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Special Issue

Meeting of the three Working Groups of the Permanent Commission on Earth Tides

Bonn, october 1992

Part I

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PREFACE

The three working groups on

1. Theoretical Tidal Model

2. Calibration

3. High Precision Tidal Data Processing

which depend on the Permanent Commission on Earth Tides, met in Bonn in October 1992. These WG are chaired by V. Dehant, B. Richter and G. Jentzsch, respectively.

The main topics of the different WG were the following :

1. Theoretical Tidal Model

At the IUGG General Assembly, Vienna 1991, new Earth tidal models were presented incorporating the effects of lateral inhomogeneities. These effects contain in particular the effects of Earth ellipticity. Presently there are discrepancies between the results compared to the Wahr-Dehant model for the Love numbers and the gravimetric factors. This session has addressed that question and all the questions relative to the theoretical tidal models; in particular, one session has been devoted to the tidal potentials.

2. Calibration of gravimeters

The progress made regarding the calibration of the superconducting gravimeter (SCG) have been discussed and the different procedures have been compared (vertical accelaration, parallel recording, ...). In addition, also the calibration of spring gravimeters was an important topic (vertical base line, other in-situ methods). Further, progress in design, handling and data acquisition of the SCG has been another topic.

3. High Precision Tidal Data Processing

We have continued our discussions on different topics such as instrumentation (advances in sensor technology, feedback systems, high resolution data acquisition, ...), preprocessing (numerical filters, data storage, handling of additional channels, ...), tidal potentials (continuation of the comparison of the new developments), tidal analysis (data correction and preparation, single-channel/multi-channel techniques, ...), tidal residuals (meteorological influences on high resolution records, ocean tidal models, ...), drift representation (and other non-tidal signals), data bank (report from ICET).

There were a lot of contributions. Many authors have sent camera-ready papers that are here after published.

There has been a lot of constructive discussions that the chairmans have summarized. These "conclusions" are printed here at first place. They allow an overview over the following papers.

The meeting again took place at the Institute for Theoretical Geodesy, University of Bonn, October 6-8, 1992. Again Prof. M. Bonatz was our host and provided us with good conditions. We would like to thank him hardly for his hospitality.

As chairmans of the working groups, we wish to thank all participants for their contributions. We all acknowledge the support from the "Deutsche Forschungsgemeinschaft".

We thank Prof. P. Melchior for publishing all the material in the Bulletin d'Information of the International Center of Earth Tides.

Conclusions drawn during the meeting of the Working Group on "Theoretical Tidal Model" Bonn, October 14 - 16, 1992.

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1 Concerning the definition of the tidal gravimetric factor:

- We are sure that the definition used by Wahr is different with respect to the definition used by ICET.
- We then wonder what definition must be used for tides or geodetic measurements like VLBI.
  - For tides, it was admitted that the ICET definition should be used so that the Wahr-Dehant model can be used for the tidal gravimetric factor.
  - For geodetic measurements, the question is still open. In practice, Wahr's definition has been used.

  There is still the question of unification of the definition. This should be discussed during the next Earth Tides meeting, before any final recommendation.
- There has been a demand for a publication for practical use of the tidal gravimetric factors of the Wahr-Dehant model for the complete set of waves like Dehant had computed and presented in Vienna. The seismic model that should be used for the computation is PREM. A paper entitled "Wahr-Dehant model for practice" will be prepared by Dehant for the next Earth Tides Symposium.

2 Concerning the tidal model itself:

- Lateral heterogeneity effects on the Love numbers and in particular on the tidal gravimetric factor have been computed by different scientists (Wang, Ivins, Li). Their results should be compared.
- Lateral heterogeneities have small effects on tides (the maximum amplitudes are less than 0.7 %, depending on the authors). There has been a recommendation that encourages the computations of minimum and maximum effects of lateral heterogeneities from different seismic tomography model.

- The effect of the Earth's ellipticity is a particular case of lateral heterogeneity effects: since lateral hetereogeneities are developed in spherical harmonics, the ellipticity corresponds to the component of degree 2 order 0 of the expansion. It is thus possible to compare the results from lateral heterogeneities on the tidal gravimetric factor with either Wahr's "apparent tidal gravimetric factor", or the Wahr-Dehant gravimetric factor, provided that the definition for the gravimetric factor is well given. One comparison shows already that there are some differences. We then propose to repeat calculations with both kinds of computation in the same conditions and compare the results. On one hand, calculations in the case of accounting for the Earth's ellipticity directly in the equation (Wahr model or Wahr-Dehant model) must be done; On the other hand, calculations in the case of a perturbation method which account for lateral heterogeneities of degree 2 and order 0 (Wang's or Li's or Ivins' computations) must be done for the same model under the same hypotheses. A simple model like a homogeneous deformable Earth should be considered for these computations. The same mean values for all the rheological parameters are required for both kinds of computation. The results should be compared during the next ET Symposium.

