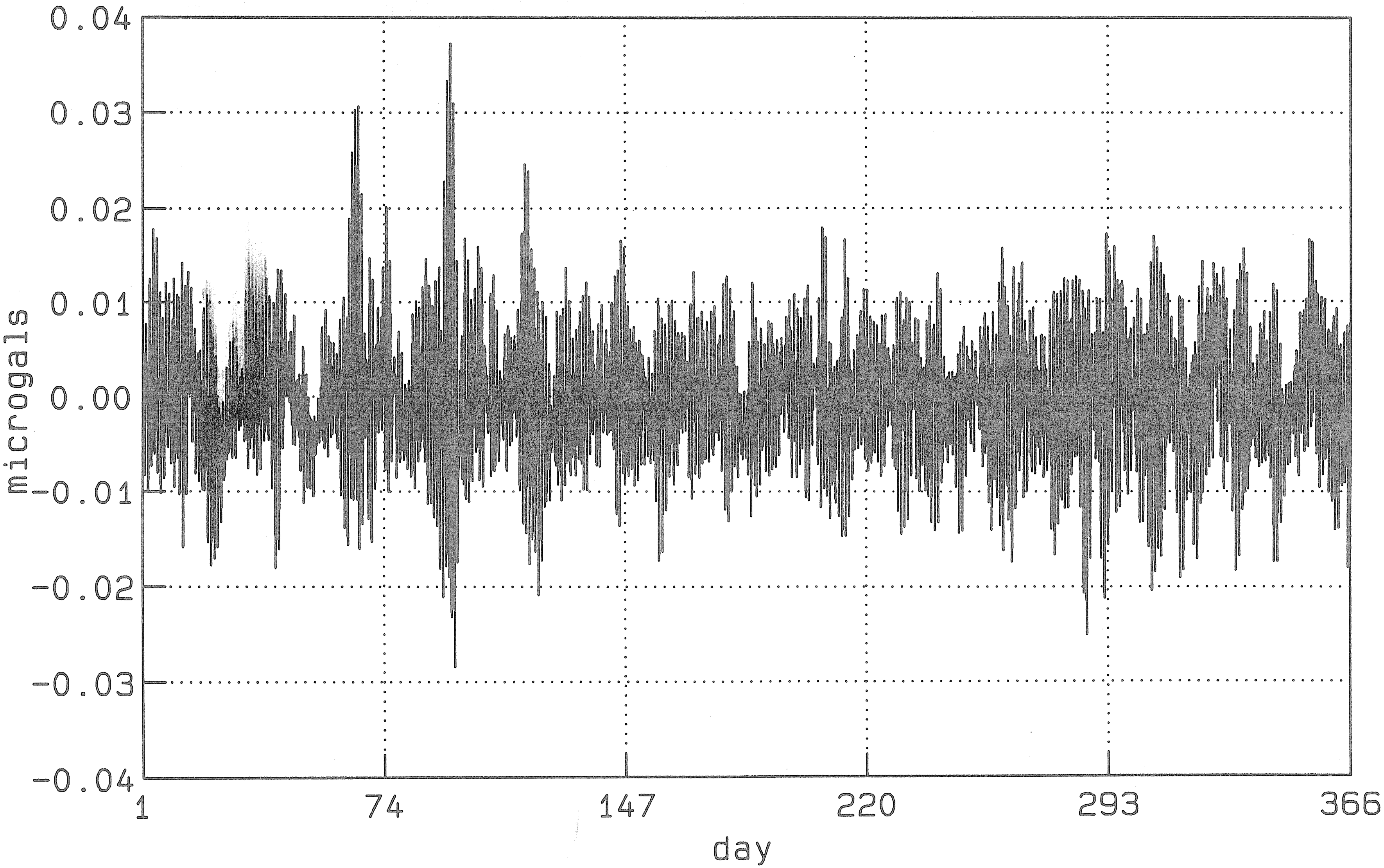

Figure 4a

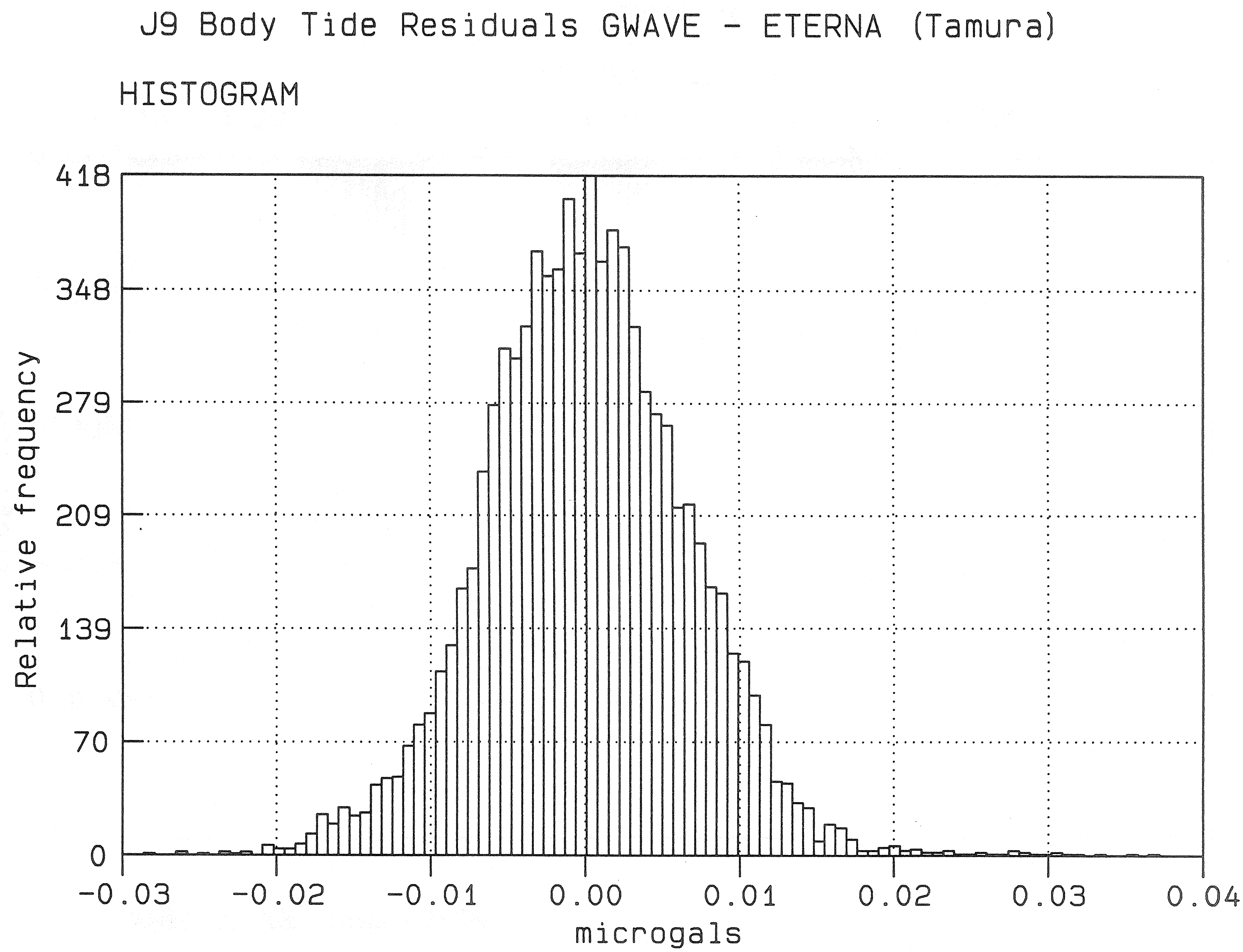
J9 Body Tide Residuals GWAVE - ETERNA (Tamura)
HISTOGRAM
Relative frequency
418
348
279
209
139
70
0
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
microgals

Figure 4b

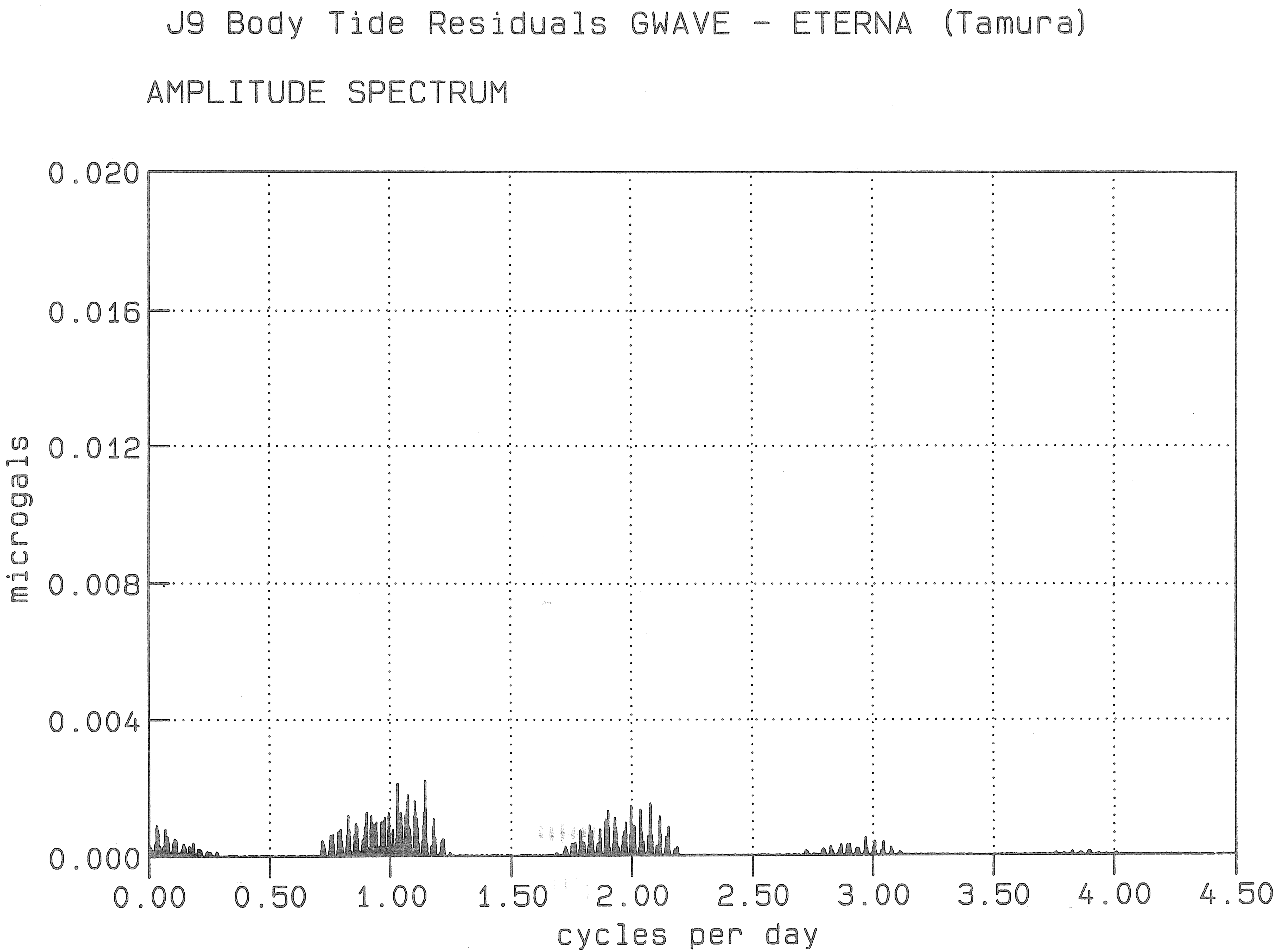
J9 Body Tide Residuals GWAVE - ETERNA (Tamura)
AMPLITUDE SPECTRUM
microgals
0.020
0.016
0.012
0.008
0.004
0.000
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
cycles per day

Figure 4c

Working Group on High Precision Tidal Data Processing
Bonn University, October 10-12, 1990.

