MAREES TERRESTRES

BULLETIN D'INFORMATIONS

1 2 1

15 MARS 1995

Association Internationale de Géodésie

Commission Permanente des Marées Terrestres

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BIM 121

15 mars 1995

Special Issue

Meeting of the Working Groups on THEORETICAL TIDAL MODEL, CALIBRATION, and HIGH PRECISION TIDAL DATA PROCESSING

Bonn, August 30 - September 2, 1994

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WARNING

A Working Meeting of the Earth Tide Commission will be held during the IUGG General Assembly at Boulder, july 1995.

The date and time table of the meeting will be fixed by the IAG Executive Committee on march 18.

P r e f a c e

During the 12th International Symposium on Earth Tides in Beijing, August 1993, the working groups on

'Theoretical Tidal Model'

'Calibration'

'High Precision Tidal Data Processing'

were prolonged until the next meeting of the Permanent Commission on Earth Tides (PCET). Therefore, the groups met again in August/September 1994 in Bonn. The results of these meetings are now being published in this volume and the following of the Bulletin d'Information Mareés Terrestres.

The main task of the group 'Theoretical Tidal Model' is to continue the considerations regarding the latitude dependance of the tidal parameters and to publish the parameters of the tidal model to be adopted by the PCET.

The 'Calibration' group should continue the discussion on different calibration methods, esp. to be used in-situ. Although special attention should be payed to superconducting gravimeters, spring gravimeters and tiltmeters were treated as well.

The third working group should continue under a changed mandate: Following the resolution no. 7 (Beijing, August 1993), the group discussed the topics

- data format and exchange, esp. in cooperation with GGP;
- study of air pressure and hydrological effects related to tides;
- identification and treatment of special problems of tidal recording in remote areas;
- cooperation in the processing of tidal signals observed using space techniques.

Within this frame some *achievements using superconducting gravimeters* and the need for a *comparison of current tidal analysis packages* were discussed as well as the *status of the data bank of the International Center for Earth Tides*.

In addition to the scientific goals of *tidal measurements in remote areas* the working group also discussed logistic and instrumental problems to develop a reliable recording equipment and to ensure the stability of the calibration esp. after hard transports. These ideas will be further developed.

There is no conclusion on the topic related to *space techniques*; this will be discussed during the next meeting.

The meeting again took place at the Institute for Theoretic Geodesy, University of Bonn, and again Prof. M. Bonatz was our host and provided good conditions for the meetings of the members of the groups and other interested scientists. In all 37 scientists from 13 countries were present.

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

As the chairman of one working group and on behalf of my colleagues V. Dehant and B. Richter 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 the International Center and esp. Prof. Melchior for publishing all the material in the Bulletin of the International Center of Earth Tides.

Gerhard Jentzsch

Conclusions

Working Group on THEORETICAL TIDAL MODEL (chaired by V. Dehant)

1. Concerning the tide generation potential.

The different aims of the WG have been explained previously (Dehant, 1991). One of the aims was to agree on a Tide Generating Potential (TGP). There has been a recommendation (Dehant, 1993) on that subject. This recommendation recognised the high precision of the recent TGP developments of Tamura (1987) and Xi Qinwen (1983). Very recently two potentials have appeared: one derived by Hartmann and one derived by Roosbeek (see the papers of these authors in this issue). The members of the WG did then agree that the two names should also be given in the recommendation which then becomes:

Considering that

- the new tidal potentials proposed by Xi Qinwen and Y. Tamura have similar precisions, ten times better than the precision of the former Cartwright-Tayler-Edden development,

- that there are other potentials under development at at least the same precision, like the tide generating potential given by F. Roosbeek or by T. Hartmann,

we recommend to use, for high precision tidal data processing,

- either Tamura's potential as given in the BIM 99 (1987),

- or Xi Qinwen's potential as given in the BIM 105 (1989),

- or one of the very new developments of F. Roosbeek or of T. Hartmann as presented in the BIM 121 (1995).

2. Concerning the definitions of the Love numbers.

The definition of the tidal gravimetric factor has not been discussed anymore. But the Love numbers h and k have been redefined. h as used from geodesists is defined along the radius and not along the normal; and k is the transfer function for the free potential everywhere outside the Earth and not only on the Earth's ellipsoidal surface. The definitions of h and k which were a part of our previous recommendation on that subject have to be replaced by:

considering the definitions used for tidal analysis and for tidal corrections in geodesy,

we define the Love number h on the ellipsoid as the Earth's transfer function (a coefficient in the frequency domain) between the tidal displacement on the ellipsoid along the radius, devided by the mean geoid tide,

we define the Love number k as the Earth's transfer function (a coefficient in the frequency domain) between the external potential associated with the mass redistribution due to the tides and the external tidal potential.

There has been a suggestion to add the definition of the strain in this recommendation. It has also been suggested that the last part which concerned the references had to be replaced by one and only one reference prepared by Dehant.
Dehant should also recompute the strain and the tilt.

3. Concerning the tidal gravimetric factor values.

Wang (1991, 1994) has computed the tidal gravimetric factors for a lateral heterogeneous rotating Earth. Because the Earth's flattening is a particular case of lateral heterogeneity (the (2,0) component), he can also compute the latitude dependent tidal gravimetric factors for an ellipsoidal, uniformly rotating Earth. He used a perturbation method. His model is incomplete because he does not account for the resonances induced by the Earth's normal modes, but for tidal waves far away from the resonances, like O_1 and M_2, he can compare with the results published by Wahr (1981) and Dehant (1987 a and b) (these two authors use different definitions but the same codes and the same method). This comparison has shown differences (in particular on the latitude dependent part of the tidal gravimetric factor) which pushed Wahr and Dehant to come back to their computations and their codes. They pointed out some errors and presented new values at the last Symposium on Earth Tides. These new results have solved the differences in the latitude dependent parts of the tidal gravimetric factors. There are presently a consensus to push them to publish the new results. It has been mentioned that G. Li from China does the same kind of computations as R. Wang.

4. Additional remark from the chairperson made after the WG meeting.

Since the meeting of the WG, Dehant and Wahr have prepared a paper summarizing the results for the Love numbers h and k as defined here above, and for the tidal gravimetric factors.

Since the meeting of the WG, G. Li came for a long-term visit to Brussels to work with V. Dehant. He computed the lateral heterogeneity effects on tides in the same way as R. Wang and obtained the same latitude dependence again.

R. Wang, G. Li and V. Dehant have then met in Brussels and pointed out discrepancies in their results in the constant part of the tidal gravimetric factor, in particular in the "Spherical Earth" part. They think that this is related to the Earth's interior model they are using (the rheological property profiles). They have then prepared a benchmark model and are comparing their results in a joint publication in preparation (Dehant et al., 1995).

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Working Group on **CALIBRATION** (chaired by B. Richter)

Recognising that the testing of body tide and ocean loading models requires accuracies of at least 0.2 % in amplitude and at least 0.1° in phase the working group of calibration
recommends
that for *gravimeters*
this should be realized applying absolute calibration methods e.q. inertial platforms, moving masses, state of the art absolute gravimeters;
that for *tilt and strainmeters*
absolute calibration methods should be developed which which are directly related to SI-units.
Furtheron, independent calibration methods should be compared to take care of systematic effects, and step response methods should be used for determining phase- and transfer functions.

Working Group on **HIGH PRECISION TIDAL DATA PROCESSING**
(chaired by G. Jentzsch)

1. **Data format and exchange, data analysis**
(esp. in cooperation with GGP)

Recognising the increase of the precision of recording gravimeters, the need to store and to exchange high rate data at intervals of e.g. 1 min, and that the so-called International Format for exchange of hourly tidal data cannot fulfill this need, the Working Group of High Precision Tidal Data Processing
recommends that the so-called PRETERNA format (Wenzel 1994) shall be used for storage and exchange of high precision tidal data.

Recognising the need for precise tidal data analysis as well as for the intercomparison of analysis results esp. with regard to GGP we
recommend an evaluation of all current methods for tidal analysis on the basis of a synthetic data set. The Working Group asks Prof. D. Crossley to organise this evaluation.

Regarding the progress of the establishment of the 'Global Geodynamics Project' (GGP) this Working Group refers to earlier conclusions and strongly
recommends that operators of new and existing SG stations be encouraged to consider the advantages of
(a) an excellent site, located away from cultural, geological and electrical noise, and
(b) a high-rate, precise data recording system with samples every 10 s or less at a precision of 7.5 digits for the gravity signal and 5.5 digits for the pressure,
(c) a timing accuracy of at least 10 msec,
to realize the benefits of new methods of data processing and interpretation.

2. Air pressure and hydrological effects related to tides

Referring to the increasing resolution and stability of tidal records and the still existing problem of modelling small scale and short period air pressure effects in gravity we
recommend that effects of short period local air pressure variations should be studied applying a regional network of air pressure stations in addition to the local air pressure record.

3. Special problems of tidal recording in remote areas;

Realizing that most ocean tidal charts due to modelling problems in Arctic areas are only valid up to 65° to 70° N and
recognizing that tidal gravity measurements provide boundary conditions for the evaluation of ocean tidal models by ocean tidal loading computations we
recommend the establishment of gravity tidal stations close or beyond the latitude of 65° N.

Recognizing that in the centers of the continents still wide areas exist lacking reliable tidal information and
regarding that tidal parameters in those areas are needed for the improvement of tidal earth models because the effect of ocean tidal loading is small we
encourage the establishment of tidal gravity stations in central Asia to achieve state of the art tidal parameters.

4. International Center for Earth Tides

Recognising the fruitful and encouraging work of the International Center of Earth Tides (ICET) for the collection and exchange of tidal data and for the documentation of the development of tidal research we
recommend that the Center should also collect all available historic earth tide data.

Realizing the increasing availability of high precision and high rate data the Working Group
recommends that the Center should develop conditions under which such high rate data can be stored and made available using modern computer networks.

Finally it was agreed that in accordance to the conclusion of the 1992 meeting of the Working Group the term

'quality factor'

has definitely to be cancelled and replaced by the term

'internal consistency factor'

A tide generating potential precise to the nanogal level

F. Roosbeek
Royal Observatory of Belgium
1994

Extended abstract

Summary. A tide generating potential (TGP), named ROOSBEEK94, has been computed using an analytical method. The lunar part of the potential has been developed to the order five and the solar part to the order three. In addition, we have considered several perturbing effects: direct and indirect planetary effects, lunar inequality, effects of the nutations in obliquity, Earth's flattening and time corrections. Finally, we have obtain a tide generating potential of 7571 terms which has a precision of 10^{-7} radian on each wave.

1. Data

For the lunar ephemerides, we have used the ELP2000-85 series from Chapront (1987). These ephemerides have a precision of about 0.5" on one century before and after the starting time J2000.0 for the longitude and latitude and of about 500 meters for the distances.

For the Solar ephemerides, the ecliptical longitude λ_s and the ratio $\left(\frac{c}{d}\right)_s$ are expanded as follows:

$$\begin{aligned}\lambda_s &= h+\left(2e-\frac{1}{4}e^3\right)\cos(h-p_s)+\frac{5}{4}e^2\sin 2(h-p_s)+\frac{13}{12}e^3\sin 3(h-p_s)+\ldots\\ \left(\frac{c}{d}\right)_s &= 1+\left(e-\frac{1}{8}e^3\right)\cos(h-p_s)+e^2\cos 2(h-p_s)+\frac{9}{8}e^3\cos 3(h-p_s)+\ldots\end{aligned}\tag{1}$$

We have added corrections for planetary perturbations, lunar inequality and time variations of e and ε to these expressions. These corrections have been found in Meeus (1962).
Besides Moon and Sun, all the planets produce also tides on the Earth. But only Venus produces tides greater than one nanogal. So, only the direct effect of Venus is considered here. We have chosen Bretagnon's Ephemerides in order to evaluate them. Bretagnon's ephemerides have a precision of $2.5\ 10^{-8}$ radians for the longitudes and latitudes and $1.8\ 10^{-8}$ UA for the distances to the Sun.
The constants that we have used are presented in table 1. Most of them come from the IERS standards (1989).

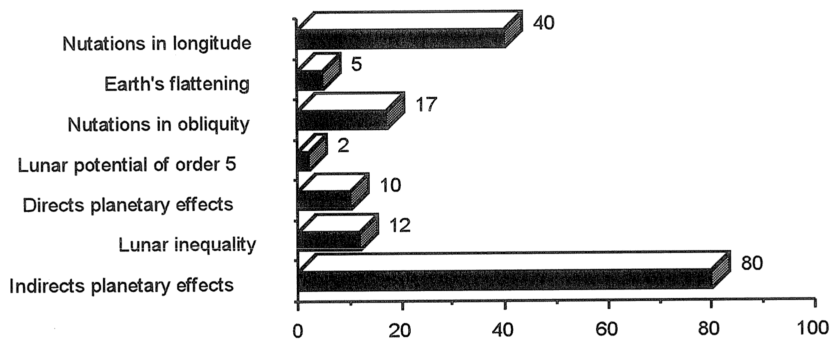
Table 1. Constants and physical parameters

a	6378140 m	equatorial radius of the Earth
J_2	0.001082626	dynamical form factor for Earth
GM_T	$3.98600440\ 10^{14}$ m^3/s^2	geocentric gravitational constant
$\sin\pi_l$	3422".451	sine of the horizontal parallax of the Moon
$\sin\pi_s$	8".794	sine of the horizontal parallax of the Sun
M_l/M_T	0.012300034	ratio of mass of Moon to that of the Earth
M_S/M_T	332946.045	ratio of mass of Sun to that of the Earth
M_S/M_V	408523.5	ratio of mass of Sun to that of Venus
a_{Ve}	0.7233298595 UA	semi-major axis of the orbit of Venus around the Sun
D_0	2.6276912 m^2/s^2	Doodson constant from Doodson
D_1	2.6335811 m^2/s^2	Doodson constant from Xi
ε	84381".444-46".8 T	obliquity of the Earth without nutation effects
e	3446".52815-514".71320 T	eccentricity of the Earth
$\Delta\varepsilon$	-5".7771121	correction for the nutation in obliquity effects
$D_S(r)/D(r)$	0.45923780	ratio of Doodson scale factor of Moon to that of the Sun

2. Numerical influence of the perturbing effects

The order of magnitude of all the perturbing effects that we have considered are summarise at figure 1. For each of them, their maximum influence on tides are indicated in nanogals.

Figure 1. Influence (in nanogals) of the perturbing effects we have considered



3. Results and comparison with Xi and Tamura

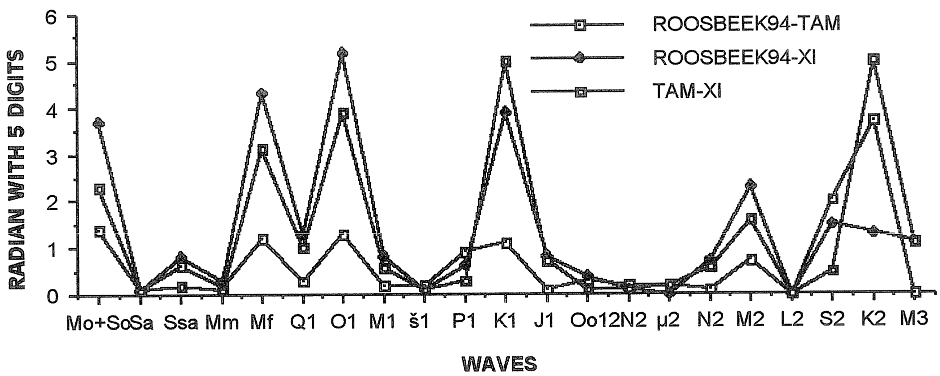
The values in the frequency domain of the principal waves for the available TGP are presented in table 2. Note that, for this comparison, each amplitude is the sum of the amplitudes corresponding to different potential orders. For example, the wave 055•555 is the sum of the amplitudes corresponding to the $P_{2,0}$ value and to the $P_{4,0}$ value. Because each potential order is separated into a time dependent part and a latitude dependent part (geodetic coefficients $g_{n,m}$) and because these $g_{n,m}$ depend on the pote.ıtial order, it is not allowed to sum the amplitudes corresponding to different orders. So the values in table 2 are only prepared for comparison, not for practical uses.

Table 2. Comparison of ROOSBEEK94 with other TGP for the principal waves

	Argument-number	ROOSBEEK94	XI2000	TAMURA2000
M_0+S_0	055•555	0.7383569	0.73832	0.738343
S_a	056•554	0.0115495	0.01155	0.011549
S_{sa}	057•555	0.0727375	0.07273	0.072732
M_m	065•455	0.0825832	0.08258	0.082581
M_f	075•555	0.1563767	0.15642	0.156389
Q_1	135•655	0.0721569	0.07217	0.072160
O_1	145•555	0.3768485	0.37690	0.376861
M_1	155•655	-0.0296418	-0.02965	-0.029644
π_1	162•556	0.0102489	0.01025	0.010251
P_1	163•555	0.1753162	0.17531	0.175307
K_1	165•555	-0.5299806	-0.53002	-0.529970
J_1	175•455	-0.0296418	-0.02965	-0.029643
O_{O1}	185•555	-0.0162255	-0.01623	-0.016229
$2\ N_2$	235•755	0.0230113	0.02301	0.023009
μ_2	237•555	0.0277699	0.02777	0.027768
N_2	245•655	0.1738974	0.17389	0.173896
M_2	255•555	0.9082526	0.90823	0.908246
L_2	265•455	-0.0256720	-0.02567	-0.025670
S_2	273•555	0.4225545	0.42254	0.422535
K_2	275•555	0.1148967	0.11491	0.114860
M_3	355•555	-0.0118806	-0.01187	-0.011881

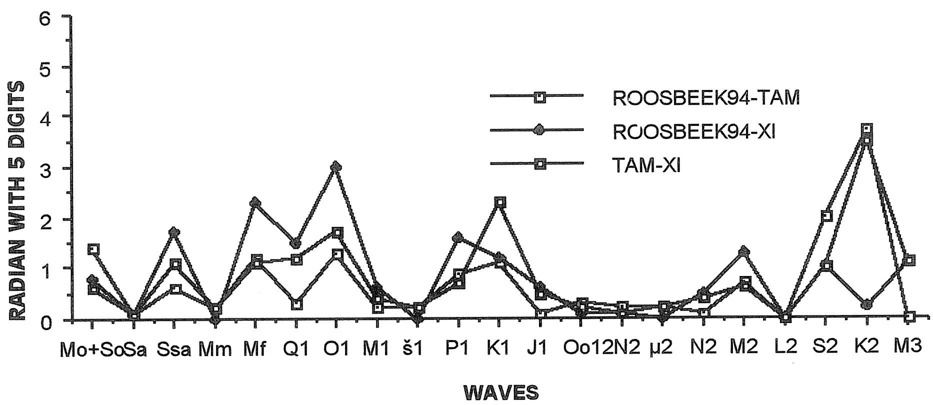
In figure 2, differences between these potentials for the same waves are given. We can see that the differences ROOSBEEK94-TAMURA2000 (0.7 mean difference, 3.7 maximum difference) are often the smallest differences and that the differences ROOSBEEK94-XI2000 (1.4 mean difference, 5.2 maximum difference) are practically at the same level than XI2000-TAMURA2000 (1.3 mean difference, 5 maximum difference).

Figure 2. Differences between available potentials for the principal waves



One part of the differences between XI2000 and ROOSBEEK94 or between XI2000 and TAMURA2000 could be explained by the fact that Xi does not consider corrections for nutation in obliquity in his calculations. Indeed, if we look in figure 3, where the development Xi2000 has been corrected for the nutation in obliquity, we can see that the differences ROOSBEEK94-XI2000 or XI2000-TAMURA2000 are now reduced.

Figure 3. Differences between available potentials for the principal waves where, in addition, Xi's values are corrected for nutation in obliquity



Availability of ROOSBEEK94

The potentials of Xi and Tamura are computed with a cut-off level of 10^{-6} radians. This gives two potentials of respectively 1178 and 1200 terms. In order to reach the nanogal level, it is necessary to retain all the terms greater than 10^{-7} radians. So, due to the exponential increase of the number of coefficients in function of the increase of the precision wanted, the total number of waves in ROOSBEEK94 is 7571 waves. In order to save a lot of paper, I do not publish the table with all these coefficients, but there is a file available under different format upon request.

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Effects of inertial forces due to the forced nutation on the gravimeter factor in the diurnal range

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Abstract

Due to the forced nutation a diurnal wobble (polhodie in the POINSOT representation) in the order up to +-15 ... 20 milliarcseconds for the pole position (m_1, m_2) exists and therefore the distance of the site to the rotation axis shows a small variation. A change in the direction and the value of the centrifugal force occurs and, due this effect, we measure a small gravity variation. This variation may be expressed by a spherical harmonic function P_2^1 ($m_1 \cos\lambda$ + $m_2 \sin\lambda$), whereby the instantaneous pole position are the coefficients.

Assuming as usual for tesseral waves a gravimeter factor $\delta = 1.16$ for sites in middle latitudes ($\vartheta = 45^0$ maximum effect) the gravity variation reaches up to the order of +- 4.2 nms^{-2}. i.e.+-0.42 μGal.

This gravity variation changes the gravimeter factor δ for the diurnal (tesseral) Earth tides in dependence on the Earth model and basing on the rotation vector (0, 0, 1) Ω. The corrections are:

	$\delta(O_1)$	$\delta(P_1)$	$\delta(K_1)$	$\delta(\Psi_1)$
Elastic Earth model:	.004015	.003818	.003803	.003823
Elastic Earth Model with Liquid Core:	**.004226**	**.003956**	**.003803**	**.004748**

The correction in the order 0.4 percent, found also by MOLODENSKIJ (1984), is far above the present inner accuracy of the parameter estimation of the Earth tides, especially for O_1, P_1 and K_1 and should applied before any other interpretation starts, for instance for the parameters of the NDFW. On the other hand, this values are not independent from the Earth model, which we are looking for because of the computation of the m_1, m_2 includes the model.

Introducing the **actual** instantaneous rotation vector in the tidal gravity equation, then the above noted correction is not needed.

1 Introduction

The polar motion in the diurnal range is due to the forced nutation of the Earth by the tidal forces of the Sun and the Moon ("astronomical nutations" (MELCHIOR (1980),). On the basis of the POINSOT - representation every nutation can be splitted up in two cones, the herpolhodie is the cone with respect to the inertial reference frame, the polhodie ("wobble", "Oppolzer terms") ones with respect to the Earth fixed coordinate system. For gravity observations the polhodie is of interest because of the instantaneous centrifugal force as an inertial force is a function of the instantaneous position of the rotation axis referring to the Earth fixed coordinate system. But also the clinometric and extensometric time series are concerned due to the variation of the resulting force vector.

Considering the accuracy of 1 nms^{-2}, i.e. 0.1 μGal, of the Superconducting Gravimeters, and the decisive role of the K_1 wave for the determination of the frequency of the nearly diurnal free wobble (NDFW), it seems to be necessary in the gravimetric Earth tidal data analysis to pay attention to this diurnal polar motion.

A raw estimation may illustrate the order of the effect: The well known long-term polar motion (CHANDLER- and yearly period) has a maximum amplitude of 300 mas and produces a gravity variation of 6 ... 7 μGal amplitude in 45° latitude (WAHR (1985)). The maximum contribution to the diurnal polar motion stems from the polhodie of the K_1 - wave and has the order 8.7 mas (= 27 cm) (see, for instance, KLEIN und SOMMERFELD (1895) p. 47-50, MELCHIOR and GEORIS (1968), MELCHIOR (1978)). It means that in the polar motion the diurnal contribution is 1/30 of the long-term value, therefore we expect for gravity 1/30 of 6 μGal, i.e. 2 nms^{-2} or 0.2 μGal in middle latitudes. This results a peak-to-peak-variation of 0.4 μGal, a signal, which can be deteced in every case by the tidal analysis.

For the gravimeter factor δ_{K_1} it means (again a first estimate): In middle latitudes the K_1-wave has an amplitude in the order of 40 μGals. The relation 0.2 μGal due to polar motion / 40 μGal due to direct tidal forces for a rigid Earth model results in a value of about $5*10^{-3}$. The analysis of modern gravimetric time series results an accuracy for the parameters, e.g. δ_{K_1} of the K_1-wave, in the order of 10^{-4}, i.e. one order higher accuracy. Therefore the effect due to daily polar motion should be taken into account now. In the beginning of the eighties S.M. MOLODENSKIJ (1980) estimated the influence on the gravimeter factor. WAHR (1981), p. 690/691 includes this effect in the gravimeter factor as body tide effects, whereas WANG (1991), p. 24 does'nt consider the polhodie effect in the tidal parameters. So it seems to be justified to explain the effect in a few lines. Numerical results will be given on the basis of data analysis of theoretical time series of diurnal polar motion. A full paper is in preparation.

2 The polar motion due to forced nutations

To study this phenomenon here are many good textbooks to explain this phenomenon, e.g. KLEIN und SOMMERFELD (1897), MELCHIOR (1978), LAMBECK (1988). Due to the ellipti-cal shape of the Earth's figure and the obliquity of the ecliptic as well of the Moon as the Sun with respect to the Earth's equator there are torques which exert a reaction of the Earth . Each of the tesseral components (degree l =2, order m =1) in the development of the tidal forces produces such a torque. Due to the fact that the Earth rotates the Earth reacts like a gyro.

According the theory we may split up the motion (e.g. MELCHIOR (1980), MOLODENSKIJ (1984)) into two cones
- a precession (= secular term in the nutation) and nutations of the axis of inertia and the axis of rotation in space (herpolhodie) and
- an almost diurnal movement of the rotation axis on a cone with respect to the Earth itself (polhodie, wobble, "cone of diurnal nutations in the Earth" (MELCHIOR (1978), "Oppolzer terms" (GROTEN (1979)).

The expression for the potential of the tesseral diurnal waves, which excert torques, may be written for a point $P(x_p, y_p, z_p)$ on the Earth surface as in a body-fixed coordinate system (MOLODENSKIJ (1984))

(1) $$V_{tessj}(P, t_i) = \frac{A_j}{a^2} z_P (x_P \cos(\omega_j t_i) + y_P \sin(\omega_j t_i))$$

whereby a the radius of the Earth, A_j and ω_j amplitude and frequency of a partial wave j and t_i the distinct time are. The corresponding gravity variation in the $\hat{r}$ -direction is

(2) $$\delta v_{rj}(P, t_i) = \frac{2V_{tessj}(P, t_i)}{a}$$

Computing the torques on the basis of the tesseral tidal waves and distinct Earth models , and using EULER's equations we obtain the polhodie, characterized by the vector $(\omega_x, \omega_y, \omega_z)$ (with $\omega_z = const = \omega_0 = 2\pi/86164$), excerted by these forces. The position of the rotation axis may be written, see i.e. LAMBECK (1988), p. 43 and p. 571 or MOLODENSKIJ (1984) in the form (for m in radians)

(3.1a) $$m_{1j}(t_i) = \omega_{1j}(t_i)/\omega_0 = c_{1j} \cdot c_{2j} \cdot c_{3j} \cdot \cos(\sigma_j t_i) = c_{1j} \cdot c_{2j} \cdot c_{3j} \cdot \cos(\omega_j t_i)$$

(3.1b) $$m_{2j}(t_i) = \omega_{2j}(t_i)/\omega_0 = \hat{j} \cdot c_{1j} \cdot c_{2j} \cdot c_3 \cdot \hat{j} \sin(\sigma_j t_i) = c_{1j} \cdot c_{2j} \cdot c_{3j} \cdot \sin(\omega_j t_i)$$

whereby $\hat{j} = \sqrt{-1}$ and σ_j is due to the retrograde movement of the rotation axis on the cone of the polhodie defined as

(3.2 $$\sigma_j = -\omega_0(1 - (\omega_0 - \omega_j)/\omega_0) = -\omega_j$$

It may be shown, that the constants are: c_{1j} according MOLODENSKIJ (1984)

(3.3) $$c_{1j} = A_j/a^2$$

c_{2j} for an rigid Earth MOLODENSKIJ (1984)

(3.4a)
$$c_{2j} = -\frac{C-A}{\omega_0\sigma_j A + \omega_0^2 (A-C)}$$

or, yields the same value, LAMBECK (1988)

(3.4b)
$$c_{2j} = -\frac{C-A}{\omega_0 A \left(\sigma_j - \omega_0 \frac{(C-A)}{A}\right)}$$

and c_{3j} gives the modification for a Earth model with an fluid outer core and a rigid mantle (i.e. LAMBECK (1988))

(3.5)
$$c_{3j} = 1 - \frac{(\omega_0 - \omega_j)\left(\frac{A_c}{A_m}\right)}{(\omega_j - \omega_0) - \omega_0 \varepsilon_c (A/A_m)}$$

Using the appropriate values for C, A, A_c, A_m we get e.g. for Q_1,, O_1, P_1, K_1

(4)
$$c_{2K_1} = 6.1523 \cdot 10^5 \qquad c_{2P_1} = 6.1872 \cdot 10^5$$
$$c_{2O_1} = 6.6366 \cdot 10^5 \qquad c_{2Q_1} = 6.905 \cdot 10^5$$

c_{3j} is for K_1 $c_{3K_1} = 1$, for other waves it depends on the value ε_c for the dynamic flattening of the core.

Inserting these coefficients in the eq. (3.1) by this way we obtain for each constituent j the polhodie $\vec{\omega}_j(t_i) = (m_{1j}(t_i), m_{2j}(t_i), 1)\,\omega_0$ at a distinct time. Summing up over all tesseral waves we find the coordinates of the rotation axis in the Earth fixed coordinate system.

3 The gravity variation due to polar motion (polhodie): first approximation

Because this polhodie represents a motion of the rotation axis with respect to her undisturbed position $(0, 0, 1)\,\omega_0$ at the time t_0 , a variation of the centrifugal force occurs. The relation between polar motion and gravity variation is well known (see, for instance BURSA (1970), WAHR (1985),VANICEK and KRAKIWSKY (1986), p. 608). The complete representation of the variation of the centrifugal potential may be written (see WAHR (1985)) in the form of the twofold vector product between the time-variable rotation vector $\vec{\omega}(t_i)$ and the vector $\vec{r}_P = (x_P, y_P, z_P)$ between the center of mass as coordinate origin and the point of observation P.

Using a spherical earth with the radius a instead of $\vec{r}_p$ for an elliptic shape of the earth (see, e.g. BURSA (1970)) and for the orientation of the gravimeter the radius vector instead of the local plumb line, neglecting the mixed products of the components of the polar motion and remembering, that the tesseral functions do not generate a temporal variation in the speed of rotation, we get following WAHR (1985) for the temporal variation of the centrifugal potential $\delta Z(P, t_i) = Z(P, t_i) - Z(P, t_0)$, whereby

$$(5) \qquad Z(P, t_i) = (1/2)\vec{r}_p \bullet (\vec{\omega}(t_i) \wedge (\vec{r}_P \wedge \vec{\omega}(t_i)))$$

(because of the **negative** potential here $(\vec{\omega}(t_i) \wedge (\vec{r}_P \wedge \vec{\omega}(t_i)))$ is used instead of $(\vec{\omega}(t_i) \wedge (\omega(t_i) \wedge \vec{r}_P))$. From

$$\delta Z(P, t_i) = 1/2(\vec{r}_P^2(\vec{\omega}(t_i) \bullet \vec{\omega}(t_i)) - (\vec{r}_P \bullet \vec{\omega}(t_i))^2 - (\vec{r}_P^2(\vec{\omega}(t_0) \bullet \vec{\omega}(t_0)) + (\vec{r}_P \bullet \vec{\omega}(t_0))^2))$$

then follows the temporal variation of the centrifugal potential in the form

$$(6) \qquad \delta Z(P, t_i) = -\omega_0^2 z_P(x_P m_1(t_i) + y_P m_2(t_i))$$

This is an expression for an **tesseral function** also. The components $m_1(t_i)$ and $m_2(t_i)$ of the instantaneous pol position are the coefficients.

The temporal variation δz_{rj} of the centrifugal force in the direction of $\vec{r}_P$, in which in a first approximation the gravimeter is oriented, is then with regard to a single tidal component j

$$(7) \qquad \delta z_{rj}(P, t_i) = \frac{2}{a}(\delta Z_j(P, t_i)) = -\frac{2}{a}\omega_0^2 z_P(x_P m_{1j}(t_i) + y_P m_{2j}(t_i))$$

Note, that this effect $\delta z_{rj}(P, t_i)$ should'nt confuse with the term $(\vec{\omega}(t_0) \wedge (\omega(t_0) \wedge \vec{u}))$ in the equation for gravity variation on a rotating elastic body with the deformation $\vec{u}$ (WANG(1991)). $\delta z_{rj}(P, t_i)$ is valid for the body-space **fixed** point $\vec{r}_p$ and is due to the variation of $\vec{\omega}_j(t_i)$, **not** due to the lengthening or shortening of the radius vector . BURSA (1970) points out also an equation for a mass point moving on an equipotential surface.

Inserting the gravimeter factor δ_{tess} we include now deformation and additional acceleration due to mass redistribution according this tesseral force. According to the tesseral force function it is convienient to use $\delta_{tess} = 1.16$ as confirmed in the tidal analysis. Isolating the constants in components in m_1 and m_2 of the diurnal polhodie (eqs. 3.1a and 3.1b) we have

$$(8) \qquad \delta z_{rj}(P, t_i) = -\delta_{tess}\omega_0^2 c_{1j} c_{2j} c_{3j} \frac{2}{a} z_p(x_P \cos(\omega_j t_i) + y_P \sin(\omega_j t_i))$$

Regarding eq. (2) this is nothing else

$$(9) \qquad \delta z_{rj}(P, t_i) = -\delta_{tess}\omega_0^2 c_{2j} c_{3j} \delta v_{rj}(P, t_i)$$

and means that the **centrifugal force variation** for each constituent j in the diurnal range **is a linear function** of the corresponding wave in the Earth tides development **by the factor** $(-\delta_{tess}\omega_0^2 c_{2j} c_{3j})$.

4 The gravimeter factor of the diurnal polar motion due to forced nutation

As usual in tidal research, the gravimeter factor δ_j is by definition the relation between the contribution for the wave or wave group j in the observed time series and those by the theoretical force function due to the tidal potential. In the observed time series all the influences of solid Earth tides , ocean tides, air pessure and polar motion $\delta z_{rj}(P, t_i)$ are summed up to an empirical delta-factor δ_{ej} .
For the centrifugal force we obtain the delta-factor δ_{zj}

$$\delta_{zj} = \frac{\delta z_{rj}(P, t_i)}{\delta v_{rj}(P, t_i)} = -\delta_{tess}\omega_0^2 c_{2j} c_{3j} \tag{10}$$

The sign should be proved very carefully: The negative sign means that the delta-factor for to the response of the solid Earth on tidal forces is diminished by δ_{zj}). By other words, δ_{zj} should be added to the empirical δ_{ej} (MOLODENSKIJ (1984). But, e.g. BURSA (1970) or VANICEK and KRAKIWSKY(1986) uses the opposite sign for $\delta z_{rj}(P, t_i)$. This "conflict" may be solved by e.g. comparison the K_1-induced polhodie and their corresponding position with respect to the site on the one hand and the K_1 theoretical tide on the other. The use must be the same as the correction for the long-term polar motion in absolute gravimetry.