3 Concerning the constant part of the Earth's gravity:

There has been an interesting suggestion to account for constant tides in the gravity field so that masses outside the Earth are considered. This would imply a change in the definition of the gravitational field. Such a change would also require the agreement of all the concerned different scientific unions and will obviously exceed the power of this working group.

4 Concerning the tidal potential:

- We can agree that the fourth order in the tidal potential must be considered to achieve a better precision.
- We can agree that the planetary perturbations must be considered for the same reason.
- Additional arguments of the tidal potential development is suggested to increase the accuracy.
- There has been a proposition to account for the 5th order of the tidal potential.
- The time scale used in the computations of tides from tidal potentials should be well defined (UT, or UT1, or UTC).
- The choice of the internal accuracy of the potential depends on the accuracy of the ephemeris tide. For a given value of that accuracy, it would be interesting to compute what is the best level of accuracy in the tidal potential.
- There has been a suggestion that the potential should be computed at the 0.1 nanogal level.
- For the comparison of tidal potentials, it is necessary to use an ephemeris tide which is more accurate than the tidal potentials and is independent of the potentials.

- New ephemeris tides have been computed and have been used for comparison with the tides generated by the different tidal potentials that exist and which already satisfy the two first points, i.e. Tamura's potential and Xi Qin Wen's potential. The residuals showing the same features in the time domain as well as in the frequency domain, none of both potentials is preferential.
- There is still a need for a new ephemeris series in order to discriminate between the potentials.
- There has been an encouragement to look in the direction of possible non-newtonian effects on the tidal potential for the computation of the next digit.

Conclusions drawn during the meeting of the Working Groups on "Calibration" and "High Precision Tidal Data Processing" Bonn, October 14 - 16, 1992.

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

1. Instrumentation (general)

Recognising the importance of tilt measurements for local geophysical signals (esp. non-tidal) we
encorage the further development of measuring devices for deep boreholes (< 1000 meters) to use the advantages of the high resolution tilt sensors.

2. Superconducting Gravimeter

Recognising the unique qualities of the superconducting gravimeter (SG), which, under careful control of operating conditions, can achieve residual gravity noise levels in non-tidal and sub-tidal bands of less than 1 nGal for harmonic signals, we
recommend 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,
to realize the benefits of new methods of data processing.

Recognising the need to calibrate superconducting gravimeters, we
recommend that the present development of an inertial gravimeter calibration system be encouraged as well as the application of a high precision portable gravimeter (e.g. SG) to facilitate in-situ calibration of SG and absolute gravimeters.

Regarding the proposal to establish a 'Global Geodynamics Project' (GGP), i.e. to establish a global network of superconducting gravimeters, this Working Group
endorses the goal of GGP and **encourages**
(a) all SG groups to participate where possible in GGP,
(b) working closely with GGP on establishing standards for data format appropriate to future exchange of raw SG data, and to
(c) provide profiles of each station to enable the development of standards.

3. Tidal analysis

Recognising the neccessity of recording high-rate data in order to extend the spectrum to higher frequencies and to improve the signal-to-noise ratio in the tidal bands we
recommend to continue the development of automatic processing programs for handling these data.

4. International Center of Earth Tides (ICET)

Recognising the fruitful and encouraging work of the International Center of Earth Tides (ICET) for

- defining new research goals,
- carrying out own research programs,
- motivating scientists in developing countries,
- collecting tidal data and exchange of information

we strongly

recommend that the Center should continue after the retirement of its founder Paul Melchior, under revised terms of reference to be discussed during the next Symposium on Earth Tides, Beijing, 1993.

Recognising that still many groups do not make their data available to the ICET data bank, and

realising that already some records were lost without a copy at the Center we

recommend that esp. gravity tidal data (including the necessary informations, e.g. air pressure) should be sent to ICET for storage in the data bank.

Recognising the existens of many old spring gravimeters esp. in East-Europe and the possibility of their use by recording in these countries we

ask the ICET to provide technical help for the modernization of these gravimeters (e.g. feed back system).

Realizing that its definition completely neglects the impact of, for instance, the calibration quality, the term

'quality factor'

has definitely to be cancelled and replaced by the term

'internal consistency factor'

Finally, all the participants of the Working Group meetings greatly acknowledge the successful work of

Prof. Paul Melchior

who, as a pioneer in earth tides research was a motor in the development of our field. We have deep respect for his achievements for tides in special and geosciences in general, and we shall continue to consider on his effort inour domain.

New additions in the Wahr-Dehant model.

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Introduction

The Permanent Commission (V) on Earth Tides of the IAG established, in 1987, a WG entitled "Theoretical Tidal Model" which I am honoured to chair. The tasks of this WG are the following :

1. The first task is to agree on one definition of the tidal gravimetric factor.
2. The second task is to agree upon a tidal model which accounts for as many physical phenomena as possible according to the advance of the technology used for the observations. By "tidal model", we mean the model of the Earth's response to the luni-solar attraction.
3. A third task would then be to agree on a tidal potential development.