CONTINUATION OF MODULATION RESEARCH

Tadeusz Chojnicki
Space Research Center, Warsaw

At the Space Research Center in Warsaw the studies of seasonal tidal wave modulation phenomena (Schwahn et al., 1988) have been continued. Preliminary results of these studies were presented in 1989 at the 11th International Symposium on Earth Tides in Helsinki (Chojnicki, 1989),(Kaczorowski, 1989). Since than as a continuation of the above mentioned studies two tasks were performed: the method for determination of modulation has been tested and the calculation of modulation for the tidal station Dourbes in Belgium has been accomplished.

To test the method used for the determination of modulation it was applied to two observation models. They were constructed as a sum of two elements: Cartwright-Tayler's tidal development and accidental errors created by random-number generator (Orzechowski, 1975). The first model KBK was constructed as a horizontal component in N-S direction with the standard error of 1 msec and the second model KG1 - as a vertical component with the standard error of 3 μgal. The both models were designed for the 12 years period. It is obvious that these models do not contain any modulation.

The fig. 1 and 2 present the results of the determination of modulation in above mentioned models for two tidal waves O1 and M2. As it is shown in the pictures, the results for particular months make the random dispersion of the mean value in the limits of the mean square error of their determination. The tests prove that the mentioned method used for calculation do not introduce any artificial modulation phenomena into observations. The tests were conduced because of certain suggestions expressed during the Symposium in Helsinki.

At the beginning of this year we have got quite a lot of observational data for our studies from International Center of Earth Tides in Brussels. The data include clinometric observations from three stations: Dourbes, Sclaigneaux and Walferdange for the period of 26 years. At each station two components NS and EW were observed, and each component was measured by means of two instruments. It was impossible to process all these numerous data in less than a year and then are still being elaborated. Up to now the modulation calculations for NS component of Dourbes station have been performed. The fig. 3 presents the results of a yearly and a half-yearly modulations determined for the O1 and M2 tidal waves. The existence of the seasonal modulation at the Dourbes station is evident while looking at the fig. 3.

The fact that the period of observations at the Dourbes station is as long as 26 years, allowed one more experiment proving the existence of the modulation phenomena. Since it is considered that to determine this phenomena 10-12 years period is sufficient, the observations of Dourbes station were divided in two 13 year periods, and for ach of them the modulations were determined. In case this phenomena is not incidental but really existing and caused by geophysical condicions characteristic for a station, it could be expected that the results for those two periods should be similar. As it is shown in the fig. 4, this is really a case.

The fig. 5 shows the comparison of the results of yearly modulation determination for the three following stations: Książ and Lohja (presented in Helsinki) as well as Dourbes. The results show the high degree of similarity. For Lohja station the results for November, December and January are not precisely determined because all the gaps in obsevations at this station happened to be in winter. In fig. 5 those results for O1-wave are missing.

In the figures 1-4 the modulation was always presented for the same station. It allowed us to show the changes of amplitudes by means of amplitude factors γ, which are abstract numbers. In the fig. 5, however, where the results coming from different stations are compared the real amplitude modulation is presented in miliseconds of arc.

It is also worth while to learn the results of the modulation determination for pseudotidal M4-wave which for three station Dourbes, Książ and Lohja are presented in the fig. 6. It is known that the presence of this wave is connected with the calibration errors (non-linearity). For Dourbes and Książ stations, where tidal measurements are taken by mean of horizontal pendula (requiring calibration) the seasonal differences between amplitudes of M4-wave in summer and winter (marked with bold-faced lines) are quite evident. At Lohja station where the measurements are taken by means of Long Water Tube, the question of calibration does not exist. As it is obvious from the fig. 6 the modulation of M4-wave does not occur at this station as well, and the values of its amplitude in summer and winter do not show any difference.

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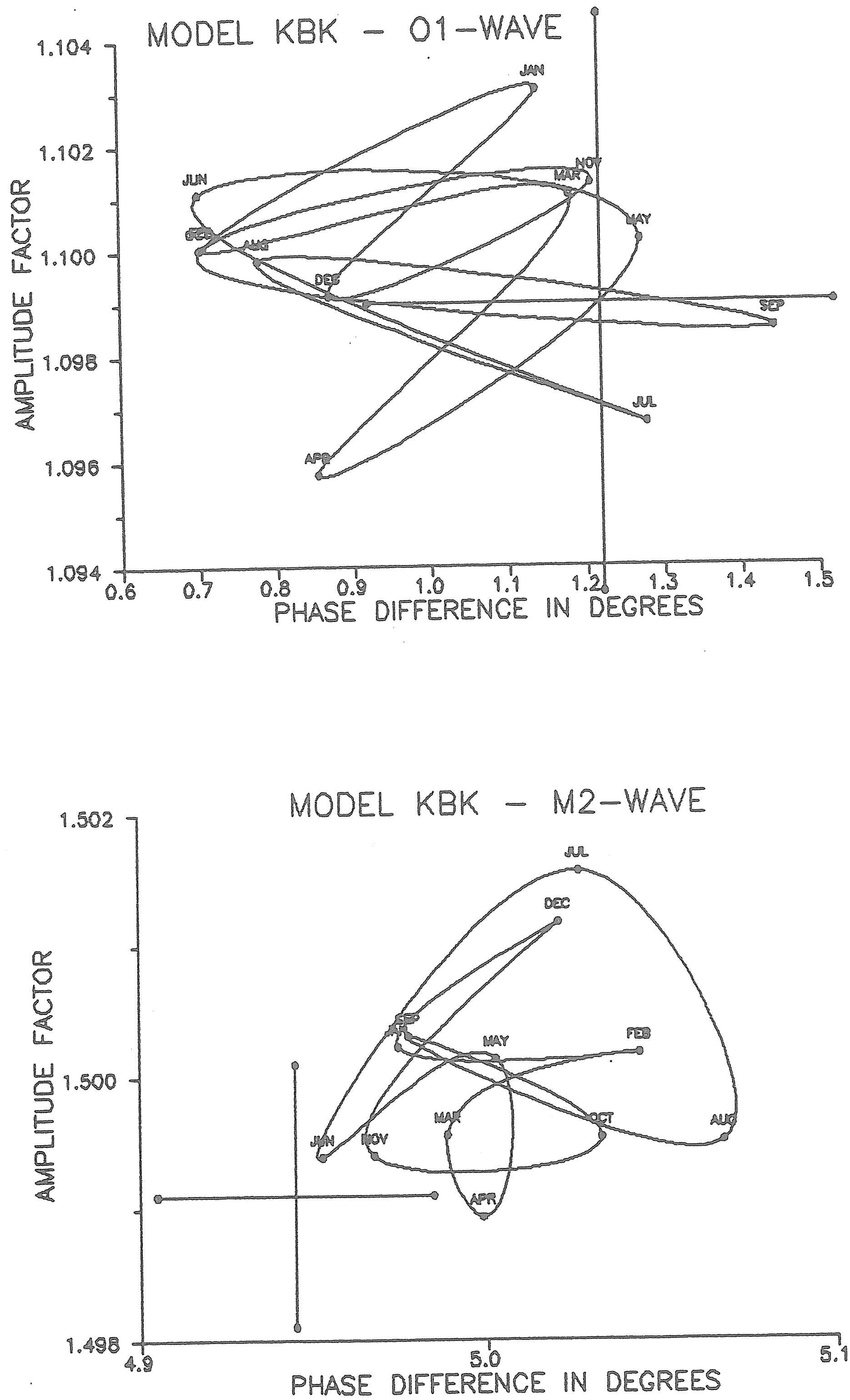
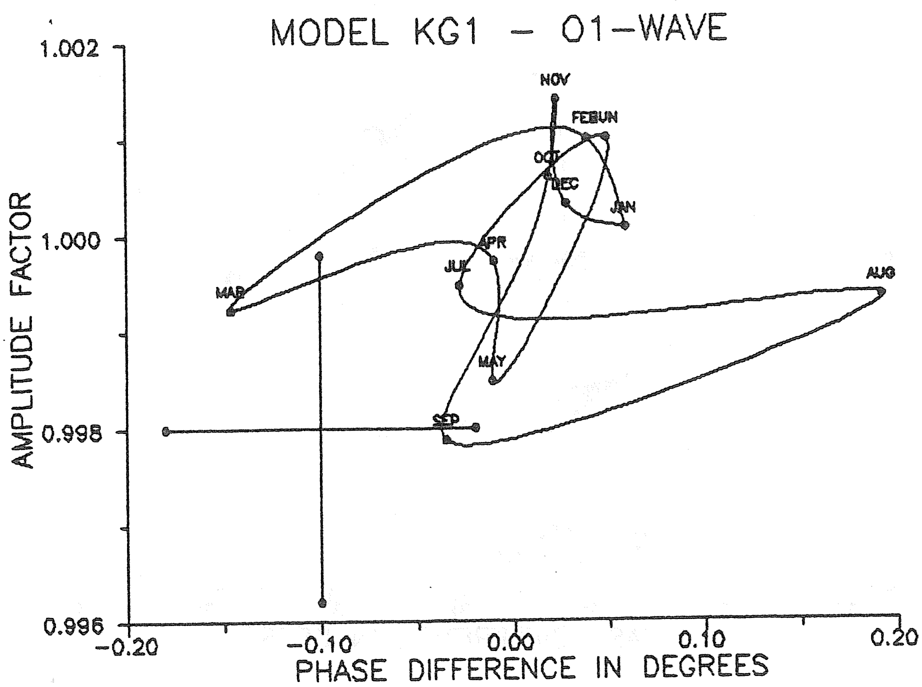


Fig. 1. The results of modulation calculation from the model KBK.



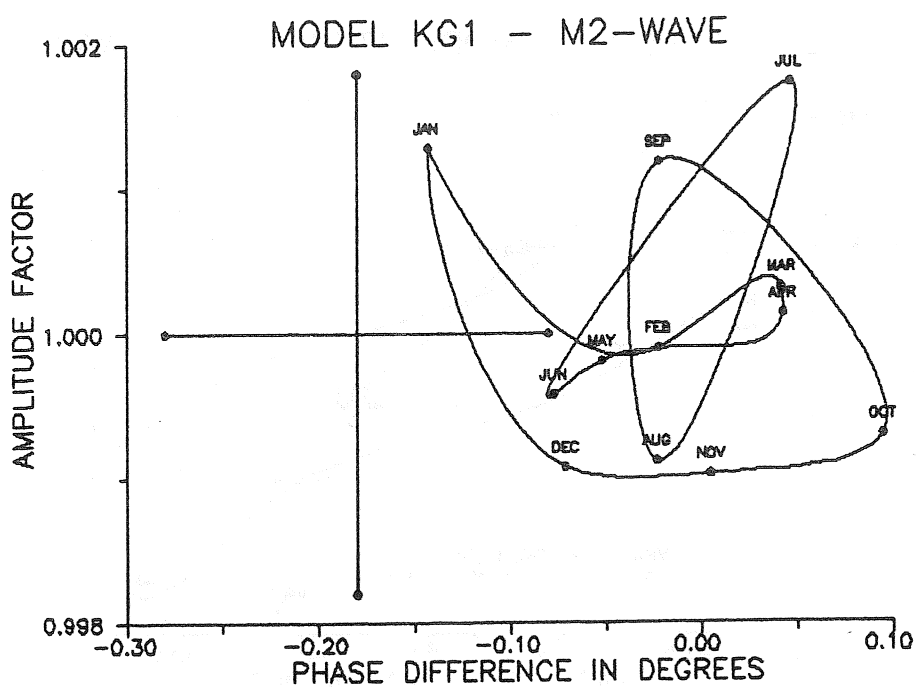


Fig. 2. The results of modulation calculation from the model KG1.