Here, in this first study, we have to look for an order of δ_{zj} . In the following we consider the absolute value only. Using the values in eq. (3.6) without special regard to c_{3j} we obtain from equ. (10) with $\delta_{tess} = 1.16$ and $c_{3K_1} = 1$ (for comparison with MOLODENSKIJ (1984) the values are given also without multiplication by 1.16)

$$\delta_{zK_1} = 0.003795 = 1.16 \cdot 3.271 \cdot 10^{-3}$$

$$\delta_{zP_1} = c_{3P_1} 0.003816 = c_{3P_1} 1.16 \cdot 3.290 \cdot 10^{-3}$$

$$\delta_{zO_1} = c_{3O_1} 0.004093 = c_{3O_1} 1.16 \cdot 3.529 \cdot 10^{-3}$$

$$\delta_{zQ_1} = c_{3Q_1} 0.004259 = c_{3Q_1} 1.16 \cdot 3.672 \cdot 10^{-3}$$

The exact value δ_{zj} in dependence on the frequency is a function of the Earth model, represented by c_{3j} in the order of 0.993 (LAMBECK (1988)) or 0.997 (MOLODENSKIJ (1984), Molodenskij-Model II) for the wave with DOODSON-number 165.565. Since c_{3j} is in the order of 1, the fundamental result is: **The influence of the diurnal polar motion due to forced nutation on the gravimeter factor is in the order of 0.4 % or 4 per mille.**

5 Numerical results using theoretical time series of diurnal wobble due to forced nutation

To prove this statement derived on a theoretical basis here I made use of the well established computation of theoretical time series of diurnal polar motion. Using the algorithm by BRZEZINSKI (personal communication) on the basis of different Earth models E_m, m=1,2,3 (BRZEZIN-

SKI (1986)) different time series of polar motion were obtained. (As usual for polar motion time series, the direction of the x-axis is the Reference meridian, the y-axis is in the direction 90 degrees West longitude, i.e. $m_2(t_i) = - y(t_i)$) In doing so the polar motion $x(t_i)$ and $y(t_i)$ of the rotation axis in the Earth fixed coordinate system 0xyz is at a distinct time t_i the sum of polhodies for 170 diurnal tidal constituents including the McCLURE's (1973) development. These time series were the basis to compute the corresponding gravimetric time series for a distinct gravimetric site using the well-known equation (WAHR (1985)), which is the equivalent to eq. (7) in spherical coordinates, whereby ϑ means the pol distance and λ the longitude, counted eastwards,

$$\text{(7a)} \qquad \delta z^{E_m}{}_r (P, t_i) = -\delta_{tess} \omega^2 a \sin 2\vartheta \, (x^{E_m}(t_i) \cos\lambda - y^{E_m}(t_i) \sin\lambda)$$

In fig. 1 the time series of the gravity variation due to the diurnal polar motion at Richmond, Fl. for 160 days were plotted.

In fig. 2 the spectrum is shown for the site Bad Homburg, Germany. In both cases the model for an elastic Earth with a fluid core was used. Here is very clearly to be seen the amplitude of the K_1-wave in the order of 1.7 nms^{-2} as predicted for mid-latitude stations. The contribution at O_1 due to the fortnightly nutation can be seen as well as M_1 and J_1 due to the monthly nutation term. The semi-annual nutation, represented by P_1, is in the order of 1/3 of the contribution at K_1 according their relation of the amplitudes of the cones of polhodie (see MELCHIOR (1978), table 2.2 p. 52).

To get a full set of tidal parameters of the gravimetric effect of the polar motion due to forced nutation a standard routine for tidal analysis was applied to obtain the tidal parameters for j = 1, ...21 wave groups in the diurnal range due this inertial force as well for an pure elastic Earth model (m=2) as well as for the elastic Earth with a fluid core (m=3), **see appendix** . The analysis confirm the statement in previous section.

6 Conclusion

The gravimeter factor due to the forded nutation is in the order of 0.4% or 4 per mille. Because of the linear relation between diurnal polar motion and variation of the centrifugal force the **gravimeter factors for the centrifugal force represents the physical properties of the model**, introduced in the computation of the nutation and the corresponding diurnal wobble. The effect of the fluid core is well pronounced (compare second and third analysis), the gravimeter factor for K_1 is independent from the Earth model.

The effect of polar motion should be taken into account for high precise gravimetric tidal analysis. The contribution is above the present accuracy.

Acknowledgments

Starting from an empirical point of view in the course of preparing this contribution I am indebted to many colleagues for their help, namely A.BRZEZINSKY who offered me during his stay at TH Darmstadt the algorithm for computing time series of theoretical polar motion, Mrs.

JURCZYK, IfAG Potsdam supported me in the numerical computations. C. ELSTNER and Z. SIMON gave me a hint on the booklet by S.M. MOLODENSKIJ, W. ZÜRN referenced on the important passage in WAHR's fundamental paper and D. CROSSLEY and J. HINDERER helped me with valuable discussions.

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APPENDIX:

GRAVIMETER FACTORS DUE TO POLAR MOTION

(the columns mean: number and notation of wavegroup, gravimeter factor and its standard dev., phase and its standard dev.) *Note: To give a better numerical resolution, in the last two parameter sets the values are enlarged by the factor 100.*

m = 3 LIQUID-CORE EARTH MODEL

Station Bad Homburg
\# Start : 1. 8. 81, 00h
\# End: 30. 7. 85, 23h
\# Original values in 10 nms^{-2} (= mikroGal)

1 SIQ1	.0045	+-.0005	-178.30	+- 6.36
2 2Q1	.0043	+-.0002	-177.69	+- 2.11
3 SIG1	.0044	+-.0001	-179.59	+- 1.74
4 Q1	..0043	+-.0000	-178.83	+- 0.29
5 RO1	..0044	+-.0001	-179.83	+- 1.50
6 O1	**.0042**	**+-.0000**	**-179.92**	**+- 0.06**
7 TAU1	.0043	+-.0003	178.82	+- 4.39
8 MM1	.0045	+- 0006	-179.29	+- 7.08
9 M1	0042	+-.0001	173.21	+- .70
10 CHI1	.0039	+-.0003	-178.55	+- 4.00
11 PI1	.0040	+-.0002	-179.79	+- 2.31
12 P1	0040	+-.0000	-180.00	+- .14
13 S1	.0040	+-.0006	-179.50	+- 8.06
14 K1	**.0038**	**+-.0000**	**180.00**	**+- 0.05**
15 PSI1	**.0048**	**+-.0004**	**-179.27**	**+- 4.68**
16 FI1	.0041	+-.0002	-179.94	+- 3.00
17 THE1	.0040	+-.0003	-179.88	+- 3.93
18 J1	.0037	+-.0000	177.23	+- .78
19 SO1	.0038	+-.0003	179.32	+- 4.78
20 OO1	.0038	+-.0001	178.90	+- 1.25
21 V1	.0037	+-.0004	178.62	+- 6.44

m = 3 LIQUID-CORE EARTH MODEL

Station Bad Homburg
\# Start : 1. 8. 81, 00h
\# End: 30. 7. 85, 23h
\#\# **Original values in 10 nms^{-2} multiplied by 100 !!**

1 SIQ1	.4517	+- .0501	-178.30	+- 6.36
2 2Q1	.4298	+- .0158	-177.69	+- 2.11
3 SIG1	.4446	+- .0135	-179.59	+- 1.74
4 Q1	.4264	+- .0021	-178.83	+- .29
5 RO1	.4399	+- .0115	-179.83	+-1.50
6 O1	**.4226**	**+- .0004**	**-179.92**	**+- .06**
7 TAU1	.4304	+- .0330	178.82	+- 4.39
8 MM1	.4486	+- .0554	-179.29	+- 7.08
9 M1	.4234	+- .0052	173.21	+- .70

10 CHI1	.3909	+- .0273	-178.55	+- 4.00
11 PI1	.3950	+- .0159	-179.79	+- 2.31
12 P1	.3956	+- .0009	-180.00	+- .14
13 S1	.4019	+- .0566	-179.50	+- 8.06
14 **K1**	**.3803**	**+- .0003**	**180.00**	**+- .05**
15 **PSI1**	**.4758**	**+- .0388**	**-179.27**	**+-4.68**
16 FI1	.4138	+- .0216	-179.94	+- 3.00
17 THE1	.4032	+- .0277	-179.88	+- 3.93
18 J1	.3675	+- .0050	177.23	+- .78
19 SO1	.3796	+- .0317	179.32	+- 4.78
20 OO1	.3843	+- .0084	178.90	+- 1.25
21 V1	.3656	+- .0411	178.62	+- 6.44

m = 2 ELASTIC EARTH MODEL

Station Bad Homburg
\# Start : 1. 8. 81, 00h
\# End: 30. 7. 85, 23h
\# **Original values in 10 nms^{-2} multiplied by 100 !!**

1	SIQ1	.4263	+- .0478	-178.31	+- 6.42
2	2Q1	.4064	+- .0151	-177.68	+- 2.12
3	SIG1	.4206	+- .0129	-179.58	+- 1.75
4	Q1	.4043	+- .0020	-178.82	+- 0.29
5	RO1	.4170	+- .0110	-179.84	+- 1.51
6	**O1**	**.4015**	**+- .0004**	**-179.92**	**+- .06**
7	TAU1	.4090	+- .0314	178.80	+- 4.40
8	MM1	.4282	+- .0528	-179.31	+- 7.07
9	M1	.4035	+- .0050	173.21	+- .70
10	CHI1	.3729	+- .0260	-178.57	+- 4.00
11	PI1	.3799	+- .0152	-179.77	+- 2.29
12	P1	.3818	+- .0009	-180.00	+- .13
13	S1	.3898	+- .0539	-179.38	+- 7.93
14	**K1**	**.3803**	**+- .0003**	**179.98**	**+- .04**
15	**PSI1**	**.3823**	**+- .0370**	**-179.28**	**+- 5.55**
16	FI1	.3819	+- .0206	-179.95	+- 3.09
17	THE1	.3831	+- .0264	-179.93	+- 3.94
18	J1	.3490	+- .0048	177.18	+- .78
19	SO1	.3617	+- .0302	179.30	+- 4.78
20	OO1	.3665	+- .0080	178.90	+- 1.25
21	V1	.3495	+- .0392	178.67	+- 6.43

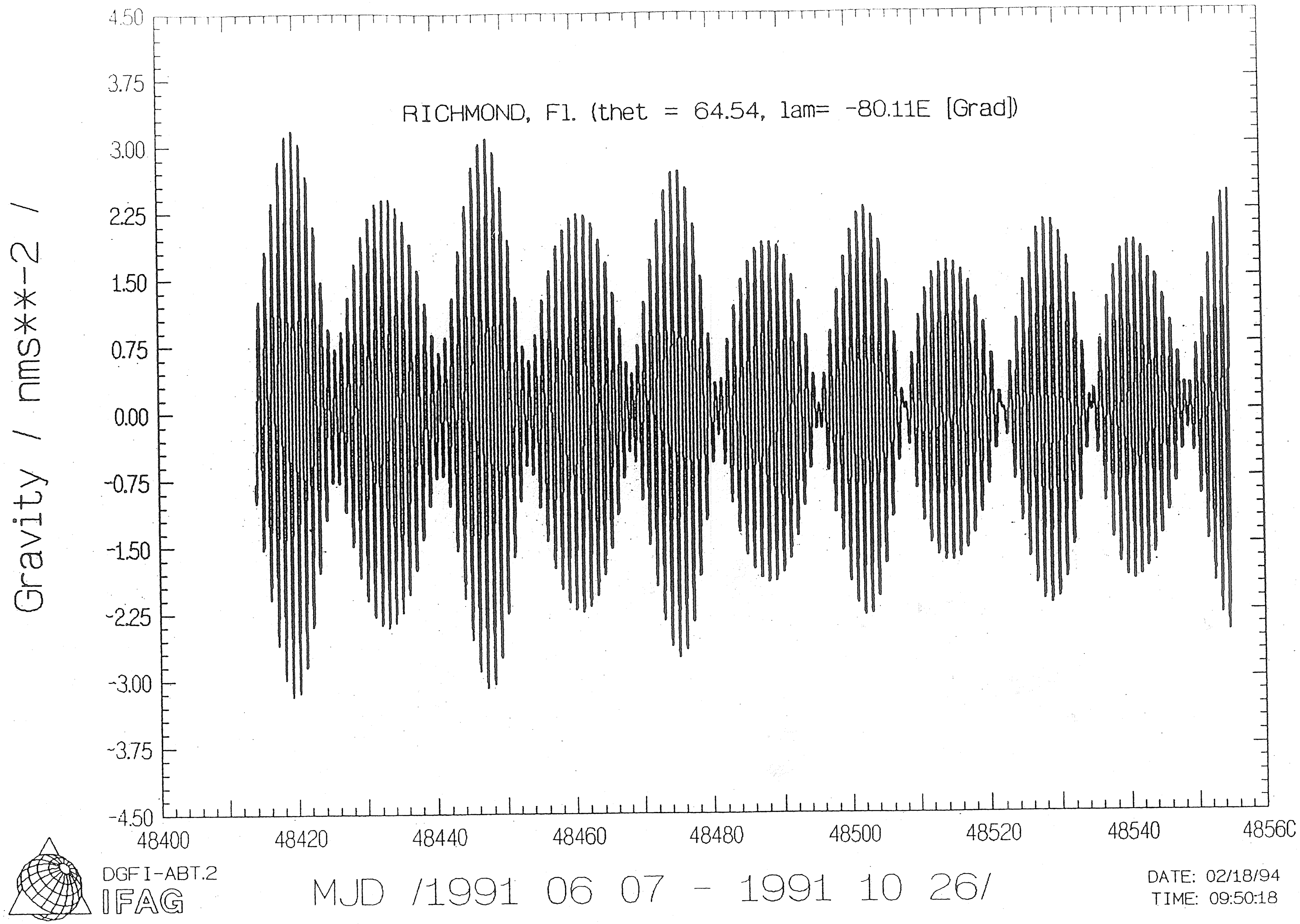

Fig. 1: Temporal variation of the centrifugal force at Richmond, Fl. (latitude 25.46 N, 80.11 W) due to forced nutation of the Earth for an elastic Earth model with a liquid outer core

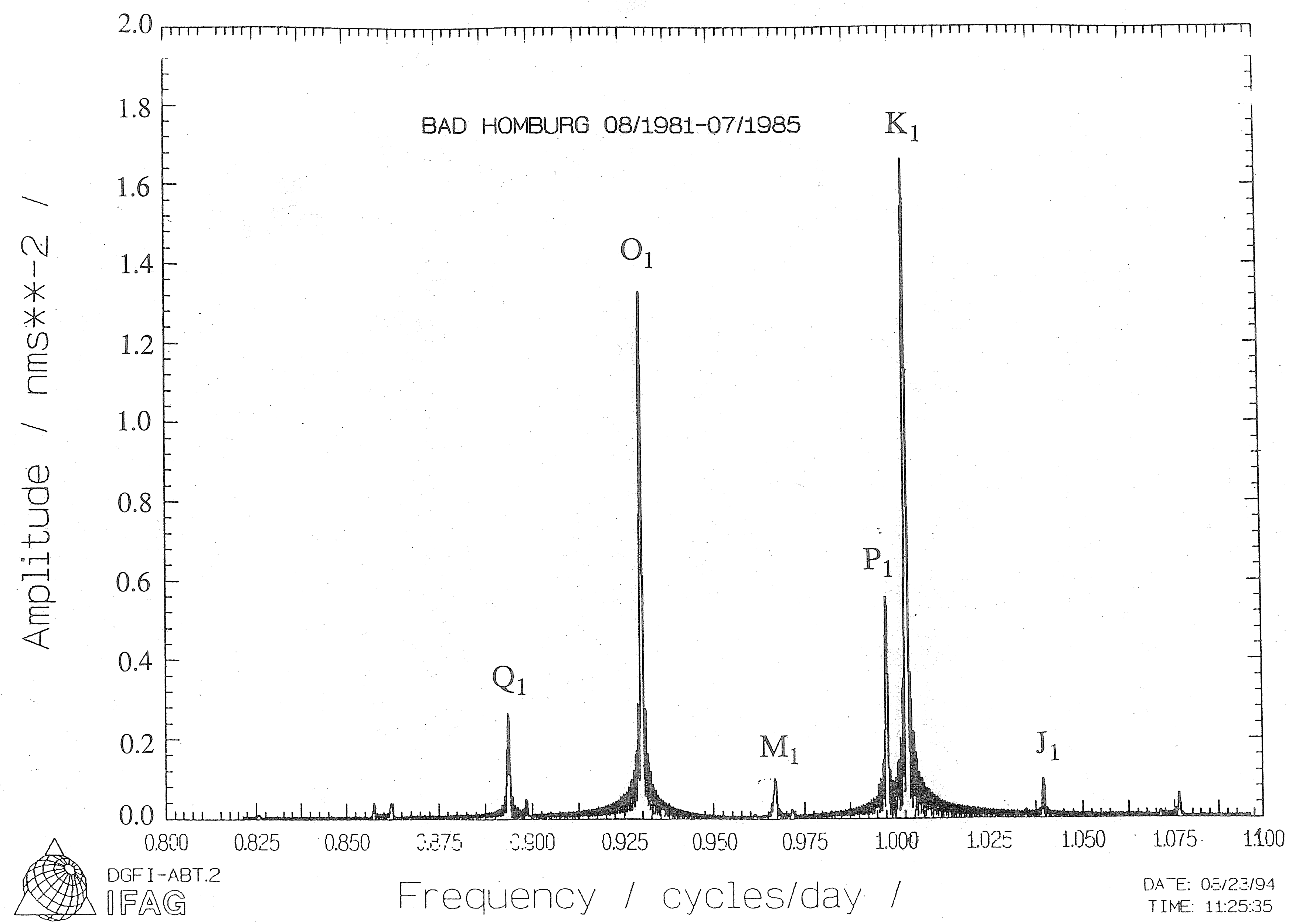

Fig. 2: Specrum of the gravity variation at Bad Homburg (latitude 50.23 N, longitude 8.61 E) due to temporal varaition of the centrifugal force due to forced nutation of the Earth for an elastic Earth model with a liquid outer core

The Frankfurt Calibration System

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The Frankfurt Calibration System is designed for the calibration of cryogenic gravimeters by sinosoidal artificial accelerations. To support the frame it is necessary to replace the gravimeter foot screws by three independent micrometer screws which were driven by step motors. One motor step corresponds to 0.2 μm and the range of the screws is ± 12.5 mm. All three step motors were controlled by a PC.

For experimental purposes instead of a gravimeter frame a platform is lifted by the calibration system. The position of the platform is controlled by a HP laser interferometer. During the experiments it is shown that screw errors and the back lashs have to be corrected individually. Therefore glass gauges are integrated at each screw to compare the driving function with the actual position. On the base of a digital feedback system the differences are minimised so that the mechanical input function is fitted better than ± 0.5 μm.

The continuous driving function (sinosoidal curve) is realized by 3000 equally time spaced linear pieces (commands for the step motor). After each command the actual position of the screw is registered. To get an idea of the resulting acceleration the positions are differenciated twice and filtered. Depending from the periods (200 s - 2400 sec) and amplitude of the driving function (10 - 25 mm, peak to peak) one can achieve accelerations between ± 980 and ± 3 μGal. At the moment the limitations in the mechanics and the mechanical gidder restike the accuracy of the achievable acceleration to ± 0.1 μGal.

In May / June 1994 during the comparison of absolute gravimeters in Sevres / France 11 LCR feedback gravimeter were calibrated by artificial acceleration with the Frankfurt calibration system. For 7 gravimeters the calibration factor is determined with an precision of 0.01 - 0.1 %. The results are in good agreement with the calibration factors for the same gravimeters determined in the adjustment of the calibration line. For the remaining 4 gravimeters the determination of the calibration factors are not satisfactory. Reasons are inert feedback systems and mechanical sensitivities to interference accelerations at special frequencies.

GRAVIMETER CALIBRATION DEVICE WITH THE USE OF A HEAVY CYLINDRICAL RING. A STATE OF ART REPORT

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Abstract

For the calibration of LaCoste-Romberg (LCR) gravimeters a device was developped which operates with a heavy ring with an inner diameter slightly bigger than the width of the gravimeter. This ring is moved up and down over the gravimeter installed on a column.

The scientific goals of the present and the future, the advantages and disadvantages of the calibration device are described in the present paper together with the main error sources of the given calibration method.

The first measurements carried out with LCR type instrument in 1991 shows a calibration accuracy of 0.2 %. After the automation of the calibration device an accuracy of 0.1 % was reached which LCR gravimeters without feedback. These as according to author knowledge the smallest calibration error value at the present obtained in laboratory conditions.

For the laboratory calibration of the gravimeters different basic principles can be used:

1. gravity changes introduced artificially
   a) displacement of the instrument in the vertical gradient (e.g. *Bonatz* 1971)
   b) measurement of the gravity effect of big, geometrically defined masses (e.g. *Groten* 1970, *Warburton et al.* 1975)

2. vertical acceleration of the gravimeter (inertial effect) (*Brein* 1962, *Valliant* 1973, *Van Ruymbeke* 1989, *Richter* 1990)

3. parallel recording of earth tides with at least one absolutely calibrated instrument (*Dittfeld et al.* 1976, *Ducarme* 1975).

For the laboratory calibration of LCR type gravimeters the version 1a was chosen by the author (*Varga* 1989) because according his experience in recording earth tides the necessary condition for a small instrumental drift and for detection small gravitational signals with acceptable accuracy is: the gravimeter must remain stationary during the calibration process. The principle of the calibration device installed at the Geodynamical Observatory Budapest is the following: a suspended cylindrical ring with an inner diameter a bit larger as the width of the LCR device to be calibrated is moved up and down vertically and moved over the gravimeter installed on a column with suitable height (Fig. 1).

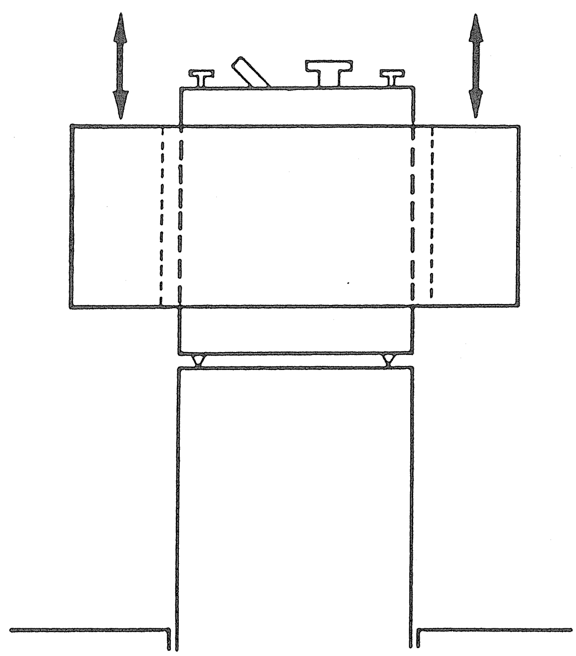

Fig. 1. Principle of the calibration device

A detailed description of the calibration device can be found in *Varga et al.* 1995.

Addition advantages of the calibration device using a heavy cylindrical ring are:

- the gravimetric effect of a vertical cylindrical ring is almost homogeneous around the extremities
- because of geometrical reasons the variation in the gravity caused by a ring is bigger than variations caused by other geometrical bodies. This favourable circumstances were demonstrated by Barta (*Barta et al.* 1986)
- no load of the floor occurs during the experiment. The tilts caused by the vertical movements of the ring are negligiable (*Csapó et al.* 1994)
- the experiment is symmetrical with respect of the gravimeter. The generated gravity variations caused by displacements of the ring has two symmetric extrema what allows to remove the effect of the instrumental drift and other external influences (lunisolar effect, long-period meteorological effect) in case of lifting and lowering the ring.

The disadvantages of the calibration device are:

- only a small variation of the gravity can be generated
- it is heavy and therefore no movable
- it seems at this time there are several error sources which can not be easily removed.

In the following this last problem will be discussed in detail.

a) Mechanical error sources

- the error of the mass measurements in 10^{-5}. The total mass of the ring with error bars is 3103.766 ± 0.021 kg. It can be concluded: this error source is not influencing the calibration accuracy at the 0.1 % accuracy level. Masses $\geq 10^3$ kg can be measured only with a 10^{-3} error value. Therefore the cylinder was constructed from cylinder sections with masses 105–450 kg

- error caused by the inaccurate determination of the ring's geometry producing an error $\leq 5 \cdot 10^{-4}$
- according to detailed study of the mass inhomogeneities this error source is very small (see e.g. *Varga et al.* 1995)
- effect of eccentric masses (*Csapó et al.* 1994) is of about 0.4 microgal ($\sim$ 0.5 %). It can be dramatically reduced if we taking into account the gravity effect of the cable and the cable support
- the effect of air masses expelled by the ring is 0.02 microgal. This effect can be exluded by the correction due to air-pressure influence
- error due to inaccurate determination of the vertical position of the gravimeter's sensor mass is less as 0.1 microgal
- the accuracy of displacement detectors is 0.2 mm. This error leads to an accuracy 10^{-5}
- error due to gravimeter's sensor eccentricity is less 0.05 %
- the error due to the pillar tilt is negligiable (*Csapó et al.* 1994).

b) Magnetic error source

Absolute magnetic measurements carried out with an Overhause proton magnetometer in the vicinity of the ring (at the distances 20 m and 5 m), on the top of it, inside the ring and under the ring show: the maximum variation of the field strength observed was 14 microtesla (one third of the total field strength of the terrestrial magnetic field). This variation in magnetic field not influences the sensitivity of a gravimeter.

c) Determination of the digital voltmeter constant used to record the gravimeter output needs special care. A change of 1 % in this value leads to an error of the order of 10^{-1} microgal. To avoid this error source the voltmeter must be calibrated with an accuracy 0.1 % before and after each campaign.

d) Problem related to the accuracy of the determination of the calculated gravity effect of the ring

To describe the gravity field of the ring at arbitrary points a special numerical solution was developped by *Hajósy* (1988). This numerical integration is based on linear combination of first and second kind Chebysev-Gauss quadratures. The numerical integration was stopped when a relative accuracy of $3 \cdot 10^{-5}$ was achieved what allows to neglect the uncertainties caused by the numerical integration.

e) Removal of the influence of the earth tides, air pressure and the drift

These three problems belong together because on the usual way the lunisolar and air pressure can not be removed good enough at the 0.1 microgal level.

As a first approximation the tidal influence was removed with the Cartwirght-Taylor-Edden development and with the use of amplitude ratios and phase differences obtained with different earth tidal instruments at Geodynamical Observatory Budapest. This procedure can not be satisfactory for 10^{-3} error level because the tidal parameters are determined safely only for the few biggest tidal waves.

The two components of the air pressure's gravimetric effect (the attraction and load of atmospheric masses from one side and the buoyancy of the ring which is different with pressure-induced changes from the another one) was removed with the use of the local air pressure admittance, what can be considered as a zeroth order approximation. Because these two above mentioned effects — namely the lunisolar and the air pressure effects — were not determined completely the rest of these influences must be removed together with the instrumental drift.

Of course, the complete and accurate removal of the drift is of the first order importance. The drift correction can be carried out by using the hypothesis: the gravity effect of the ring on the gravimeter is exactly the same at a given ring position. By the repeated up and down moving of the ring a drift curve can be obtained which allows usually to remove the drift effect with the reliability of 0.1 microgal. In some cases the instrumental drift was excluded on iterative way: the effect was determined by using gravity values obtained at different ring positions.

f) The microseismic noise is an important error source at error level 0.1 % of the gravimeter calibrations carried out at the Geodynamical Observatory Budapest. The microseisms are generated by influences from the atmosphere and from the sea. These waves are always present on gravimetric records but with strongly varying intensity. The nature of the waves is not yet clear exactly. According to *Bath* (1979) the microseisms can have the follong clasification:

- short term ($T < 2$ s) microseisms depend on local meteorological and technical (e.g. traffic) conditions

- cyclons at some hundred kilometer distances generate waves with period $T \sim 6$ s

- large low-pressure areas at greater distances (North Sea, North Atlantic) produce seismic noise $T = (9\text{–}10)$ s

- long periodic microseisms [$T = (17\text{–}20)$ s] are more seldom and they are ascribed to coastal effects.

On Fig. 2 microseisms recorded at Budapest in 1985 during disturbed and quiet days are shown. On the basis of Fourier analysis of such records it can be concluded that the typical microseism frequency is at the Geodynamical Observatory Budapest 6.5 s. Amplitudes during disturbed days vary between 1 and 30 microgals. This variation in course of quite days is between 1 and 4 microgals. What is dangerous for the accuracy of calibrations the systematic beating with periods from 1 to 5 minutes.

This influence can be reduced to some extent by increasing the number of the measurements. On the basis of many times repeated experiments (see Table 1) the influence of microseismic noise can be reduced to 0.2 %. A further reduction of the microseismic noise is a complicated task and therefore the calibrations should be performed at times of low microseismic noise.

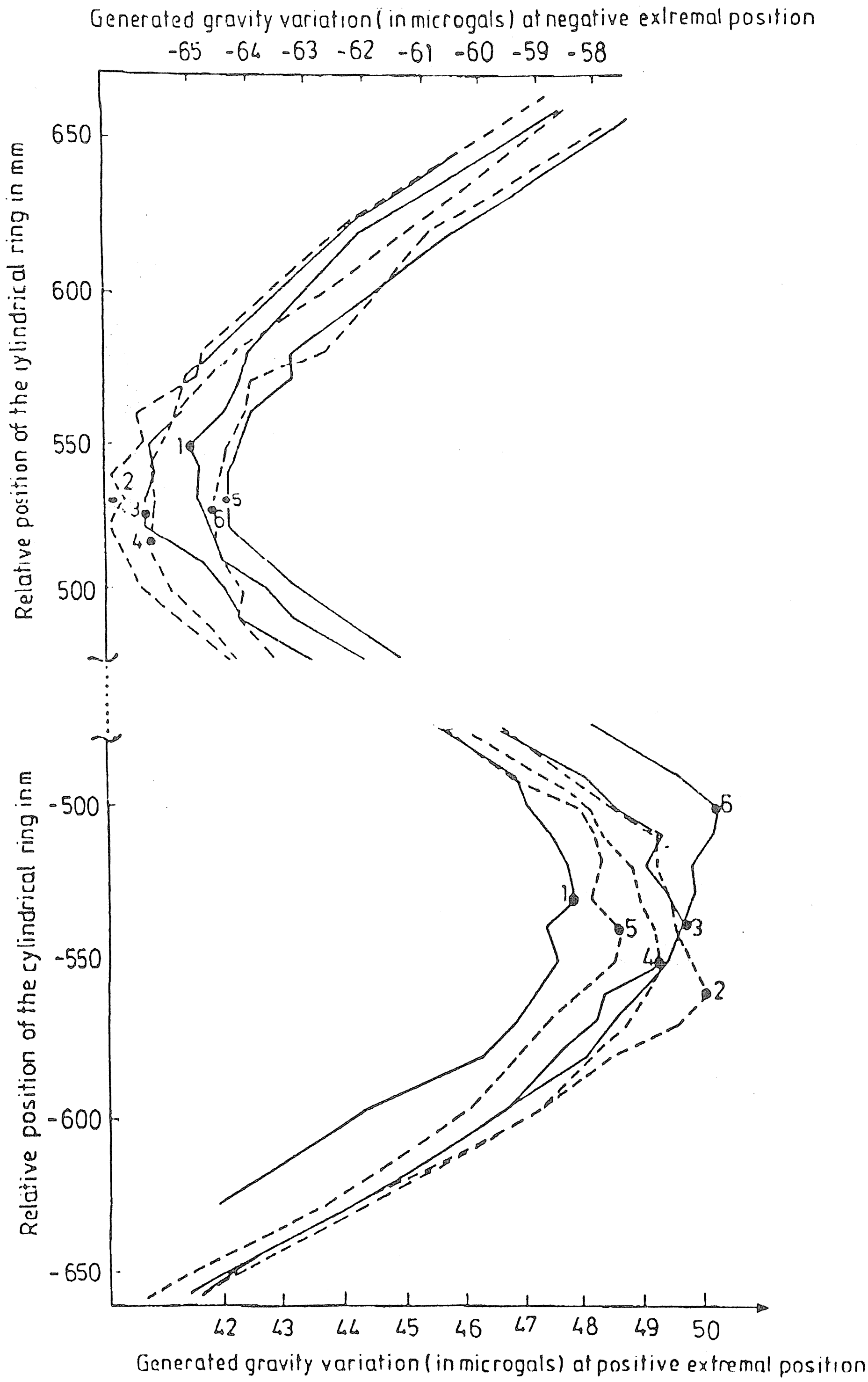

Fig. 2. Microseisms recorded with a gravimeter at Budapest Geodynamical Observatory in 1985 during disturbed (a) and quiet (b) days

Table 1. Behaviour of the r.m.s. error values in microgal (and relative to the expected theoretical variation in the gravity) in case of different numbers of observations (n). Observations were carried out with LCR G-936 (without feedback)

n	*r.m.s. error*
6	*0.47 (0.40 %)*
12	*0.41 (0.26 %)*
40	*0.29 (0.25 %)*
50	*0.25 (2.22 %)*
70	*0.25 (0.22 %)*

A special case of microseismic noise is the short periodic (T < 2 s) one. It is not clear yet exactly rather this type of microseisms influencing or not the gravimetric observations. Seismic prospecting of the Observatory was carried out with a standard seismograph in 1990. The short periodic noise at the time was not big. The short periodic microseisms when they are higher can be dangerous becouse of the possible envelope effect observed at longer periods. The relative variations of the short periodic seismic noise within the Observatory is 1:4. The most quite place is the house of the recording gravimeters (relative noise level = 1.0) and the most noisy is the pillar for the absolute gravity measurements (relative noise level = 4.0). The relative noise level at the gravimeter calibration device is 2.5.