The first two tasks of the WG have been considered carefully in the last five years and a model called by the Earth tide community the "Wahr-Dehant" model has been retained. The effects of new additions to this model are considered here and numerical evaluations of these additional effects are computed in order to stress the eventual necessity of taking them into account in a new model. The third task of the WG has been discussed using, as a starting point, the work of Ducarme (1989) and the discussion was reported in the WG report presented at the last meeting on Earth tides (Dehant et al., 1991). New discussions are expected in the last but one session of this meeting (see Qin-Wen, Tamura, and Wenzel, 1992).

1. Tidal gravimetric factor (first task of the WG)

It was not possible before the establishment of the WG to compare the theoretical "apparent tidal gravimetric factor" of Wahr (1979, 1981) to the observed tidal gravimetric factor as defined by the ICET. Dehant and Ducarme (1987) have made the definition uniform; Dehant (1987b) has recomputed a theoretical tidal gravimetric factor (δ) according to the definition used at the ICET which is then proposed for adoption. The altitude above the ellipsoid, which was not taken into account in the definition, has been shown by Dehant (1992) to be negligible except for very high altitude stations for which the observer must correct δ. The remaining question concerns the effects of lateral heterogeneities inside the Earth. Whether they have to be taken into account or not is the next question addressed to the WG.

2. Tidal model (second task of the WG)

The adopted tidal model was Wahr's model for an elliptical, oceanless, hydrostatically prestressed, and uniformly rotating Earth which has an elastic inner core, a liquid outer core, and an elastic mantle (Wahr, 1979, 1981). Dehant (1987a) computed the effect of mantle inelasticity on the tidal gravimetric factor and showed that the amplitudes were increased by about 0.1 % and the phases were of the order of −0.005° (see also Dehant and Zschau, 1989). These results were depending on the model used for the profiles of the Earth's rheological properties (shear and bulk moduli). In front of the disparity of the results for the different inelastic models there is, for the moment, no agreement on one specific set of values for inelastic-model gravimetric factors. Moreover, the results for the elastic PREM model (Dziewonski and Anderson, 1981) are proposed for adoption. The role of the inner core in the theory of Earth tides has also been examined (see de Vries and Wahr, 1991, Dehant et al., 1992, Legros et al., 1992). Indeed, although the inner core existed in Wahr's theory (1979, 1981), the resonance induced by its associated free nutation, called the Free Inner Core Nutation (FICN), was not accounted for. The FICN is a normal mode of the Earth due to the existence of an elliptical, deformable, elastic inner core inside an elliptical, liquid outer core and due to the possibility of having an angle between the instantaneous rotation axis of the inner core and the instantaneous rotation axis of the outer core. It is a prograde quasi-diurnal mode which has a frequency of about − (1−1/470) cycle/day. The associated effects on the tidal gravimetric factor have been shown to be at the limit of being negligible (see Dehant et al., 1992, Legros et al., 1992, Dehant, 1992). Again, the effects of lateral variations in the density, such as those observed by seismic tomography, are not yet taken into account in the tidal model. These lateral heterogeneities induce gravity variations which have been evaluated by different scientists (Ivins, 1992, Wang, 1991, 1992, Rautenberg, 1992). Their results must still be compared and discussed by the WG.

3. Atmospheric pressure

The formalism introduced to compute the FICN resonance in the tidal gravimetric factor could also be used in order to compute the effect of the atmospheric pressure on the different waves and in particular on the S_1 tidal gravimetric factor (see Dehant, 1992, Dehant et al., 1992, Legros et al., 1992). We have evaluated numerically the effect of a S_1 atmospheric tesseral pressure at the station of 10 Pa and shown that the contribution to δ was of the order of 2.5 % which is quite large. This has been shown for an Earth without inner core by Legros and Hinderer (1991) and extended for the presence of an inner core by Dehant et al. (1992) and Legros et al. (1992) (see also Dehant, 1992). Moreover, if one assumes that the S_1 atmospheric loading is modulated by an annual period, contributions due to atmospheric pressure at the P_1− and K_1−frequencies are obtained. For a modulation amplitude of 100 %, the atmospheric loading effect on K_1 is of the order of 0.3 % and on P_1 it is of the order of 0.8 %. These values are certainly not negligible.

4. Discussion and conclusions

The recent discovery of a new normal mode of the Earth due to the presence of the inner core has been thought to be a possible candidate to explain the still existing discrepancy between the theoretical and observed tidal gravimetric factor. But the numerical values have shown that the effects were at the level of some hundredths of a percent for the S_1 wave which is the tidal wave nearest to the resonance and which thus should have the most important effect.

The present model contains an elastic or inelastic, elliptical, rotating, non-homogeneous, deformable mantle, a liquid, elliptical, rotating, non-homogeneous outer core, and an elastic, elliptical, rotating, deformable inner core. It allows for the resonances induced in particular in the diurnal frequency band. With this model one can compute the Earth's response to the luni-solar attraction, namely the tidal gravimetric factor. It still does not include lateral heterogeneities.