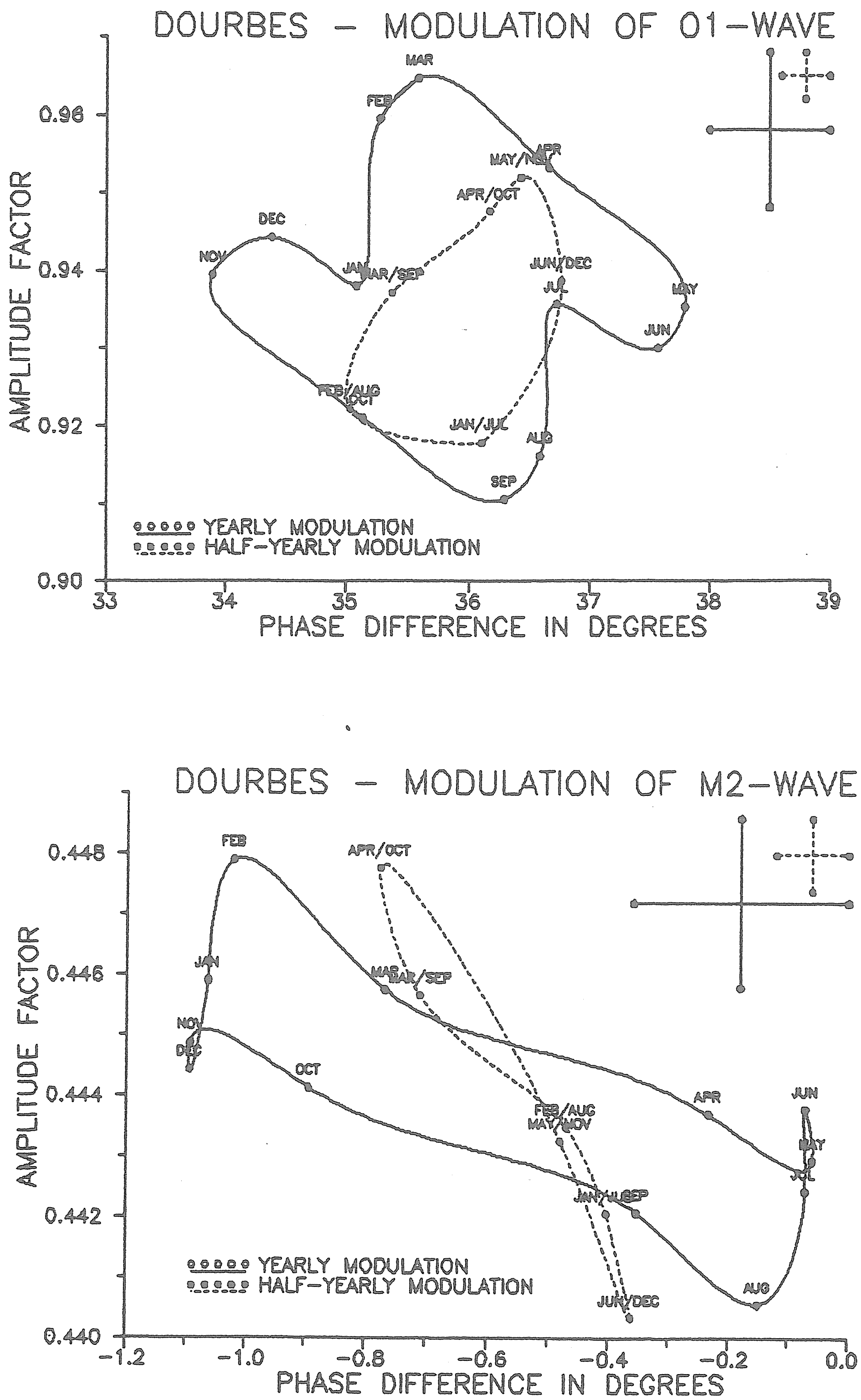
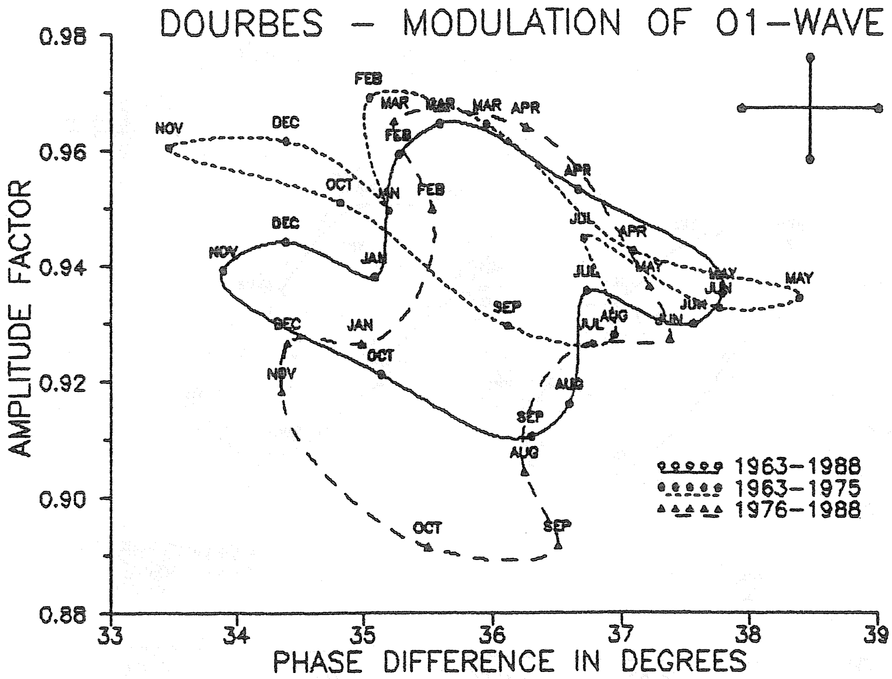
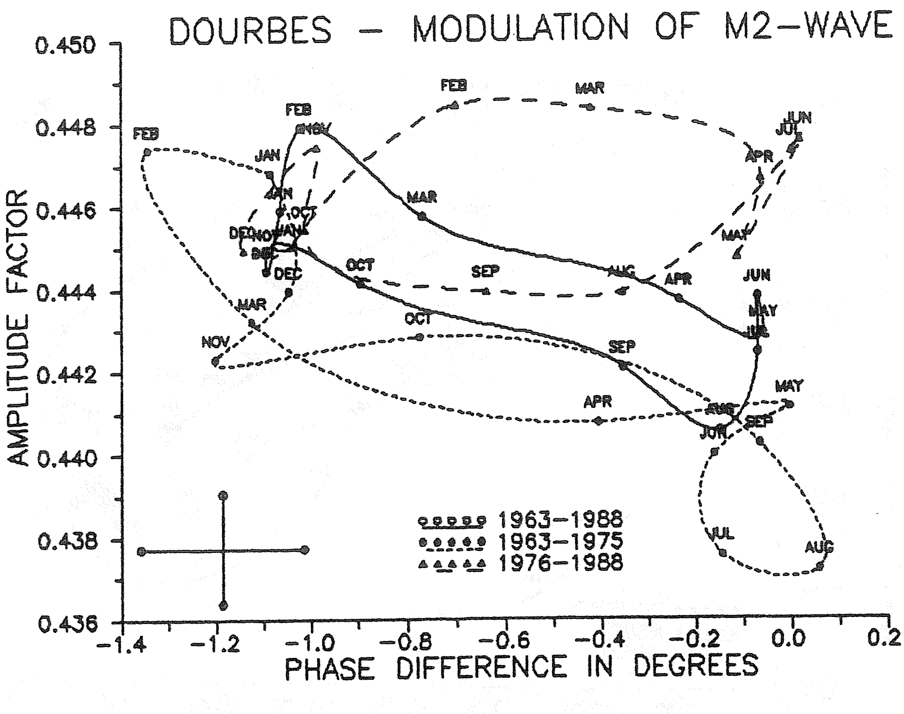
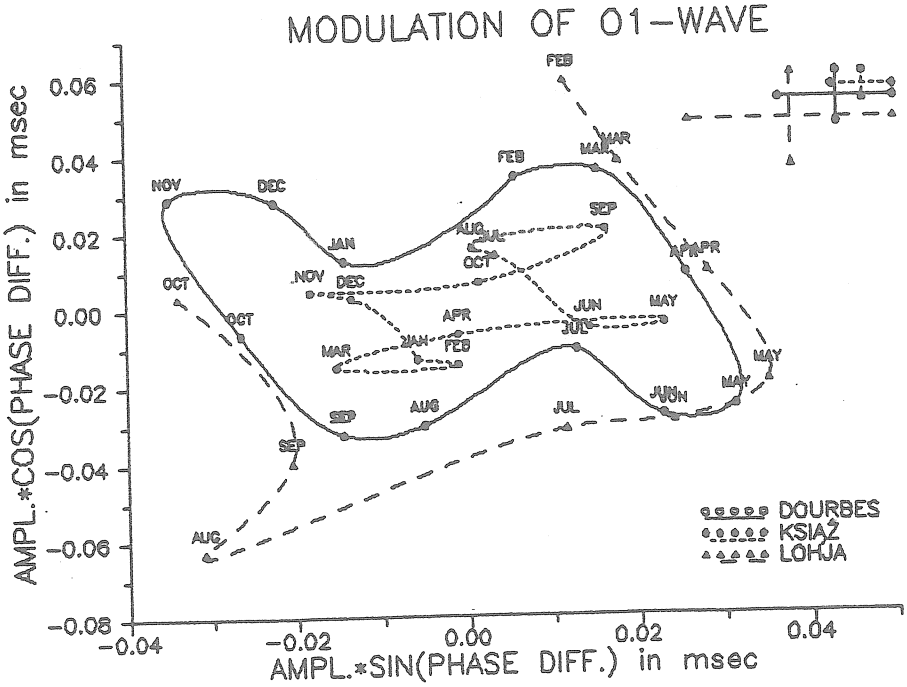


Fig. 3. The results of modulation calculation for Dourbes station.





Rys. 4. Modulation at the Dourbes station for different periods.



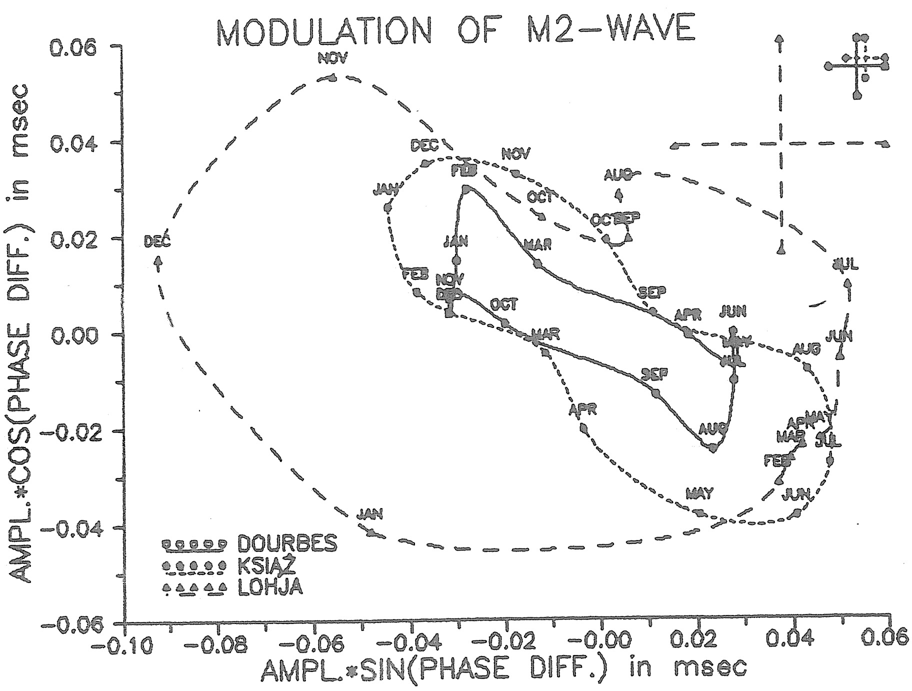


Fig.5. Comparison of the modulation results at different stations.