In the course of 1993 different calibration campaigns were carried out with the G-821 and G-963 gravimeters not equipped with electrostatic feedback (*Varga et al.*, 1995). About 24 hours were needed for each run. One run consists six up and down movements of the cylindrical ring. The number of the measurements taken at each extreme position varies between 4 and 20 in dependence of the observed by recording gravimeter noise. Altogether 449 minimum and 437 maximum values were used and the mean of the all measurements is in a very good agreement with the theoretically predicted value while the r.m.s. of all observations is equal to 0.12 microgals (0.1 %) (Table 2).

According to our knowledge it is the most accurate laboratory calibration carried out until now. Its result confirms the calibration carried out in 1991

Table 2. Minimum, maximum and total (Δ) gravity variations generated with the heavy cylindrical ring as measured by gravimeters LCR G-821 and G-963. Gravity values are in *microgal*. n – number of the measurements on basis of which the corresponding extreme gravity — as a mean value – was calculated

G-821

Date	*Minimum* n	*Minimum* g_{min}	*Maximum* n	*Maximum* g_{max}	Δ_{821}
11.09.93	*9*	*-63.8*	*7*	*46.8*	*110.6*
	9	*-64.0*	*8*	*47.5*	*111.5*
	10	*-64.7*	*9*	*48.0*	*112.7*
	10	*-64.0*	*10*	*46.8*	*110.8*
	10	*-63.7*	*10*	*48.5*	*111.2*
	10	*-64.9*	*9*	*48.2*	*113.1*
	58	*-64.2±0.2*	*53*	*47.6±0.3*	
25.09.93	*11*	*-132.6*	*13*	*-21.0*	*111.6*
	13	*-133.3*	*13*	*-21.7*	*111.6*
	13	*-130.9*	*12*	*-20.4*	*110.5*
	15	*-131.5*	*10*	*-21.3*	*110.2*
	7	*-132.6*	*10*	*-21.7*	*110.9*
	11	*-132.8*	*8*	*-19.5*	*113.3*
			13	*-19.6*	
	70	*-122.3±0.3*	*79*	*-20.7±0.3*	
				$\Delta_{821_{mean}}$	*111.6±0.3*

G-963

Date	*Minimum* n	*Minimum* g_{min}	*Maximum* n	*Maximum* g_{max}	Δ_{963}
03.12.93	*16*	*-174.5*	*11*	*-61.2*	*113.3*
	13	*-174.1*	*14*	*-61.4*	*113.0*
	11	*-173.8*	*15*	*-62.4*	*111.4*
	20	*-174.0*	*7*	*-63.0*	*111.0*
	10	*-174.0*	*13*	*-62.9*	*111.1*
	16	*-174.5*	*10*	*-61.8*	*112.7*
	96	*-174.2±0.1*	*70*	*-62.1±0.3*	
04.12.93	*19*	*-170.0*	*17*	*-57.6*	*112.4*
	19	*-168.7*	*18*	*-57.4*	*111.3*
	18	*-170.3*	*10*	*-57.7*	*112.6*
	18	*-169.1*	*19*	*-57.1*	*112.0*
	74	*-169.5±0.3*	*64*	*-57.5±0.1*	
05.12.93	*13*	*-137.8*	*13*	*-25.6*	*112.2*
	14	*-137.3*	*16*	*-24.5*	*112.8*
	19	*-136.7*	*17*	*-24.7*	*112.0*
	17	*-136.0*	*16*	*-24.3*	*111.7*
	15	*-138.0*	*20*	*-24.7*	*113.3*
	14	*-138.5*	*16*	*-25.3*	*113.2*
	92	*-137.4±0.4*	*98*	*-24.8±0.2*	
18.12.93	*3*	*-86.3*	*5*	*22.4*	*108.7*
	3	*-86.0*	*2*	*26.4*	*112.4*
	3	*-86.1*	*2*	*26.4*	*112.5*
	3	*-86.4*	*3*	*25.3*	*111.7*
	3	*-86.8*	*4*	*25.3*	*112.1*
	3	*-86.0*	*3*	*25.9*	*111.9*
	3	*-86.3*	*2*	*26.2*	*112.5*
	3	*-86.4*	*4*	*25.9*	*112.3*
	24	*-86.3±0.1*	*25*	*25.5±0.4*	
19.12.93	*5*	*-63.3*	*6*	*49.0*	*112.3*
	5	*-63.3*	*6*	*48.8*	*112.1*
	4	*-63.1*	*6*	*49.1*	*112.2*
	4	*-63.0*	*6*	*49.2*	*112.2*
	4	*-63.3*	*6*	*49.8*	*113.1*
	5	*-62.4*	*6*	*48.7*	*111.1*
	4	*-63.3*	*6*	*48.7*	*112.0*
	4	*-63.4*	*6*	*49.9*	*113.0*
	35	*-63.1±0.1*	*48*	*49.1±0.2*	
				$\Delta_{963_{mean}}$	*112.1±0.2*

Average of the runs carried out with gravimeters LCR G-821 and G-963

Date	*Instrument*	$\Delta = g_{max} - g_{min}$
11.09.93	*G-821*	*111.8*
25.09.93	*G-821*	*111.6*
03.12.93	*G-963*	*112.1*
04.12.93	*G-963*	*112.0*
05.12.93	*G-963*	*112.6*
18.12.93	*G-963*	*111.8*
19.12.93	*G-963*	*112.2*
		112.01±0.12

before the automation of the calibration device together with M.Becker (TU Darmstadt, Germany) with the LCR F-258 gravimeter owned by the Technical University Darmstadt. At that time we got a r.m.s. error 0.2 % on the basis of four movements up and down of the ring.

A typical experimental example is shown on Fig. 3 (*Varga et al.*, 1985) where the results near to extrema are plotted in case of the campaign 11th September 1993 with the use of the G-821 gravimeter of the Eötvös Loránd Geophysical Institute of Hungary. Random oscillations can be observed up to

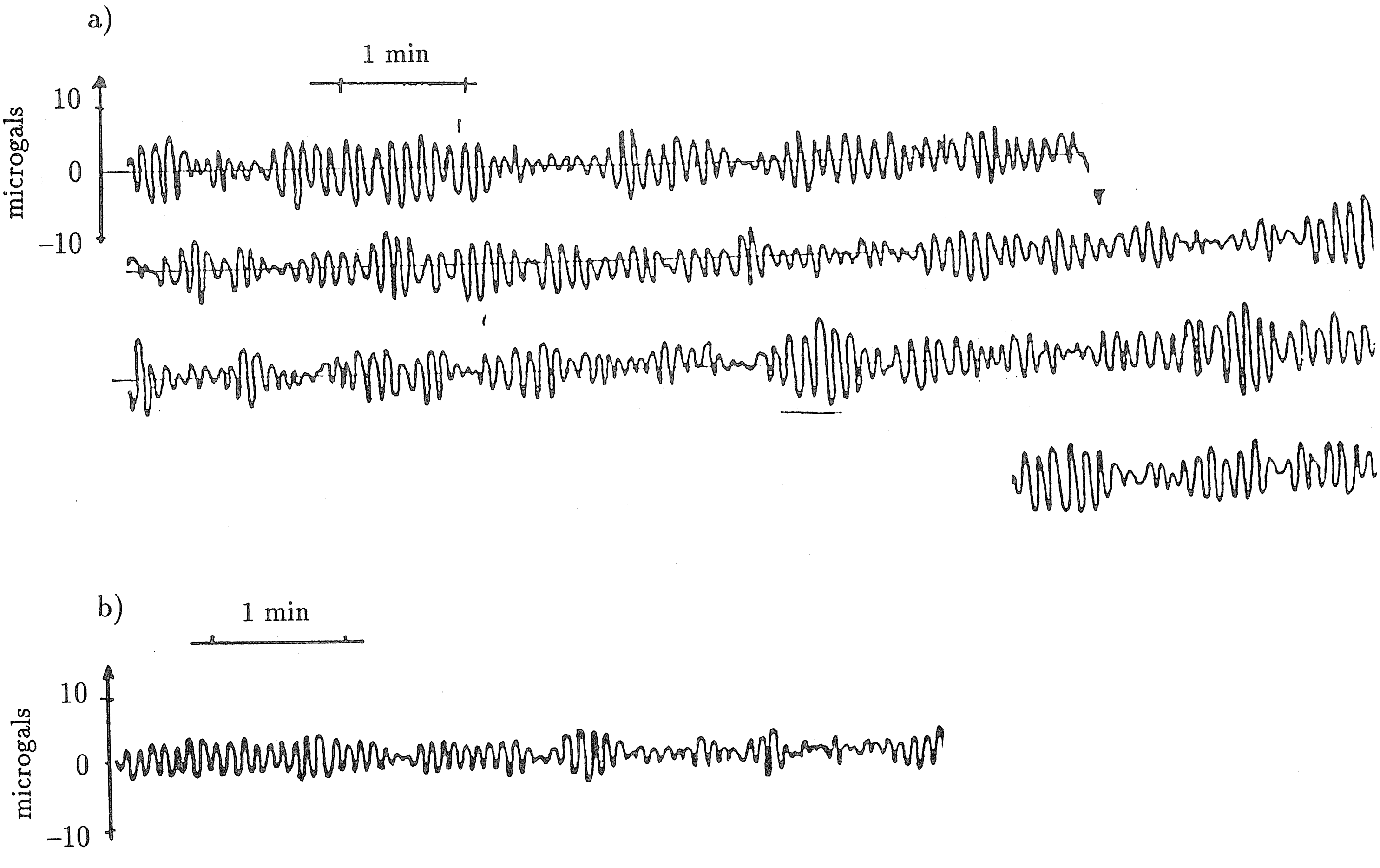

Fig. 3. Results of the measurements carried out with LCR G-821 on November 11th, 1993

2 microgals both at the minimum and the maximum position. These oscillations are possibly related to the microseismic activity. This effect was reduced effectively, if the number of measuments at the extrema increased. A statistical investigation of this values shows that they distribution is not Gauss-type normal distribution. Therefore the simple average value or a least square smooting of the observed data can lead to systematic deviations from the real value. Therefore in the nearest future we are going to carry out robust adjustment calculations using L_1 and L_2 norms or their mixtures.

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CHECK OF THE CALIBRATION OF A TIDAL RECORD BY ABSOLUTE GRAVITY MEASUREMENT

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Only gravimeters Askania have been used on tidal station Pecný so far. The main apparatus Gs 15 No. 228 was installed in 1975 in cooperation with Prague Technical University. The technique of measurement used eliminates influence of the micrometer nonlinearity on the calibration of the tidal record. The accuracy of the amplitude factors of the main tidal waves should lie beetween 0.1% and 0.2 % (Šimon, Brož 1993).

The high precision absolute measurements can provide an independent verification of the gravity record calibration (Barta et al., 1986), (Ducarme et al., 1993). A group of experts from Defense Mapping Agency (USA) performed measurements with AXIS FG5 No.107 absolute gravimeter on Pecný in September 1993. The measurements took 48 hours and one set of 100 drops was realized every hour. Each set took 16.5 minutes, the inner accuracy of the results of one set is 14 nm s^{-2} (all corrections included). After elimination of the tidal corrections we can compare the results of the sets, with synthetic tides, similarly as (Ducarme et al,. 1993). These tides were computed for the mean time of every set with parameters derived at Pecný Observatory. The difference between the average of 100 values of the tidal corrections and the value for the mean time of set was neglected. The relative decrease of the tidal amplitudes is of the order 10^{-4}.

Synthetic tidal variations of gravity were computed from the results of the tidal measurements with Gs 15 No. 228 performed at Pecný Observatory in the period 1976 - 1992 using computer code SLT505 by J.Kostelecký. Tidal potential development CTED was divided into 15 groups of diurnal , 9 groups of semidiurnal and 1 group of terdiurnal waves. The tidal analysis was accomplished using ETERNA (H.-G.Wenzel, Universität Karlsruhe) code with the elimination of atmospheric pressure effect. Regresion coefficient of -0.356 nm s^{-2} hPa^{-1} was obtained. For longperiod waves an amplitude factor $\delta = 1.16$ (for the M_0+S_0 wave $\delta = 1.0$) and a phase lag $\kappa = 0$ were used.

The relationship between measured and unknown quantities can be written under the form (Ducarme et al., 1993)

$$g_i = g_0 + \alpha \; T_i + \beta \; (P_i - P_n) \; ,$$

where

g_i - observed value of g in i-set. (the local atmospheric pressure effect was eliminated with the coefficient 0.300 nm s^{-2} hPa^{-1}),

g_0 - constant term,

α - scale factor of synthetic tides,

T_i - synthetic tide (mean value for each set),

β - atmospheric pressure coefficient,

P_i - mean value of the atmospheric pressure for each set,

P_n - normal atmospheric pressure.

We used the least squares adjustment to determine unknown values of g_0, α, β. We took into account errors in the values g_i only, which were supposed to be of equal accuracy. Input data are summarized in Tab.1. The range of the tidal variations was 1630 nm s^{-2}. A least squares adjustment was carried out on an IBM PC using the MNC code (J.Kostelecký) with following

Table 1. Input data

Set number i (1)	Resulting gravity DMA [m s^{-2}] (2)	Tidal correction DMA [nm s^{-2}] (3)	P [hPa] (4)	g [m s^{-2}] (2)-(3)-11 nm s^{-2}	T [nm s^{-2}] (5)
1	9.809332796	-828	947.600	9.809333613	781.7
2	9.809332813	-768	947.477	9.809333570	718.0
3	9.809332804	-681	947.651	9.809333474	629.8
4	9.809332816	-601	947.720	9.809333406	552.1
5	9.809332809	-557	947.469	9.809333355	511.6
6	9.809332818	-559	947.295	9.809333366	519.5
7	9.809332817	-601	946.611	9.809333407	567.9
8	9.809332826	-659	946.246	9.809333474	631.4
9	9.809332827	-698	945.868	9.809333514	673.9
10	9.809332847	-682	945.511	9.809333518	658.2
11	9.809332832	-583	945.000	9.809333404	558.0
12	9.809332840	-394	944.948	9.809333223	366.5
13	9.809332825	-133	945.239	9.809332947	101.8
14	9.809332821	161	945.582	9.809332649	-195.7
15	9.809332815	435	945.728	9.809332369	-470.9
16	9.809332810	632	945.746	9.809332167	-667.7
17	9.809332814	707	945.863	9.809332096	-741.9
18	9.809332805	641	945.744	9.809332153	-673.6
19	9.809332822	442	945.441	9.809332369	-471.9
20	9.809332797	146	944.876	9.809332640	-173.8
21	9.809332826	-191	944.796	9.809333006	164.5
22	9.809332809	-509	944.389	9.809333307	480.8
23	9.809332821	-752	944.169	9.809333562	720.9
24	9.809332813	-886	944.171	9.809333688	850.8
25	9.809332796	-905	943.908	9.809333690	863.7
26	9.809332800	-826	943.730	9.809333615	779.7
27	9.809332793	-690	944.085	9.809333472	640.0
28	9.809332782	-547	944.254	9.809333318	495.5
29	9.809332802	-443	944.010	9.809333234	394.0
30	9.809332800	-411	943.751	9.809333200	367.0
31	9.809332821	-459	943.903	9.809333269	421.6
32	9.809332825	-568	943.802	9.809333382	538.2
33	9.809332843	-699	943.752	9.809333531	674.9
34	9.809332814	-799	943.658	9.809333602	778.2
35	9.809332821	-819	943.559	9.809333629	798.2
36	9.809332805	-725	942.815	9.809333519	702.5
37	9.809332798	-515	942.562	9.809333302	487.6
38	9.809332805	-215	942.564	9.809333009	182.3
39	9.809332800	121	942.927	9.809332668	-157.7
40	9.809332825	422	942.701	9.809332392	-461.7
41	9.809332814	623	942.199	9.809332180	-662.2
42	9.809332802	674	942.046	9.809332117	-711.6
43	9.809332792	561	941.529	9.809332220	-595.1
44	9.809332832	304	940.840	9.809332517	-334.9
45	9.809332814	-42	940.176	9.809332845	15.1
46	9.809332835	-408	939.633	9.809333232	382.0
47	9.809332833	-718	939.201	9.809333540	691.8
48	9.809332809	-916	938.776	9.809333714	887.1

P_n=950.723 hPa

result:

$$g_0 = 9.809\ 332\ 845 \pm\ 5.4 \times 10^{-9}\ [\mathrm{m\ s^{-2}}],$$

$$\alpha = 1.00159 \pm 0.00329,$$

$$\beta = 1.20665 \pm 0.76764\ \ [\mathrm{nm\ s^{-2}\ hPa^{-1}}],$$

$$m_0 = 11.6\ \ [\mathrm{nm\ s^{-2}}]\ \ (\text{ mean square error of } g_i).$$

There is a high correlation between the absolute term g_0 and the coefficient β (R = 0.9368) because variations of the atmospheric pressure were very small during absolute measurements. Therefore another fit was carried out in which the atmospheric pressure coefficient β was neglected, with the following results:

$$g_0 = 9.809\ 332\ 837 \pm 1.9 \times 10^{-9}\ [\mathrm{m\ s^{-2}}],$$

$$\alpha = 1.00206 \pm 0.00332\ ,$$

$$m_0 = 11.8\ \ [\mathrm{nm\ s^{-2}}]\ \ (\text{mean square error of } g_i).$$

The resulting value of the coefficient α = 1.0021 confirms that the system of the tidal station Pecný is correct within the limits of obtained accuracy 0.33%. The value of m_0 is in good agreement with accuracy estimate of one set of absolute measurements.

Finally, we present a comparision of amplitude factor δ of the main tidal waves as determined at Pecný corrected for oceanic tidal effect with theoretical values $\delta_{W\text{-}D}$ of the Wahr-Dehant model of Earth tides for PREM (Dehant,1987) , see Tab.2. The weighted average of the δW-D/δ ratio differs from one only by 0.0007±0.0005.

Table 2. Measured and theoretical amplitude factors at Pecný Observatory

Wave	δ	δ_{W-D}	δ_{W-D}/δ
Q1	1.1500 ± 0.0014	1.1523	1.0020
O1	1.1512 ± 3	1.1523	1.0010
P1	1.1474 ± 6	1.1471	0.9997
K1	1.1331 ± 2	1.1320	0.9990
N2	1.1586 ± 9	1.1562	0.9979
M2	1.1584 ± 2	1.1563	0.9982
S2	1.1547 ± 4	1.1563	1.0014
K2	1.1521 ± 14	1.1563	1.0036
		weighted average	0.9993
		m.s.e.	0.0005

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ELIMINATION OF TIDAL INFLUENCES ON ABSOLUTE GRAVITY MEASUREMENTS

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1. Introduction

In (Vanka, 1994) the results of absolute gravity measurements performed in 1993 at the station Pecný by the Defense Mapping Agency (DMA) of USA with the gravimeter AXIS FG 5 are compared with the tides computed on the basis of the results of the long term tidal measurements at that station with the Askania Gs 15 gravimeter. It was shown, among others, that the mean square error of the results of individual sets of absolute measurements (100 free falls) actually ranges close to 1 microgal.

Therefore, it is necessary to ensure the corresponding accuracy of all geophysical corrections of these highly precise measurements, among them also of tidal corrections.

However, it is difficult to determine individual values of tidal corrections with an accuracy of 1 μGal or better, because we usually do not know the parameters of tidal waves, i.e. the amplitude factors δ and the phase lags κ with sufficient accuracy. But we shall show that the tidal influences can be eliminated from the final results of absolute measurements with an accuracy much better than 1 μGal, even if we do not know anything about the tidal parameters for the station.

2. Shortperiodic tides (D,SD,TD)

The best way to compute the tidal corrections is to use the parameters δ and κ determined from long term tidal measurements at the station. They also include the effect of ocean tides. However, a near tidal station is not always available and if that is the case, its results may be considerably affected by systematic errors in the record calibration.

Alternatively, the parameters given by a model of the Earth tides can be used corrected for the oceanic effect using an ocean tide model. But the validity of the models for the absolute station may be a question.

If we do not use the exact values of tidal parameters, the individual computed corrections may be erroneous up to several few microgals. But the noneliminated residuals of tides have a quasiperiodical character, they represent a sum of harmonics with tidal periods and very small amplitudes.

Therefore, it is sufficient to distribute the sets of absolute measurements equally over the period of 24 hours, 48 hours, etc. Then the residuals of the shortperiodic tides are practically eliminated in the mean of the results of all sets even if we use very rough values of δ and κ. With 48 sets of measurements in two days the coefficient of the amplitude decrease of these residual waves is $\alpha = \sin 24\omega / 24\omega$. On the frequencies ω of the waves O1, K1, M2, S2 the corresponding values are 0.073, 0.003, 0.034, 0.

This method was used in processing the above mentioned DMA absolute measurements at Pecný. The tidal corrections for each set were computed twice. With the use of common parameters $\delta = 1.16$ and $\kappa = 0$ for all waves on the one hand and of correct parameters from the tidal measurements at the station on the other hand. They ranged from about -86 to +74 μGal. The differences between both corrections reach the values from -1.8 up to +1.2 μGal, see Fig. 1. But the mean of the 48 differences is only 0.01 μGal.

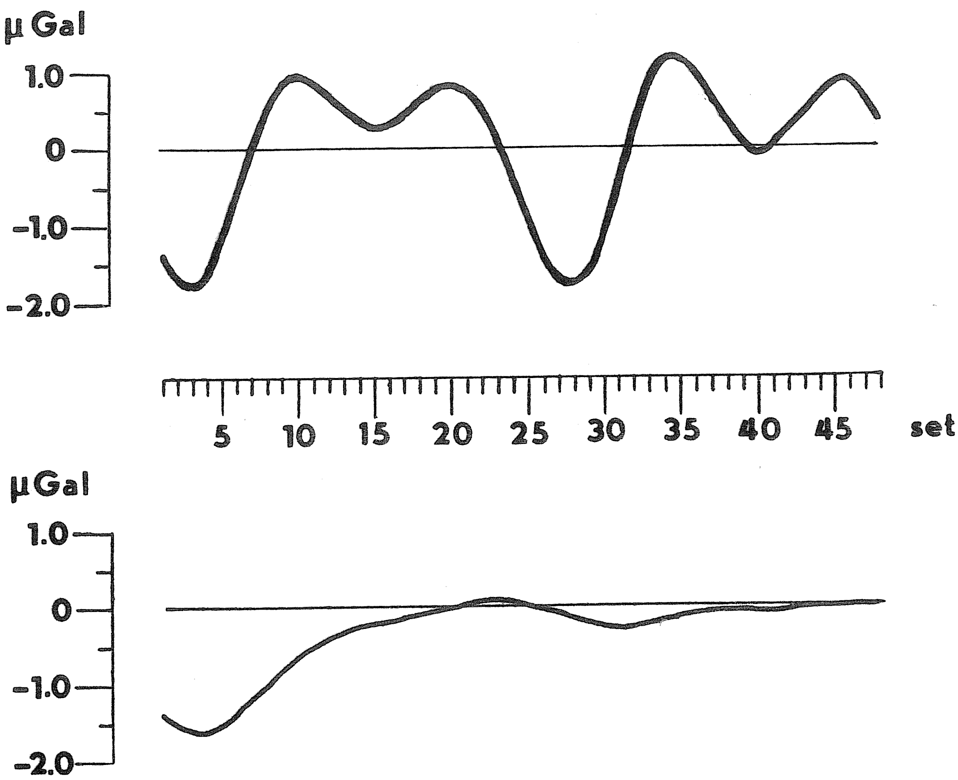

Fig. 1. Differences between two kinds of tidal corrections

Progressive means of the differences

3. Longperiodic tides (LP)

The effect of longperiodic tides during the absolute measurements is of systematic character. Moreover, up to now the longperiodic tides have been determined only at few stations and also the tidal models are not without problems in this respect. But the influence of the inaccuracy of their parameters is restricted because their amplitudes are smaller than those of the shortperiodic tides.

To estimate the magnitude of the whole longperiodic tides, we can use simplified formulae (Melchior,1966):

$$\delta^{\mathfrak{C}} g_{LP} \doteq -\frac{1}{3}\, C\,(1-3\sin^2\delta_{\mathfrak{C}})\,(1-3\sin^2\varphi) \qquad \text{for the Moon and}$$

$$\delta^{\circ} g_{LP} \doteq -\frac{1}{3}\, C\,(1-3\sin^2\delta_{\odot})\,(1-3\sin^2\varphi) \qquad \text{for the Sun.}$$

Here C = 82.5 μGal, φ is the latitude of the station, $\delta_{\mathfrak{C}}$ and $\delta_{\odot}$ are the declinations of the celestial bodies. A substantial part of both expressions is constant in time:

$$\delta^{\mathfrak{C}} g_0 = -0.504/2\; C\,(1-3\sin^2\varphi),$$

$$\delta^{\circ} g_0 = -0.234/2\; C\,(1-3\sin^2\varphi).$$

According to the recommendation of the IAG these constant tidal effects shoud be included in the corrections with the amplitude coefficient $\delta = 1$ (Rapp, 1983).

After substitution for C we have the differences (in microgals)

$$\delta^{\mathfrak{C}} g_{LP} - \delta^{\mathfrak{C}} g_0 \doteq [\,-27.5\,(1-3\sin^2\delta_{\mathfrak{C}}) + 20.8\,]\,(1-3\sin^2\varphi),$$

$$\delta^{\circ} g_{LP} - \delta^{\circ} g_0 \doteq [\,-12.6\,(1-3\sin^2\delta_{\odot}) + 9.7\,]\,(1-3\sin^2\varphi).$$

The maximum absolute values we get for $\varphi = \pm 90°$, $\delta_{\mathfrak{C}} = \pm 28.5°$, $\delta_{\odot} = \pm 23.5°$. With these values and the amplitude factor 1.16 we have

$$|\delta^{\mathfrak{c}} g_{LP} - \delta^{\mathfrak{c}} g_0| \leq 28.0\ \mu\text{Gal}, \qquad |\delta^{\circ} g_{LP} - \delta^{\circ} g_0| \leq 7.2\ \mu\text{Gal},$$

The part of the longperiodic tides, for which we need to know the tidal parameters δ and κ, is therefore at any time and place smaller than 40 μGal, usually much smaller. Even if with all the waves the systematic error would be of 2% in the δ factors or 1° in phase lags κ, the errors of the tidal corrections remain smaller than 0.8 μGal.

4. Conclusion

In conclusion we can make a practical recommendation for the absolute gravity measurements: if possible, to distribute the sets of measurements equally over the period of a whole number of days. Then the tides will be eliminated from the final result with an accuracy much better than 1μGal even if we do not use the exact values of the tidal parameters in computation of the tidal corrections.

From the point of view of tidal corrections the most important point is a unique approach to the constant tide which should be used with the amplitude coefficient equal to 1. According our experience, this recommendation is not always respected.

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In-situ calibration of quartz tube extensometers

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Abstract

A network of quartz-tube extensometers was established in the Pannonian Basin for the observation of the recent crustal movements. The measurements are influenced not only by the cavity, topography and other environmental effects but very intensively by the instrumental instabilities, too. A regular calibration by magnetostrictive coils is carried out to diminish these latest effects. The interpretation of the measurements can be very difficult if the calibration has itself a systematic error due to the different calibration factors of the induvidual instruments. This problem can be solved by the in-situ calibration of the instruments. In the paper a calibration method and the first results obtained by the calibration of two extensometers in Budapest recording electrically by means of capacitive transducers and of one in Vyhne recording on a photodrum are given.

1. Introduction

Figure 1 shows the extensometric network established in the Carpathian-Balkan region. All of the extensometers are calibrated by means of a magnetostrictive coil tested just before the installation of the instruments. The extensometers at the observatories in Budapest and Sopron record electrically by means of a capacitieve transducer developed in the Geodetic and Geophysical Research Institute in Sopron. The other instruments work by means of photorecorders.

The extensometers were installed at different times, therefore usable data for our purposes have been obtained since 1990. The first data were analysed by Varga at al (1993). The results showed that the records at different observatories can be connected to real external geodynamical processes, however, the nature and the regionality of these correlatios are still doubtful and need further investigations and considerations. To an the incorrect interpretation of the measured data it is necessary to reduce the instrumental errors. First of all, the uniform calibration of the instruments is very important. For this purpose the high precision calibration apparatus developed for the calibration of magnetostrictive coils and crapoudines (Mentes, 1992) is very suitable due to its portability.

2. The calibration apparatus

The principle of operation of the calibration apparatus can be seen in Fig. 2. The apparatus consists of a precise vertical rotation axis fixed to a very rigid baseboard. An arm rotates around the precise axis and the angular displacement of the arm is sensed by two differential capacitive transducers placed at the extremities of the arm. A differential amplifier subtracts the output signals of the two capacitive transducers from each other. This solution ensures a double sensitivity and eliminates the errors of the rotation axis (excentricity, radial clearance and other processing errors) and minimizes the influence of the environmental parameters (temperature, air pressure, humidity). Thus, the output signal of the differential amplifier depends only on the the displacement of the ball point and by doing so it is strictly proportional to the displacement of the end of the extensometer connected to the ball point.

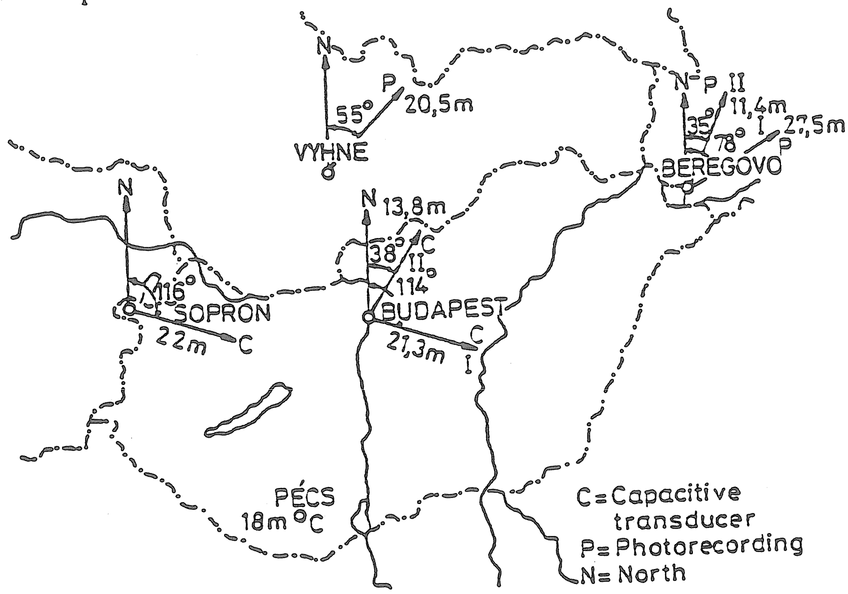

Figure 1. The extensometric network established for the investigation of the crustal movements in the Pannonian Basin.

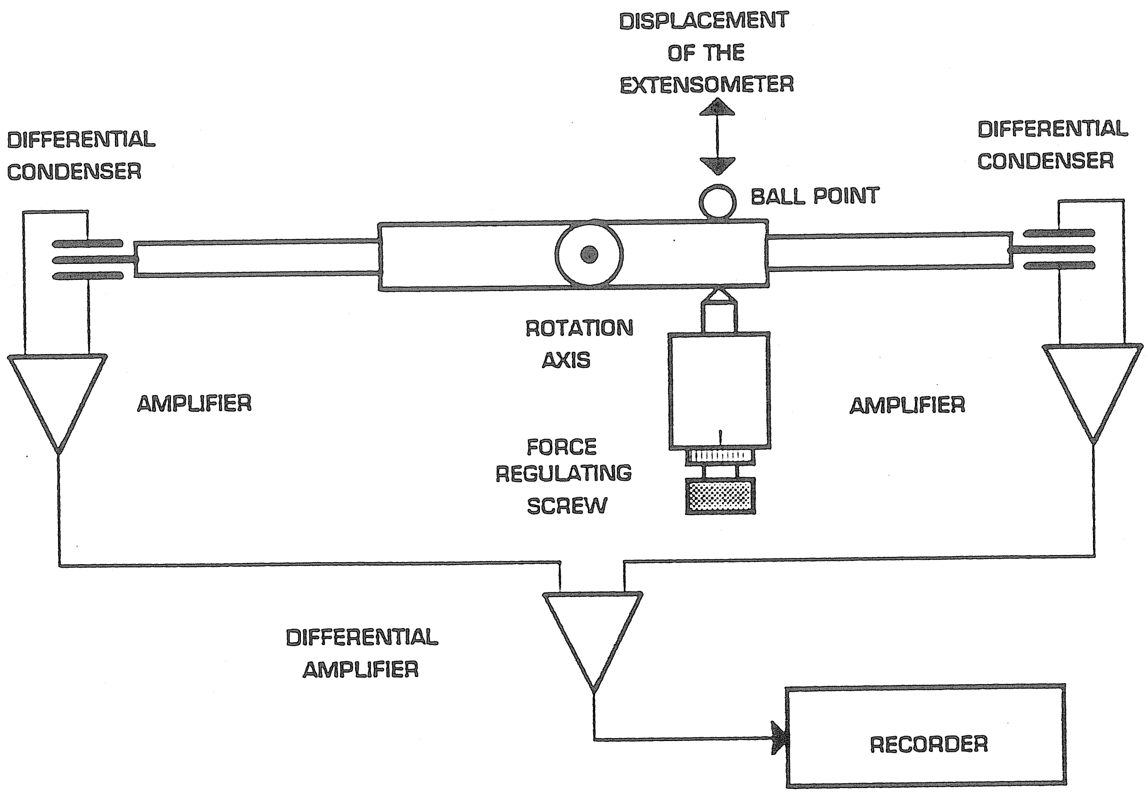

Figure 2. The principle of the calibration apparatus

Figure 3 shows the mechanical construction of the calibration apparatus.The extensometer to be tested actuates the arm at the ball point near to the rotation axis. The movement of the arm is sensed at the extremities. This solution ensures a mechanical leverage ratio of about 5 to increase the sensitivity. The force regulating screw is used to push the ball point against the rigid plate clamped to the tube of the extensometer (Fig.4.) which transfers the displacements of the extensometer to the calibration apparatus.The arm of the calibration apparatus rotates in a horizontal plane, thus it can be very easily installed without disturbing the work of the extensometer. The calibration apparatus is tested by means of a laser interferometer before and after of the calibration of the extensometers and hereby the linearity errors of the calibration apparatus can be taken into account during the evaluation of the measured data.