The effects of atmospheric loading on the tidal gravimetric factor seem to be responsible for large changes at the tides S_1, P_1, and K_1 : 2.5%, 0.8%, and 0.3% respectively for an example of a 10 Pa atmospheric S_1-pressure and a 100% annual modulation. This stresses the necessity to investigate carefully local or regional atmospheric pressure on gravity variations or to do a global stacking of worldwide gravimeter data.

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Influence of permanent tides on the shape and gravity field of the Earth: Comparison of different approaches.

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1 Introduction

The expressions for tidal influence of the Moon and of the Sun upon the gravity field of the Earth contain the so-called constant part which does not depend on time and changes only with geographical latitude. It is a real part of the Earth gravity field which shares in forming not only the shape of the sea level but also the shape of the Earth body. In the geodetic literature there is recently discussed the problem whether or not exclude the constant part of the Earth tides from geodetic observations together with the periodical parts of the Earth tides.

2 Permanent part of the tidal potential

The zonal part of the expansion of the Moon's or Sun's tidal potential ($p = ☾$ or $\odot$) is given by expression

$$\delta V_p(P) = \frac{GM_p}{\Delta_{\oplus p}} \sum_{n=2}^{\infty} \left(\frac{\rho}{\Delta_{\oplus p}}\right)^n \mathrm{P}_n(\sin\Phi)\, \mathrm{P}_n(\sin\delta_p), \tag{1}$$

where GM_p is selenocentric or heliocentric gravitational constant, ρ, Φ geocentric radius-vector and latitude of P on the Earth's surface, $\Delta_{\oplus p}$ distances between the mass centres of perturbing bodies and the Earth, δ_p declination of the Moon or Sun.

If we express $\Delta_{\oplus p}$ as a function of time, use Doodson's modification, where $c_{\oplus p}$ is mean value of $\Delta_{\oplus p}$ and compute mean integral values for long-term periods, we get acoording to (Zadro, Marussi, 1973) expression for permanent (time independent) part of the Moon's or Sun's tidal potential

$$\begin{aligned}\delta V_p(P) &= \frac{GM_p}{c_{\oplus p}} \sum_{n=2}^{\infty} \left(\frac{\rho}{2c_{\oplus p}}\right)^n \mathrm{P}_n(\sin\Phi) \sum_{k=0}^{n/2} (-1)^k \frac{(2n-2k)!\,(n+1)!}{k!\,(n-k)!} \times \\ &\times \sum_{r=0}^{n} \frac{e_p^r}{(n-r+1)!\,(r!!)^2} \sum_{s=0}^{n-2k} \frac{\sin^2\varepsilon_0 (\sin i_p)^{(n-2k-s)}}{(s!!)^2\,[(n-2k-s)!!]^2}\,.\end{aligned} \tag{2}$$

$e_☾ = 0.05490$, $e_\odot = 0.01671$ are the eccentrities of the orbits, $i_☾ = 5°\,09'$, $i_\odot = 0$ are the inclinations to the ecliptic, $\varepsilon_0 = 23°\,26'\,21.4"$ (obliquity of ecliptic), r and s both assume only even values.

This permanent part of tidal potential reduced to the term $n = 2$ is given by expression

$$\delta V_{2,p}(P) = \frac{GM_p}{c_{\oplus p}} \left(\frac{\rho}{c_{\oplus p}}\right)^2 \mathrm{P}_2(\sin\Phi) \left[\frac{3}{4}\sin^2\varepsilon_0 + \frac{9}{8}e_p^2\sin^2\varepsilon_0 - \frac{3}{4}e_p^2 + \frac{3}{4}\sin^2 i_p - \frac{1}{2}\right]. \tag{3}$$

For simplification, when $\sin i_p = 0$ and $e_p = 0$, the terms of degree $n = 2$ and $n = 4$ are then

$$\delta V_{2,p}(P) \approx \frac{GM_p}{c_{\oplus p}} \left(\frac{\rho}{c_{\oplus p}}\right)^2 \mathrm{P}_2(\sin\Phi) \left[\frac{3}{4}\sin^2\varepsilon_0 - \frac{1}{2}\right], \tag{4}$$

$$\delta V_{4,p}(P) \approx \frac{GM_p}{c_{\oplus p}} \left(\frac{\rho}{c_{\oplus p}}\right)^4 \mathrm{P}_4(\sin\Phi) \left[\frac{105}{64}\sin^4\varepsilon_0 - \frac{15}{8}\sin^2\varepsilon_0 - \frac{3}{8}\right] . \tag{5}$$

Ekman (1979) reaches Eq. (4) using nearly the same procedure.