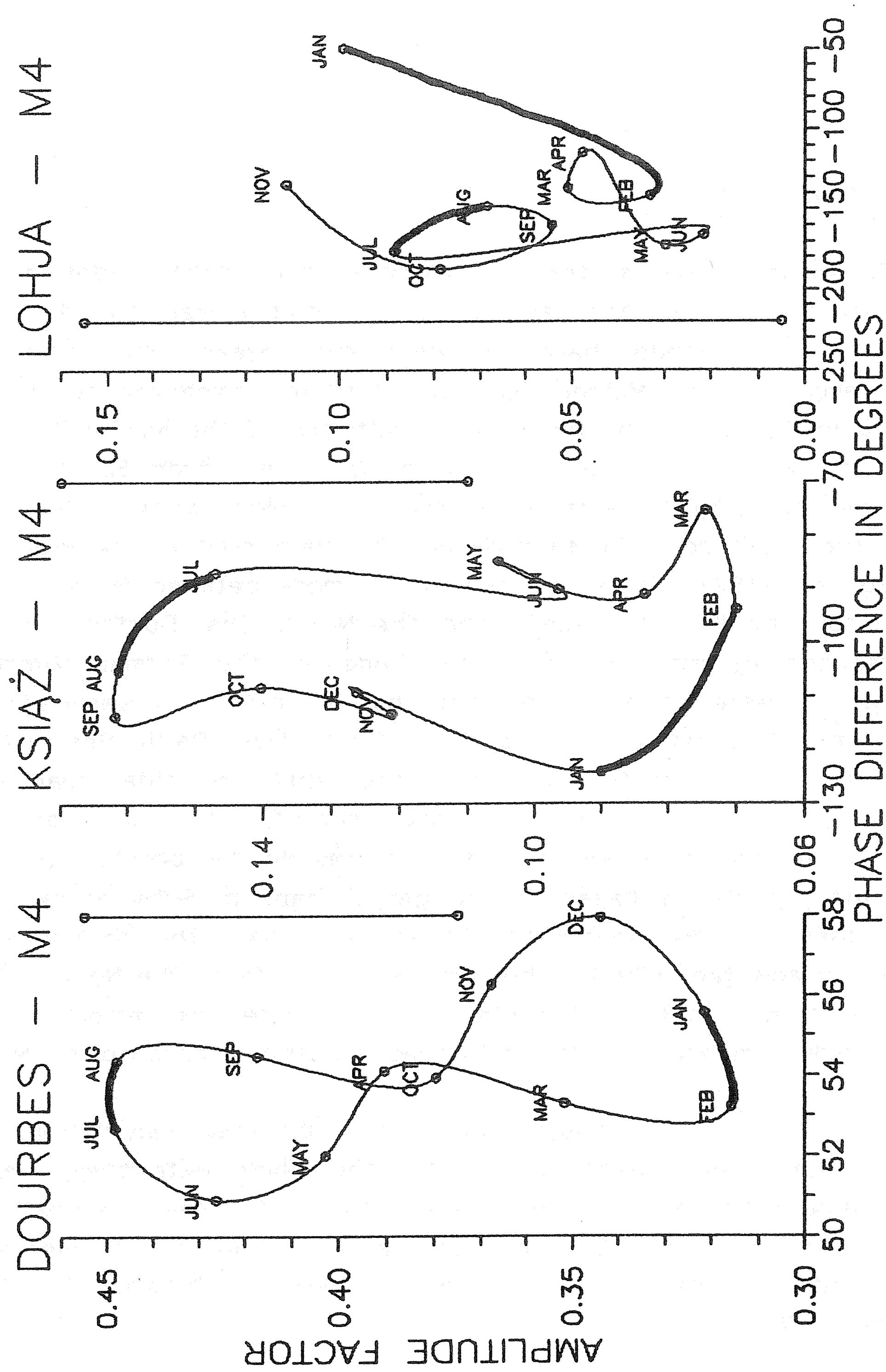


Fig. 6. The results of modulation calculation of M4-wave.

A massconserving Ocean Tide Model for the North Sea and adjacent Sea Areas

T. Jahr*

1. Introduction

In summer 1989, at the 11th Symposium on Earth Tides, an M2 ocean tide model for tidal load calculation in Denmark was introduced (Jahr et al., 1991). This model based on calculated ocean load effects (Farrell, 1972), according to Molodenskys Earth model, compared to the observed loading in Denmark. The observed amplitudes of the M2 loading are in the order of 1 µgal in Denmark and the phases reach from 52° to 86°.

The resulting M2 ocean tide model is a combination of different ocean tide models and contains four parts. The main part is the global model of Schwiderski (1979). It is improved by a more detailed model from Flather (1976) for the British Islands and the North Sea. Further improvements are realized by adopting the local model of the German Hydrographical Institute (Soetje et al., 1986) and by an extension eastwards for the Skagerrak, Kattegat, Belt Sea and the South-West Baltic Sea (Jahr, 1989).

This model enable to explain the observed tidal load effects in Denmark and off course it can be used for M2 load calculations of gravity, displacement and tilt. But it has to be pointed out that this preliminary model is based on the global maps of Schwiderski, which are not conserving the watermass. In addition only the former model from Flather is adapted, whereas his new model contains the North Atlantic, too (Flather, 1986). On the other side the theoretical load effects, due to this model, are compared to the observed loading according to Molodenskys model.

An improved M2 ocean tide model for load calculations in North Europe should be massconserving for the whole watermass, Flathers new model should be included and the results of the load calculations should be compared to the observed load effects, due to Molodenskys Earth model and the rotating model of Wahr (1981) or Dehan/Wahr (Dehan and Ducarme, 1987).

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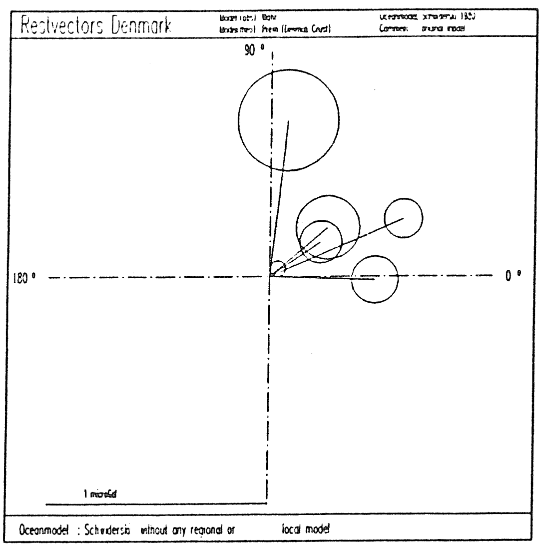
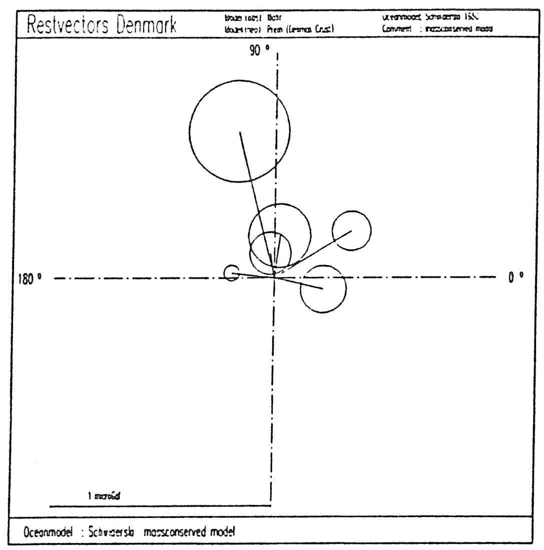
2. Massconservation of the global ocean tide model

For the estimation of the M2 ocean tide model the rest- or residual vectors at six stations in Denmark are considered, describing the differences of the observed and theoretical loadvectors. The following investigation deals with the observed load effects, due to Molodenskys model (constant tidal parameter of 1.16) and Wahrs model. The tidal parameters, calculated by the Dehant/Wahr Earth model differ only less than 0.5 %, corresponding to load differences of ≈ 0.05 µgal, from the models mentioned above.

The massconservation of the model from Schwiderski is realized by adding a small constant tide to each cell of this 1°*1° global model. The additional amplitude is 0.7 cm with a phase of 332°. The improvement, due to massconservation is shown in fig.1: The amplitudes of the restvectors, calculated by the massconserved ocean model are smaller than for the original model. The restvectors of Molodenskys and Wahrs model are similar and the improvement, due to massconservation can be shown for both models.



Original M2 model of Schwiderski (1979)



Massconserved M2 model of Schwiderski

Fig. 1: Restvectors for six different stations in Denmark. The error circles derived from the spectral analysis of the residuals. (biggest: Møgeltønder in South-West Jutland; smallest: Copenhagen).

3. Adaption of the regional M2 ocean tide model (North Atlantic and North Sea)

The regional ocean tide model of the North Atlantic and the North Sea is constructed in a grid of 1/2° in longitude by 1/3° in latitude. On the one side the former model (Flather, 1976) was extended to the North Atlantic, which is very important because the North Atlantic produces the strongest M2 load effects in Europe. On the other side the new model contains the Skagerrak and the Kattegat, too. This model is adapted to the massconserved global model of Schwiderski.

The loadvectors, due to this combined model, leads to restvectors with amplitudes comparable to the original model of Schwiderski, but the phases are all orientated in the same direction. This fact refers to a systematical error in the ocean tide model used. These results are demonstrated for Molodenskys and for Wahrs model in fig. 2.

However, we have to take into account the massconservation, mentioned above, because this combined ocean tide model is not conserving the watermass anymore. It is corrected by carrying out a massnormalization of Flathers model to Schwiderskis model for the same ocean area. For this a small constant tide with an amplitude of 0.2 cm and a phase of 142° is added to the amplitudes and phases of the regional model from Flather.

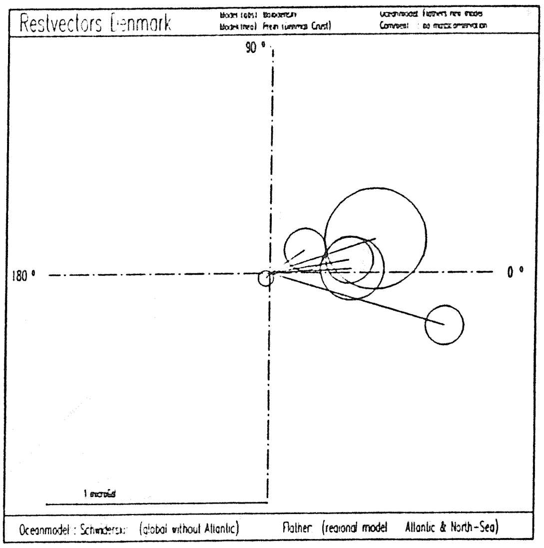
The result is a combined ocean tide model, which is conserving the Sea water, moved by tides (M2). This model is not producing or reducing any watermass, that means it is correct also in a physical point of view.

The restvectors point out the improvement of the model, due to massconservation (fig. 2): The amplitudes are decreased, and the phases are not as strongly orientated as before.

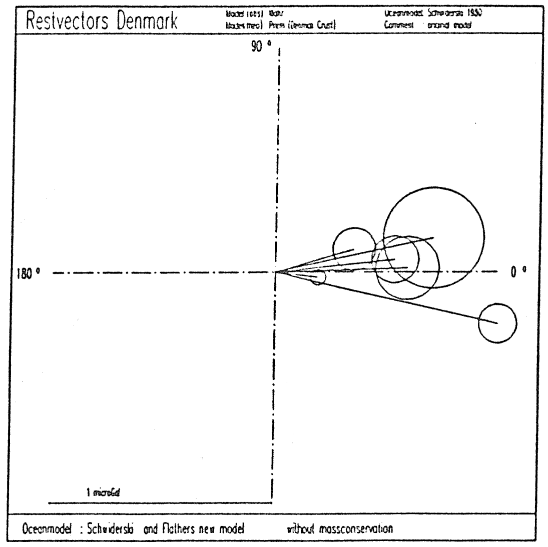
4. Discussion and conclusion

These results are based on observations, due to Wahrs- and Molodenskys Earth model. The significance of the improvement can be shown especially for Molodenskys model: The mean amplitude of the restvectors is reduced from 0.34 µgal for the original model of Schwiderski to less than 0.22 µgal for the combined and massconserving model (fig. 2).