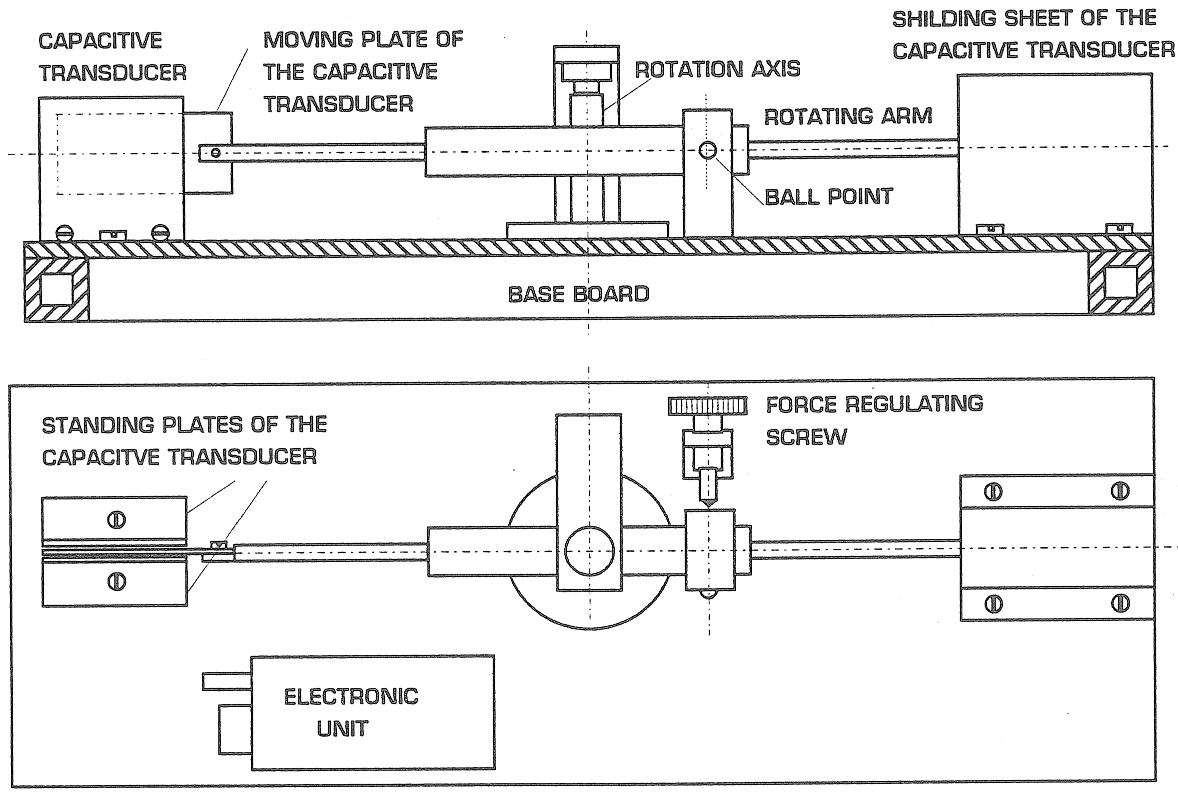

Figure 3. The mechanical construction of the calibration apparatus.

3. The measuring method

Figure 4 shows the principle of the in-situ calibration procedure of the quartz-tube extensometers. An additional clamp holding a rigid plate is mounted on the quartz tube. The ball point of the moving arm of the calibration unit is pressed against the rigid plate by means of the force regulating screw of the calibration unit (Fig.3.).Thus, the movements of the quartz tube can be simultaneously recorded by means of the calibration unit and the transducer of the extensometer. The coil of the magnetostrictive transducer is energized by means of a high stability current regulator used for regular calibration of the extensometer. The adjustment of the current can be controlled by a digital current meter. Thus, the linearity of the whole extensometer, together with the magnetostrictive transducer can be investigated at different currents within the whole operating range.

The calibration was made as followes: a current was set by the regulator and it was periodically switched on and off and the displacements of the extensometer were recorded at

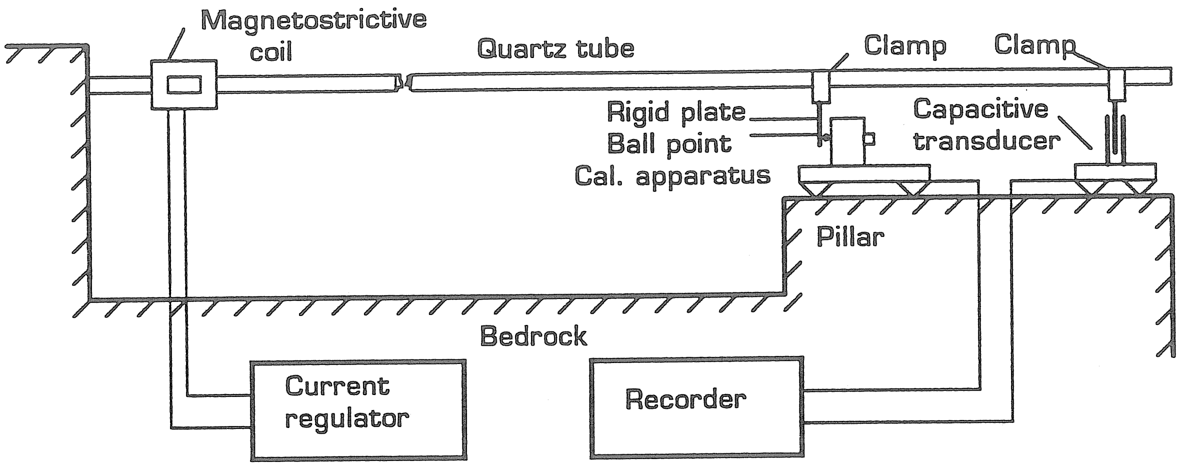

Figure 4. The principle of the in-situ calibration of the extensometers

different currents by means of an analogous recorder. The magnitudes of the rising and falling edges of the displacement pulses were not constant due to the drift of both high sensitive instruments, therefore a lot of measurements were made at a current value to get the best average. Figure 5 shows the histograms of the determination of the displacement values measured by the extensometer to be tested and the calibration apparatus at a current of 32 mA.

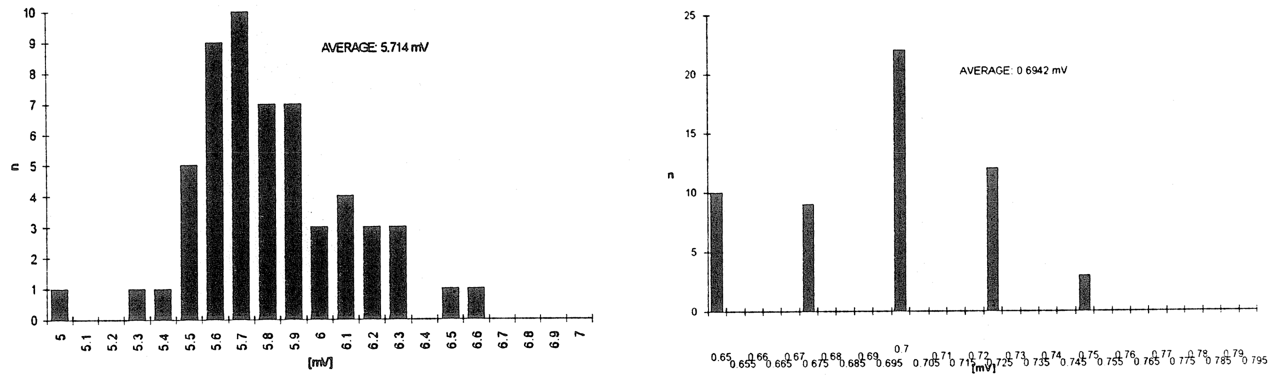

Figure 5. Histograms of the calibration values measured by the extensometer and the calibration apparatus.

The histograms show that the distribustion of the measured values is near to the normal. Thus, it can be supposed that the scatter of the measured values has a random character and we can state that the average of more than 20 measured data (magnitudes of rising and falling edges) can be well used for the calibration. The highest error of the calibration calculated from the measurements stays below 4%.

Figure 6 shows the average values calculated from the measured data at different currents in case of the extensometers in Budapest. The values measured by the calibration apparatus are multipied by ten to plot the data in one diagram. In Fig. 7. the data measured by the extensometer to be calibrated are plotted against the ones measured by the calibration apparatus. Figure 8 shows the similar curves measured in Vyhne. At this last extensometer difficulties arised at the photorecorder. The switch period of the calibration curve had to be long enough to see the pulses on the film and therefore the time to carry out the measurements was much longer.

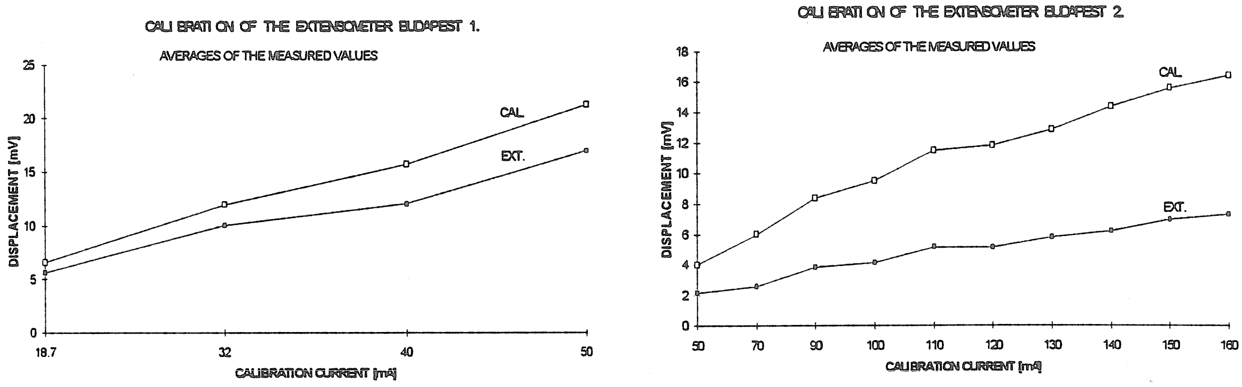

Figure 6. The measured average values at different calibration currents (Budapest 1, 2.)

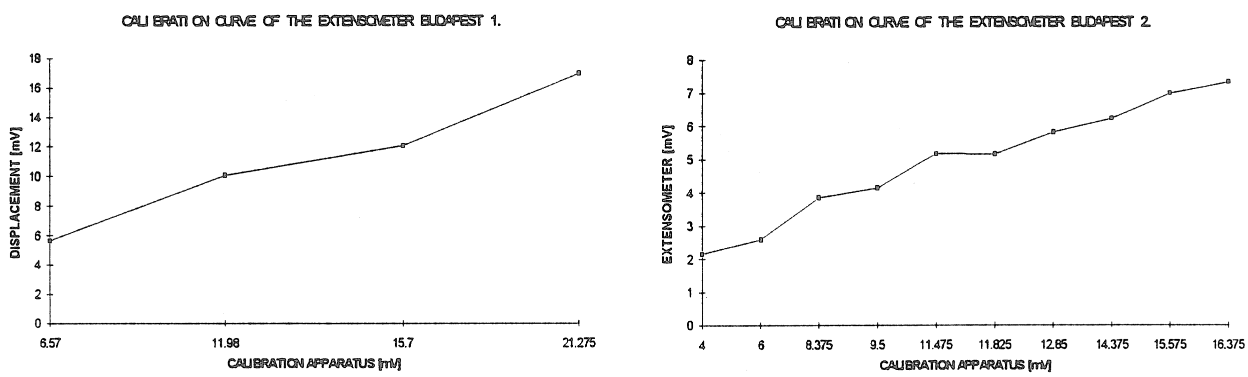

Figure 7. The calibration characteristics of the extensometers Budapest 1, 2.

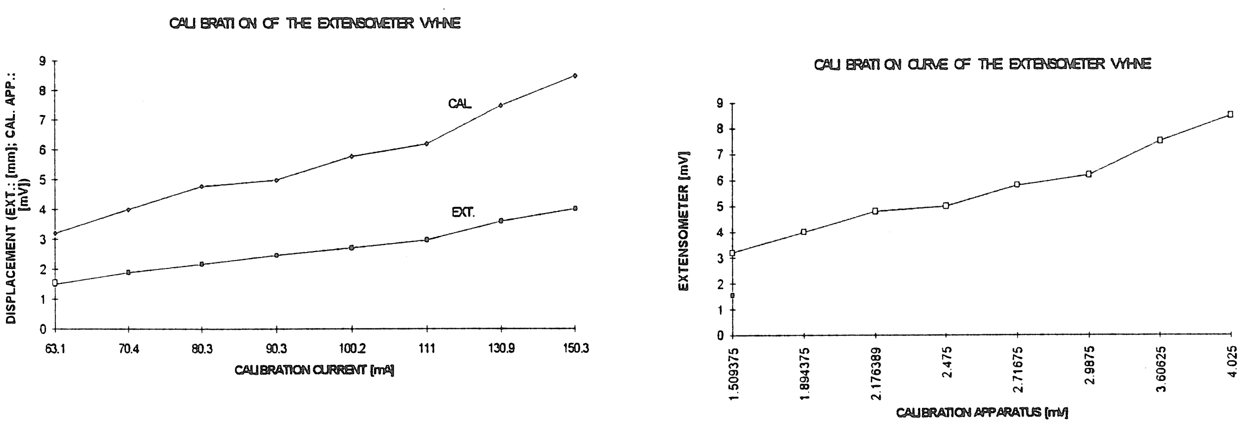

Figure 8. The calibration curves of the extensometer in Vyhne

4. Conclusions

The measurements had shown that the calibration accuracy of the extensometers can be increased by the in-situ method especially when the rising and falling edges of the displacement pulses can be determined much accurately. It can be done applying a much higher paper speed at the analogous recorder or a digital recorder with high sampling rate. An other possibility is to use a function generator to energize the magnetostrictive coil by a sinusoidal calibration current. In this case the disturbing drift effect could be eliminated by applying a suitable frequency. The frequency characteristics of the extensometers can be determined by this method.

It would be better to make parallel records with frequent calibrations for longer, at least for some weeks or some month. In this case, better evaluation methods (e.g. Earth tide analysis) could be applied to determine the calibration coefficients.

The in-situ calibration method makes possible to calibrate the magnetostrictive coils in built-in state. This would be very important because the displacement of these coils at an energizing current depends on the loading force, too (Mentes, 1993). Therefore the laboratory calibrations can only be used to test the construction and the properties of the magnetostrictive coils. From the differences of the laboratory and in-situ measurements the force hampering the free motion of the quartz tubes can be determined.

The main advantage of the in-situ method is that the same calibration instrument is used to calibrate all of the extensometers. Thus, the individual extensometers are with relatively high accuracy calibrated to each other which makes easier to interpretate the measured data in a large area as the Pannonian Basin. On the basis of the first experiences we plan the complex calibration of all extensometers in the Pannonian Basin, as mentioned above. The calibration coefficients calculated in nm and the other parameters for all of the extensometers in the Carpathian-Balkan region will be summerised in a next paper.

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ASKANIA borehole-tiltmeters: Test of nine different instruments regarding the orthogonality of both channels

by

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Abstract

The ASKANIA borehole-tiltmeter is a vertical pendulum with two orthogonal read-out systems and an in-situ calibration device (ball calibration). In order to benefit from the quality of the tiltmeter the orthogonality of both the read-out systems and the ball calibration must be guaranteed. The test of nine different instruments revealed, that the two channnels were mostly not well enough adjusted, and that the observed cross-coupling of the calibration is due to another misadjustment of the calibration devices, too. Thus, as a sum of both a difference between the true and the expected azimuth of up to 5 degrees could be found.

The calibration pulses proved to have an inner accuracy of better than 0.2 %. Thus, the misadjustment must be corrected.

1. Introduction

The ASKANIA borehole-tiltmeter was originally constructed before 1966 (Jacoby, 1966) and later produced by BODENSEEWERKE. Although only less than 25 instruments were produced they were used in several geodynamic research projects in Germany (Bonatz et al., 1983; Flach et al., 1975) and Fennoscandia (Alms et al., 1991a; 1991b; Asch & Jentzsch, 1986), in earthquake research in Turkey (Berckhemer et al., 1991) and California (Johnson et al., 1993), in connection with ocean tidal loading (Peters & Beaumont, 1985), and in observatories like the Black-Forest-Observatory (e.g. Neuberg & Zürn, 1986) and Xiangshan, China (Hou et al., 1994).

In the frame of the monitoring of deformations within the research mine Asse in Northern Germany nine tiltmeters of the ASKANIA type will be installed. They were already used in other research mines in connection with the test of these locations for the disposal of nuclear and chemical waste. Thus, these tiltmeters had to be checked, overhauled and recalibrated in order to prepare these measurements. Following Zürn (1992, pers. comm.) who reported a strong non-orthogonality in one of his tiltmeters of the same type we decided to check the adjustments, too.

Two measurements were necessary: The orthogonality of the read-out systems was investigated in the laboratory with the help

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of a special device, and the calibration was tested in the boreholes available in the basement of our institute in Clausthal. Since the read-out systems and the ball cages of both channels are independent we had to determine four angles for each instrument.

2. Test of the orthogonality of the electronic read-out

For the test of the orthogonality we constructed a special device which consists of a sledge on a turnable table. The tiltmeter was disassembled and installed in a vertical frame. Than, the pendulum carrier (outer pendulum) was adapted to the sledge. This carrier covers the inner pendulum. The read-out systems for both channels measure the movement of the inner pendulum relative to the outer pendulum. This carrier of the inner pendulum is also called 'pendulum' because it is movable to allow the adjustment of the range of the inner pendulum as the sensor of the tilt changes.

A micrometer screw was used to move the lower end of the pendulum carrier creating an angle between the free inner pendulum and the carrier. We used five consecutive steps of 50 mikrometers each. This procedure was applied to different azimuth angles: 0°, ± 10°, ± 20° as well as to the opposite direction. All measurements were repeated several times to allow for the determination of statistical errors.

The evaluation of the data was done separately not only for both channels but also for the difference angle (non-orthogonality). This leeds to independent error bars. The deviation from zero degrees means the difference from the correct adjustment. The angles are counted anti-clockwise looking onto the tiltmeter from above. The errors obtained are in the order of 0.5°; since we reinstalled the tiltmeter before each individual measurement we think that this is an upper bound for the error estimation.

The results of this test are given in tab. 2.1. As can be seen the deviation of the individual channels is up to nearly ± 3°, and the biggest difference angle of both channels denoting the non-orthogonality is - 2.94°.

Table 2.1: Results of the test of the orthogonality (values in degrees).

no. of tilt-meter	channel X	channel Y	difference X -Y
102	-2.72 ± 0.65	0.22 ± 0.43	-2.94 ± 0.86
103	-0.54 ± 0.65	-1.15 ± 0.61	0.61 ± 0.66
104	-0.72 ± 0.52	-1.01 ± 0.40	0.29 ± 0.59
108	-0.31 ± 0.56	0.77 ± 0.67	-1.20 ± 0.47
109	-1.85 ± 0.31	-2.93 ± 0.27	1.08 ± 0.49
110	1.26 ± 0.37	-0.98 ± 0.29	2.24 ± 0.32
111	-0.96 ± 0.50	0.17 ± 0.56	-1.13 ± 0.45
112	-0.86 ± 0.26	-1.19 ± 0.47	0.34 ± 0.66
113	1.60 ± 0.29	0.93 ± 0.70	0.67 ± 0.72

3. Test of the calibration

One advantage of this type of tiltmeter is the availability of the in-situ calibration by means of a small iron ball moved in a cage between two well defined positions. These cages (one for each channel) are fixed to the inner pendulum. This method proved to be very stable and the accuracy of the calibration is on the 0.2 % level (comp. Flach et al., 1971). Properly adjusted the calibration of one channel should not affect the other (orthogonal) direction. But nearly all users report about a significant cross-coupling of the calibration between both channels. This means, that a calibration pulse created by the move of the ball results in a small but significant pulse on the other channel. The observed cross-couplings between X and Y (calibration X) and Y and X (calibration Y) are not the same. Fig. 3.1 gives an example for the two calibration pulses.

Weise (1989; 1992) discusses possible reasons for this fact; but it was clear that the misadjustment could only be separated after the check of the orthogonality of the read-out systems.

The calibration was tested over a period of about four weeks during which the tiltmeters were recording in our boreholes. During this period about thirty calibrations were carried out such that one pulse lasted about ten minutes. Between X and Y calibration we waited another ten minutes in order to have enough data before and after the pulses and the cross-couplings to allow for a proper evaluation of the steps (comp. fig. 3.1).

Fig. 3.2 gives an example of the results obtained for tiltmeter no. 110: The X calibration pulse has an amplitude of about 50.5 mV, and the cross-coupling amounts to about 1.2 mV. For

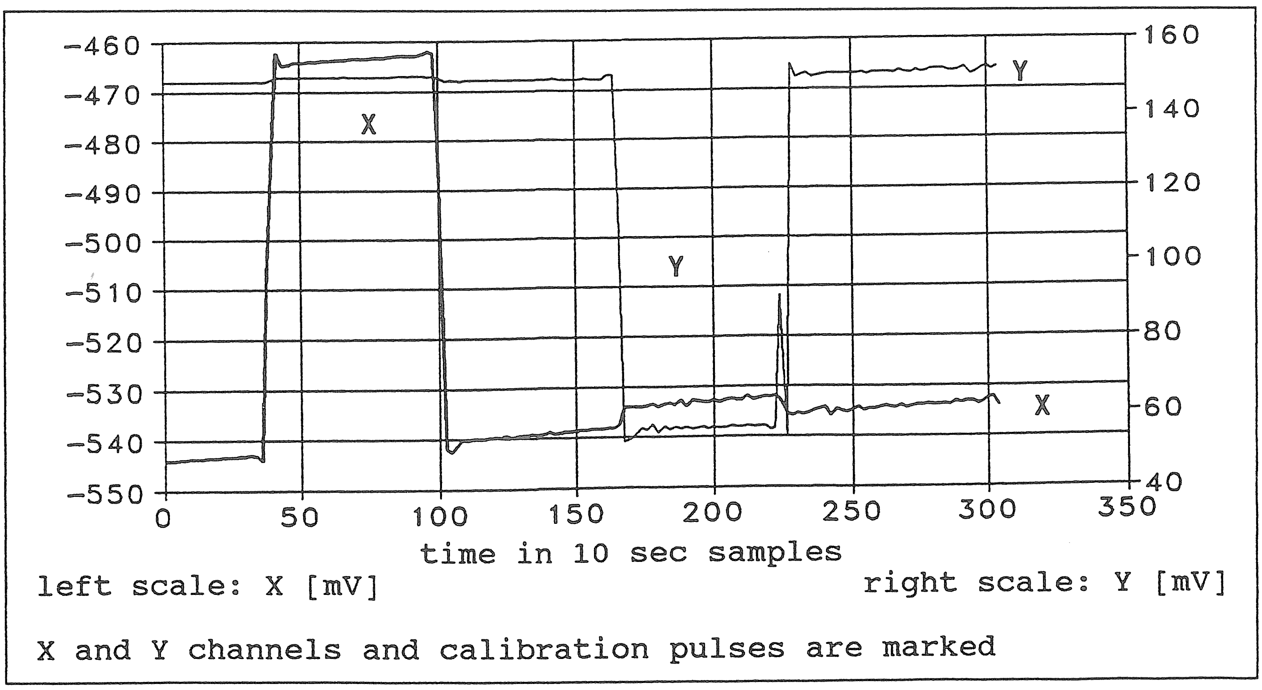

Figure 3.1: Calibration pulses and cross-coupling observed with tiltmeter no. 110; bold line and left scale: channel X, thin line and right scale: channel Y; time in 10 seconds; thus, one pulse covers about 10 minutes.

the Y calibration the values are 71.5 mV and -2.3 mV, respectively. In tab. 3.1 the results for the calibration pulses and the cross coupling for all nine tiltmeters are are compiled. The calibration factors are given in tab. 3.2.

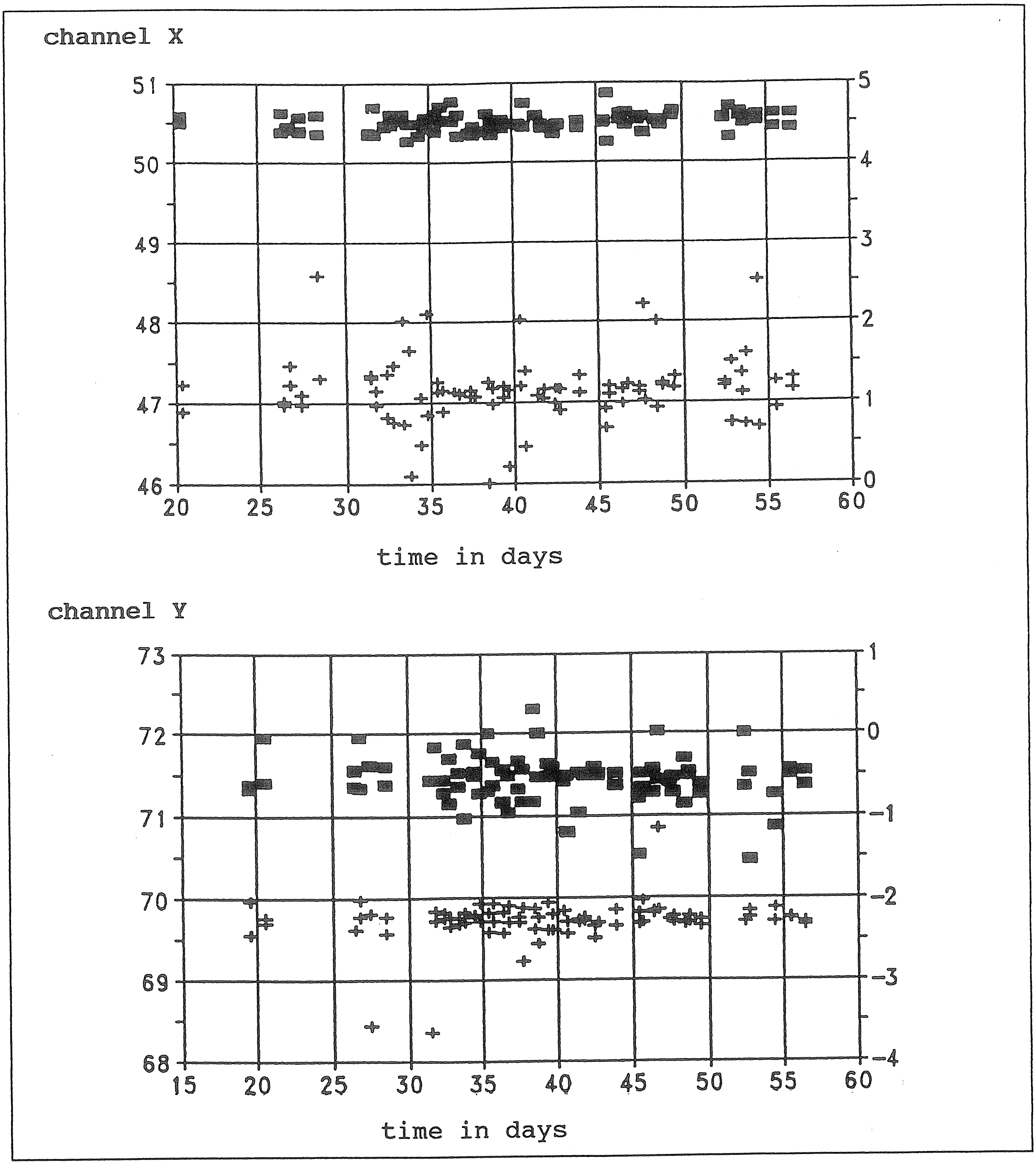

Figure 3.2: Results for the individual calibration pulses and cross-coupling observed with tiltmeter no. 110; black squares and left scales denote the calibration pulse; crosses and right scales denote the cross-coupling; amplitudes in millivolts.

Table 3.1: Calibration pulses and cross coupling (values in millivolts, errors in percent).

no. of tilt-meter	channel X [%]	[%]	channel Y [%]	[%]
102	74.34 ± 0.19	1.42 ± 4.77	89.40 ± 0.20	3.98 ± 5.41
103	86.36 ± 0.11	-3.15 ± 4.16	88.97 ± 0.13	1.27 ± 7.41
104	99.00 ± 0.21	-0.49 ±43.36	87.65 ± 0.20	-0.66 ±19.29
108	71.74 ± 0.21	-0.17 ±64.95	75.39 ± 0.24	2.23 ± 6.42
109	50.18 ± 0.16	-0.13 ±62.13	57.37 ± 0.25	-0.72 ±18.41
110	50.50 ± 0.23	-2.29 ±19.89	71.47 ± 0.66	1.24 ±41.52
111	87.47 ± 0.19	0.31 ±48.28	86.24 ± 0.19	-0.10 ±81.36
112	43.45 ± 0.24	-0.79 ±14.05	42.03 ± 0.28	-0.41 ±19.06
113	78.02 ± 0.13	-4.00 ± 2.31	94.15 ± 0.14	1.03 ±13.29

Table 3.2: Calibration factors of all nine tiltmeters (values in millisecond per millivolt); the errors are less than ± 0.3 %.

no. of tilt-meter	102	103	104	108	109	110	111	112	113
X	278	579	503	429	411	592	385	730	419
Y	231	555	531	414	360	421	386	764	348

4. Discussion

In fig. 4.1 all the results of the misadjustments are compiled: the two columns left belong to channel X, the columns right are for channel Y. As can be seen, there is no general trend. In some cases the sum of the misadjustments for one channel amount to nearly 5 degrees.

Details for the values obtained for the ball cages are not presented here for two reasons: A misadjustment of ball cages of 4 degrees (maximum found) results in a damping of the amplitude of only 0.24% which is equal or below the calibration error. Further, it turns out that this misadjustment cannot be corrected because of the fact both channels have to be calibrated first; thus, we need calibration factors for this correction which we do not have at this stage. The application of the values for the angles of misadjustment found for the correction would only result in a rough estimation, but might be useful if really needed.

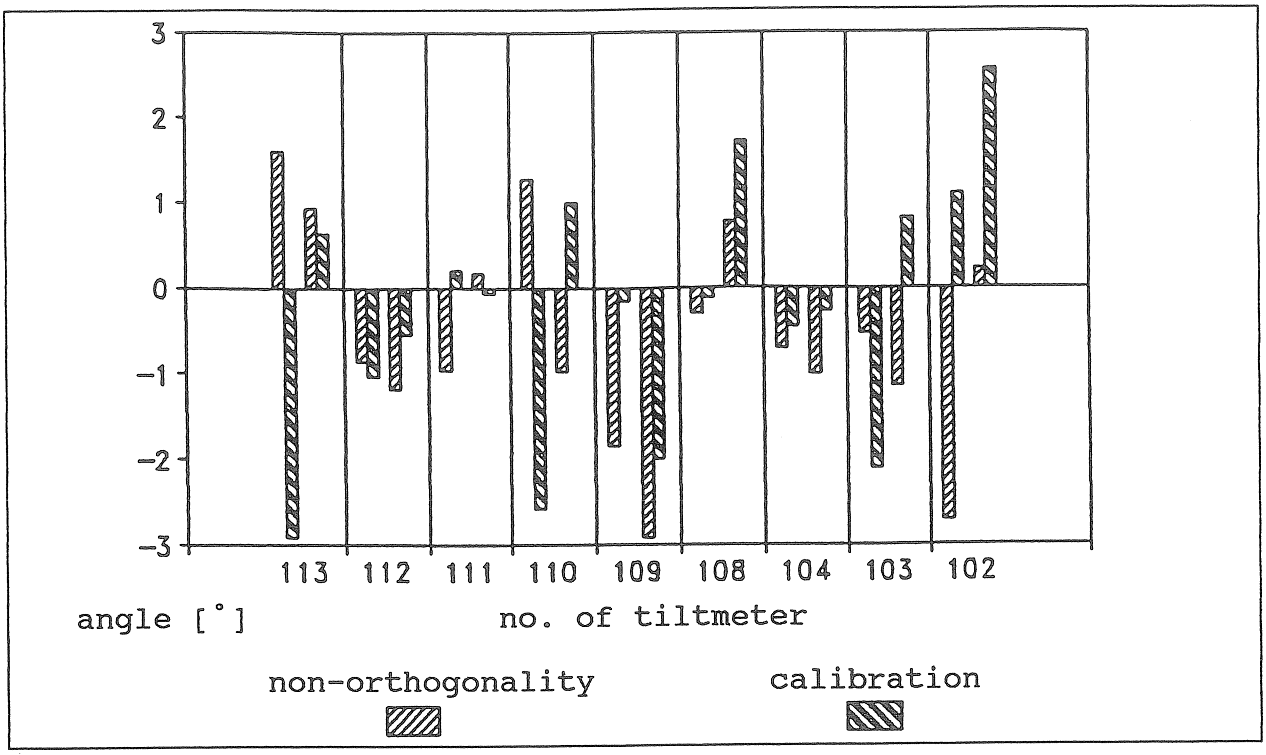

Figure 4.1: Comparison of the misadjustments of the read-out systems (non-orthogonality) and the ball cages (calibration); X: left columns, Y: right columns.

The properties of the electronic filters (anti-aliasing) and the amplification of all tiltmeters was also tested by applying the step-response method. Typically, a low-pass filter with a corner period of 8 seconds and an amplification of factor 10 is used. The values found for all tiltmeters agreed very well.

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INSTRUMENTAL TESTS OF QUARTZ RECORDING GRAVIMETER SODIN-209

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Abstract

Quartz gravimeter Sodin-209 transformed for tide recording using digital registration system based on CCD-scale and transportable tilting installation has a drift of 3-5 μGal/day, st. dev. of about 1 μGal and calibration precision of about 0.2 %.

Introduction

Calibration accuracy better than 0.1 % is needed to detect suspected spatial variations of δ-factors that could reach 0.5 % only. It could be obtained only with joint recording with at least 3-5 relative gravimeters calibrated by means of different in-situ methods (inertial acceleration, ring torus mass). Development of new independant calibration methods seems necessary too.

Registration system for quartz Sodin gravimeters

This device with sensitive system similar to Sharp has an accuracy in laboratory conditions of about 5 μGal [KOPAEV, 1990]. An original digital optical registration system has been developed to employ it for continuous recording. It is based on CCD-scale with 1 μm resolution that produces linear digital output with 1 sec sampling time. IBM AT-286 lap-top resamples it to 1 min values and stores on hard disc. Special halogen lamp located outside of gravimeter is connected with it using optical fiber. Special cirquit prevents the influence of light intensity variations.

Continuous recording tests

Preliminary testing of transformed Sodin-209 gravimeter included 1 month of recording without barocontrol (fig. 1). Scale factor has been determined by means of steps method (using micrometer) with an relative precision of about 1 % only. The results of ETERNA [WENZEL, 1994] application demonstrate:

- mean drift rate 3-5 μGal/day,
- relative precision of $\delta(O_1)$ and $\delta(M_2)$ of about 0.5 %,
- standard deviation of 1-hour value of about 1.0-1.5 μGal,
- noise level in diurnal and semi-diurnal bands of about 0.1 μGal.