It is possible to find out simply that permanent part of the tidal field of the Moon and Sun is generated at the points on the Earth's surface by two mass circles with radii R_p located in the plane of the Earth's equator and containing the uniformly distributed masses of the Moon and Sun – see (Zeman, 1987)

$$V_p(P) = -\frac{GM_p}{2R_p}\left(\frac{\rho}{R_p}\right)^2 \mathrm{P}_2(\sin\Phi) . \tag{6}$$

We can see equality with Eq. (4) for the radii

$$R_p = c_{\oplus p}\left(1 - \frac{3}{2}\sin^2\varepsilon_0\right)^{-1/3} = c_{\oplus p}\left[\frac{1}{2} - \mathrm{P}_2(\sin\varepsilon_0)\right]^{-1/3} . \tag{7}$$

As regards the Sun and the Moon, $R_p \approx 1.094 c_{\oplus p}$, because the inclination of the ecliptic as well as the mean inclination of the Moon's orbit to the plane of the Earth's equator are roughly 23.5°.

3 Inclusion of the permanent part of the tidal potential to the parameters defining the normal Earth.

In (Burša, Fialová, 1992) there is set a condition of constant gravity potential $W(E)$ on the surface of the tri-axial ellipsoid equal to real gravity potential W_0 on the geoid. The expressions for coefficients of tidal potential expansion contain then also terms, describing the permanent part of tidal potential. Defining parameters of the tri-axial ellipsoid a (maximum semi-axis), f (the maximum polar flattening), f_1 (the equatorial flattening) and Λ_a (the longitude of the prime meridian) are then expressed as functions of R_0 (the geopotential scale factor), q (factor of potential of centrifugal force) and parameters J_2, $J_{2,2}$, $S_{2,2}$, corresponding to the actual Earth and containing consequently the contributions from permanent part of tides. It is shown that the significant influence of permanent part of tides exists only on values a, f. If we mark the changes of these values as δa, δf we get according to (Burša, Fialová, 1992) expressions, acuracy of them correspond to accuracy of determination of Stokes parameters

$$\delta a = CR_0\left(\frac{3}{4}\sin^2\varepsilon_0 - \frac{1}{2}\right)\left(-\frac{1}{2} + \frac{137}{420}q\right) , \tag{8}$$

$$\delta f = C\left(\frac{3}{4}\sin^2\varepsilon_0 - \frac{1}{2}\right)\left(-\frac{3}{2} + \frac{61}{28}q - \frac{51}{14}J_2\right) , \tag{9}$$

$$C = \left[\frac{GM_{☾}}{GM_\oplus}\left(\frac{R_0}{c_{\oplus ☾}}\right)^3 + \frac{GM_\odot}{GM_\oplus}\left(\frac{R_0}{c_{\oplus\odot}}\right)^3\right] .$$

Expressions (8) and (9) describe only direct effect of permanent tides. Complete effect (direct and indirect) would be given by multiplication of mentioned equations by factor $(1+k)$, where k is Love number. The problem remains to determine its numerical value.

On the basis of numerical values of other parameters (Stokes' parameters from model GEM-T2) the authors (Burša, Fialová, 1992) obtained the parameters of tri-axial ellipsoid, first of all without the effect of permanent tides (tide free)

$$\begin{aligned} a &= (6\,378\,171.36 \pm 0.30)\ \mathrm{m}, \\ 1/f &= 297.7738 \pm 0.03, \\ 1/f_1 &= 91\,449 \pm 60, \\ a &= (14.93° \pm 0.05°)\ \mathrm{W}. \end{aligned}$$

After inclusion of complete effect of tides the parameters $1/f_1$ and Λ_a will not change and the changes of others will be according to Eqs. (8) and (9)

$$\delta a = 0.099(1+k)\ \mathrm{m}, \quad \delta f = 4.62 \times 10^{-8}(1+k)$$

and so

$$\begin{aligned} \tilde{a} &= (6\,378\,171.46 + 0.099k)\ \mathrm{m}, \\ 1/\tilde{f} &= 297.7697 - 0.0041k. \end{aligned}$$

Analogously for ellipsoid of revolution

$$\begin{aligned} a &= (6\,378\,136.49 \pm 0.30)\ \mathrm{m}, \\ 1/f &= 298.2577 \pm 0.0003, \\ \tilde{a} &= (6\,378\,136.59 + 0.099k)\ \mathrm{m}, \\ 1/\tilde{f} &= 298.2536 - 0.0041k. \end{aligned}$$

If we accept for Love parameter numerical value $k = 0.3$, we get the parameters of bi-axial ellipsoid with complete permanent tidal effects (direct and indirect) corresponding to the so-called "mean" values

$$\begin{aligned} \tilde{a} &= 6\,378\,136.62\ \mathrm{m}, \\ 1/\tilde{f} &= 298.2524. \end{aligned}$$