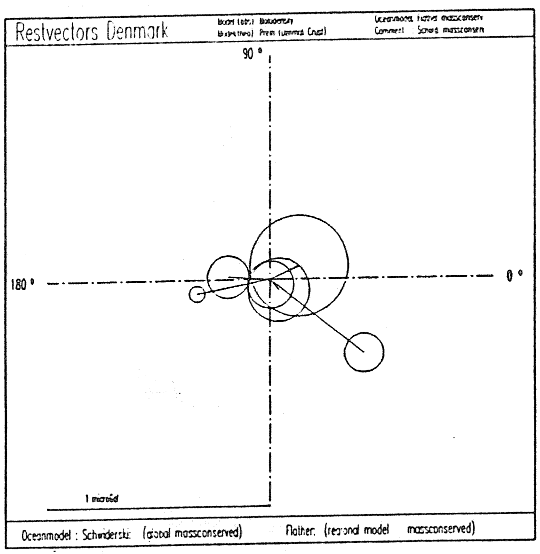
This model was used for calculation of the regional M2 load effect in Denmark (fig. 3). The amplitude of the gravity effect vary from 1.5 µgal at the westcoast to about 0.9 µgal in the east and north part of the country. Corresponding to the observations the phases are between 90° and 50°. The vertical deformation, due to the M2 load effect is about 6 mm in West-Jutland, decreasing eastwards to ≈ 4 mm. The tilt computation to east and north direction show that the effects amount up



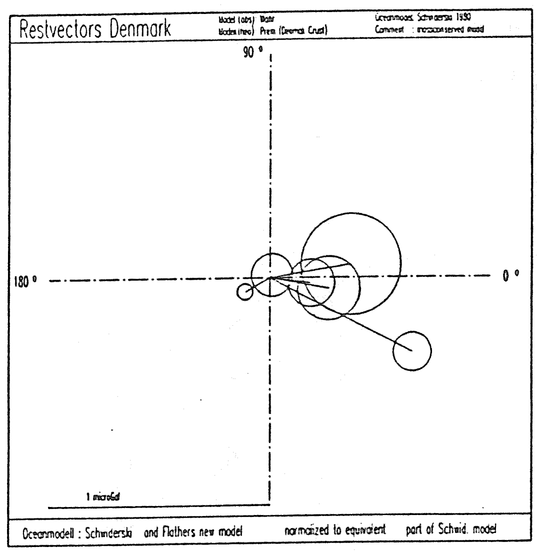
observed load : Molodensky
regional model: Flather
global model : Schwiderski



observed load : Wahr
regional model: Flather
global model : Schwiderski

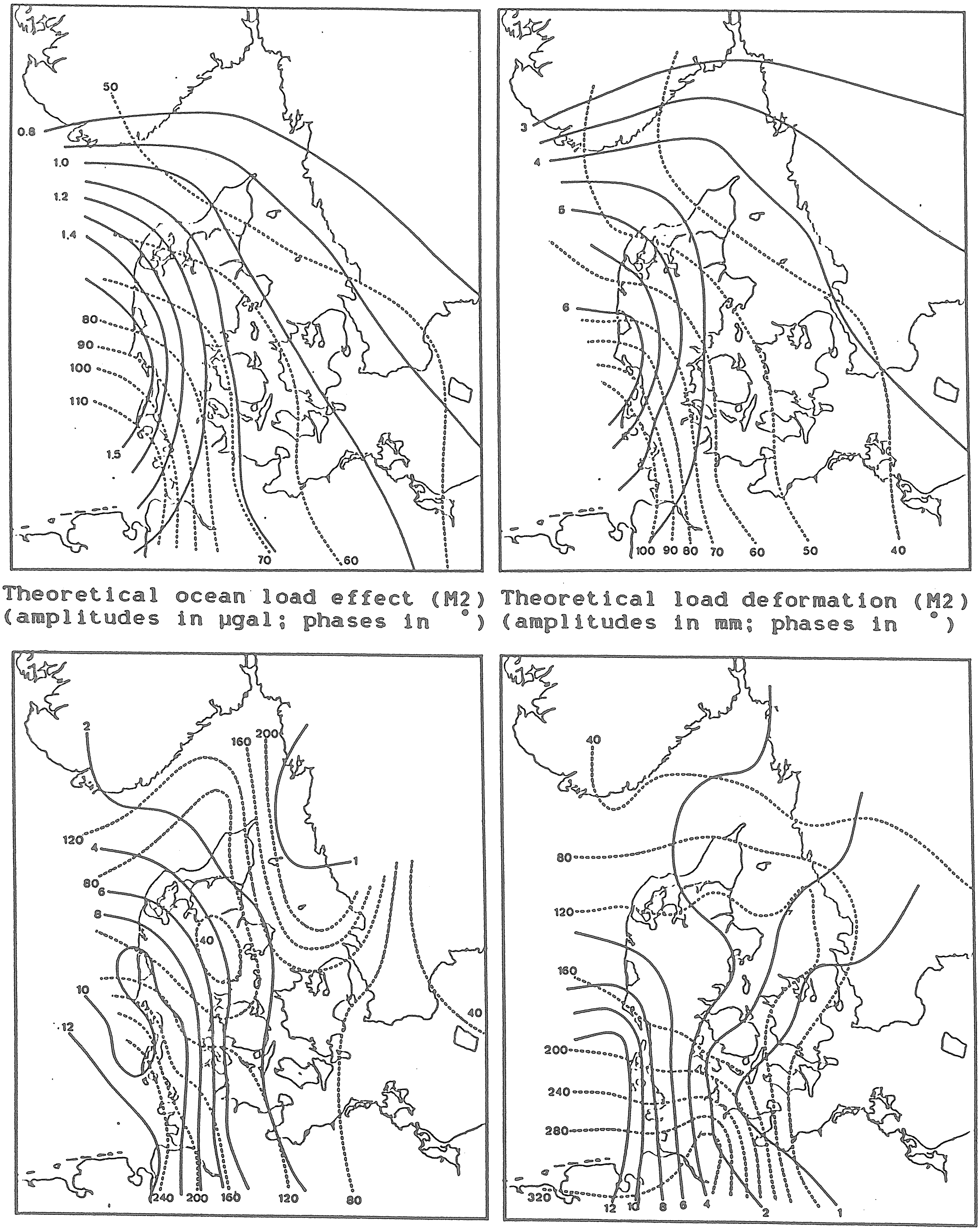


observed load : Molodensky
combined model with
massconservation



observed load : Wahr
combined model with
massconservation

Fig. 2: Restvectors for the combined- and for the combined and massconserved M2 ocean tide model. The observed load was estimated according to Molodenskys and Wahrs Earth models.



Theoretical ocean load effect (M2) (amplitudes in µgal; phases in °)

Theoretical load deformation (M2) (amplitudes in mm; phases in °)

Theoretical tilt to East (M2) (amplitudes in msec; phases in °)

Theoretical tilt to North (M2) (amplitudes in msec; phases in °)

Fig. 3: Ocean load effect in Denmark, calculated with the resulting combined and massconserved model for the M2 tidal wave.

to 10 msec near the North Sea coast. Off course, we have to keep in mind the errors of about 0.1 to 0.2 µgal, corresponding to 10 to 20% of the mean load effect. But it is shown, that we have a main gradient eastwards and a smaller one in North direction in West-Jutland.

Summarising the results we can conclude three points: First, the M2 load calculations for stations in Denmark can be improved by using Flathers new model for the North Atlantic and the North Sea. Second, the improvement, due to massconservation of this combined ocean tide model is confirmed by the observations in Denmark. This is shown for Wahrs and for Molodenskys model. Third, the resulting restvectors are comparable to these, introduced on the 11th Symposium on Earth Tides, but the new ocean tide model is not only constructed for specialized load investigations in Denmark and it can be applied at other sites in North Europe.

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NUMERICAL REPRESENTATION OF OCEAN TIDES IN CANADIAN WATERS AND ITS USE IN THE CALCULATION OF GRAVITY TIDES

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ABSTRACT

Advances in gravity instrumentation have made possible the detection of well-known but often poorly understood phenomena such as, postglacial rebound, tectonic deformation, polar motion, atmospheric mass movements and tides. It is believed that other hypothesized phenomena such as, core undertones, atmospheric oscillations, and core-mantle interactions could also be detected by gravimetry. In order to reduce any possible tidal contamination in these measurements to below the ambient noise level of the gravimeter, tide predictions are required to a precision of better than 1 microgal for absolute gravity field measurements and better than 0.1 microgal for continuous high-precision recording of gravity.

With these objectives in mind a numerical representation of the near-shore ocean tide load constituents (M2, S2, N2, O1, K1) was prepared using recently available ocean tide modelling results for Canadian coastal waters. The detailed near-shore tidal representation is designed to supplement the global 1° x 1° model of Schwiderski (1980). The near-shore ocean tides are represented by a grid of cells in which the amplitude and phase lag of tidal constituents are constant and which are bounded, in general, by lines of constant latitude and longitude. The numerical representation around Canada is divided into three regions: the north-central region (Hudson Bay, James Bay, Foxe Basin, and Hudson Strait); the eastern region (Bay of Fundy, Gulf of Maine, Scotia Shelf, Grand Banks, East Coast Newfoundland, Gulf of St. Lawrence, St. Lawrence River); and the western region (Hecate Strait, Queen Charlotte Sound, coastal Vancouver Island, Strait of Juan de Fuca, Georgia Strait, and Puget Sound) (Figure 1). The dimensions of the cells employed in the different regions depend on the spatial variability of the tides and the variability of the coastline.

The gravity effect of the ocean tide for a given tidal constituent at a typical Canadian station is calculated by convolving numerically a complex Green's function representing the response of the earth with a set of complex mass loads representing the particular constituent of the ocean tide. The load associated with each cell in the grid is assumed to act at the centre of mass of a cell. A Green's function for a viscoelastic, anisotropic and rotating earth (Pagiatakis, 1988) was employed and the convolution was carried out using the programs LOADSDP 3.0 and LOADSDP 3.1. The total predicted ocean tide effect on gravity is calculated by summing in the time domain the contributions of all constituents in the Schwiderski global model and the contributions of the five constituents of the Canadian coastal model.

A number of regularly observed absolute gravity sites in Canada have been established for the purpose of monitoring postglacial rebound and tectonic processes. A significant reduction of the variations in absolute gravity residuals was observed at all such sites within a few tens of kilometres of the coast when the near-shore cells were included in the convolution. Improvements were also noted at the 0.1 microgal level at the Canadian Superconducting Gravimeter Installation, Cantley,Quebec (Ottawa). Further improvements are expected for absolute gravity sites very near the coast with the addition of corrections based on an even finer local grid.