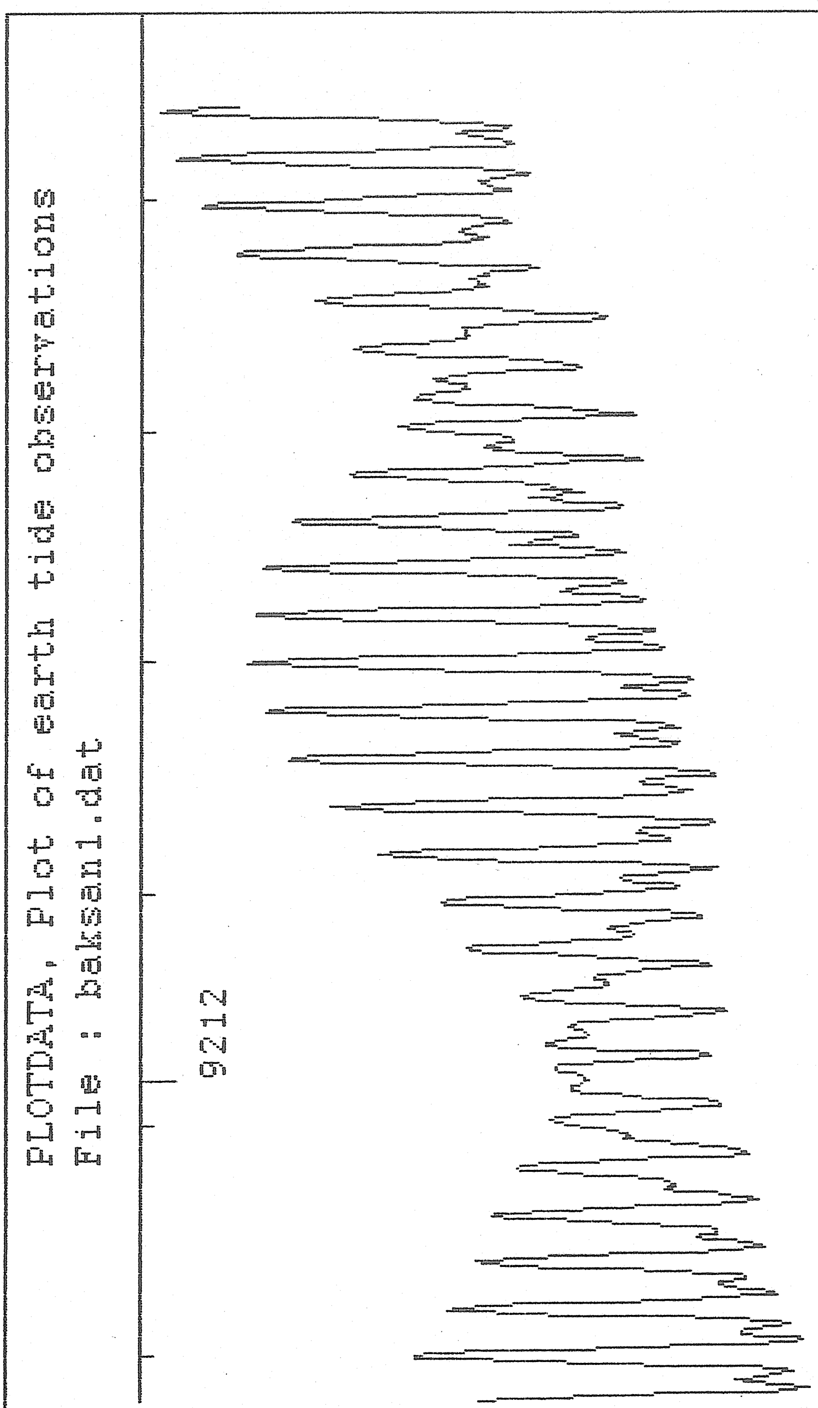


Fig. 1 Test record with Sodin-209
Duration: 921226-930126

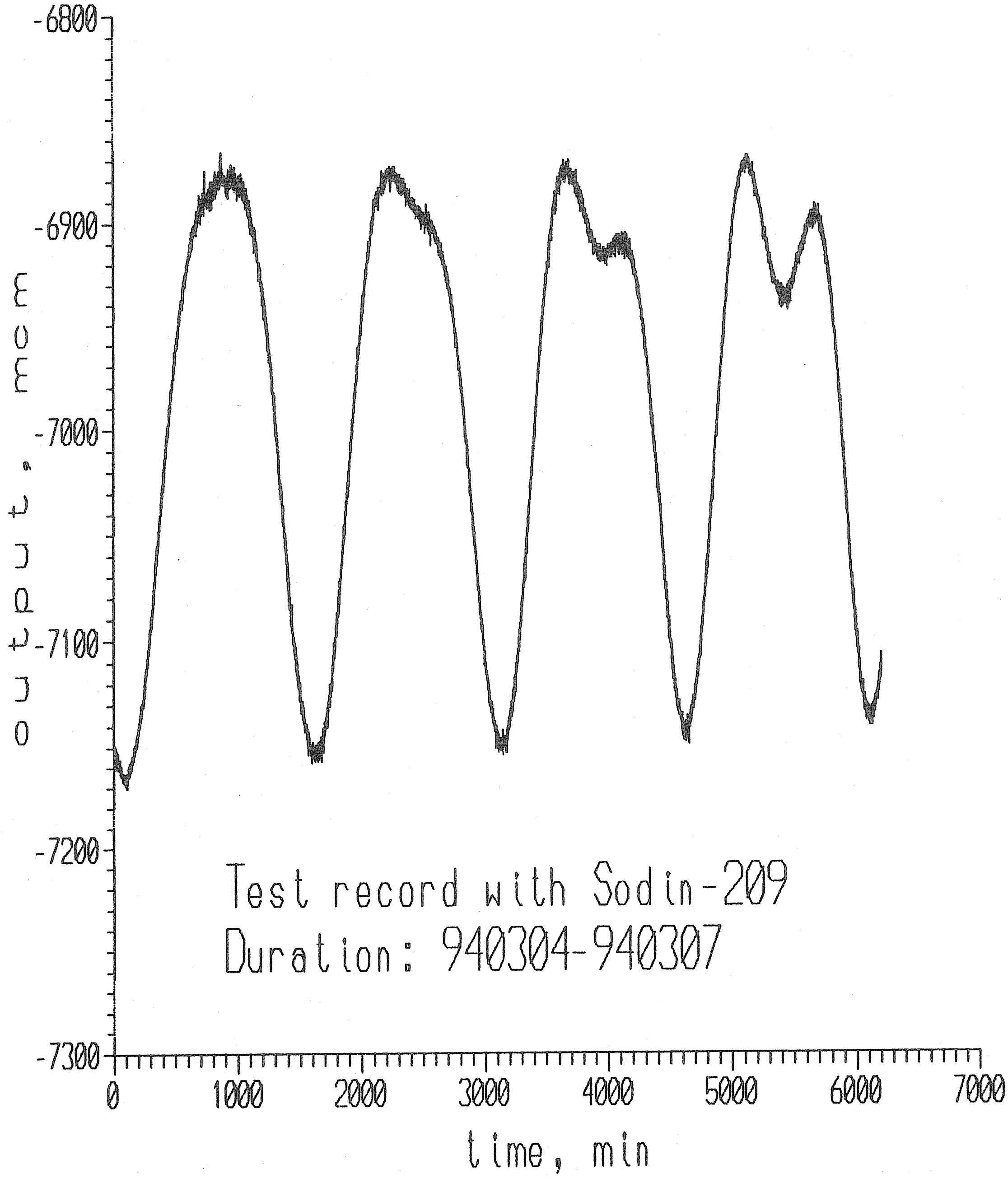

-6800
-6900
-7000
-7100
-7200
-7300
output, mcm
Test record with Sodin-209
Duration: 940304-940307
0
1000
2000
3000
4000
5000
6000
7000
time, min

Fig. 2

After applying ocean correction according to prof. Melchior calculations values of $\delta(O_1)$ and $\delta(P_1S_1K_1)$ agree with W-D model within 0.5 % whereas $\delta(M_2)$ and $\delta(S_2K_2)$ are 2 % and 6 % larger respectively that could result from absence of barocontrol, calibration errors and scale non-linearity. [KOPAEV ET AL, 1993].

Short-period noise is of about 0.5 μGal (fig. 2) that is near to thermal noise limit for 1 min sampling time.

Tilt calibration tests

Micrometer calibration procedure changes horizontal coordinate of main spring upper end that modifies the astatization and results in systematic errors up to 3-5 % in calibration.

To overcome this problem tilt method based on well-known formula is applied to determine scale factor C:

$$C = \frac{1}{\Delta r_i} \Delta g_i = \frac{1}{\Delta r_i} (g_0 - g_0 \cos\alpha_i) \cong g_0 \frac{\alpha_i^2}{2\Delta r_i}, \qquad (1)$$

where Δg_i denotes effective gravity difference corresponding to given tilt angle α_i and output change Δr_i, g_0 represents rough absolute gravity value. Common tilt calibration procedure includes gravimeter tilting in opposite directions to the same angles α_i and least-squares fitting of (1).

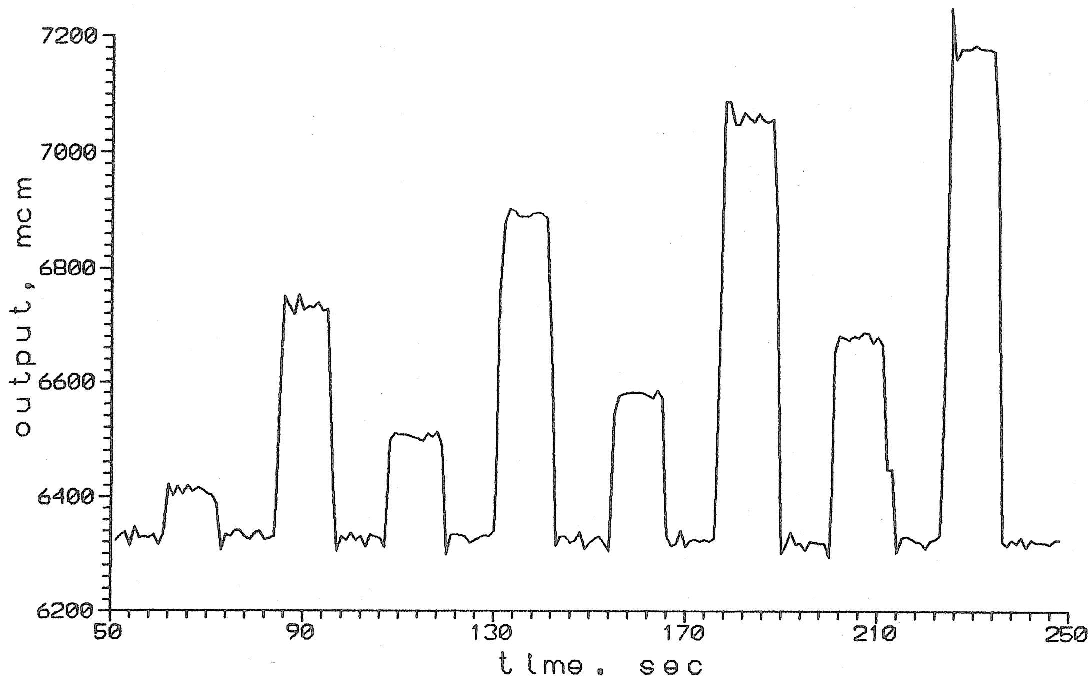
Sensitive system construction of Sodin, Sharp and Worden (lever suspension using horizontal torsion wires) permits to tilt it in plane perpendicular to lever without astatization changes.

Standard transportable tilting installation (produced in Russia commercially) includes:

- tiltable heavy base that ensures the horizontality of gravimeter tilting axes (precision $\cong 5''$);
- tilting micrometric mechanism (precision $\cong 0''.5$),
- autocollimation theodolit (precision $\cong 0''.5$);
- gravimeter fixation system that permits also to turn it in horizontal plane (precision $\cong 0^\circ.1$) in order to adjust the lever perpendicular to the tilting plane and to tilt it relative to the vertical (precision $\cong 5''$) in order to adjust it to the minimum sensitivity to the tilt.

One of this devices has been combined with Sodin-209. Calibration program includes tilting gravimeter to the angles corresponding equally spaced gravity differences 100, 150, 200, 250 μGal (fig. 3). In order to diminish systematic effects due to

calibration of Sodin-209 using tilt method
tilt angles:
+/-93.1, +/-114.0, +/- 131.7, +/-147.2 arc.sec.
dg = 100, 150, 200, 250 mcGal



calibration of Sodin-209 using tilt method
tilt angles:
-/+93.1, -/+114.0, -/+ 131.7, -/+147.2 arc.sec.
dg = 100, 150, 200, 250 mcGal

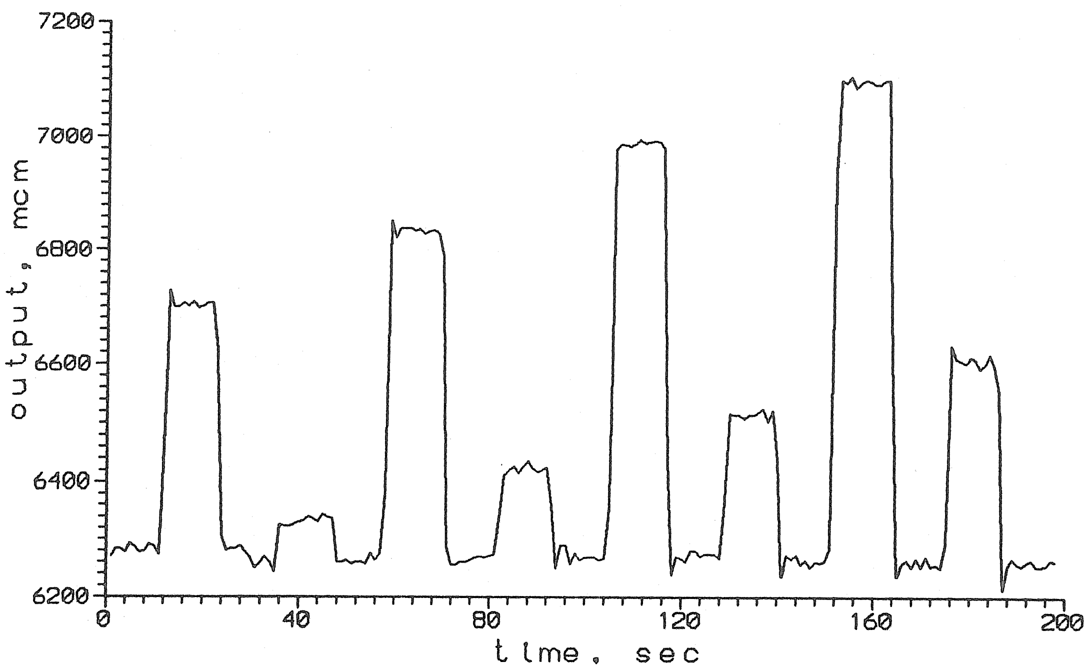


Fig. 3

the stresses in quartz system during the tilting two tilt sets with different order of tilting were used. Ultimate results of both sets (fig. 4) demonstrate the presence of small scale non-linearity. Calibration cicle (fig 3) takes about 1 h and gives relative precision of about 0.5 % that is confirmed through the comparison with synthesized tides. Internal precision of 0.2 % has been obtained after 10 cicles but the question on systematic errors is open.

Instrumental phase lag is very small ($\cong 0.02^{\circ}$ for D group and $\cong 0.04^{\circ}$ for SD group, according to [RICHTER, WENZEL, 1991]) due to high elasticity of fused quartz, see relaxation process on fig. 5.

Conclusion

Advantages of continuously recording Sodin gravimeters consist on the possibility of independant in-situ calibration by means of tilt method and another (comparable to LCRs) influence of microseisms, magnetic field, temperature and atmospheric pressure changes.

After some improvements and comprehensive testing it could be used for tide gravity recording especially in Russia.

Acknowledgements

Authors are very indebted to profs. P.Melchior and B.Ducarme for their attention and advices and to prof. H.-G.Wenzel for providing ETERNA and PRETERNA programs and fruitful discussions.

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Scale non-linearity of Sodin-209
obtained by means of tilting in both directions
Combined LSM-estimates: linear term=0.402+/-0.002
quadratic term=0.000024+/-0.00001

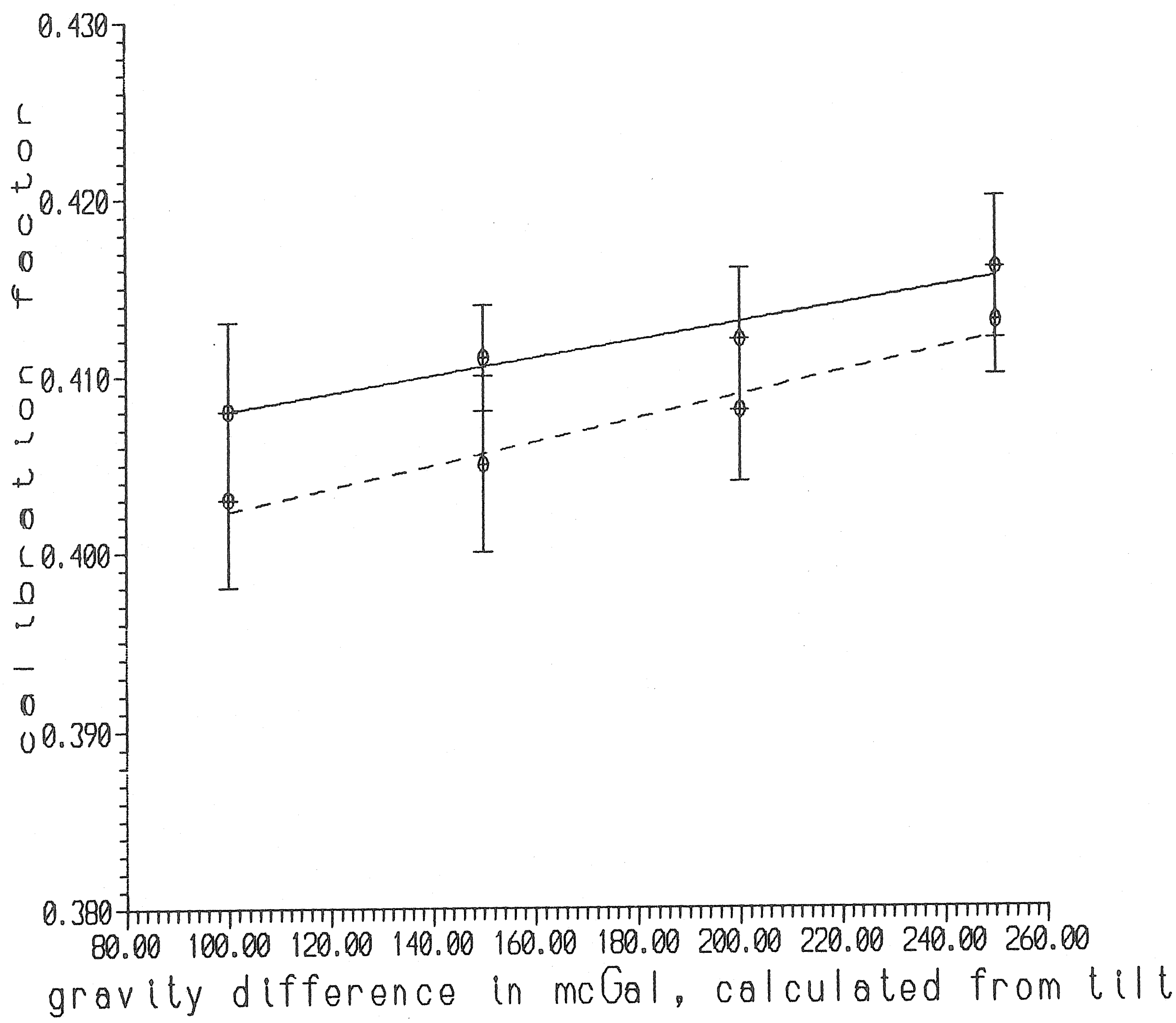

Fig. 4

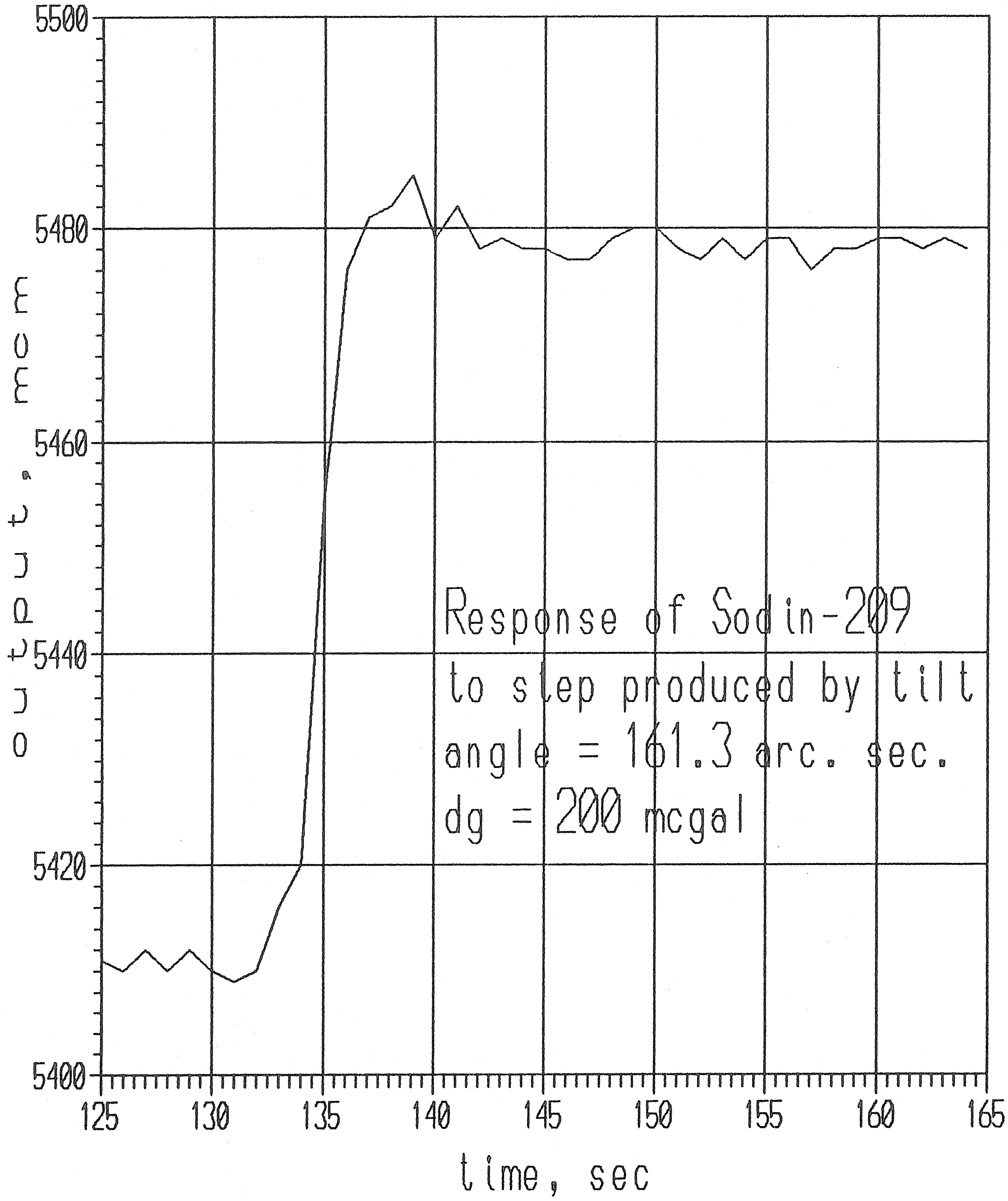
5500
5480
5460
5440
5420
5400
output, mom
125
130
135
140
145
150
155
160
165
time, sec
Response of Sodin-209
to step produced by tilt
angle = 161.3 arc. sec.
dg = 200 mcgal

Fig. 5

On the inversion problem for determining the azimuth of borehole tiltmeters

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Abstract

Tilt measurements have found application in a wide field of geophysics and industry. Sometimes it is not possible to get the direction of the borehole tiltmeter for a variety of reasons, it brings about a difficulty for the interpretation of tilt. In this paper an inversion method for determining the azimuth of the borehole tiltmeter from the earth tide signals is expounded.

key words: Tilt measurement, Inversion, Azimuth, Borehole tiltmeter

1. Introduction

Tilt measurements relate to the instantaneous direction of the gravity vector, they can be used in a wide field of geophysical and technical investigations. The results of high resolution observations from borehole tiltmeters contain some information about the earth's interior such as earth deformation and local structures. Moreover, they can be used to determine the change of earth tide parameters as a function of stress changes. The direction of borehole tiltmeters is necessary for the data analysis. Sometimes it is not possible to get the direction for a variety of reasons, such as an inclined borehole. Therefore it is very important to determine the azimuth of the borehole tiltmeter.

2. Inversion for determining the azimuth of borehole tiltmeter

As we know the theoretical value (prediction) of tilt with the azimuth α can be written as follows

$$\varphi_{\alpha} = \varphi_{sn} \cos\alpha + \varphi_{ew} \sin\alpha \qquad (1)$$

where φ_{sn} and φ_{ew} are the theoretical values of tidal tilts for direction SN and EW respectively. They can be obtained in advance.

Considering the difference between the observation value ψ_α and the theoretical value φ_α in amplitude and phase, we have

$$s\psi_\alpha = \delta\varphi_\alpha(t-\Delta t) \tag{2}$$

where s is the scale factor of the observations, δ similar to the tidal factor and Δt the time delay.

From formula (2) we get

$$\begin{aligned}\psi_\alpha &= \frac{\delta}{s}\varphi_\alpha(t-\Delta t) = D\varphi_\alpha(t-\Delta t)\\ &= D\varphi_\alpha(t) - D\Delta t\varphi'_\alpha(t)\end{aligned} \tag{3}$$

where $\varphi'_\alpha(t)$ is the first derivative of $\varphi_\alpha(t)$ and $D=\frac{\delta}{s}$.

The drift of the observations can be expressed in a time polynomial, so formula (3) is rewritten as follows

$$\psi_\alpha = D\varphi_\alpha(t) - D\Delta t\varphi'_\alpha(t) + \sum_{i=0}^{2} k_i t^i \tag{4}$$

considering formula (1), from formula (4), we get

$$\begin{aligned}\psi_\alpha = \varphi_{sn}(t)D\cos\alpha + \varphi_{ew}(t)D\sin\alpha - \varphi'_{sn}(t)D\Delta t\cos\alpha\\ - \varphi'_{ew}(t)D\Delta t\sin\alpha + \sum_{i=0}^{2} k_i t^i\end{aligned} \tag{5}$$

If we take a row vector

$$a = (\varphi_{sn}(t) \quad \varphi_{ew}(t) \quad -\varphi'_{sn}(t) \quad -\varphi'_{ew}(t) \quad 1 \quad t \quad t^2) \tag{6}$$

and a column vector

$$\begin{aligned}X &= (D\cos\alpha \quad D\sin\alpha \quad D\Delta t\cos\alpha \quad D\Delta t\sin\alpha \quad k_0 \quad k_1 \quad k_2)^T\\ &= (x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad x_7)^T\end{aligned} \tag{7}$$

then the equation of a tilt observation with the azimuth α is expressed by

$$\psi_\alpha = aX \tag{8}$$

For all tilt observations, the equation is written in matrix form

$$AX = L \tag{9}$$

Now the equation above can be solved by the use of the least squares method. However, from formula (7) we can see that the unknowns x_1, x_2, x_3 and x_4 are not independent, some conditions must exist between them. Generally, the conditions are non–linear, in our case the form is

$$x_1x_4 - x_2x_3 = 0 \tag{10}$$

it can be linearized by the use of

$$X = X_0 + \Delta X \tag{11}$$

where X_0 is the approximate value of X. The linearized condition is expressed as follows

$$B\Delta X = W \tag{12}$$

moreover, the observation equation (9) should be replaced by

$$A\Delta X = L - AX_0 \tag{13}$$

In order to obtain the least squares solution of equations (12) and (13), we use the method of adjustment of indirect observation with condition equations. The condition equations (12) is the restriction equations, so this program is a restricted inversion. The solution must be obtained from following equation

$$\left.\begin{aligned} &A^T A\Delta X + B^T K = A^T L - A^T AX_0 \\ &B\Delta X \qquad\qquad\quad = W \end{aligned}\right\} \tag{14}$$

The interactive method is used to solve the equation (14), X_0 should be changed using formula (11) in each interactive loop. The interaction is convergent and the convergence rate is fast, by my experience, it is no more than 10 cycles.

The azimuth α can be obtained from the unknown X,

$$\alpha = arctg\frac{x_2}{x_1} \qquad or \qquad \alpha = arctg\frac{x_4}{x_3} \tag{15}$$

as we have the restriction condition, so both of the α derived from formula (15) are the same. Furthermore

$$D = \sqrt[2]{x_1^2 + x_2^2} \qquad or \qquad D = \sqrt[2]{x_3^2 + x_4^2} \tag{16}$$

$$\Delta t = \frac{x_3}{x_1} \qquad or \qquad \Delta t = \frac{x_4}{x_2} \tag{17}$$

3. Some examples of the inversion.

As the drift of the observations are non–linear, the adjustment can be processed using 2 days data of observations to obtain the azimuth α of the borehole tiltmeter.

In order to show the effectiveness of the inversion method, we give some examples here. In the following tables, each row correponds to one interval of 2 days.

(1) The inversion using the theoretical values of the tilt as the observations with $\alpha = 0°$ and $\Delta t = 0$ minutes.

No.	D	α	Δt	Δt_1	Δt_2	No. of loops	m
1	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
2	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
3	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
4	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
5	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
6	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
7	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
8	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
9	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
10	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
11	1.00000	0°.00000	.00000	.00000	.00000	3	± .00000
12	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
13	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
14	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
15	1.00000	0°.00000	.00000	.00000	.00000	3	± .00001
		0°.00000					

(2) The inversion using the theoretical values of the tilt as the observations with $\alpha = 3°$ and $\Delta t = 0$ minutes.

No.	D	α	Δt	Δt_1	Δt_2	No. of loops	m
1	0.99994	3°.00005	.01080	.01080	.01081	3	± .00494
2	1.00002	3°.00100	.00113	.00113	.00113	3	± .00398
3	0.99989	3°.00620	−.01978	−.01978	−.01978	3	± .00411
4	1.00002	2°.99372	.02347	.02347	.02347	4	± .00494
5	0.99982	3°.00535	−.01062	−.01062	−.01062	4	± .00416
6	0.99979	3°.00706	−.02425	−.02425	−.02425	3	± .00431
7	0.99971	2°.99279	.02622	.02622	.02622	4	± .00462
8	1.00018	3°.00758	−.02794	−.02794	−.02794	4	± .00401
9	0.99991	3°.00237	−.01037	−.01037	−.01037	3	± .00364
10	1.00005	2°.99882	−.00777	−.00777	−.00777	3	± .00443
11	0.99997	2°.99762	.00406	.00406	.00406	4	± .00465
12	0.99989	3°.00460	.00813	.00813	.00814	3	± .00399
13	1.00012	2°.99949	.01368	.01368	.01368	4	± .00371
14	1.00002	2°.99466	.01940	.01940	.01941	3	± .00434
15	1.00013	2°.99520	−.00156	−.00156	−.00155	3	± .00381
		3°.00043					

(3) The inversion using the theoretical values of the tilt as the observations with $\alpha = 45°$ and $\Delta t = 12$ minutes.

No.	D	α	Δt	Δt_1	Δt_2	No. of loops	m
1	.99515	45 ° .07830	11.90725	11.90725	11.90725	4	± .02417
2	.99546	45 ° .06491	11.93183	11.93183	11.93183	4	± .02784
3	.99557	45 ° .06657	11.94630	11.94630	11.94630	4	± .02756
4	.99555	45 ° .07351	11.92521	11.92521	11.92521	4	± .01788
5	.99531	45 ° .09553	11.90134	11.90134	11.90134	4	± .01281
6	.99457	45 ° .09989	11.85670	11.85670	11.85670	4	± .00967
7	.99494	45 ° .07976	11.87127	11.87127	11.87127	4	± .01460
8	.99547	45 ° .06449	11.93616	11.93616	11.93616	4	± .02137
9	.99540	45 ° .07490	11.93838	11.93838	11.93838	4	± .02374
10	.99547	45 ° .06972	11.94916	11.94916	11.94916	4	± .02723
11	.99537	45 ° .07777	11.92313	11.92313	11.92313	4	± .02386
12	.99532	45 ° .06053	11.93385	11.93385	11.93385	4	± .01659
13	.99475	45 ° .06157	11.89738	11.89738	11.89738	4	± .00927
14	.99486	45 ° .08954	11.87704	11.87704	11.87704	4	± .01413
15	.99549	45 ° .06105	11.96164	11.96164	11.96164	4	± .02391
		45 ° .07454					

(4) The inversion using the observations of the borehole tiltmeter at Xiangshan station of Beijing.