From the changes of parameters of bi-axial ellipsoid then the changes of gravity acceleration γ on its surface follow (γ_a, γ_b - gravity accelerations on the equator and at the poles, respectively). Computations for all above mentioned cases (tide free, zero and mean values) we shall carry out using the expressions

$$\begin{aligned} \gamma_a &= \frac{GM_\oplus}{ab}\left(1 - \frac{3}{2}m - \frac{3}{14}me'^2\right), \\ \gamma_b &= \frac{GM_\oplus}{a^2}\left(1 + m + \frac{3}{7}me'^2\right), \end{aligned} \tag{10}$$

where $m = \omega^2 a^2 b / GM_\oplus$ and $e'^2 = (a^2 - b^2)/b^2$. When $GM_\oplus = (398\,600.441 \pm 0.001) \times 10^9\ \mathrm{m^3 s^{-2}}$, $\omega = 7\,292\,115 \times 10^{-11}\ \mathrm{rad\,s^{-1}}$, and when we denote values with only direct effect by a bar and the values withh both direct and indirect effects (mean values) by tilde, then

$$\begin{aligned} \gamma_a &= 9.780326756\ \mathrm{m\,s^{-2}} & \gamma_b &= 9.832106648\ \mathrm{m\,s^{-2}} \\ \gamma_{\bar{a}} &= 9.780326900\ \mathrm{m\,s^{-2}} & \gamma_{\bar{b}} &= 9.832186342\ \mathrm{m\,s^{-2}} \\ \gamma_{\tilde{a}} &= 9.780326944\ \mathrm{m\,s^{-2}} & \gamma_{\tilde{b}} &= 9.832186251\ \mathrm{m\,s^{-2}} \\ \gamma_{\bar{a}} - \gamma_a &= +14.4\ \mu\mathrm{Gal} & \gamma_{\bar{b}} - \gamma_b &= -30.6\ \mu\mathrm{Gal} \\ \gamma_{\tilde{a}} - \gamma_a &= +18.8\ \mu\mathrm{Gal} & \gamma_{\tilde{b}} - \gamma_b &= -39.7\ \mu\mathrm{Gal} \end{aligned}$$

4 Inclusion of the permanent part of the tides to the definition of gravity field of the normal Earth.

In (Zeman, 1987) the problem of permanent part of the tidal field is solved by such definition of normal gravity field, which this part of tidal field includes. This approach is analogous to elimination of the field of centrifugal force.

If we suppose according to (Yurkina, Šimon, Zeman, 1986) that in the expression for perturbing potential T the permanent part of the tidal potential is either in the real gravity potential W or in the normal gravity potential U, we can define it this way

$$T^* = W - U^* . \tag{11}$$

New definition of the normal gravity potential U_0^* on the surface of equipotential ellipsoid of revolution then, using development according to (Heiskanen, Moritz, 1967) will be

$$U_0^* = \sum_{n=0}^{\infty} A_n P_n(\sin\beta) + \frac{1}{2}\omega^2(b^2 + E^2)\cos^2\beta + \Delta V , \tag{12}$$

where ΔV is the symbol for permanent part of the tidal potential, β is so-called "reduced" latitude, $E^2 = a^2 - b^2$, ω the angular velocity of the Earth's rotation and A_n are coefficients of zonal terms of the expansion.

Simply we can show that the potential ΔV is generated just by two mass circles, containing uniformly distributed masses of the Moon and the Sun according to Eqs. (6) and (7). The expression (6) we shall only write in this form now

$$\Delta V = -\frac{G\rho^2}{2} \sum_{p=☾,\odot} \frac{M_p}{R_p^3} \mathrm{P}_2(\sin\Phi) \, . \tag{13}$$

Comment: Possibility to express the permanent part of the tidal field of the Moon and of the Sun by help of two mass circles is significant for geometric interpretation of the gravity field of the normal Earth. Newly defined normal gravity field is given by gravity field of the equipotential ellipsoid of revolution as usual and by the gravitational effect of two mass circles, located in the plane of the Earth's equator and containing the masses of the Moon and the Sun with radii $R_☾$ and $R_\odot$.

If we express the radius-vector ρ of the ellipsoid in the ellipsoidal coordinates and neglect the difference between the geocentric and "reduced" latitude, we get for normal gravity field on the surface of the ellipsoid the expression

$$U_0^* = \sum_{n=0}^{\infty} A_n \mathrm{P}_n(\sin\beta) + \frac{1}{2}\omega^2 a^2 \cos^2\beta - \frac{G}{2}(b^2 + E^2\cos^2\beta) \sum_{p=☾,\odot} \frac{M_p}{R_p^3} \mathrm{P}_2(\sin\beta) \, . \tag{14}$$

The third part of the right hand side of this equation we have to rearrange this way

$$-\frac{G}{2}(b^2 + E^2\cos^2\beta) \sum_{p=☾,\odot} \frac{M_p}{R_p^3} \mathrm{P}_2(\sin\beta) = \left[\frac{GE^2}{15} - G\left(\frac{a^2}{2} - \frac{11E^2}{42}\right)\mathrm{P}_2(\sin\beta) + \right.$$

$$\left. + \frac{6}{35} GE^2 \mathrm{P}_4(\sin\beta)\right] \sum_{p=☾,\odot} \frac{M_p}{R_p^3} . \tag{15}$$

Numerical analysis leads to conclusion that we can confine ourselves only to the term with maximum value

$$\frac{1}{2} G a^2 \sum_{p=☾,\odot} \frac{M_p}{R_p^3} \mathrm{P}_2(\sin\beta) \le 2.7\,\mathrm{m^2 s^{-2}} .$$

Other terms are at least two orders smaller. The term

$$\frac{GE^2}{15} \sum_{p=☾,\odot} \frac{M_p}{R_p^3} \approx 2.4 \times 10^{-3}\,\mathrm{m^2 s^{-2}} ,$$

which would has to be included to the redefinition of the normal gravity potential on the surface of the ellipsoid is sufficiently small to be neglected.