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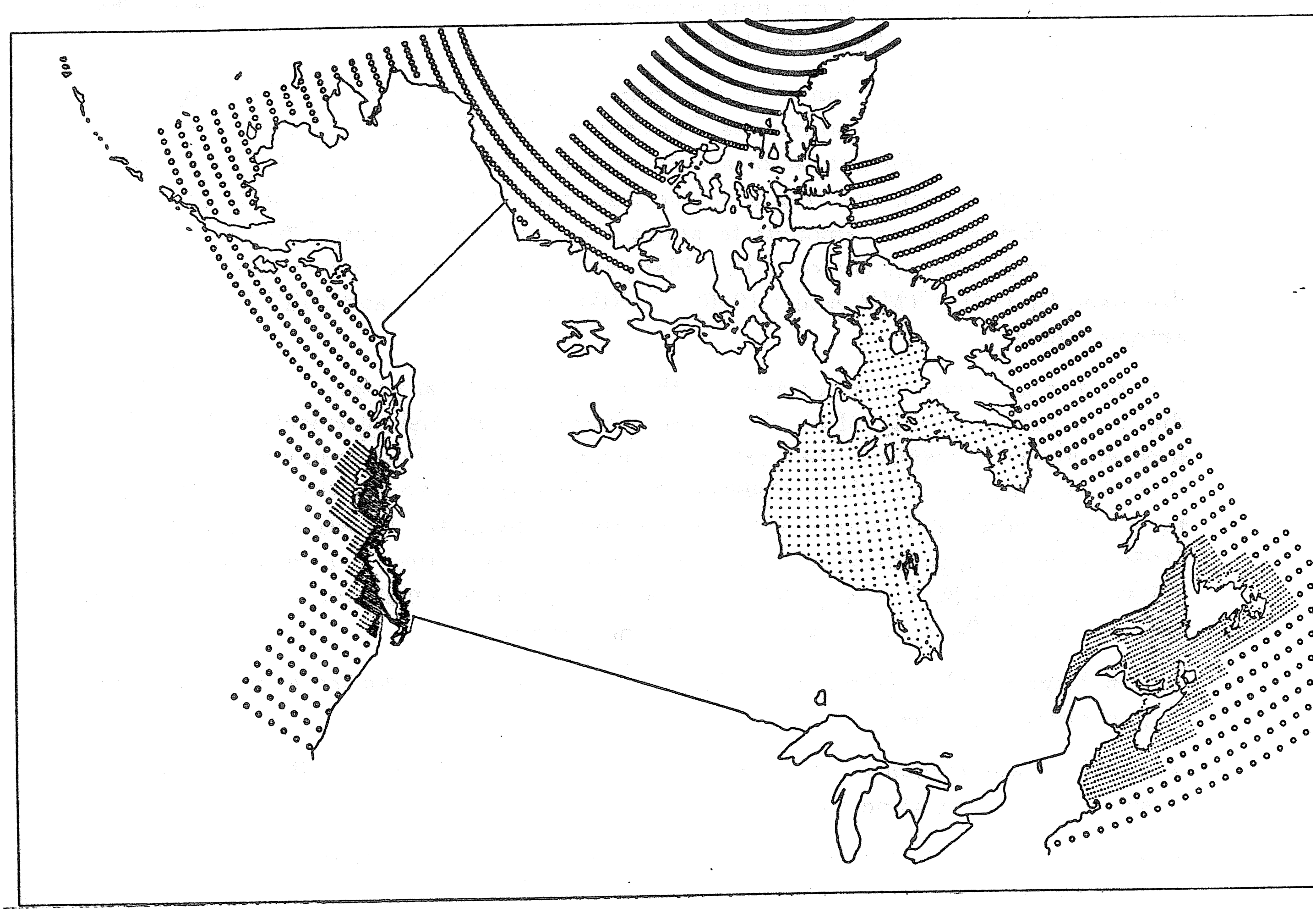

Figure 1. Canadian coastal waters gridded for enhanced ocean loading calculations. Cells of the regional grids are represented by small dots. Cells of the Schwiderski global model are represented by large open dots.

REMARKS CONCERNING THE RELIABILITY OF TIDAL REDUCTIONS

by

H.-J. Dittfeld[1] and L. Timmen[2]

With increasing instrumental accuracy, gravity reductions also have to be revised and eventually improved. Here, we concentrate on earth tides reductions. On the one hand, tidal modelling is straight forward as the physical changes of the tidal forces are well known. On the other hand, uncertainties in the model cause systematical errors which do not become apparent during data processing and evaluation. In this paper we shall discuss some of the problems involved.

Tidal reductions or, with opposite sign, tidal prognoses are often calculated by means of an adopted set of tidal parameters. For example, the theoretical values $\delta = 1.164$ and $\kappa = 0.00°$ for the amplitude factor and the phase shift, are often used for all the waves of the tidal spectrum, not regarding the difference between diurnal and semidiurnal amplitude factors which amounts to about 3% in central Europe. The effect of local variations and different choice of the tidal parameters on tidal reductions was already discussed by DUCARME et al. (1980), TORGE et al. (1987) and DITTFELD (1981), among others.

During the last years, the demands on the accuracy of tidal prognoses have increased, due to a higher quality of absolute and relative gravity measurements. Particulary, modern absolute gravity meters require accurate reduction models in order to preserve their high precision. TORGE (1990) states a long-term repeatability of $\pm 0.06\ \mu m/s^2$ for gravity values determined with the absolute gravimeter JILAG-3. PETER et al. (1989) achieved a precision of $\pm 0.01 \ldots 0.04\ \mu m/s^2$ over a time interval of one year for JILAG-4. LAMBERT et al. (1989) derived a precision of $\pm 0.03\ \mu m/s^2$ from field tests with JILAG-2. We shall discuss the following questions:

- how large are the differences in tidal reductions if either adopted or measured tidal parameters are used,
- are there any significant differences in the reductions, based on different tidal measurements in the same region,
- are there any differences in the reductions, based on parameter sets of the same instrument at different epochs,
- is there any remarkable influence of different potential developments,

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- are the so called practical tidal parameters like weighted mean values for the single frequency bands useful or not.

The results of about 15 years continuous tidal registration at ZIPE Potsdam will be used for these investigations. The complete observation series as well as parts of it have been evaluated for this purpose, cf. table 1. Tidal predictions were calculated for a period of one year (the year 1990).

Tab. 1: Different tidal models used for earth tide prognosis

model	No. of tidal parameters [$pair(\delta, \kappa)$]	observation period [$year.month$]
A1	1 (1.164, 0.00°)	
A2	34	74.03...88.12
A3	3 (diurnal, semid., terd.)	74.03...88.12
A4	19	82.12...84.03
A5	19 (M1 min. δ)	77.06...78.09
A6	19 (M1 max. δ)	81.12...83.03
A7	19 (N2 min. κ)	81.06...82.09
A8	19 (N2 max. κ)	85.03...86.06

The tidal-like variation of the discrepancy between a prognosis based on 34 observed parameter pairs (A2), analyzed from a fourteen years record, and a prognosis calculated with $\delta = 1.164$ and $\kappa = 0.00°$ (A1), can reach 64 nm/s^2 in the year 1990 (Fig. 1b, Tab. 2). Maximum variations naturally occur within about six hours. In the worst case, relative gravity measurements over this time could be affected by this maximum difference. In model A3, the weighted mean values of the tidal parameters for the main frequency bands are applied. Calculating a prognosis by means of three pairs (diurnal, semidiurnal and terdiurnal) of parameters leads to similar results (Tab. 2) with differences smaller by about 10% (Fig. 1c). The discrepancy between the calculations based on the full set and on three pairs of parameters is oscillating in the order of about 10 nm/s^2. The maximum difference is 18 nm/s^2. Although this calculation is in good agreement with A2, the reductions should be calculated with the full set of observed parameters. Using efficient computers, the calculation time for A2 and A3 differs only slightly.

Tab. 2: The influence of different parameter sets in 1990

data set 1	data set 2	max. difference [nm/s^2]	r.m.s. discrepancy [nm/s^2]
A1 (1.164; 0.0)	– A2 (34P: 7403..8812)	64.3	11.7
A1 (1.164; 0.0)	– A3 (3P: 7403..8812)	52.6	10.0
A2 (34P: 7403..8812)	– A3 (3P: 7403..8812)	18.0	3.9
A1 (1.164; 0.0)	– A4 (19P: 8212..8403)	60.9	12.0
A6 (19P: 8112..8303)	– A5 (19P: 7706..7809)	20.6	3.3
A8 (19P: 8503..8606)	– A7 (19P: 8106..8209)	27.7	7.6

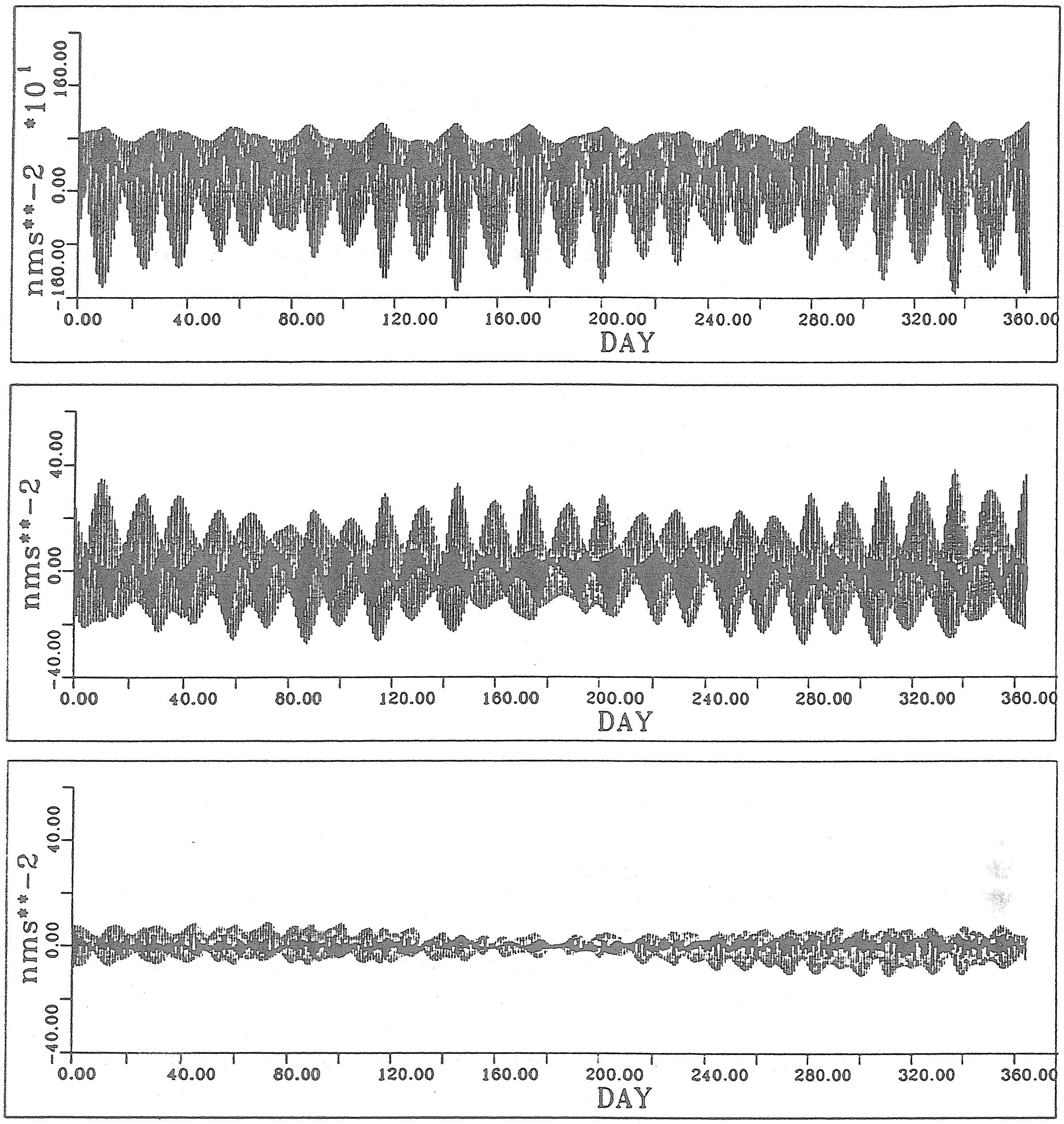

Fig. 1: Tidal prognosis for station Potsdam for the year 1990
a. (upper fig.): behaviour of the tidal effect
b. (middle fig.): discrepancy between prognosis A1 (δ=1.164, κ=0.00°) and A2 (34 pairs, 1974/03...1988/12)
c. (lower fig.): discr. between A2 and A3 (3 pairs: diurnal, semidi., terdi.)