No.	D	α	Δt	Δt_1	Δt_2	No. of loops	m
1	.11711	−60 ° .66276	30.88025	30.88025	30.88025	5	± .14027
2	.11027	−65 ° .08559	33.51437	33.51437	33.51437	6	± .30180
3	.09314	−72 ° .39377	43.12905	43.12905	43.12905	6	± .29690
4	.11251	−46 ° .80720	2.96577	2.96577	2.96577	6	± .25724
5	.08971	−64 ° .23995	30.12169	30.12169	30.12169	5	± .09589
6	.11653	−53 ° .71841	28.35331	28.35331	28.35331	5	± .14599
7	.15919	−28 ° .79659	−9.15378	−9.15378	−9.15378	5	± .15758
8	.09905	−71 ° .87702	52.70575	52.70575	52.70575	6	± .20802
9	.11422	−58 ° .86668	21.91934	21.91934	21.91934	5	± .19049
10	.10469	−67 ° .83854	32.65653	32.65653	32.65653	6	± .31128
11	.10386	−63 ° .65259	25.70843	25.70843	25.70843	6	± .25480
12	.10417	−62 ° .28437	19.48343	19.48343	19.48343	5	± .07627
13	.10589	−45 ° .28286	5.95613	5.95613	5.95613	5	± .14556
14	.11356	−53 ° .39914	29.59645	29.59645	29.59645	5	± .08142
15	.12009	−54 ° .80463	29.24031	29.24031	29.24031	5	± .17735
		−57 ° .98067					

No.	D	α	Δt	Δt_1	Δt_2	No. of loops	m
1	.06824	29 ° .35387	−19.37366	−19.37366	−19.37366	6	± .23891
2	.06196	32 ° .45385	−28.91811	−28.91811	−28.91811	6	± .26236
3	.05554	37 ° .91695	−37.68231	−37.68231	−37.68231	6	± .20496
4	.07641	24 ° .90089	−9.69949	−9.69949	−9.69949	5	± .12148
5	.04682	66 ° .48308	69.23855	−69.23855	69.23855	6	± .07832
6	.07427	22 ° .93318	4.69238	4.69238	4.69238	5	± .11471
7	.08274	27 ° .40768	−12.22047	−12.22047	−12.22047	5	± .04535
8	.06371	35 ° .82616	−38.32848	−38.32848	−38.32848	6	± .14117
9	.06434	32 ° .07369	−26.24109	−26.24109	−26.24109	6	± .15972
10	.06005	35 ° .48404	−38.94638	−38.94638	−38.94638	6	± .17043
11	.05300	39 ° .63073	−45.08093	−45.08093	−45.08093	6	± .21465
12	.04661	50 ° .43284	−54.42711	−54.42711	−54.42711	6	± .20986
13	.06799	40 ° .05987	−23.46629	−23.46629	−23.46628	6	± .10799
14	.06802	33 ° .50183	−21.55527	−21.55527	−21.55527	6	± .14337
15	.07059	25 ° .28590	−13.31807	−13.31807	−13.31807	6	± .25190
		35 ° .58297					

(5) The inversion using the observations of the tube tiltmeter at Xibozi station of Beijing.

No.	D	α	Δt	$Δt_1$	$Δt_2$	No. of loops	m
1	.63134	−10 ° .10065	31.15549	31.15549	31.15549	5	± .24697
2	.61743	−8 ° .18132	32.05552	32.05552	32.05552	6	± .31086
3	.70017	−0 ° .57707	12.41348	12.41348	12.41348	6	± .80225
4	.72188	−4 ° .83751	20.73685	20.73685	20.73685	4	± .23302
5	.70780	0 ° .22803	2.99247	2.99247	2.99247	6	± .65636
6	.69478	−4 ° .74128	13.30206	13.30206	13.30206	5	± .54820
7	.70657	−1 ° .54573	3.97259	3.97259	3.97259	6	± .59850
8	.66269	−7 ° .05592	18.73502	18.73502	18.73502	5	± .29040
9	.66984	5 ° .13845	−15.84395	−15.84395	−15.84395	4	± .25684
10	.64938	−2 ° .77433	20.18808	20.18808	20.18807	5	± .29891
11	.78042	1 ° .81560	3.18548	3.18548	3.18548	4	± .44146
12	.71114	−13 ° .39001	38.04030	38.04030	38.04030	5	± .70461
13	.69241	8 ° .91321	−21.85015	−21.85015	−21.85015	6	± .96283
14	.72656	−0 ° .08228	0.79579	0.79579	0.79579	6	± .52431
15	.68126	−6 ° .78412	17.43550	17.43550	17.43550	5	± .32683
		−2 ° .93166					

No.	D	α	Δt	$Δt_1$	$Δt_2$	No. of loops	m
1	.63644	−80 ° .99164	−8.08128	−8.08128	−8.08128	5	± .42134
2	.61513	−81 ° .89414	−5.71526	−5.71526	−5.71526	6	± .53652
3	.63060	−79 ° .86184	0.16049	0.16049	0.16049	5	± .28752
4	.62564	−83 ° .26492	−0.09326	−0.09326	−0.09326	5	± .48630
5	.62780	−80 ° .87014	−6.33312	−6.33312	−6.33312	5	± .70441
6	.64146	−84 ° .74916	−3.42394	−3.42394	−3.42394	5	± .42515
7	.63437	−78 ° .27946	−14.07580	−14.07579	−14.07580	4	± .31788
8	.62705	−78 ° .37914	−13.51087	−13.51087	−13.51087	5	± .36076
9	.61295	−82 ° .20760	−6.91498	−6.91498	−6.91498	6	± .30375
10	.60123	−85 ° .78507	6.14807	6.14807	6.14807	5	± .31932
11	.64776	−80 ° .50031	2.79874	2.79874	2.79874	5	± .28689
12	.63540	−87 ° .26701	5.62329	5.62329	5.62329	5	± .44297
13	.64020	−76 ° .81827	−11.36971	−11.36971	−11.36971	5	± .58358
14	.63411	−78 ° .89784	−10.45719	−10.45719	−10.45719	5	± .44488
15	.63510	−72 ° .87809	−19.02334	−19.02334	−19.02334	3	± .28202
		−80 ° .84297					

No.	D	α	Δt	$Δt_1$	$Δt_2$	No. of loops	m
1	.63854	−48 ° .03597	7.81172	7.81173	7.81172	5	± .56070
2	.60100	−45 ° .71050	8.85506	8.85506	8.85506	6	± .35896
3	.71549	−34 ° .75685	−6.29541	−6.29540	−6.29541	5	± .62375
4	.71293	−40 ° .36258	3.43748	3.43749	3.43748	4	± .26159
5	.68114	−39 ° .22591	−1.29900	−1.29900	−1.29900	5	± .67391
6	.67391	−44 ° .56634	5.68966	5.68966	5.68966	4	± .22482
7	.69161	−38 ° .01841	−7.19964	−7.19964	−7.19964	5	± .52476
8	.66224	−43 ° .36564	−0.99791	−0.99791	−0.99791	6	± .73997
9	.66376	−38 ° .97228	−4.67322	−4.67322	−4.67322	5	± .25314
10	.63944	−39 ° .66601	1.63713	1.63713	1.63713	5	± .37405
11	.74102	−33 ° .96987	1.83997	1.83997	1.83997	5	± .40558
12	.75306	−44 ° .29453	11.60603	11.60603	11.60603	5	± 1.04611
13	.70053	−30 ° .90311	−17.32281	−17.32281	−17.32281	6	± 1.13738
14	.70246	−36 ° .72748	−9.31362	−9.31362	−9.31362	5	± .56689
15	.69399	−39 ° .87024	−4.76415	−4.76415	−4.76415	5	± .29429
		−39 ° .89638					

Format and structure for the exchange of high precision tidal data

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Abstract

The so-called International Format for the exchange of earth tide data (e.g. Melchior 1994) has become obsolete because

- it does not allow the storage of high precision earth tide data (only 5 digits per sample available),
- it is not suitable for the storage of multi-channel data,
- it does not allow the storage of high rate data (e.g. with 1 min interval).

Additionally, it is difficult to use the International Format after 1999, because it allows 2 digits only for the year (years 1901 and 2001 are stored as 01 in the International Format and can thus not be distinguished).

Since about two years the PRETERNA preprocessing program package (Wenzel 1994) for earth tide data recorded at high rate (e.g. 1 min) is available for the scientific community. This software package uses a data format and structure (hereafter called PRETERNA format), which is suitable for the storage and exchange of high rate (down to 1 s interval) and high precision (up to 10 digits) data. There has not been found any problem with the PRETERNA data format and structure. Therefore I propose that the PRETERNA format shall be adopted for international data exchange of high precision and/or high rate earth tide data. The Global Geodynamics Project (GGP) has adopted the PRETERNA format and structure for the exchange of high rate data within it's user group (Crossley 1994).

1 Introduction

A number of institutions are nowadays using digital data acquisition systems, which digitize the signals produced by the earth tide sensor at high rate (1 s ... 20 s) and process these high rate data in order to be used later on for earth tide analysis and for the detection of signals of non-tidal origin. We have created and made available to the scientific community preprocessing software (e.g. Wenzel 1994, Vetter and Wenzel 1995) which is able to remove spikes and steps, to interpolate gaps in the recorded series and to decimate the sampling interval to 1 hour after apropriate numerical filtering. Until now, there does not exist a standardization of the data format and structure for high rate data. A standardization could enable a better exchange of the recorded series and software packages for data acquisition and data processing.

2 The International Format

In the 1960'ies, the International Center for Earth Tides (ICET) has created the International Format (e.g. Melchior 1994) for the storage and exchange of earth tide data recorded at hourly interval. This data format and structure (see Table 1) has served for about 30 years for the storage and exchange of earth tide data, but clearly reflects the difficulties of data storage in the punched card era. There are stored 12 hourly samples in one record, and there are available 5 digits only for each sample in integer format. The International Format was created at a time when the noise level of the gravimeters was in the order of a few μgal (1μgal $= 10$ nm/s^2).

Data storage in integer format was used in former times in order to save one column for the point, which can create errors resulting from wrong description of the conversion factor from integer counts to data. Nowadays, 5 columns are no more apropriate to store high precision data from superconducting or LaCoste-Romberg gravimeters with electrostatic feedback. Because a number of groups (e.g. Richter 1987) has demonstrated that their gravimeters are able to resolve a few ngal (1 ngal $= 0.01$ nm/s^2), we need a resolution of about 0.1 ngal to store high precision gravimeter readings. With a gravity variation of about ± 1000 nm/s^2, we need 9 columns to store a sample of e.g. -1000.123 nm/s^2 with a resolution of 0.001 nm/s^2 corresponding to 0.1 ngal.

Another deficiency of the International Format is that the time of the first observation of the record is coded with one integer only (column 20, see Table 1), beeing 0 if the first observation was made at 0^h UTC and beeing 2 if the first observation was made at 12^h UTC. This restricts the sampling interval to one hour, and the start of the data series to either 0^h or 12^h UTC. Thus, the International Format is not capable to store high rate data (it was not made for that purpose, because in the 1960'ies nobody could predict that we would today sample the signal of a gravimeter with few seconds interval).

Since a number of years it has been found necessary that signals from a number of additional sensors (e.g. barometer, thermometer) are recorded together with the signal from a precise earth tide instrument. This is the **multi-channel concept**, and the modern earth tide analysis programs are capable to handle multi-channel data (e.g. Schüller 1986, Wenzel 1995). Although it is in principle allowed to store multi-channel data in the International Format (e.g. Melchior 1994), the International Format is not suitable for multi-channel data recording and storage. With the data acquisition systems, we obtain the data from different channels at the same time, and it is quite natural to store the data recorded at the same time for different channels within one record. For the processing and analysis of the data later on, the data from all channels recorded at the same time have to be used together. This is not easy to achieve with the International Format because 12 samples of the same channel are stored in one record.

The last deficiency of the International Format is that there exist only two columns describing the year of the observation, e.g. 77 in column 14 and 15 of Tab. 1 means the year 1977. Thus, it becomes difficult to use the International Format after 1999, because the years 1901 and 2001 cannot be distinguished. But there exist practically no digital earth tide data sets recorded before 1950 as P. Melchior, Director of the International Center for Earth Tides, has pointed out. Thus one could use the International Format after the year 2000 by implicitely defining that years below 50 given in the International Format are understood as years in the 21st century.

3 The PRETERNA Format

A preprocessing program package for high rate earth tide data called PRETERNA (Wenzel 1994), which is able to detect and to remove spikes and steps, and to interpolate short gaps has been made available to the scientific community. This program has recently been supplemented by an interactive graphical editor called PREGRED (Vetter and Wenzel 1995), which enables the management of problems under control of the user, which could not be solved by PRETERNA (e.g. several small steps within short time interval). For the PRETERNA package, it was necessary to create a format and data structure for the storage of high rate, high precision multi-channel earth tide data, which is described below. The PRETERNA format is also used in the most recent version of the earth tide analysis package ETERNA (Wenzel 1995).

A PRETERNA data file (see Table 2) consists of a file header and a file body. The file header contains alphanumerical information describing the contents of the file and is used like a notebook to store all necessary information for the file. The file header will not be used by any program, but records the different computations, data editings and manipulations that have performed on the data. The file header ends with a record starting with C*********.

In the file body, we use one record per sample instant and we store all samples observed for different channels within one record. The data record starts with the date (year, month, day) in columns 1...8 and the time (hours, minutes, seconds) in columns 10...15. The time is assumed to be UTC and it is assumed to be an exact time point (e.g. 145600 means $14^h\ 56^m\ 00.000^s$). The record continues with 10 characters for each channel (columns 16...25, 26...36, etc.). The format for each channel is F10.6 for uncalibrated raw data (in Volt with a resolution of 1 μV) and F10.3 for calibrated data (with a resolution of 0.001 nm/s^2 = 0.1 ngal for gravity). It should be noted that a decimal point given in the record overwrites the default format. Step corrections (to be added to all subsequent data of the channel) may be input via a code 77777777 in columns 1...8. The end of the data series is marked by 99999999 in columns 1...8. Additional codes for the first 8 columns could be defined, which was not necessary until now. The number of channels and their contents is not standardized. There has not been found any problem with this data structure and format: the PRETERNA format may be applied in the next century, it has enough resolution (0.01 ngal) for the next generations of gravimeters, it may be used for sampling intervals down to 1 s, and it is in use since about two years by several groups.

4 Conclusion

It has been shown that the International Format is not suitable for the storage of high rate or high precision earth tide data. The PRETERNA format used in the PRETERNA preprocessing program package (Wenzel 1994) for earth tide data recorded at high rate (e.g. 1 min) is identical to the data structure and format used in the ETERNA program package for earth tide analysis (Wenzel 1995). This data format and structure is suitable for the storage and exchange of high precision data (up to 10 digits) as well as high rate data (down to 1 s interval) and low rate data (hourly interval). There cannot be seen any problem with the PRETERNA data format and structure. Because both the PRETERNA and ETERNA packages are widely spread in the earth tide community, the PRETERNA format is already in use by a large number of groups and individuals. Therefore I conclude that the International Format can be replaced by the PRETERNA format without problems.

Table 1: Example of the International Format

```
InstStat     Date      00h  01h  02h  03h  04h  05h  06h  07h  08h  09h  10h  11h

0003071143375770820019521194261933919289192701928919344194131948319536195611956З
00030711433767708202195481952019495194831949419530195861965019697197291972619689
00030711433767708210196131952219433193531930219271192911932919390194581951219558
0003071143377770821219590196091960419601196091961519636196681969519740197481972 9
0003071143377770822019680196041951419422193371927219236192281926019306193641942 9
00030711433787708222194971954719580196001960219593195841959819616196401966419676
00030711433787708230196551961519544194501935419253191721911419094191071915319228
00030711433797708232193321942119494195471957619579195691955419552195621959619620
00030711433797708240196361964019613195511945719350192381913919074190521906619131
00030711433807708242192321935819476195821963019648196301961319589195611957719605
00030711433807708250196351967219677196511959319501193731926519126190421901519062
00030711433817708252191221927119413195321963819683196801963119595195421951919541
00030711433817708260195691962319666196941967319606194911936819238191151902618995
```

Table 2: Example of the PRETERNA format

```
File     : TEST.TID          Status   : 19921206
Start    : 19921125 14:08    End      : 19921227 23:59
Contents : Detided 1 min data from BFO-TLD1 data acquisition,
           station Karlsruhe.
           column 3 is recording gravity with LCR-G299-SW02      in nm/s**2,
           column 4 is recording air pressure with BMS5          in hPascal,
           column 5 is recorded temperature                      in degree ,
           column 6 is recorded groundwater                      in mm     .
C*******************************************************************************
                      0.000      0.000      0.000      0.000
19921125 140900   1227.583      6.903     23.645   1127.527
19921125 141000   1228.986      6.941     23.641   1127.395
19921125 141100   1230.650      6.954     23.645   1127.360
19921125 141200   1232.677      6.935     23.647   1127.480
19921125 141300   1234.756      6.899     23.647   1127.542
19921125 141400   1236.523      6.867     23.644   1127.321
19921125 141500   1237.978      6.855     23.649   1126.922
19921125 141600   1239.538      6.875     23.641   1126.842
19921125 141700   1241.461      6.931     23.649   1127.365
19921125 141800   1243.540      7.012     23.644   1128.213
19921125 141900   1245.359      7.089     23.646   1128.777
19921125 142000   1246.867      7.133     23.643   1128.818
19921125 142100   1248.374      7.125     23.646   1128.519
77777777            10.000      0.000      0.000      0.000
19921125 142200   1240.037      7.062     23.645   1128.019
19921125 142300   1241.752      6.973     23.648   1127.404
19921125 142400   1243.676      6.907     23.647   1127.155
19921125 142500   1245.651      6.887     23.641   1127.264
99999999
```

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PREGRED - AN INTERACTIVE GRAPHICAL EDITOR FOR DIGITALLY RECORDED TIDAL DATA

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Abstract

An interactive graphical editor called PREGRED for digital recorded tidal data has been written in Borland C++ language to supplement the tidal data preprocessing package PRETERNA (Wenzel 1994a). Both programs use the same standard format (Wenzel 1994b). The graphical editor is able to plot simultaneously the tidal data channel and a meteorological data channel for one day on the screen of a personal computer at different computation steps of the PRETERNA program. Vertical and/or horizontal zooming is possible. The main purpose of the graphical editor is to enable the user to manually delete disturbed data, and to manually correct the data for steps. Problems which cannot be solved by the preprocessing program PRETERNA (e.g. several steps within short time interval) can be managed with the graphical editor PREGRED under control of the user.

1. Introduction

The instruments which are used for earth tide observations are a sensor, an analog to digital converter, a clock connected to a personal computer (PC), and a personal computer to carry out the data recording and to store the data. The earth tide sensor (e.g. gravimeter, tiltmeter, strainmeter) usually provides an analog voltage as output, which is proportional to the earth tide signal to be observed. This analog voltage is generally analog filtered (to prevent alias effects) and digitized at high rate (0.1 ... 1 sample per second) using an accurate analog to digital converter, controlled by an accurate clock. The digital data are stored (eventually after numerical filtering and decimation to a lower rate of e.g. 1 sample per min) with the PC.

Because it is convenient to use a sampling interval of 1 hour for the earth tide analysis, the data digitally recorded with high rate (1 sample per min or higher) have to be decimated after appropriate numerical filtering to 1 hour interval. Additionally, one has to calibrate the data, to remove eventual steps, to remove eventual spikes e.g. during earth quakes and to fill eventual gaps. This is the task of the earth tide data preprocessing and may be carried out using the program package PRETERNA (Wenzel 1994a).

PRETERNA uses a remove-restore technique in order to detect and correct very small errors. The data digitally recorded for one earth tide sensor and one barometer with 1 min sampling interval are calibrated and model tides and the air pressure effect on gravity are removed. The remaining signal, i.e. the sensor's drift plus noise, is subsequently checked and corrected for steps, for spikes and for gaps. The a priori thresholds for steps and spikes are controlled and updated by the preprocessor using estimated statistical parameters, which depend on the noise level of the recorded data. Finally, the a priori tides and the a priori air pressure contribution is restored and the data are numerically filtered and decimated to 5 min sampling interval and subsequently to 1 hour sampling interval. The data preprocessing with PRETERNA is semi-automatic, because it may be controlled and updated by the operator between different computation steps assisted by a screenplot program. The PRETERNA preprocessor has been applied successfully to several recorded tidal gravity data sets.

During the application of PRETERNA, it has been found to be very time consuming to flag gaps in the data file with a standard alphanumeric editor. Additional, some special cases have been found where the step detector built into PRETERNA failed (e.g. several steps within short time interval, very small steps in noisy parts of the record). Thus, the graphical editor PREGRED has been developed in order to support the data preprocessing with PRETERNA (see Fig. 1). We describe in the following the program PREGRED version 3.01.

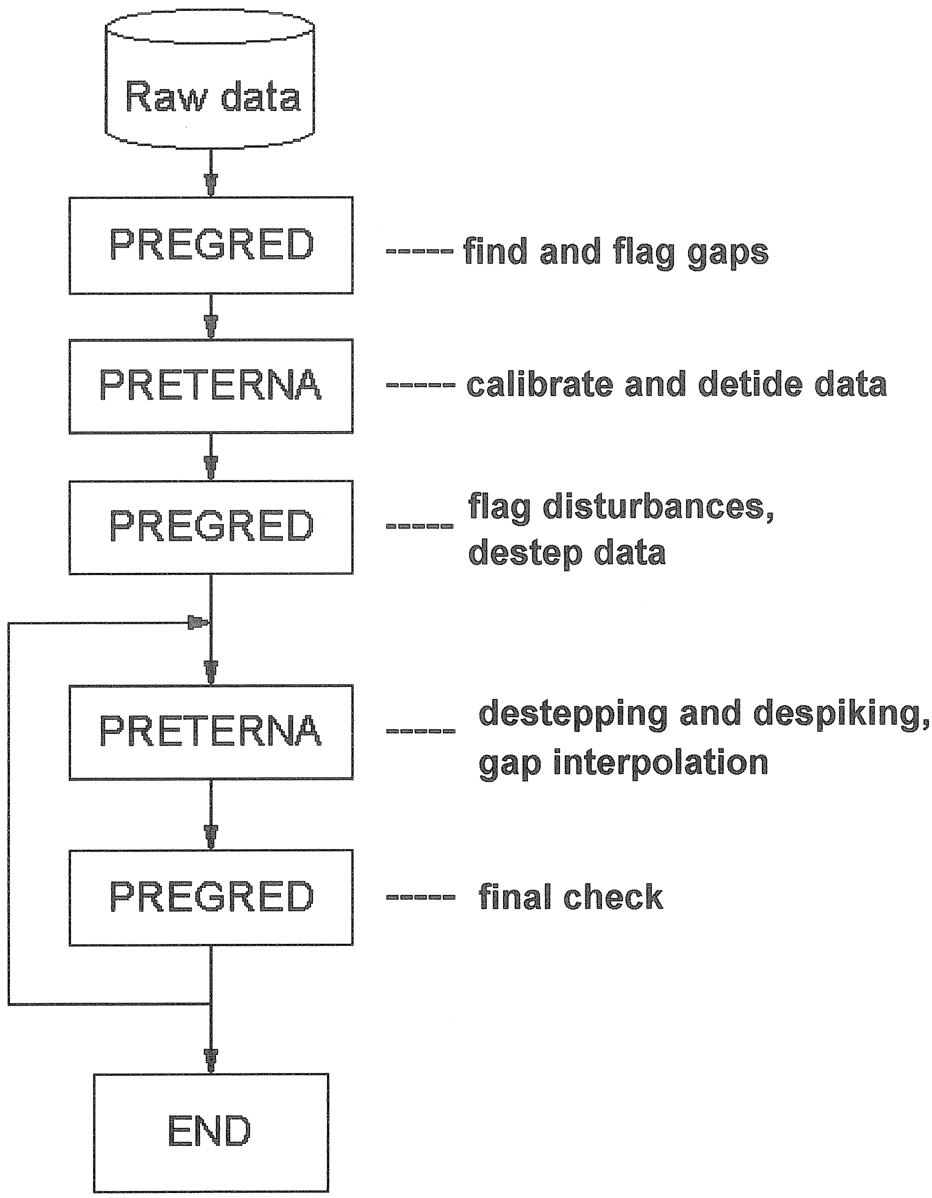


Fig. 1: Combination of programs PRETERNA and PREGRED for the preprocessing of tidal data

2. The Graphical Editor PREGRED

While reading the data from the input file, PREGRED runs a sequence test that checks for gaps in the data file and for formal correct time instants. In case of faults in these data, the user may decide to terminate the program or to allow PREGRED to correct these data automatically.

After the sequence test, PREGERED plots the data of the first 24h on the screen. Up to two channels can be displayed simultaneously. (see Fig. 2, first data page and additional informations). Changing the displayed data channels and flicking forward and backward through all data pages enables a complete visual control. In case of disturbed data, the user can correct offsets (see Fig. 3) and delete spikes (see Fig. 4) manually. For all functions of PREGRED, an online helpscreen is available by hitting F1-Key (see Fig. 5).

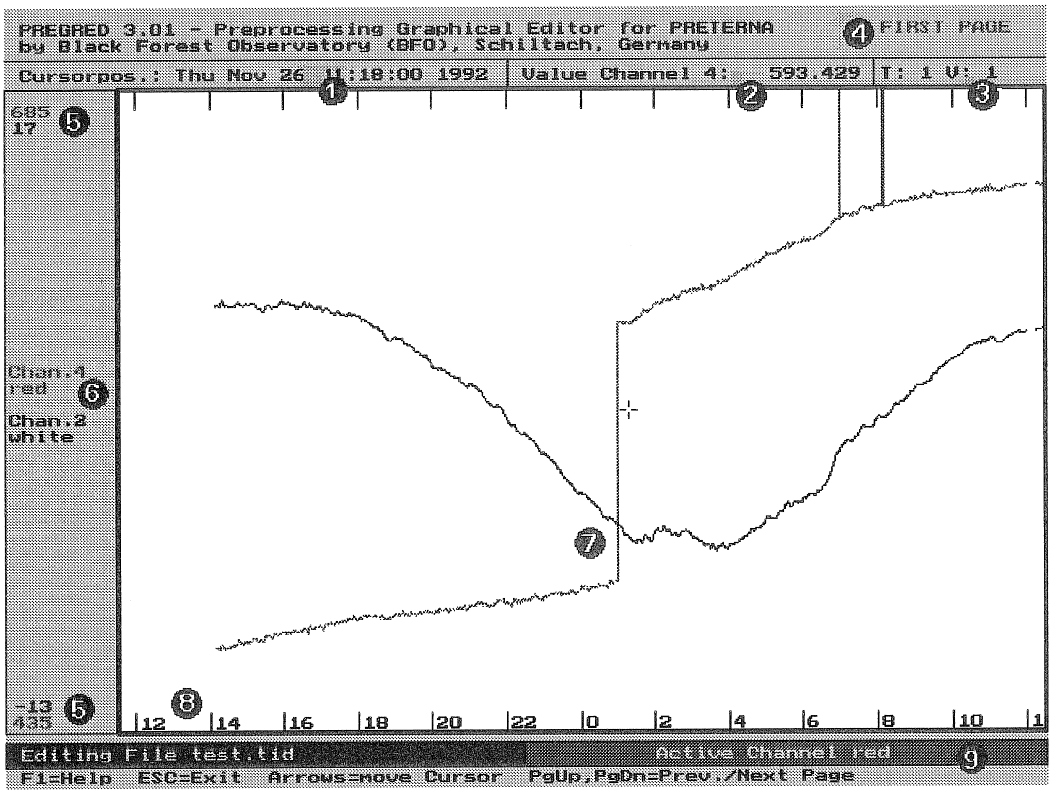


Fig.2: Items of the graphical editor

1 actual cursorposition in time-axis
2 number of the active channel (4), the value of the channel at the time of the actual cursorposition
3 zoomfactor of time (T) and value (V) axis.
4 message first - last page of data
5 range of the values of both displayed channels
6 channel numbers in the datafile plotted in red / white
7 dataplot (simultaneously 2 channels max.)
8 time-scale
9 channel to be edited (active channel) red / white

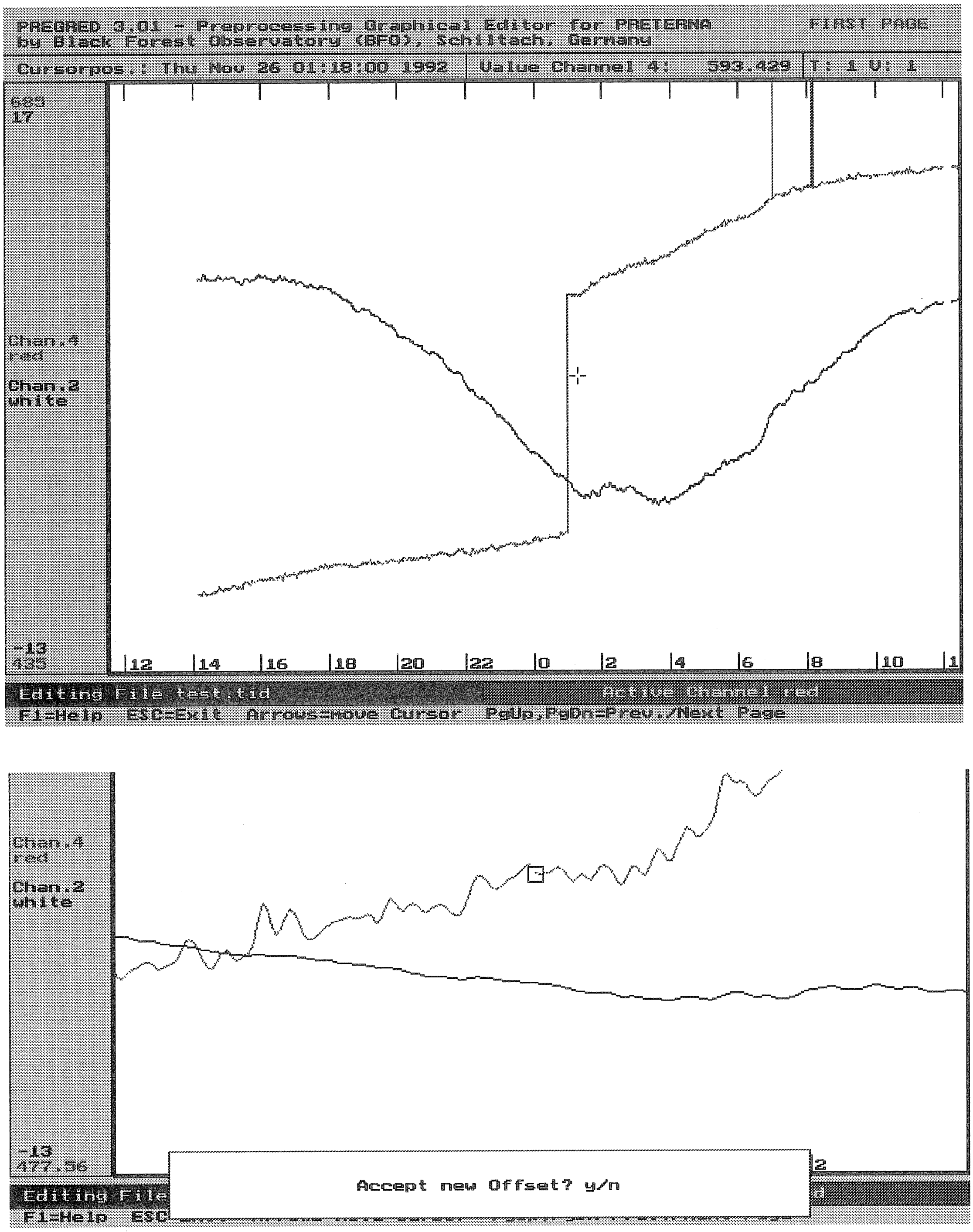
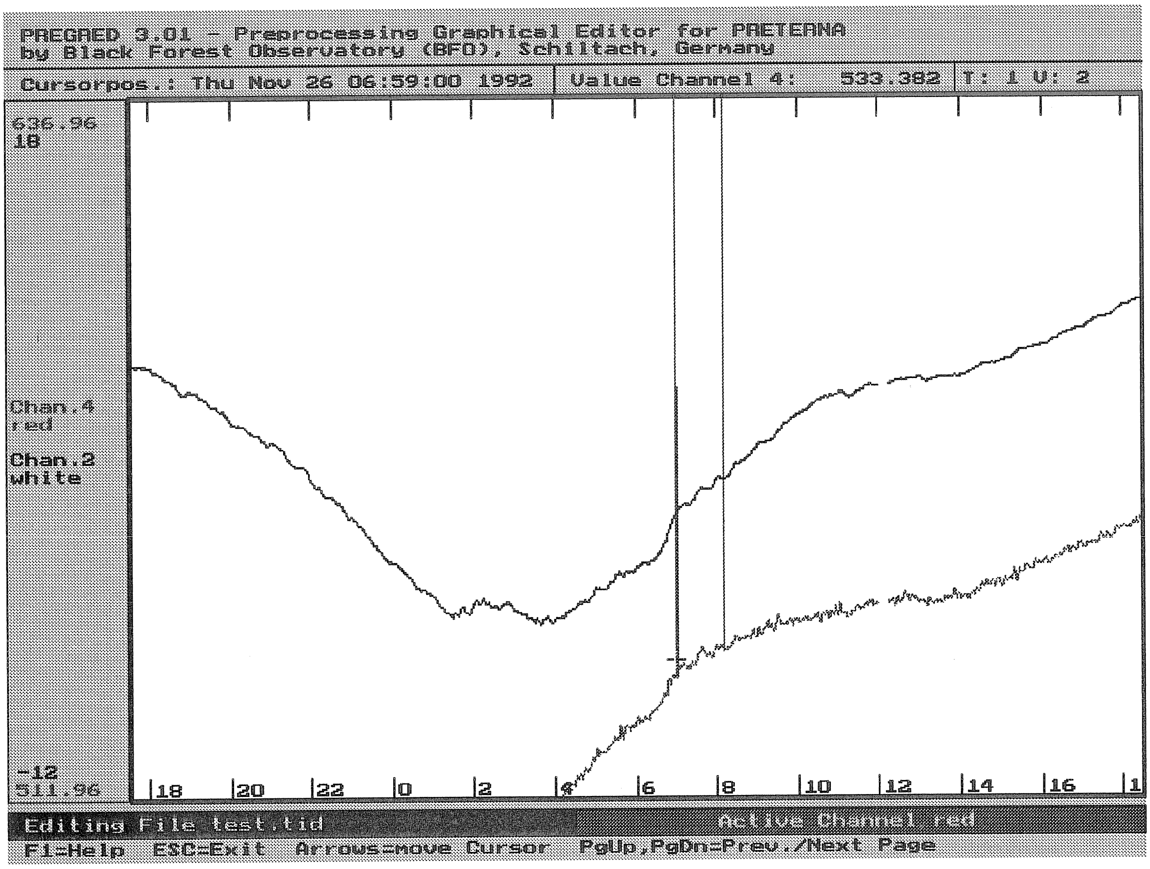


Fig. 3: Offset correction.
Upper part is in original scale before offset correction. The exact new position can be found easily by zooming the plot.
Lower part is zoomed 8 times in both axis, the offset correction has been carried out manually but need to be confirmed.