Further development is analogous to that in (Heiskanen, Moritz, 1967) and more detailed it is in (Zeman, 1987). If we accept above mentioned simplifications, following Eq. (15), this very important equality is valid

$$U_0^* = U_0 = \frac{GM_\oplus}{E} \tan^{-1}(E/b) + \frac{1}{3}\omega^2 a^2 . \tag{16}$$

Further development leads after some algebra to the expressions for outer gravity potential of equipotential ellipsoid

$$U^*(u,\beta) = \frac{GM_\oplus}{E} \tan^{-1}(E/u) + \left(\frac{1}{3}\omega^2 a^2 + \frac{1}{2} G a^2 \sum_{p=☾,\odot} \frac{M_p}{R_p^3}\right)\left(\frac{q}{q_0}\right) \mathrm{P}_2(\sin\beta) +$$

$$+ \frac{\omega^2}{2}(u^2 + E^2)\cos^2\beta - \frac{G}{2}(b^2 + E^2\cos^2\beta) \mathrm{P}_2(\sin\beta) \sum_{p=☾,\odot} \frac{M_p}{R_p^3} , \tag{17}$$

where u is the semi-minor axis of ellipsoid just coming through given outer point, q and q_0 are symbols for zonal terms of second degree of Legendre's functions of second kind with complex arguments $z = i(u/E)$ and $z_0 = i(b/E)$, $(i = \sqrt{-1})$ – see (Heiskanen, Moritz, 1967).

Normal gravity acceleration on the surface of equipotential ellipsoid is then after some more algebra

$$\gamma_0^* = \frac{GM_\oplus}{a}(a^2\sin^2\beta + b^2\cos^2\beta)^{-1/2} \left\{ \left[1 + 2m' + \left(\frac{m}{3} + m'\right)\frac{e' q_0'}{q_0}\right] \sin^2\beta + \right.$$

$$\left. + \left[1 - m - m' - \frac{1}{2}\left(\frac{m}{3} + m'\right)\frac{e' q_0'}{q_0}\right] \cos^2\beta \right\} , \tag{18}$$

where

$$m = \frac{\omega^2 a^2 b}{GM_\oplus}, \quad m' = \frac{a^2 b}{2M_\oplus} \sum_{p=\mathbb{C},\oplus} \frac{M_p}{R_p^3}, \quad \frac{e' q_0'}{q_0} = 3(1 + \frac{3}{7}e'^2 \ldots).$$

More detailed development is in (Zeman, 1987).

The normal acceleration of gravity on the equator ($\beta = 0°$) and at the poles ($\beta = 90°$) then comes out as

$$\begin{aligned} \gamma_a^* &= \frac{GM_\oplus}{ab}\left(1 - \frac{3}{2}m - \frac{3}{14}me'^2 - \frac{5}{2}m' - \frac{9}{14}m'e'^2\right), \\ \gamma_b^* &= \frac{GM_\oplus}{a^2}\left(1 + m + \frac{3}{7}me'^2 + 5m' + \frac{9}{7}m'e'^2\right). \end{aligned} \tag{19}$$

The difference as compared to the normal acceleration of gravity on the equator and at the poles, as defined by the G.R.S. 1980, is given by the terms with m' . Numerical values are then

$$\begin{aligned} \gamma_{a,1980} &= 9.7803267715\,\mathrm{m\,s^{-2}}, & \gamma_{b,1980} &= 9.8321863685\,\mathrm{m\,s^{-2}}, \\ \gamma_a^* &= 9.7803260005\,\mathrm{m\,s^{-2}}, & \gamma_b^* &= 9.8321879005\,\mathrm{m\,s^{-2}}, \\ \gamma_a^* - \gamma_{a,1980} &= -77.1\,\mu\mathrm{Gal}, & \gamma_b^* - \gamma_{b,1980} &= +153.2\,\mu\mathrm{Gal}. \end{aligned}$$