It will not be possible in every case to get tidal results with a resolution of 34 wave groups. By calculating the reductions by means of 19 pairs of parameters (A4), we practically found the same discrepancies as in the case (A1 – A2). Therefore we recommend the use of observed parameter sets. The different resolutions in the tidal model (19 pairs or 34 pairs) are of less importance.

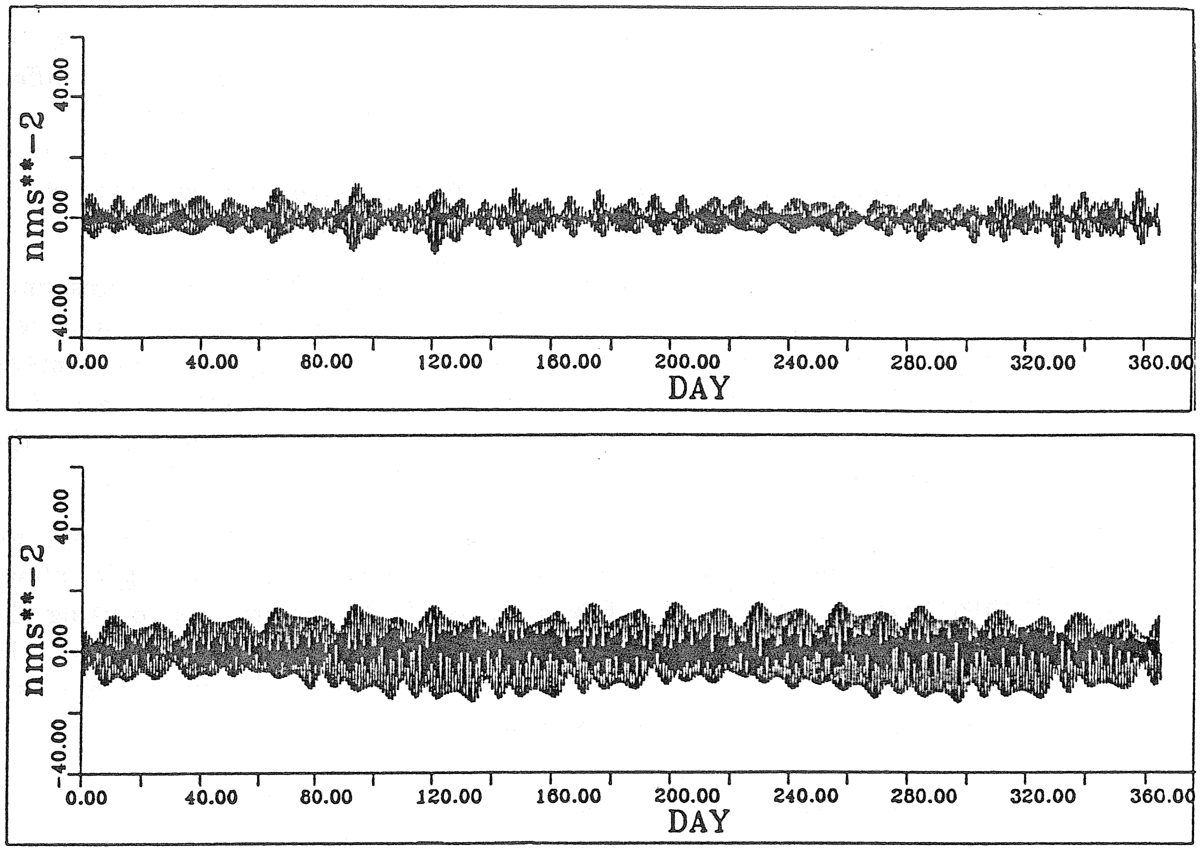

Fig. 2: Discrepancy betweeen two tidal prognosis for station Potsdam (1990)
a. (upper fig.): A6 (1981/12...1983/03) minus A5 (1977/06...1978/09)
b. (lower fig.): A8 (1981/06...1982/09) minus A7 (1985/03...1986/06)

The long term tidal registration at Potsdam was analyzed with the CHOJNICKI method (program A15K, CHOJNICKI 1973) by dividing the complete data set in 16 months parts, and processing each part. Temporal variations of the tidal parameters up to 2.5 nm/s^2 in amplitude and some degrees in phase have been detected by this procedure (DITTFELD 1989). For the constituents M1, N2 and L2, these variations are explained by interferences between the main wave and a third order potential wave inside the wave group (SCHWAHN et al. 1989). Variations of parameters of other wave groups can not be explained physically until now, although they seem to be significant using standard analysis methods. It is of interest to compare tidal prognoses calculated by parameter sets of the same site, but derived from different epochs. Figure 2 shows discrepancies between prognoses calculated with tidal results from analysis intervals of about 480 days registration period. A5 and A6 in figure 2a represent the maximum amplitude difference of the M1 wave (2.5 nm/s^2), as observed at Potsdam. The difference of the prognoses shows maximum values of 21 nm/s^2 around the 120th day. The r.m.s. discrepancy is about 3 nm/s^2 during this year. When looking for "microgal accuracy" (= 10 nm/s^2) in the reductions, the deviations between both prognoses may not be neglected. Before starting a field project the days with uncertain earth tides prognoses should be predicted to schedule the gravity measurements.

The shape of figure 2b is completely different. Here prognoses, based on the analyses A7 and A8, are compared. The corresponding data sets include the maximum phase difference of N2, observed within the Potsdam analysis results (about 1.2°). The amplitude of the differences varies during one year and is in the order of 20 nm/s^2. Thus, if relative measurements are performed at a day of maximum difference, an error of 28 nm/s^2 may occur. The r.m.s. discrepancy between both prognoses amounts to 7.6 nm/s^2.

It has to be noted that the fading period of the constituents M1, N2 and L2 corresponds to the period of the perigeum of the moon (8.85 yrs). We conclude, that tidal measurements must be performed in the same time interval as the gravity measurements in order to ensure a tidal reduction accuracy of better than 10 nm/s^2. In this connection, one also has to discern if the analysis programs take different Love parameters for the second and third order tidal potential into account.

During an absolute gravity measurement at Potsdam (14./15.01.1990) we found, for instance, discrepancies between the prognoses using different parameter sets, of about 14 nm/s^2 (TORGE et al. 1990). The first tidal computation was made using the parameters 1.164 and 0.00° ("field-processing"). The post-processing employed the full set of 34 parameter pairs. The differences of the tidal reduction for the absolute observation at station Potsdam are shown in table 3.

Tab. 3: Comparison of the tidal reductions for the absolute gravity determination at Potsdam on January 14/15, 1990

data set 1	data set 2	discrepancy [nm/s^2]
A1 (1.164; 0.0)	– A2 (34P: 7403..8812)	+14.1
A1 (1.164; 0.0)	– A3 (3P: 7403..8812)	+11.5
A2 (34P: 7403..8812)	– A3 (3P: 7403..8812)	– 2.6
A1 (1.164; 0.0)	– A4 (19P: 8212..8403)	+12.5
A6 (19P: 8112..8303)	– A5 (19P: 7706..7809)	+ 2.0
A8 (19P: 8503..8606)	– A7 (19P: 8106..8209)	– 5.1

Using a different number of observered parameters results in only small discrepancies. The effect of different analysis periods also has a rather small influence. This is partly due to the fact that the absolute observations have been performed over a time interval of two days. Through this procedures, the uncertainties in the tidal reduction averaged out to a certain extent. In absolute gravimetry it is always critical to apply the theoretical tidal parameters. For instance, in China 1990 the field tidal reductions (1.164, 0.00°) to absolute measurements with JILAG-3 have been improved by up to 45 nm/s^2 during the post-processing.

The effect of regional variations may be investigated by interpolating between adjacent stations, as well as by contemporary tidal measurements, especially necessary in coastal regions. Therefore, we have investigated how tidal prognoses are affected by parameter sets, interpolated between the results of neighbouring stations.

Table 4 compares the prognoses for the station Hannover calculated by linear interpolation and by using a reference data set with observed parameters (TORGE and WENZEL 1977). The interpolation was performed by using the results of Potsdam and Bad Homburg (RICHTER 1987), Potsdam and Brussels (DUCARME et al. 1985), and Potsdam and Schiltach (WENZEL et al. 1990). The differences reach more than 30 nm/s^2, on the average they are less than 10 nm/s^2.

Tab. 4: Comparison of gravity tidal prognoses calculated by interpolation and by using observed parameters at Hannover (calculation time interval is 1990)

Interpolation for Hannover between	maximum difference [nm/s^2]	r.m.s. discrepancy [nm/s^2]
Bad Homburg and Potsdam	30.9	6.1
Brussels and Potsdam	17.0	3.2
Schiltach and Potsdam	27.0	4.7

If we simply use the parameter sets derived at other stations with distances of some 100 km, instead of the results obtained at Hannover, we get differences in the order of 30 nm/s^2 (table 5). The r.m.s. discrepancies in table 4 and 5 are of similar order. Consequently, an interpolation is not necessary.

Tab. 5: Differences of tidal reductions derived from given parameters of neighbouring stations, for the station Hannover, for the year 1990

station where tidal parameters have been derived	maximum difference [nm/s^2]	r.m.s. discrepancy [nm/s^2]	distance from Hannover [km]
Bad Homburg	36.0	7.7	250
Brussels	19.0	4.4	390
Potsdam	30.4	5.1	210
Schiltach	20.9	4.6	510

The reliability of the tidal parameter set does not only depend on the distance to the earth tide station, which provides the data set, but also on the calibration quality of the earth tide gravimeter.

At our numerical investigations, we calculated the differences between the prognoses based on the CARTWRIGHT-TAYLER-EDDEN-DOODSEN 1973 (505 partial tides, CHOJNICKI 1973) and the TAMURA 1987 (1200 partial tides) potential development for every reduction model. The maximum differences are in the order of 2.5 nm/s^2 and may be neglected at present, at the establishment of gravity networks.

Our investigations show that errors in the tidal reduction models may affect the accuracy of gravity determinations. In practice, measurements are generally carried out in such a way that most of the effects are minimized. An improvement of the tidal reduction will only decrease the figures of the error estimates, and not the gravity results. But this already may be of interest, e.g. for the assessment of instrumental precision.

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A STUDY OF THE NATURE OF THE DRIFT CURVE RECORDED WITH DIFFERENT QUARTZ TUBE EXTENSOMETERS

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With extensometers we are able to observe a very wide spectrum of movements taking place in the solid Earth. In this way different movements from long period earthquake waves (10^{-3} – 1 μm/s), through earth tides (10^{-1} – 1 μm/day) to recent crustal movements (1 – 10^{2} μm/year) can be observed. Usually there is no doubt about the origin of the higher frequencies observed by this type of instruments but the real physical content of the low frequency range of observations (1 – 10^{2} μm/year) is still discussed. It is not clear whether this variations are connected to instrumental drift or whether their origin is external. If the long term variations are connected to natural phenomena we have to investigate the problem further: either it is connected to the local geological variations or they have a regional origin. (We are not discussing effects of meteorological and hydrological origin here, which naturally are also present in this part of the spectrum of observed deformations. Concerning our experience at the Geodynamical Observatory in Budapest a variation of 1°C outdoor air temperature causes a corresponding displacement of about 1 μm. We could not find any connections with the variations of the karstic water-level).
Since 1980 we are observing annual variations in deformation in the range of a magnitude between (40–80) μm/year with a quartz tube extensometer which is 21m long. To be able to compare this value with the ones observed at other stations we completed Table 1 (Varga, 1984). This table allows us to draw the following conclusions:

- There is no correlation of the secular rate of strain with the tectonic position of the station
- it seems that the observed rates are too big

As a basis for this last conclusion serves the stress which in principle can be accumulated in the Earth. The maximum strain according to the estimation of Kasahara (1981) cannot be higher than 3 . 10^{-6}/year. For the average strain of the 28 stations listed in Table 1 we obtained 2.1.10^{-6}. The same conclusion can be found in the paper of Emter concerning tiltmeter drifts (1989), which concludes that the observed drift rates are at least one order of magnitude higher than tectonically reasonable ones.
The sensitivity of extensometers is generally given as the ratio between the smallest range of distance yet measurable and the length of the instruments. This value is in general 10^{-7} – 10^{-10}.
To investigate the nature of the secular strain rate as a first attempt we used the two quartz tube extensometers of Budapest station (Fig.1) (N°1: W 24°, length : 21.3 m and N°2: N 38°, length: 13.8m). The rates observed between 01.02.90 and 05.06.90 are plotted on Fig.2.
The observed long periodic strain rates are in the case of N° 1 1.5.10^{-6} (extension) and in the case of N°2 2.5.10^{-6} (compression). To check the two extensometers above mentioned we produced two short so-called micro-extensometers (see Fig.1) with a length of about 1 m, which are parallel to the extensometers N°1 and N°2 and crossing tectonic faults. At the same time Ra emanation measurements were carried out at our station by A. Varhegyi (Mecsek Ore Mining Enterprise, Pécs, Hungary) during May–June 1990.