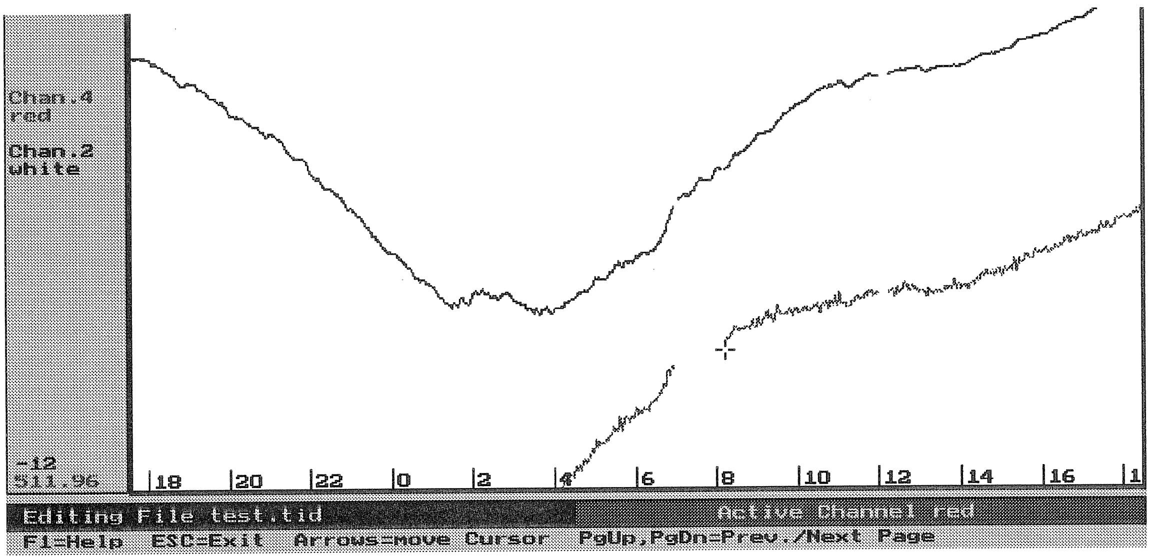


Fig 4: Despiking by deleting bad data.
Upper part shows two spikes in channel 2 (red). The displayed value of the data (Mark 2 in Fig. 1) enables to select and delete a minimal number of epochs.
Lower part shows the despiked data.
In both figures, only the vertical axis are zoomed (2x).

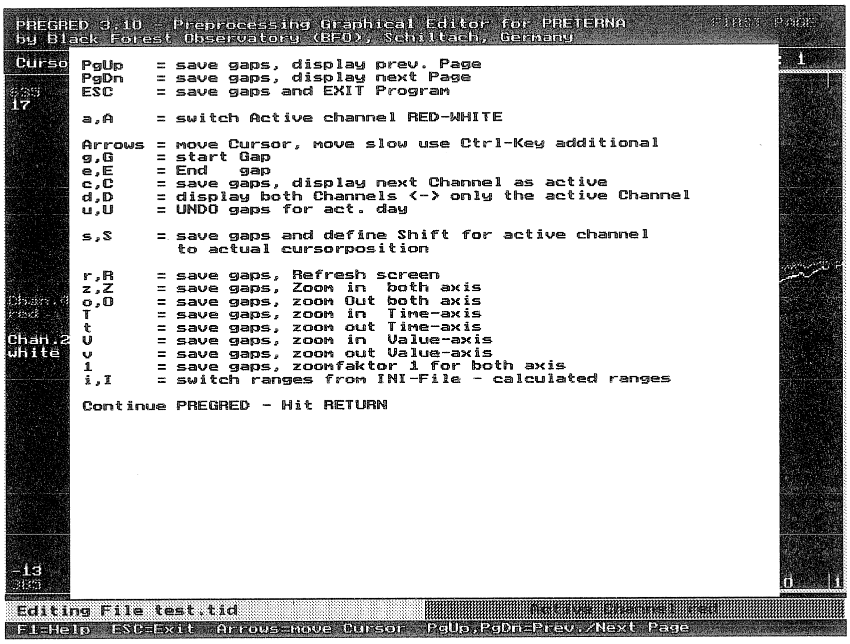


Fig.5: Helpscreen of PREGRED

3. Hardware Requirements

PREGRED runs on an IBM-compatible personal computer with at least 640kB RAM, preferably with a color screen. The graphics adapter should be EGA-,VGA-Standard or higher. Due to the high effort of graphical editing, an PC with 80486 66Mc CPU or higher is recommended.

4. Conclusions

The graphical editor has been tested with different data sets; the combination of PRETERNA and the graphical editor PREGRED has been proved to be a very efficient tool for high precision tidal data preprocessing. The graphical editor is available on request from the authors.

Acknowledgements

A number of people have supported this investigation. We especially thank J. Neumeyer, Geoforschungszentrum Potsdam, who initiated the establishment of the graphical editor PREGRED by supplying his programs ALPHA and BETA to us. H.-J. Dittfeld and J. Neumeyer (Geoforschungszentrum Potsdam) and F.Rehren and L. Timmen (Institut für Erdmessung Hannover) were so kind to test the graphical editor and to give valuable comments.

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THE COMPUTER PROGRAM NSV USED IN MADRID FOR TIDAL DATA PROCESSING

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1. Introduction.

The main function of NSV is tidal analysis by a method which will be referred as MV66. Its original version can be found in (Venedikov, 1966a,b, Melchior & Venedikov, 1968, Melchior, 1978, 1981). In NSV are also used ideas and algorithms for various kinds of processing of Venedikov (1979, 1981, 1984, 1986), Venedikov & Ducarme (1979), Simon et al. (1989), Toro et al. (1990, 1991, 1993), Fernandez et al. (1993) as well as suggestions made by Baker (1978a,b), De Meyer (1980) and others.

MV66 is applied since a lot of time, successfully surviving a tremendous development of the computers as well as a considerable increase of the precision. This makes necessary to refresh the information about this method. Therefore we shall give in the next Sections 2, 3 and 4 its basic principles. We shall try to do this in a way which can be better understood than before.

However, NSV is not a simple standard application of MV66. It is a computational device through which, we hope, the processing can become an interesting research work in two directions:

(i) the user can apply MV66 in many variants, actually creating and testing different methods of analysis and

(ii) he can use various options which allow to study the data, looking for perturbations and particular phenomena.

Indeed, concerning (i), the user cannot completely escape from the fundamental scheme of MV66 which consists in the stages:

(a) filtration of intervals of length n, e.g. $n = 48$, without overlapping, i.e. with a shift between the intervals $s = n$ (or $s > n$ in the case of a gap) and

(b) processing of the filtered numbers by MLS (the Method of the least Squares).

Nevertheless, he is allowed, if he does not like our $s = n = 48$ to use other values of n or s. Although $s < n$ is theoretically unacceptable, experimentally he can use such values, even $s = 1$ which is totally transforming our way of filtration into a moving filtration.

He can change and test the grouping of the tides, the model of the drift, to determine the LP tides in many variants, to look for relations with non-tidal data and so on.

Concerning (ii) through NSV can be computed residuals, drift, amplitude and phase variations and search for new tidal and non-tidal frequencies in different variants.

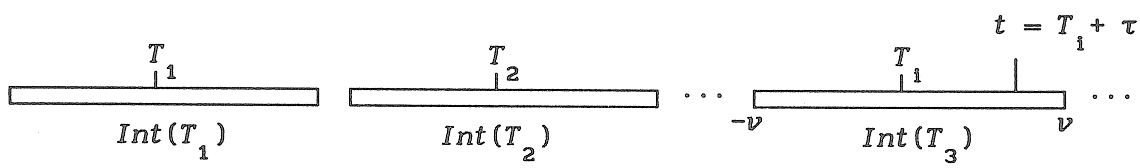
2. General principles of MV66.

Let $y(t)$, $t = 1,2,...N$ are hourly tidal observations. We shall suppose that there are some ideal conditions, e.g. no drift, which allow to apply the Fourier series. Then, if ω is a tidal angular frequency (AF), we have to compute

$$(1) \qquad x = (2/N) \sum_{t=1}^{N} \mathrm{Exp}(i\omega t)\, y(t), \qquad (i = \sqrt{-1}).$$

Let $N = qn$ and the data can be divided as shown in Scheme 1.

Scheme 1. Data partitioned into intervals $Int(T)$ of length n, e.g. $n = 48$, without overlapping.



$T = T_1, T_2, \ldots T_q$ are central epochs of $Int(T)$,

$\tau = -\nu, -\nu + 1, \ldots \nu$, $\nu = (n - 1)/2$ is time measured in every $Int(T)$,

e.g. $n = 48$, $\nu = 23.5$ and $\tau = -23.5, -22.5, \ldots +23.5$.

Then just the same x as in (1) can be computed in the following stages:

$$(2)\quad \left.\begin{aligned} u(T) &= (2/n)\sum_{\tau=-\nu}^{\nu}\cos\omega\tau\; y(T+\tau) \\ v(T) &= (2/n)\sum_{\tau=-\nu}^{\nu}\sin\omega\tau\; y(T+\tau) \end{aligned}\right\}\text{(a)}\quad \begin{array}{l}\text{filtration}\\ \text{of } Int(T) \text{ by even}\\ \text{and odd filters}\end{array}$$

$$\left. x = (1/q)\sum_{i=1}^{q}\mathrm{Exp}(i\omega T_i)\,[u(T_i) + iv(T_i)]\right\}\text{(b)}\quad \begin{array}{l}\text{processing of the}\\ \text{filtered numbers}\\ u(T),\ v(T).\end{array}$$

By the way, the computation after (2) is much faster than (1), i.e. more computing time is not always necessary for better results.

We see, generally, that the stages (a) and (b) of MV66, formulated in Section 1, are not so unnatural.

In the following the filters in (2) will be called FFIL (Fourier filters), while $u(T)$,$v(T)$ will denote generally filtered numbers.

If there is a drift we have to apply MLS instead of Fourier. In (Venedikov 1964b) is shown that the application of MLS on $y(t)$ has also the stage (a) filtration of $Int(T)$. We have also FFIL but they have to be orthogonalized with respect to the drift polynomials. I.e. we have filters which eliminate the drift with the least possible deviations from FFIL. From this stage we get $u(T)$,$v(T)$ which are further processed.

In (Venedikov, 1964a) and, later, in (Wenzel, 1976, 1977, Chojnicki, 1978, De Meyer, 1980) has been established that the hourly $y(t)$ are correlated (non-white noise). On the contrary, for various reasons, one of them the distance n between $Int(T)$, $u(T)$,$v(T)$ are not correlated or considerably less correlated than $y(t)$. Follows the natural idea the second stage to be made as (b) in Section 1, i.e.

(b) Processing of $u(T)$,$v(T)$ by MLS as observations instead of $y(t)$.

Again in (Venedikov, 1964b) is shown that in this way we shall get estimates of the unknowns very close to the direct processing of $y(t)$. In the same time we shall have a more correct application of MLS with a rigorous estimation of the precision. The latter will reflect the effect of the drift and meteorological perturbations, which are frequency dependent, i.e. different for the main tidal species.

Since the orthogonalization in (a) can be an element of MLS, this stage is made as an application of MLS on $Int(T)$. This idea has been realized in

(Venedikov, 1966a,b) and further developed in (Venedikov, 1984) and NSV, as it will be demonstrated in the next Section.

3. The filtration procedure of NSV.

It consists in the approximation of the data separately for every $Int(T)$ through the model (observation) equations

(3) $$z_o p_o(\tau) + \ldots + z_k p_k(\tau) + \sum_j (u_j \cos \omega_j \tau + v_j \sin \omega_j \tau) = y(T + \tau)$$

where $\tau = -\nu, -\nu + 1, \ldots + \nu$, $\nu = (n - 1)/2$,

$p_l = (\tau/\nu)^l$, $l = 0, \ldots k$,

ω_j are a few selected tidal AF,

$u_j = u_j(T)$ and $v_j = v_j(T)$ are unknowns related with ω_j and

$z_l = z_l(T)$ are drift unknowns.

A default option of NSV is

(4) $n = 48$, $k = 2$

and tidal components S1, O1, S2, M2, S3, S4, S5, S6,

i.e. ω_j in (3) are $\omega(S_1)$, ω(O1), ... ω(S6).

If LP are to be determined, there is another default option with $n = 360$.

The coefficients in (3) are one and the same in all $Int(T)$. Therefore the solution is obtained through filters and the estimates of the unknowns are filtered $u(T), v(T)$.

Among them we can use

filtered numbers	with amplified:	and eliminated:	for determination of the tides:
u_1, v_1	S1	S2, M2, S3, S4, S5, S6	D (diurnal)
u_2, v_2	S2	S1, O1, S3, S4, S5, S6	SD (semidiurnal)
u_3, v_3	S3	S1, O1, S2, M2, S4, S5, S6	TD (terdiurnal)
u_4, v_4	S4	S1, O1, S2, M2, S3, S5, S6	QD (quarterdiurnal)
u_5, v_5	S5	S1, O1, S2, M2, S3, S4, S6	FD (fifthdiurnal)
u_6, v_6	S6	S1, O1, S2, M2, S3, S4, S5	D6 (sixthdiurnal)

In order to get a good approximation and separation it may be necessary to deal with 2, even more tides of one and the same species, e.g. S1 and O1. Then (3) cannot be directly solved. Therefore NSV first makes an orthogonalization of such components, then (3) is solved. E.g. if in (3) are included S1, O1, Q1 then O1 is made orthogonal to S1 and Q1 - orthogonal to both S1 and O1.

In the application of NSV all elements of the filters can easily be changed. It is even possible to make them amplify and eliminate selected non-tidal frequencies.

In Figure 1 is shown that the default filters (4) of NSV do not considerably deviate from the FFIL.

Very important characteristic of a filter is the quantity which we shall call RSTN (ratio signal-to-noise), computed through

$$\text{(5)} \qquad \text{RSTN} = (2/n)\text{Var}(y_t)/\text{Var}(h)$$

where h is a filtered signal of power 1, amplified by factor 1. The variances are computed theoretically, under the assumption of a white noise.

Through NSV we can obtain

for the filters in MV66: RSTN ≅ 0.75, 0.80
while for the optimum Fourier filters: RSTN = 1.

We loose about 20-25% of precision and information which is the price of the elimination of the drift.

A high RSTN is of crucial importance. It is a guarantee that we remain close to the theoretically motivated scheme in (Venedikov 1964b) and that we can process the $u(T)$ and $v(T)$ instead of $y(t)$.

Therefore MV66 cannot use high pass filters without a separation of the main species. Such filters have much lower RSTN than pass band filters like our filters. For example, the filter of Pertsev, applied as a high pass filter eliminating the drift, has a low RSTN = 0.06. Nevertheless, this filter remains an excellent device for the estimation of the drift. Then it is a low pass filter which is also a pass band filter with a very high RSTN = 0.81.

In Figure 2 is shown the response of some of the filters of NSV. Compared to FFIL, we have a better elimination of the low frequencies (the drift) and better separation of the main species. The FFIL eliminate the non-tidal frequencies 7.5, 22.5 and 37.5. Our filters do not eliminate them because there has never been evidences for particular power concentrated at these domains of the spectrum.

4. Processing of the filtered numbers.

The second stage of the analysis is based on Scheme 2 where ξ and η are tidal unknowns proposed in (Venedikov, 1961, 1966a).

Scheme 2. Subdivision of the frequency axis ω into intervals or tidal groups with constant tidal parameters.

$$\overset{\Omega_1}{|\!-\!-\!-\!|}\;\overset{\Omega_2}{|\!-\!-\!-\!|}\;\ldots\;\overset{\Omega_j}{|\!-\!-\!-\!|}\;\ldots\longrightarrow\;\omega$$

$\omega \in \Omega_1$	$\omega \in \Omega_2$		$\omega \in \Omega_j$	
tidal group 1	tidal group 2	...	tidal group *j*	...
$\delta = \delta_1 =$ const.	$\delta = \delta_2 =$ const.		$\delta = \delta_j =$ const.	
$\kappa = \kappa_1 =$ const.	$\kappa = \kappa_2 =$ const.		$\kappa = \kappa_j =$ const.	
$\xi_1 = \delta_1 \cos \kappa_1$	$\xi_2 = \delta_2 \cos \kappa_2$		$\xi_j = \delta_j \cos \kappa_j$	
$\eta_1 = -\delta_1 \sin \kappa_1$	$\eta_2 = -\delta_2 \sin \kappa_2$		$\eta_j = -\delta_j \sin \kappa_j$	

The basis of Scheme 2 for the Earth tide data is the theory of Love, various theoretical models and a considerable experience. The same Scheme is coherent with the pragmatic model of Munk and Cartwright (1966) referred to by De Meyer (1982). Hence, all methods for analysis using ξ and η can be applied to both Earth and ocean data (Carvajal, 1993).

Through Scheme 2 we get the observation equations

$$(7)\qquad \begin{aligned} &\sum_{j=1}^{\mu} [c_{ju}(T)\,\xi_j + s_{ju}(T)\,\eta_j] = u(T) \\ &\sum_{j=1}^{\mu} [-s_{jv}(T)\,\xi_j + c_{jv}(T)\,\eta_j] = v(T), \qquad T = T_1, T_2, \ldots T_q \end{aligned}$$

whose coefficients are

(8)
$$c_{jl}(T) = \sum_{\omega \in \Omega_j} \rho_l(\omega)\, h_\omega \cos(\varphi_\omega + \omega T),$$

$$s_{jl}(T) = \sum_{\omega \in \Omega_j} \rho_l(\omega)\, h_\omega \sin(\varphi_\omega + \omega T),$$

where $l = u$ or v and

$\rho_u(\omega)$ is response of the even filter procuring $u(T)$,

$\rho_v(\omega)$ is response of the odd filter procuring $v(T)$.

Since ω is multiplied by T and the shift between the intervals is $s = n$ (if there are not gaps), it seems that ω can be considered as $s\omega$, e.g. 48ω, with heavy aliasing problems. Actually, the coefficients remain functions of the initial ω through $\rho(\omega)$ and they can easily be solved. All suspected aliases are either eliminated through low $\rho(\omega)$ or they can be taken into account in the equations, if it is necessary.

5. Options and questions in NSV.

The options to be used are selected in a dialogue. About every option is a question. For example, the option to change the default value $n = 48$ of the length of the filtered intervals depends on the question

2.1. (NFINT) NEW LENGTH n OF THE FILTERED INTERVALS ?

The answer of every question, written in the same line, can be:

Y or **y** - accepted option,

H or **h** - NSV will provide explanations about the option,

directly RETURN key - rejected option, remains a default variant.

After a **Y** NSV may need additional information, e.g. the new value of n.

An example of the explanations given by NSV after an answer **H** is:

1.8. (TIDS1) SEPARATE S1 FOR SERIES SHORTER THAN 1 YEAR ?   H

If the data are shorter than 1 year S1 cannot be successfully separated from the neighbouring K1 and P1. In the same time, if the length is 6 months or so, S1 is approximately orthogonal to (i.e. separable from) other waves, e.g. O1 and Q1.

Yes: S1 is replaced by a component S10 which is orthogonal to P1 and K1 and the analysis is made under the variants DETY or YEAR (see 1.6. VGR). The components of S1 which are along P1 and K1 remain as an inevitable

perturbation of these waves but S1 is separated from the remaining waves.

....

After the explanations the question is repeated.

The questions/options of NSV are:

SOME ADDITIONAL OPTIONS ?

1. (CHAN) CHANGES IN THE ANALYSIS ?

1.1. (DEV) TO CHANGE THE TIDAL POTENTIAL DEVELOPMENT ?
1.2. (ADDW) ADDITIONAL WAVES ?
1.3. (LONG) DETERMINATION OF THE LONG PERIOD (LP) WAVES ?
1.4. (SHORT) CHOOSE AMONG THE TIDAL SPECIES, D, SD,... ?
1.5. (WGHT) WEIGHTS OF THE FILTERED NUMBERS ?
1.6. (VGR) CHOOSE THE VARIANT OF GROUPING ?
1.7. (ADDGR) ADDITIONAL TIDAL GROUPS ?
1.8. (TIDS1) SEPARATE S1 FOR SERIES SHORTER THAN 1 YEAR ?

2. (FIL) CHANGES IN THE FILTERS ?

2.1. (NFINT) NEW LENGTH n OF THE FILTERED INTERVALS ?
2.2. (SHIFT) NEW SHIFT s OF THE FILTERED INTERVALS ?
2.3. (KELIM) NEW POWER k OF THE DRIFT POLYNOMIALS ?
2.4. (TIDEF) NEW TIDAL CONSTITUENTS OF THE FILTERS ?
2.5. (RESPF) WEIGHTS AND RESPONSE OF THE FILTERS TO SOME TIDES ?
2.6. (SPECF) SPECTRUM OF THE FILTERS ?

3. (TVAR) TIME VARIATIONS ?

3.1. (RESIN) RESIDUALS AND DRIFT IN THE FILTERED INTERVALS ?
3.2. (RESAN) HOURLY RESIDUALS AND DRIFT AFTER THE ANALYSIS ?
3.3. (FAST) FAST AMPLITUDE AND PHASE VARIATIONS ?
3.4. (RESFN) RESIDUALS OF THE FILTERED NUMBERS ?
3.5. (FILN) PRINT THE FILTERED NUMBERS ?
3.6. (SLOW) SLOW AMPLITUDE AND PHASE VARIATIONS ?

4. (CROSS) CROSS REGRESSION (SECOND INPUT CHANNEL) ?

4.1. (TORO1) MODEL 1 OF DE TORO, VENEDIKOV, VIEIRA ?
4.2. (TORO2) MODEL 2 OF DE TORO, VENEDIKOV, VIEIRA ?

5. (OTHER) OTHER OPTIONS ?

5.1. (PRDEV) PRINT THE TIDAL POTENTIAL DEVELOPMENT ?
5.2. (OUT4) OUTPUT WITH ONLY 4 DECIMALS OF DELTA ?
5.3. (NOP3) SUPPRESS THE CORRECTIONS FOR POTENTIAL OF ORDER 3 ?
5.4. (ELONG) ELIMINATE THE LONG PERIOD WAVES ?
5.5. (ARTW) ADD AN ARTIFICIAL WAVE ?
5.6. (NOINC) NO INERTIAL CORRECTION FOR THE GRAVIMETERS ?
5.7. (DKCOR) DELTA AND KAPPA CORRECTIONS ?
5.8. (COPY) COPY THE DATA ?

The processing is usually so fast that the dialogue can take more time than the computations. Therefore we can avoid some of the questions or all of them in one of the following ways.

(i) If the initial SOME ADDITIONAL OPTIONS ? is not accepted, (RETURN key) NSV proceeds directly a standard analysis, without more questions.

(ii) The questions which are underlined are main questions to which is corresponding a set of questions. If a main question is rejected none of the corresponding questions is set up.

E.g. if 1. **(CHAN)** is not accepted will follow directly 2. **(FIL)**. If, on the contrary, 1. **(CHAN)** is answered Y, follow the questions 1.1 through 1.8.

(iii) Each data file has a control data file with coordinates and name of the data. Some of the options can be made permanent if they are included in the control file using the acronyms given in the parentheses. Then the corresponding option is used but the question is excluded from the dialogue.

For example, if **TIDS1** is written in the control file, the option will be applied without displaying 1.8. **(TIDS1)**....

(iv) The acronyms are also designed to make the dialogue faster. After some experience, it is enough to read only the acronym.

Through some of the options, the user can get a series of analysis results. For the selection of a most reliable result NSV compute the values of the criterion of Akaike (Sakamoto et al., 1986) AIC. If one and the same data are processed, the results with the lowest value of AIC should be accepted.

6. Short comments of some options.

We think that the best and easiest way to understand the options is to use NSV, the explanations which can be displayed after an H and making experiments. Therefore in the following we shall briefly concern only few options which seem to be more obscure. We shall write again the corresponding question and give short comments after it.

1.1. **(DEV) TO CHANGE THE TIDAL POTENTIAL DEVELOPMENT ?**

The default option is the development of Tamura. Through **DEV** the development of Cartwright-Tayler-Edden can be used.

In both developments are added a few high frequency waves which allow to deal, in addition to the usual LP, D, SD and TD species with

QD - quarterdiurnal, including M4 group and a tide S4,

FD - fifthdiurnal, including tides M5 and S5,

D6 - sixthdiurnal, including tides M6 and S6.

1.2. (ADDW) ADDITIONAL WAVES ?

It is possible to deal with some waves which are not included in the potential developments. They can be added to one of the existing species or they can form a new species called AW.

1.5. (WGHT) WEIGHTS OF THE FILTERED NUMBERS ?

The $u(T), v(T)$ can be weighted by the estimated variances through the solution of (3). The option can be efficient in dealing with records having strong perturbations.

1.7. (ADDGR) ADDITIONAL TIDAL GROUPS ?

Initially, the equations (7) are created separately for the main species, D, SD,... considering on their separation by the filters. Through **ADDGR** we can add some tidal groups of one species to the equations for another species, e.g. SD and TD groups to the equations for the D filtered numbers.

3.1. (RESIN) RESIDUALS AND DRIFT IN THE FILTERED INTERVALS ?

The residuals are computed through the approximation (3) separately for every $Int(T)$. The drift is computed through the unknowns $z_o,\dots z_k$ which are also obtained as filtered numbers.

3.2. (RESAN) HOURLY RESIDUALS AND DRIFT AFTER THE ANALYSIS ?

After the analysis is made, the filters are applied again but now using a moving filtration, i.e. with a shift $s = 1$ hour. For the ordinate after the central epoch T is computed the adjusted or smoothed value of the tidal signal using the results of the analysis. The drift is computed in the same way as in 3.1 **RESIN**. After this we get hourly residuals.

3.3. (FAST) FAST AMPLITUDE AND PHASE VARIATIONS ?

The parameters δ and κ are computed for every $Int(T)$. If a shift $s = 1$ is chosen, we get these quantity hour by hour.

We get poor estimates of δ and κ which are accepted to be one and the same for all tides of one and the same species. Due to this there are theoretical variations of δ and κ. NSV offers a possibility to reduce these variations.

3.6. (SLOW) SLOW AMPLITUDE AND PHASE VARIATIONS ?

The record is partitioned into intervals defined by the user. The analysis is made of all intervals. The intervals can be with overlapping but then we get correlated, i.e. smoothed variations.

After that the method of analysis of the variances is applied in order to establish whether there are significant variations. A way to establish neglected variations of the sensibility is also applied.

4. (CROSS) CROSS REGRESSION (SECOND INPUT CHANNEL) ?

4.1. (TORO1) MODEL 1 OF DE TORO, VENEDIKOV, VIEIRA ?

4.2. (TORO2) MODEL 2 OF DE TORO, VENEDIKOV, VIEIRA ?

In principle the idea of De Meyer (1982) is used but through our model (Simon et al., 1989, Toro et al., 1991, 1993). Now this is done in the following way.

Let $u(T)$ and $v(T)$ are obtained from data FILE1 while $p(T)$ and $q(T)$ are filtered numbers obtained in the same way as $u(T)$ and $v(T)$ from data FILE2. E.g. FILE1 are gravity data and FILE2 are air-pressure data.

If **MODEL** 2 is accepted, the equations (7) are modified into

$$(9)\qquad \sum_{j=1}^{\mu} [c_{ju}(T)\,\xi_j + s_{ju}(T)\,\eta_j] + b_1 p(T) - b_2 q(T) = u(T)$$

$$\sum_{j=1}^{\mu} [-s_{jv}(T)\,\xi_j + c_{jv}(T)\,\eta_j] + b_1 q(T) + b_2 p(T) = v(T),$$

Here b_1 and b_2 are regression coefficients which can be represented as

(10) $b_1 = b\cos\beta,\ b_2 = b\sin\beta,$ where

b is a coefficient of proportionality and

β is a phase lag of the effect of FILE2 on FILE1.

We get b_1 and b_2 separately for the main species.

If **MODEL** 1 it applied, it is accepted that $\beta \equiv 0$ and we get only one regression coefficient $b_1 = b$.

7. A few examples.

Example 1, options **SLOW** and **TORO1**.

Table 1 is a copy of the output provided by NSV. B1 are values of the coefficients b_1 in (9). We have got B1 frequency and time depending.

We have an application of SLOW with intervals of length 30 days and shifted by 30 days. The last interval has 46 days because there are left 16 days of data which cannot shape an interval of the selected length.

The output using this option as well as the output of all options for time variations is in a form suitable to use a plotting program. Therefore the dates are written in a not very convenient form.

In addition to this output we get the values of δ and κ for selected tides for the same time intervals and similar format.

Table 1. Output when the options **SLOW** and **TORO1** are applied.
Data used: Station Brussels, Superconducting gravimeter.

TIME VARIATIONS OF THE REGRESSION COEFFICIENTS

NR INT	INTERVAL FROM	TILL	CENTRAL EPOCH DAYS	DATA USED DAYS	B1(D)	B1(SD)	B1(TD)	B1(QD)
1	86111500	86121423	15.0	30.0	-0.325	-0.421	-0.359	-0.075
2	86121500	87011323	45.0	30.0	-0.354	-0.351	-0.441	-0.237
3	87011400	87021223	75.0	30.0	-0.458	-0.214	-0.223	-0.075
4	87021300	87031423	105.0	30.0	-0.378	-0.463	-0.508	0.017
5	87031500	87041323	135.0	30.0	-0.377	-0.241	-0.428	-0.733
6	87041400	87051323	165.0	30.0	-0.351	-0.298	-0.692	0.048
7	87051400	87061223	195.0	30.0	-0.444	-0.395	-0.228	-0.310
8	87061300	87071223	225.0	30.0	-0.309	0.012	-0.099	-0.441
9	87071300	87081123	255.0	30.0	-0.344	-0.435	-0.228	-0.223
10	87081200	87091023	285.0	30.0	-0.313	-0.188	-0.183	-0.040
11	87091100	87101023	315.0	30.0	-0.342	-0.289	-0.298	-0.320
12	87101100	87112523	353.0	46.0	-0.350	-0.418	-0.330	-0.304

Example 2. Options **LONG**, **TORO1**, **TORO2** and **VGR**.

In table 2 we have variants of the results of the analysis about the long period waves. In the title is given part of the output when only one of the variants is applied.

When **VGR** is not applied, the tidal group called MF unify all LP tides. However, the filter which amplify MF are retaining or eliminating the longer tides, e.g. SSA and SA.

When **VGR** is applied, we have the variants

VGR(MTM): the LP tides are separated in groups MF and MTM

VGR(MTM,MSOM): the LP tides are separated in groups MF, MTM and MSOM. However, the results in Table 2 are only for MF.

Table 2. Application of the options **LONG**, **TORO1**, **TORO2** and **VGR**.

Data: Station Brussels, Superconducting gravimeter, 21.04.82-20.01.93. and air-pressure for the same interval.

FILTERED INTERVALS OF LENGTH 360 HOURS
SHIFT (DISTANCE BETWEEN THE EPOCHS) OF THE INTERVALS 360 HOURS
APPROXIMATION IN THE INTERVALS BY DRIFT POLYNOMIALS OF POWER 1
AND TIDES: MF S1 O1 Q1 S2 M2 N2 S3
TIDAL POTENTIAL DEVELOPMENT OF TAMURA, 1200 COMPONENTS
ANALYSIS ON 24-NOV-94, START: 11:54:08, END: 11:54:26
TOTAL COMPUTER TIME USED 18 SEC. FOR DATA OF LENGTH 10.75 YEARS
DATA USED: 3927 DAYS, 92520 READINGS, 3 BLOCKS, 257 INTERVALS
82.04.21.00/82.06.09.11 82.06.02.00/86.10.29.23 86.11.15.00/93.01.19.23

Options used	δ(MF)	$\sigma(\delta)$	κ(Mf)	$\sigma(\kappa)$	$\sigma(y)$	AIC
LONG	1.1463	0.0163	1.262	0.811	21.00	4594.
LONG, TORO1	1.1483	0.0046	0.007	0.231	5.98	3305.
LONG, TORO1, VGR(MTM)	1.1467	0.0047	0.016	0.234	5.96	3307.
LONG, TORO2	1.1482	0.0046	0.006	0.231	5.98	3308.
LONG, TORO2, VGR(MTM)	1.1466	0.0047	0.014	0.234	5.97	3309.
LONG, TORO1, VGR(MTM,MSOM)	1.1467	0.0047	0.009	0.234	5.97	3312.

Table 2 is also an example how the criterion AIC can be used. We have an important reduction of AIC at the first step LONG ⇒ (LONG,TORO1). Further we have not any improvement, even AIC is slightly raising. We have to remain at the lowest value, i.e. to accept the result (LONG,TORO1).

Example 3. Options **RESFN** and **TORO1**.

In Figure 3 are given the D residuals of the filtered numbers, obtained using **RESFN**. The same residuals are computed after **TORO1** is proceeding a regression on air pressure data. Obviously, there is a considerable reduction of the magnitude of the residuals.

However, the effect is not so strong for the SD residuals.

Example 4. Option **SLOW** used to check up variations of the sensibility.

If in a record are variations of the sensibility they will affect equally the D and SD tides, i.e. we shall have a strong correlation between the variations of given D and given SD tide. Therefore **SLOW** can represent

δ of given wave as a function of δ of another wave.

In Figure 4 is represented $\delta(M2)$ as a function of $\delta(O1)$. In the case of non-calibrated data we have an obvious linear relation. After the calibration is introduced, i.e. the variations of the sensibility are taken into account, the relation has practically disappeared.

Acknoledgments.

In the first applications of NSV we have been helped by the staff of ICET and the Belgian Royal Observatory, in particular by Prof. Melchior, Prof. P. Pâquet and Dr. B. Ducarme. Dr. Ducarme has taken part in the development of the program.

One of the authors (Venedikov) has been helped to stay and work in Madrid by the Sabatical Program of the University Complutense and the Superior Council for Scientific Investigations of Spain.