In Fig.3 the residuals of the extensometric observations are plotted in the lower part of the figure together with the results of the radon measurements (Ra). It can be concluded that the curve of the residuals of extensometer N°2 correlates with the results of the radon measurements (however, the time basis for the comparison is too short). It is also worth mentioning that the residuals of extensometers N°1 and N°2 correlate relatively well in the first part of the observation period (the end of this time interval is shown by an arrow) when the instruments moved in opposite direction (see Fig.2). On the contrary, during the second half of the observation period the residual curves are running in opposite directions.
On the upper part of Fig.3 the curves observed with micro-extensometers (m.e.) are plotted together with the corresponding temperature variations (temp. m e.1 and temp. m.e.2) observed at these equipments.
As it is shown in Fig.1 m.e.1 is parallel to extensometer N°2 while m.e.2 is parallel to N°2. It is evident (Fig.3) that some extremums observed by m.e.1 coincide with the extremums at residuals of extensometers N°1 and N°2. In the case of m.e.2 this correlation was probably not observed every time due to the fact that this instrument is not far enough from the entrance of the station. This fact is reflected on the right hand side of the curve, where the increasing temperature (temp.m.e.2) is followed by the curve of micro-extensometer 2.
On the basis of our investigations carried out in the first half of 1990 it can be concluded that the long period rate of the extensometric measurements contents tectonic components, too, nut they are about one order smaller than the observed "secular" rate.

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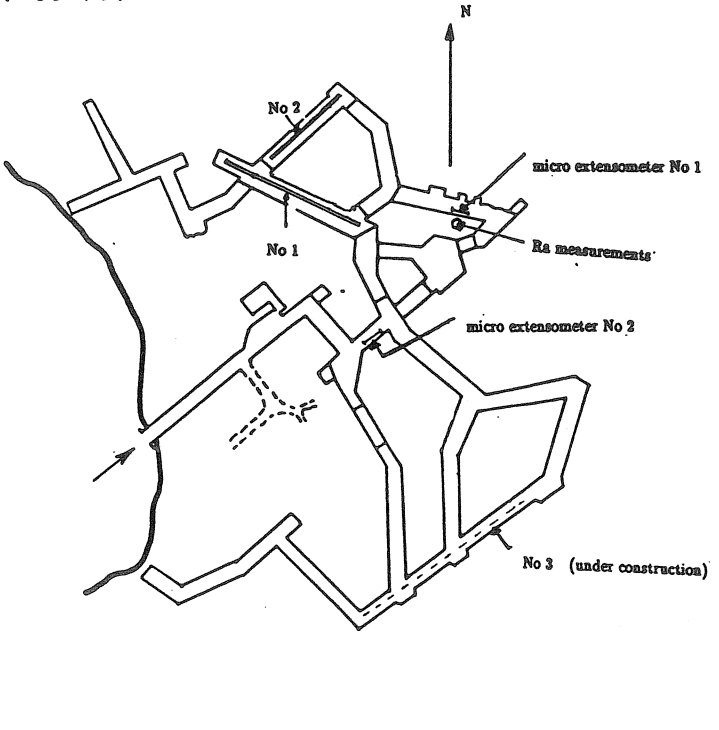

Fig.1. Scheme of the position of the strainmeters of Budapest station/Latinina et al., 1984

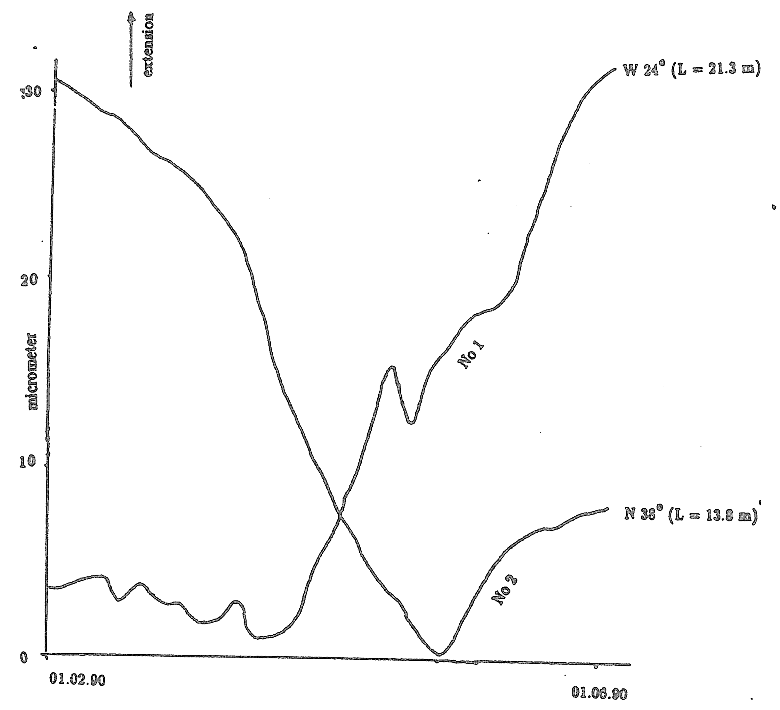

Fig. 2 Strain rates observed in Budapest between 01.02.90 and 05.06.90

No 1 extension $1.5 \cdot 10^{-6}$

No 2 compression $2.5 \cdot 10^{-6}$

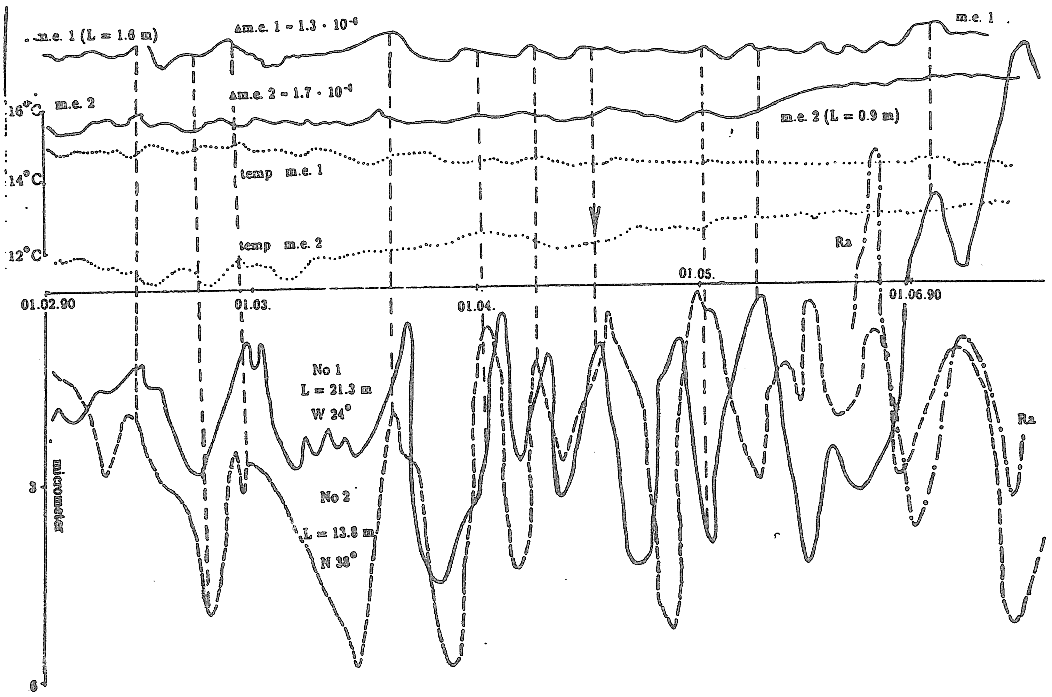

Fig. 3 A comparison of records of micro–extensometers with the residuals of extensometers No 1 and No 2 and with Ra observations

Table 1

Continent (Country)	Station	Type of extenso-meter	Secular rate of strain x 10^{-6}/year
North America			
USA	California	Q	1.0
	Ogdensburg	Q	0.1
	Poorman mine	L	0.6
	La Jolla	L	0.2
	Nevada	Q	2.0
	Pinon Flat	L	0.3
	Aleuts	Q	3.0
			Mean 1.0
Europe			
Great Britain	Yorkshire	W	0.2
		L	0.7
		W	5.0
		W	5.0
Germany	Tiefenort	W	2.2
	Schiltach	W	10.0
Hungary	Budapest	Q	2.0
USSR	Protvino	Q	0.5
	Tbilisi	Q	4.0
			Mean 3.2
Asia			
Japan	Osakayama	W	2.0
	Amagasa	W	1.2
	Kamigao	W	4.0
	Esashi	Q	0.2
	Erimo	W	0.2
USSR	Talgar	Q	1.0
	Garm	Q	0.5
	Turgen	Q	6.0
	Tschusal	Q	1.5
	Inguri	Q	2.0
			Mean 1.8
Australia Oceania			
Australia		Q	2.0
New Zealand		W	5.0
			Mean 3.5
			Mean of all measurements 2.1

Q – quarz extensometer; W – wire extensometer; L – laser extensometer

Barometric Pressure Effects on the Gravity Measurements

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Abstract

Japan Meteorological Agency routinely calculates global barometric pressure distribution twice daily for a 1.875x1.875 grid system. Based on this data(GANL data), we investigated the influences of the global pressure changes on the gravity measurements. Atmospheric mass gives two effects on an observed gravity; direct effect(air mass attraction) and indirect effect(effect of an elastic deformation of the solid earth due to an air mass loading). By summing up these two effects from each mesh over the entire surface of the earth, we computed the time variations of gravity at Esashi, Japan. Two kinds of gravity time series's were calculated based on two different assumptions for the ocean response to the barometric pressure changes; an inverted barometer ocean(IB model) and a non-inverted barometer ocean(NIB model). Applying an auto regressing model to these time series's, we estimated the frequency response functions (admittances) of gravity to the local pressure changes at the site mesh predicted from the GANL data. The calculat admittances are, for example at the frequency of 0 Hz, 0.387 and 0.296 micro Gal/mb for the data calculated with the IB model and those with the NIB model, respectively. The observed admittance using the data from a supper conducting gravity meter and a barometer installed at Esashi, is 0.386 micro Gal/mb for the same frequency. These results suggest that the IB model is consistent with the observation rather than the NIB model. The magnitude of the atmospheric gravity effects at Esashi is about 18 micro Gal in maximum for the period compared here, i.e. 14 months from May, 1988 to June, 1989. Although the contribution from the site mesh occupies the above 80 % of the total amount of the gravity changes integrated over the whole surface of the earth, but the pressure data observed at the site, alone, is not sufficient to correct the barometric pressure effect at the accuracy better than 1 micro Gal.