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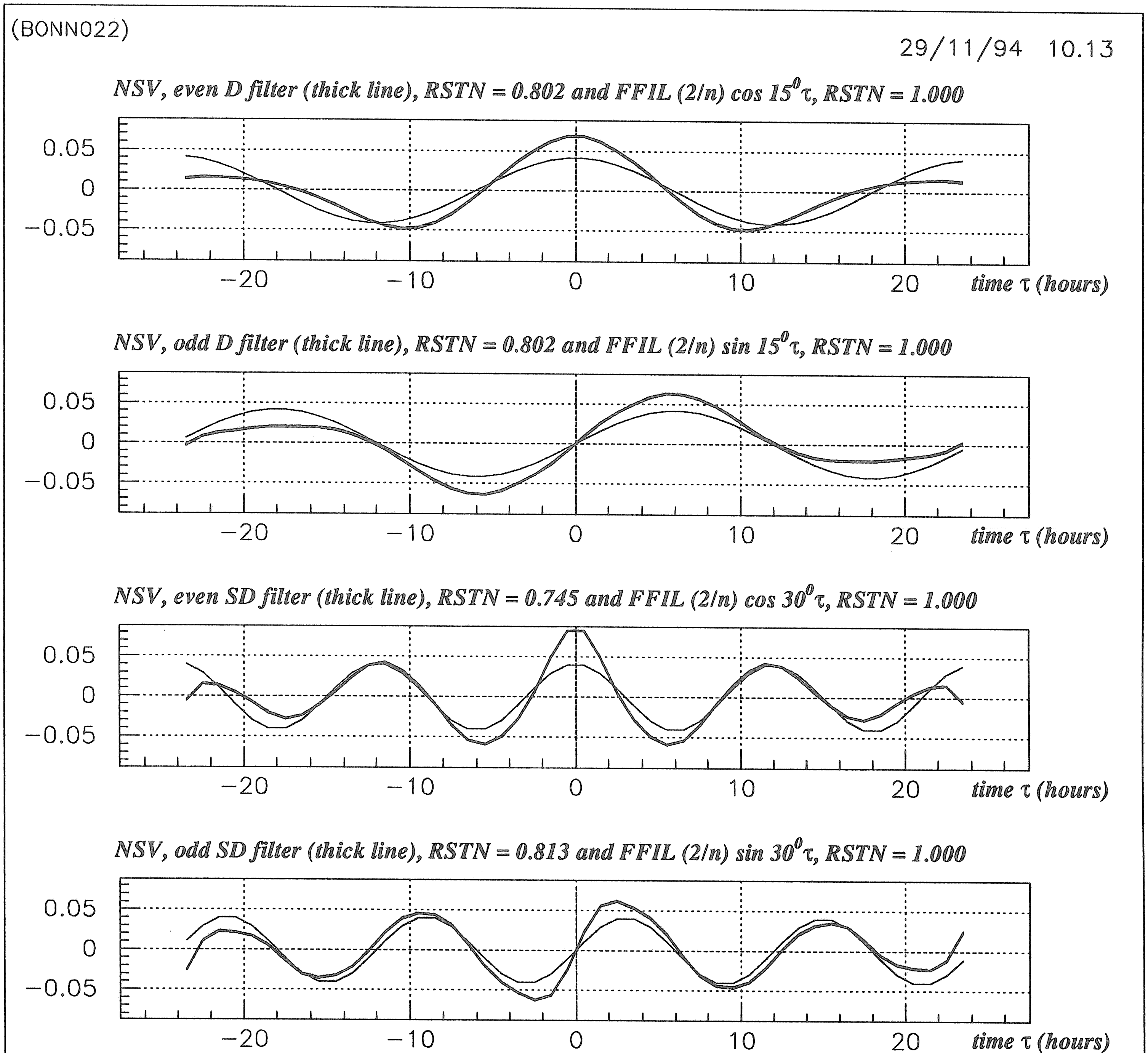

Figure 1. Default filters of NSV and Fourier filters FFIL in the time domain, n = 48.

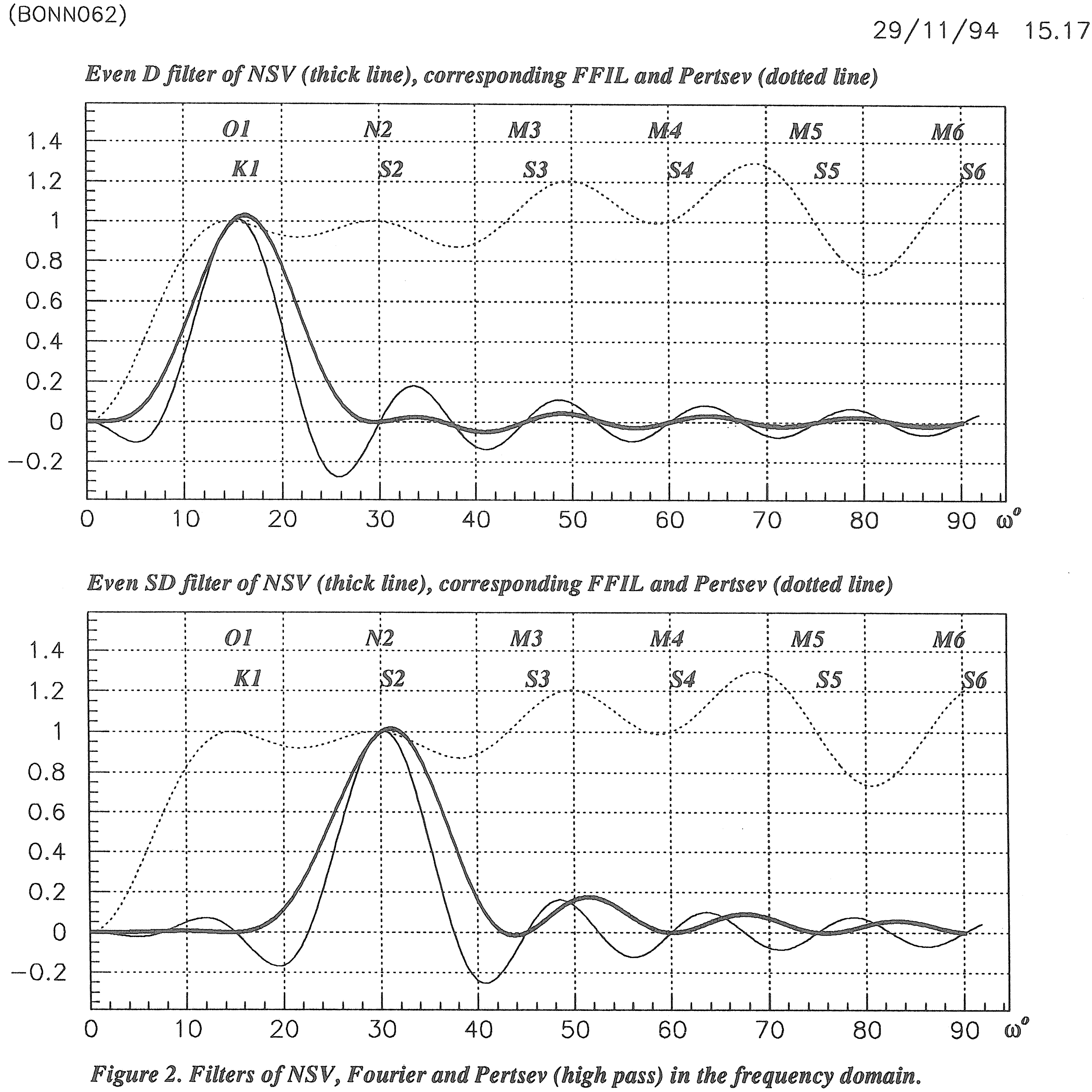

Figure 2. Filters of NSV, Fourier and Pertsev (high pass) in the frequency domain.

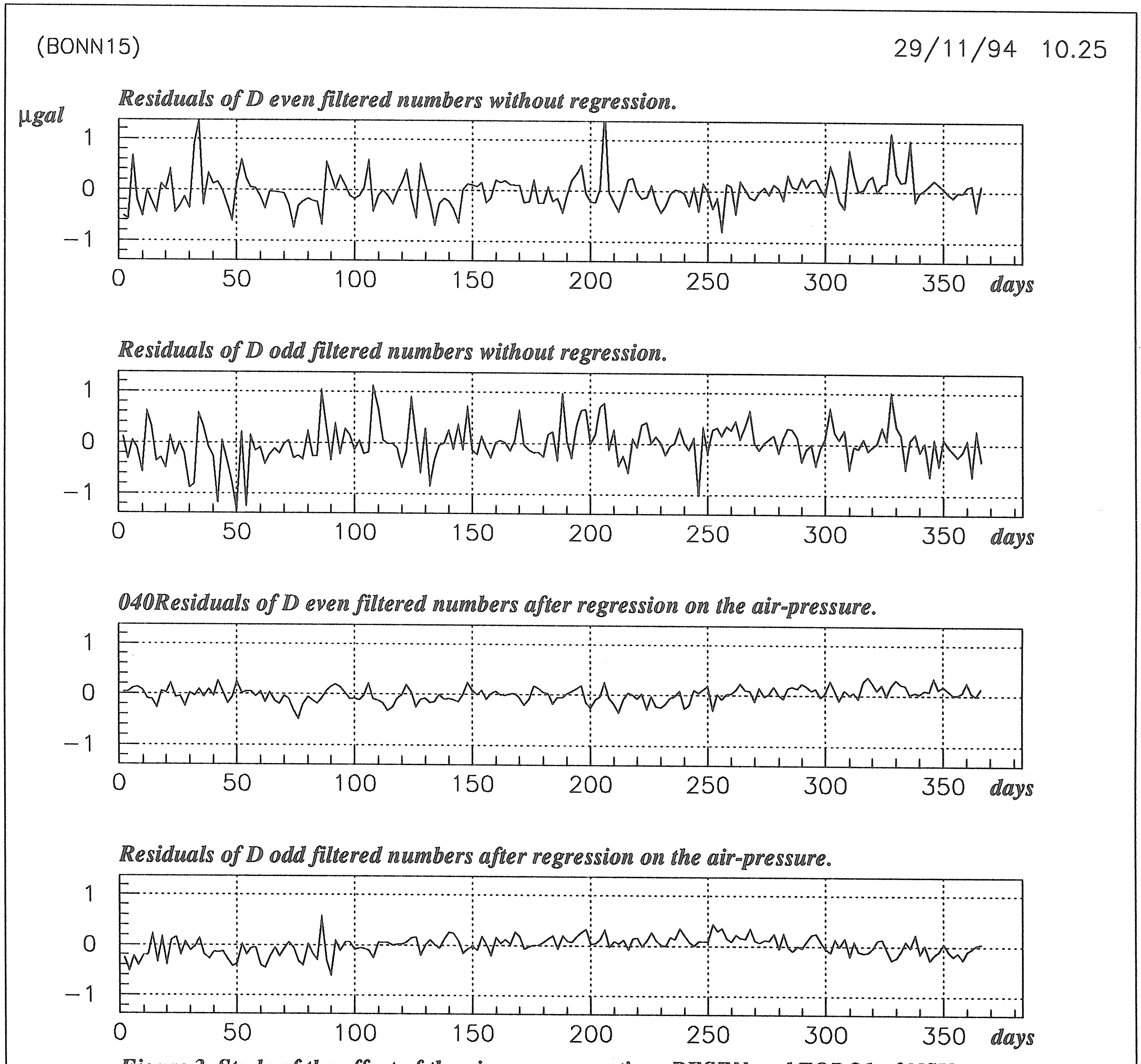

Figure 3. Study of the effect of the air pressure, options RESFN and TORO1 of NSV. Data from superconducting gravimeter, Brussels, 15.11.1986-15.11.1987

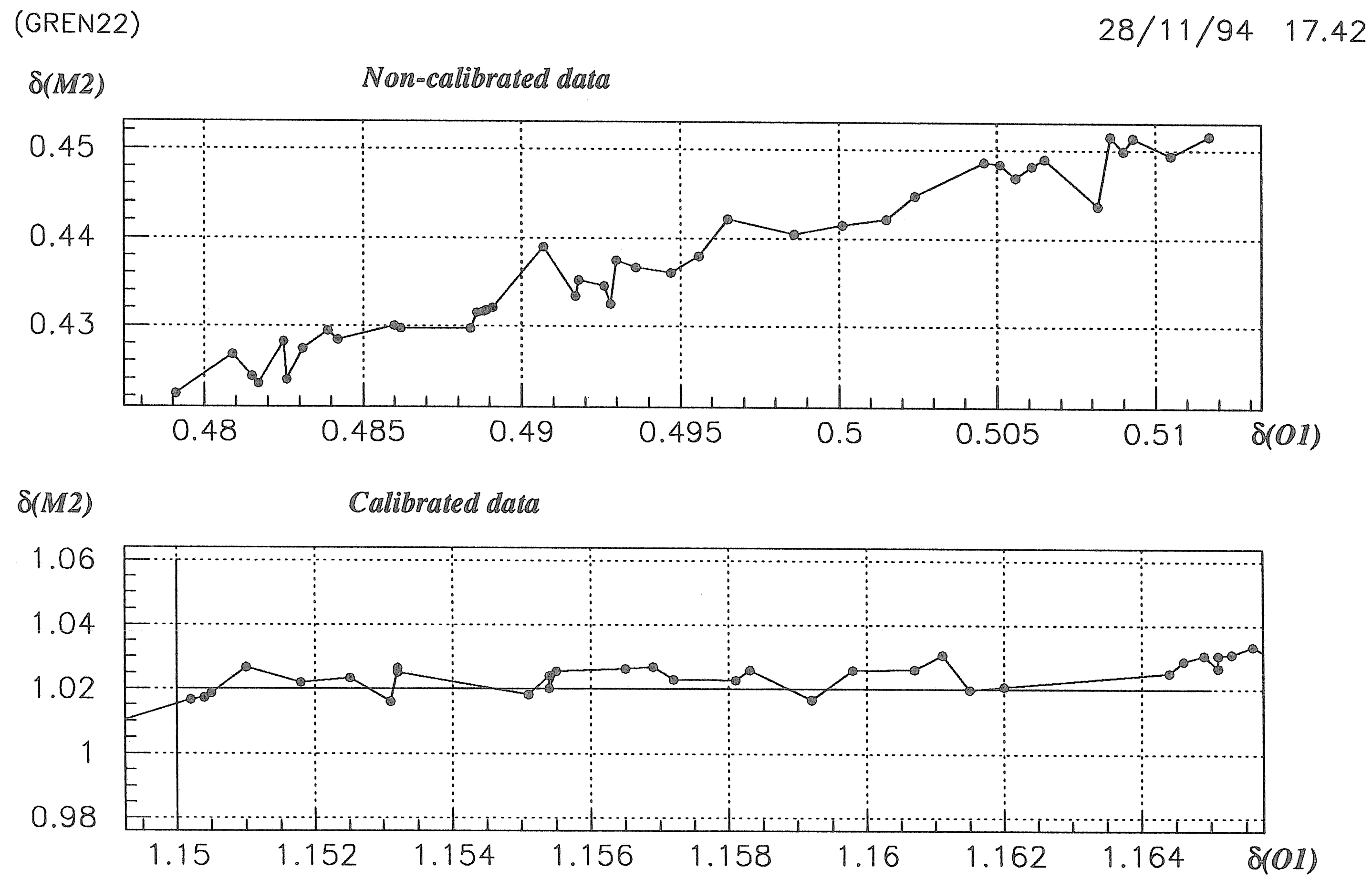

Figure 4. Program NSV, option SLOW, intervals of length 30 days without overlapping.

δ(M2) plotted as function of δ(O1)

Station Lanzarote, gravimeter LCR 434, 14.05.87-13.06.1991

REMARKS ABOUT THE MV66 AND ETERNA 3.1 TIDAL ANALYSIS METHODS

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These remarks concern the paper (Wenzel, 1994, here and further referred as WEN) and the tidal analysis method called MV66 (Venedikov, 1966a, 1966b, Melchior & Venedikov, 1968, Melchior, 1978, 1981).

We highly appreciate the efforts of prof. H.-G. Wenzel in searching a solution of the tidal analysis problem, in particular the creation of the ETERNA program and method. We think, however, that some of the conclusions in WEN are a product of misunderstanding and they may mislead the readers.

1. Summary.

Here we shall give short comments (after a VEN:) of some statements made in the Abstract of WEN.

WEN: ... A modification of this program (e.g. Ducarme 1975) ...

VEN: MV66 is not a given program. It is a method or algorithm which can be applied using different programs, even different filters. If necessary, a program like the program of Ducarme can be further improved or new programs can be created. An example is the program recently developed by Venedikov, Vieira, and Toro (1994, here and further referred as NSV).

By the way, Prof. Wenzel has been informed about NSV after WEN has been prepared.

WEN: ...but is now (MV66) obsolete...

VEN: We would agree if there were other methods with (i) a better theory and (ii) different results.

ETERNA is certainly a good method but (i) it has not a good theoretical background compared to MV66 and (ii) its results are close to MV66 (Melchior, 1994).

ETERNA accepts, like Chojnicki, that correlated data (non-white noise) can be processed by MLS (the Method of the Least Squares) as non-correlated data (white noise). Due to this they have to apply a particular way for the estimation of the precision (Wenzel, 1976, 1977, Chojnicki, 1978). Therefore their estimates are not MLS estimates. This makes problematic the use of other statistical tools in the interpretation of the results.

It is an error to consider these methods as classical MLS because they do not deal directly with hourly observations. They deal with filtered data, like MV66. MV66 uses pass band filters with high ratio signal-to-noise (RSTN). Chojnicki and ETERNA use high pass filters with low RSTN. This makes obligatory a moving filtration, hour by hour which, unfortunately, is further raising the initial correlation.

WEN: The MV66 method was not designed for the precision we obtain today...and creates errors...

VEN: There are not obstacles to modify or create a program for MV66 with an as high as necessary precision. We think that the program of Ducarme in ICET guarantees a good enough precision. Nevertheless, in some cases, it can be useful to apply in parallel other programs.

WEN: The re-sampling of band pass filtered data at 48^h intervals violates the sampling theorem, and thus the parameters suffer from leakage of noise outside the tidal bands (e.g. Schüller, 1978).

VEN: If MV66 has violated a mathematical theorem it would give catastrophic results in all applications. On the contrary, there is a huge number of successful applications and we do not know about any failure.

It only seems that we make a sampling with a step $n = 48^h$. Actually, MV66 is a two stage application of MLS on the hourly data which is an approximation to a direct use of MLS.

This topic will be further discussed in the next Sections. We would like also to recall (Venedikov, 1979) which is a comment to a similar criticism of Schüller (1978).

WEN: The residuals of the MV66 method cannot be used for any post-fit analysis or interpretation.

VEN: Directly, MV66 is providing residuals of the filtered numbers for every 48^h. It is only question of programming to get hourly but correlated residuals (see NSV).

The methods of Chojnicki and ETERNA cannot compute directly hourly residuals. They work with filtered numbers and provide also residuals of filtered numbers, i.e. residuals of correlated hourly quantities.

WEN: It (MV66) does not allow the processing of multi-channel data.

VEN: MV66 allows the processing of multi-channel data (see NSV).

WEN: It (MV66) does not allow the analysis of long periodic tides.

VEN: MV66 allows the analysis of the LP tides (Venedikov & Ducarme, 1979, Venedikov, Melchior & Ducarme, 1986, Venedikov, 1989 and NSV).

2. About the aliasing problem.

In WEN is shown that some waves, e.g. waves of AF (angular frequency) $\omega = 22.6^{\circ}/h$ and $\omega = 7.475^{\circ}/h$ affect the results of MV66. This does not yet mean that such ω are aliases. It only means that they are not taken into account in the equations. If necessary, they can be taken into account and their effect can disappear.

It is well known what is an alias in the case of the Fourier series. In MV66 we use more sophisticated relations and the aliasing needs a concrete consideration.

Let y is a vector of observations and there are equations like

$$(1) \qquad \sum_i (c_i \alpha_i + s_i \beta_i) = y.$$

where α_i and β_i are unknowns related with AF (angular frequency) ω_i, while c_i and s_i are vectors of known coefficients, also related with ω_i.

Let ω_j is a tidal AF in which we are interested. Given ω_k can be considered as alias of ω_j if

(2) (a) $c_k \neq 0$ and/or $s_k \neq 0$

and

(b) c_j, s_j, c_k, s_k are linearly dependent.

Then ω_k exist in the data but it cannot be included in the equations (1) and will affect α_j and β_j.

If (a) is not satisfied, ω_k does not exist and is not interesting. If (a) is satisfied but (b) is not satisfied, ω_k can be taken into account and we can get correct estimates of α_j and β_j.

If a simple way of processing is applied on hourly data y_t, like the Fourier series, we have equations like

(3) $$\sum_i (\cos \omega_i t \ \alpha_i + \sin \omega_i t \ \beta_i) = y_t .$$

Then the vectors c_i and s_i will be

(4) $$c_i = [\cos \omega_i t] \quad \text{and} \quad s_i = [\sin \omega_i t]$$

where t take a set of values.

The condition (a) is never considered because it is always satisfied.

In this case a trivial example of aliases is

(5) $$0 < \omega_j < 180^\circ \text{ and } \omega_k = - \omega_j$$

because $c_j = c_k$ and $s_j = -s_k$, i.e. (b) is satisfied.

Now we shall show that if more complicated equations are used, the trivial example (5) is no more trivial.

Let there are two sets of hourly data, u_t and v_t, with equations

(6) $$\sum_i (\cos \omega_i t \ \alpha_i + \sin \omega_i t \ \beta_i) = u_t ,$$

$$\sum_i (-\sin \omega_i t \ \alpha_i + \cos \omega_i t \ \beta_i) = v_t .$$

Then, under the condition (5), $\omega_j = - \omega_k = \omega$,

(7) $$c_j = \begin{bmatrix} \cos \omega t \\ \\ -\sin \omega t \end{bmatrix}, \quad s_j = \begin{bmatrix} \sin \omega t \\ \\ \cos \omega t \end{bmatrix}, \quad c_k = \begin{bmatrix} \cos \omega t \\ \\ \sin \omega t \end{bmatrix}, \quad s_j = \begin{bmatrix} -\sin \omega t \\ \\ \cos \omega t \end{bmatrix}.$$

These vectors are linearly independent. E.g. for $t = 1,\ldots 48$ and $\omega = 15^\circ$ they are even orthogonal. There are no obstacles to deal with both ω_j and $\omega_k = - \omega_j$, i.e. ω_j and $\omega_k = - \omega_j$ are not aliases.

If the filtered intervals in MV66 are of length 48^h, the coefficients in the observation equations depend on AF like $\Omega = 48\omega$ where ω is given tidal AF in °/hour. Therefore,

(8) the tidal frequencies:

ω_{TID} = 15, 30, 45, 60 °/hour

and the non-tidal frequencies:

ω_{NTID} = 7.5, 22.5, 37.5, 52.5 °/hour

seem to be aliases. Through $\Omega = 48\omega$ and subtraction of 2π all of them become 0°/48 hours.

Something more, AF like

(9) ω_{TID} = 14.5, 15.5, 29.5, 30.5 °/hour

which are close to tidal AF

become

Ω = -24, +24, -24, +24 °/48 hours,

i.e. they also seem to be aliases.

If it was so, all coefficients used in MV66 would be linearly dependent. We would not be able to get any result neither good, nor wrong.

The fact that MV66 is providing some results, which are certainly not too bad, is already a proof that the situation is neither so desperate, nor so elementary.

Generally, the coefficients used in MV66 look like $\rho(\omega)C(\Omega)$ where $\rho(\omega)$ is the response of the filters used. They depend on $\Omega = 48\omega$ but they remain depending on the initial ω. Therefore ω, which seem aliases after they are transformed in Ω, are not aliases.

For example, S1 and S2 should be aliases. Nevertheless, we can determine the D tides, including S1, because S2 has $\rho(\omega) = 0$, i.e. the condition (2a) is not satisfied. For other supposed aliases we may have small but non-zero $\rho(\omega)$. Then the condition (2b) is not satisfied and we can take them into account in the equations.

There is a very simple explanation why MV66 does not obey the elementary theory of the aliases. MV66 is not a processing of samples of y_t. As said in Section 1, it is a two stage application of MLS on y_t which is very close to a direct processing of y_t. The reason of using two stages is to avoid the correlation of y_t and find a way for correct application of MLS, mainly in order to get rigorous estimation of the precision.

More on this is can be found in NSV.

3. *Analyses using different shifts between the filtered intervals.*

Although MV66 can take into account frequencies which seem to be aliases, it is under question whether this is necessary. An important principle is to use the least possible number of unknowns. We shall waste the precision if suspicions about ghostly frequencies oblige us to violate this principle.

MV66 is applying filters with a shift $s = n$, e.g. $s = 48 = n$, but we can try $s \neq n$. If there are neglected non-tidal frequencies, e.g. ω_{NTID} in (9), their effect will depend on s, disappearing at $s = 1$.

Using various s we have got the results given in Example 1. The effects which had to disappear at $s = 1$ has not appeared at any other s although there are great s which should generate terrific aliases.

Example 1. Analyses of data of the superconducting gravimeter in station Brussels by the method MV66, program NSV, default filters $n = 48$.

Data used: 02.06.1982 - 28.11.1987.

The mean square errors (deviations) σ are multiplied by 10^4.

shift	data	O1		M2		K1		S2	
s	used	δ	σ	δ	σ	δ	σ	δ	σ
1	4800%	1.1532	± 0.5	1.1841	± 0.2	1.1403	± 0.4	1.2029	± 0.4
2	2400%	1.1532	0.7	1.1841	0.3	1.1403	0.5	1.2029	0.5
3	1600%	1.1532	0.9	1.1841	0.3	1.1403	0.6	1.2029	0.7
4	1200%	1.1532	1.0	1.1841	0.4	1.1403	0.7	1.2029	0.8
12	400%	1.1532	1.8	1.1841	0.7	1.1403	1.3	1.2029	1.4
16	300%	1.1532	2.0	1.1841	0.8	1.1403	1.4	1.2029	1.5
24	200%	1.1532	2.5	1.1841	0.9	1.1403	1.8	1.2029	1.9
48	100%	1.1532	3.4	1.1840	1.3	1.1403	2.5	1.2029	2.7
64	75%	1.1532	4.0	1.1841	1.5	1.1403	2.9	1.2030	3.2
96	50%	1.1528	4.9	1.1842	1.9	1.1399	3.5	1.2031	3.9
192	25%	1.1529	7.1	1.1842	2.7	1.1399	5.1	1.2033	5.6
256	19%	1.1533	6.9	1.1839	3.2	1.1404	5.0	1.2026	6.5
1024	5%	1.1530	17.5	1.1832	6.9	1.1388	11.6	1.2011	14.9

In the first part these results $s < 48 = n$ (overlapping). Practically, we use n/s times the same data. Thus, if $s = 1$ (like in the methods of Chojnicki and ETERNA), we use the data 4800%. The effect is a falsely low σ and an overestimated precision.

In the last part $s > 48$, i.e. we have gaps of $(s - 48)$ hours between the intervals. This is improving the independence of the filtered values but, of course, the precision is lower because some data are not used. Due to this there are small variations in the results. They can be fully explained using the estimation of the precision, which is now correctly made, compared to $s < n$.

It is remarkable that using such small parts of the record as 19%, even 5%, we get still reliable results. We hope that this will be instructive for people who are afraid of the gaps and like better to use interpolated, i.e. artificially created numbers.

It is important that for all s we have

$$\sigma(s)/\sigma(48) \cong (s/48)^{1/2}. \tag{15}$$

This is a confirmation that the filtered numbers for $s = n = 48$ are not seriously correlated.

4. *The models SIMA in WEN.*

In these models a non-random noise (a systematic error) is simulated. Artificial waves $A(\omega_{WEN})$ of $\omega_{WEN1} = 7.475°/h$ (SIMA1) and $\omega_{WEN2} = 22.6°/h$ (SIMA2) are added to some data Y. In WEN is supposed that ω_{WEN} are aliases to the main tidal ω.

The addition to Y is not necessary. If δ is a result of Y and $\delta + \Delta\delta$ is the result of $Y + A(\omega)$, $\Delta\delta$ will be the result of the analysis of $A(\omega)$ alone. The effect $\Delta\delta$ of $A(\omega)$ is independent of Y and δ. Therefore our results in the following are obtained through the analysis of pure $A(\omega_{WEN})$.

We have analysed by NSV $A(\omega_{WEN})$ with amplitudes of 300 μgal using the default filters of NSV with $s = n = 48$.

Usually, we pay attention to the tidal frequencies around ω_{TID} in (8). There are not evidences for accumulation of energy at the frequencies ω_{NTID}, e.g. $\omega = \omega_{WEN}$. Therefore the filters which are used by MV66 do not eliminate ω_{WEN}. Also, frequencies like ω_{WEN} are not included in the equations of the second stage of the analysis.

If one can persuade us that these frequencies are important, we can easily take measures for their elimination. At the moment (see again Example 1) this does not seem necessary, except for models like SIMA.

An option of NSV is to add to the usual equations unknowns corresponding to waves with arbitrary non-tidal ω. Using this option we have processed the models $A(\omega_{WEN})$. The effect of $A(\omega_{WEN})$, with their giant amplitudes of 300 μgal, became a pile of zeros, some of them given in Example 2.

Example 2. Output of NSV of the analysis of data representing a wave named A226 of $\omega_{WEN} = 22.6^\circ/h$ and amplitude 300 μgals. The elements of A226 are also considered as unknowns, i.e. A226 is an additional tidal wave/group, associated with the D tides (option ADDW of NSV).

For the phases NSV provides conventional numbers $\kappa = 90^\circ$ and $\sigma(\kappa) = 360^\circ$ when we have a division on zero.

Since A226 is not a tidal wave, NSV is providing its amplitude only.

The output of the other tidal species, e.g. SD and TD, as well as the results for $\omega_{WEN} = 7.475^\circ/h$ looks the same way.

```
DATA USED:  381 DAYS,  9120 READINGS,  1 BLOCKS,  190 INTERVALS
A WAVE OF ANG.VELOCITY  22.600 AND AMPLITUDE 300.0 IS ADDED
87.01.01.00/88.01.17.11
-----------------------------------------------------------------
  WAVE GROUP     ESTIMATED     AMPLIT.               PHASE
ARGUM.    N WAVE  AMPL.  M.S.D.  FACTOR   M.S.D.      DIFF.    M.S.D.
-----------------------------------------------------------------
1B9-11X  49 SIGQ  0.000 0.000  0.00000 0.00000   90.0000 360.0000
123-126  23 2Q1   0.000 0.000  0.00000 0.00000   90.0000 360.0000
127-12X  20 SIG1  0.000 0.000  0.00000 0.00000   90.0000 360.0000
:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
184-187  23 OO1   0.000 0.000  0.00000 0.00000   90.0000 360.0000
190-1J3  67 NU1   0.000 0.000  0.00000 0.00000   90.0000 360.0000
A226 ANG.VELOCITY:   22.6000 AMPLITUDE:300.00000 M.S.ERROR:   0.00000
-----------------------------------------------------------------
STANDARD DEVIATIONS:  D   0.000
-----------------------------------------------------------------
```

5. About the leakage between the main tidal species, e.g. D and SD.

In Test case 1 of WEN the program ETVEN for MV66 (created by Wenzel) has shown biases which seem tremendous compared to very small biases of ETERNA. The question is: is this important and the answer is: not at all.

For PSI1 MV66/ETVEN has a bias $\Delta\delta = 0.00049$. For this wave, using 11 years data of a superconducting gravimeter we have got a MSE (mean square error or deviation) $\sigma(\mathrm{PSI1}) \cong 0.01$. Even if we shall soon get 10 times better results the bias given above will be estimated through

(16) $\Delta\delta = 0.0005 \pm 0.0020$ (confidential probability 95%).

The inference of (16) is that $\Delta\delta$ is clearly not significant. It makes no difference if the result is $\delta = 1.00000$, 1.00049, 0.99951, 1.00199, etc.

Same are all biases in Test case 1 and 2 of WEN. For any real data of today or the recent and not so recent future they are not significant.

Example 3. Analyses of model data of WEN using different programs. The biases of δ from the model value $\delta = 1.00000$ are given.

The mean square errors (deviations) for real data are obtained from the analysis of 11 years data of a superconducting gravimeter (Brussels).

wave	method MV66, program ETVEN	better result ETERNA or ETVEN ?	method Wenzel, program ETERNA	better result ETERNA or NSV ?	method MV66, program NSV	mean square errors real data
Q1	0.00015	ETERNA	0.00004	=	0.00004	± 0.00052
O1	1	=	1	NSV	0	10
M1	6	=	6	NSV	4	116
K1	0	=	0	ETERNA	1	7
PSI1	78	ETERNA	19	ETERNA	25	923
PHI1	33	ETERNA	8	ETERNA	45	535
J1	12	ETERNA	11	NSV	8	117
OO1	13	=	13	NSV	12	165
2N2	24	ETVEN	37	ETERNA	40	288
N2	19	ETERNA	5	ETERNA	7	38
M2	1	=	1	NSV	0	7
L2	15	ETVEN	21	ETERNA	46	223
S2	1	=	1	NSV	0	18
K2	3	ETVEN	4	NSV	2	46
M3	207	ETERNA	142	NSV	32	252
M4			270	ETERNA	344	18612

In the first columns of Example 3 are compared results of MV66/ETVEN and the ETERNA program for Test case 2 of WEN. If these results could be a criterion, ETERNA has given better results for 6 waves (Q1, PSI1, PHI1, J1, N2, M3). For other 6 waves (O1, M1, K1, OO1, M2, S2) the results are the same and in 3 cases (2N2, L2, K2) the results are in favor of ETVEN. Shall we then recommend for 2N2, L2 and K2 to use ETVEN instead of ETERNA?

Of course not. These results are very poor to be applied in real situations. But one is clear - the conclusion made by WEN: "For all five test cases, the ETERNA 3.1 results are much superior than the MV66 results" is too strong, at least it is not observed at 9 waves for taste case 2.

The bias in ETVEN is due to a small leakage between the main species, because they are not perfectly separated. If we remain to the elementary conception about the aliasing effect, this would be irreparable, because the D, SD and TD waves are aliases.

It is not so. In NSV are options, which allow to include in the analyses terms corresponding to the leakage, e.g. D and TD tidal groups when the D tides are determined. The results when these options have been used, are given in the same Example 3, column NSV.

Surprising or not, the conclusion could be that MV66 is superiour to ETERNA - NSV is better for 8 waves, while ETERNA is better for 6 waves only.

We think that this conclusion is generally right but not on the basis of these results.

In the last column of Example 3 are given estimates which provide a realistic idea what is the precision we can obtain. Having in mind this precision we can conclude that all biases in Table 3 are not significant, i.e., with respect of such model data, ETERNA, MV66/ETVEN and MV66/NSV are completely equivalent.

It is certainly interesting and useful to check a program using theoretical models like those of WEN. However, a reasonable comparison of methods and programs needs more sophisticated theoretical and empirical studies, using real data and models with random noise.

In our opinion (Venedikov, 1978) the model data have to include: stationary noise, noise with randomly varying variance, random jumps, drift with random changes of its behaviour, randomly varying meteorological waves, calibrations with stationary noise etc.

6. Conclusions.

Although we have been defending MV66, we are far from the idea that it is a perfect solution of our problem. Therefore it is very important other good methods, like ETERNA and Chojnicki to be developed and applied. The computations are very sophisticated and it is encouraging to see that other methods provide similar results to yours. We also hope that soon will be created better methods than MV66.

At the moment, our general conclusions from the discussion above and in WEN can be formulated in one item:

(i) it is still early to state that MV66 is obsolete.

Acknowledgments.

We are thankful to Prof. Wenzel for our fruitful discussion which has been maintained in a personal way, as well as through the critical WEN and, we hope so, will continue. He has been so kind to provide us his valuable theoretical model data.

We are also thankful to Prof. Wenzel for his appreciation of the service made by MV66, in particular for that he has mentioned the tidal unknowns ξ and η as our contribution.

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