5 Solution of the problem by simple corrections to the gravity anomalies

In (Yurkina, Šimon, Zeman, 1986) there is newly defined boundary value condition

$$\frac{\partial T}{\partial H} - \frac{T}{\gamma}\frac{\partial \gamma}{\partial H} = -g + \gamma_{HQ} - \frac{W_0 - U_0}{\gamma}\frac{\partial \gamma}{\partial H} + \frac{P}{\gamma}\frac{\partial \gamma}{\partial H} - \frac{\partial P}{\partial H}, \tag{20}$$

containing only the actual values of the geodetic observations. In Eq. (20), there is H_Q normal height and P is the symbol used here for constant part of the tidal potential (the direct effect only). However, the last two terms are here the new ones, contrary to the usual form of the boundary value condition. Both these correction terms have the same values, it is clear from their spherical approximation $(P/\gamma)(\partial\gamma/\partial H) \approx -2P/R$ and $\partial P/\partial H \approx 2P/R$, when R is the mean radius of the Earth. Then we can write the boundary value condition as

$$\frac{\partial T}{\partial H} - \frac{T}{\gamma}\frac{\partial \gamma}{\partial H} = -g + \gamma_{HQ} - \frac{W_0 - U_0}{\gamma}\frac{\partial \gamma}{\partial H} - \frac{4P}{R}. \tag{21}$$

Physical meaning of the mentioned last two terms of Eq. (20) is clear too. Term $\partial P/\partial H$ is the correction of the measured gravity acceleration from the influence of the outer masses and the term $(P/\gamma)(\partial\gamma/\partial H)$ is the correction of the normal gravity acceleration as a consequence of the fact that the heights are measured at real gravity field. Then it is quite enough to correct only the gravity anomalies by the correction $4P/R$ which is +61 μGal on the equator, and −122 μGal at the poles.

6 Conclusions

Three approaches to the solution of the problem of permanent part of tidal field are presented:

– The solution according to (Burša, Fialová, 1992) is based on the definition of the parameters of ellipsoid, following from the expansion of real gravity potential, containing also the permanent part of the tidal field of the Moon and the Sun. If we restrict ourselves on the development for ellipsoid of revolution only, the discussed solution leads to the changes of semi-major axis and polar flattening. The change of the shape brings the change of gravity acceleration. Numerical values of the changes are given in this text. The question arises, if when only "zero" value of J_2 parameter is respected in the case of ellipsoid of revolution, the changes of the ellipsoid parameters lead to real values of changes of the gravity acceleration from the influence of the permanent part of the tidal field.

– The solution according to (Zeman, 1987) in which the direct effect of permanent part of the tidal field is included to the outer normal gravity field of the Earth, without the influence on the parameters of reference ellipsoid and with some simplification also without the influence on the value of normal gravity potential U_0^* on its surface. Numerical values, given in text, witness to significant greatness of the corrections of gravity acceleration from the influence of time independent part of the tidal field of the Moon and the Sun.

The great merit of this approach to the solution is the fact that when the direct effect of permanent tides is included to the definition of the normal gravity field, the gravity anomaly (difference between measured value of g without periodic part of tidal field only, and normal gravity acceleration γ^* defined this way) will have features of the so-called "zero" value, which can be used exactly in the sense of IAG recommendation.

The significant merit of this approach is also the fact that normal heights H_Q^* would be given in the case of new definition of normal gravity acceleration by the expression – see (Zeman, 1991), from which it follows that the changes of heights will be, in contrast to other approaches, very small (only in units of 10^{-4} m even for extreme conditions).

– The solution according to (Yurkina, Šimon, Zeman, 1986) is based on the same presumption as in the previous case according to (Zeman, 1987), but it restricts itself only to the purpose of the computation of geoid heights from gravity anomalies.

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Self similarities in the harmonic development of tides? (extended abstract)

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There is increasing evidence that self-similarity is a widespread phenomenon in nature. When looking at a line spectrum of the harmonic development of e.g. gravity tides - log of amplitudes over frequency -, one may wonder whether self-similarity is also hidden in that kind of data: Individual harmonic constituents are grouped in tidal bands; within each band the constituents are arranged in subgroups; the subgroups themselves are subdivided in sub-subgroups, and so on; a few constituents have big amplitudes, e.g. bigger than 1 μgal; quite many have amplitudes bigger than 10 ngal; still, much more have ampltidues bigger than 0.1 ngal, etc. What would be the relation between, on one hand, the amplitude of some constituent, and, on the other hand, the number of constituents having an amplitude bigger than this one? The latter question is similar to asking for the frequency - magnitude relation of tidal constituents (instead for that of earthquakes in a specified region within a representative period of time).

I analysed the frequency - magnitude relations of the following developments of the harmonic tidal potential: Doodson (1921), Cartwright, Edden & Tayler (1971, 1973), Büllesfeld (1985), Tamura (1987), and Xi Qinwen (1987, 1989). The number of <u>different</u> tidal frequencies taken into account by these authors are 379, 505, 649, 1200, and 2845, respectively. Let $\mathbb{A}$ denote the dimensionless amplitude of an arbitrary harmonic constituent, and $\mathbb{N}(\mathbb{A})$ the number of constituents of amplitude greater or equal to $\mathbb{A}$. The log-log-plot of $\mathbb{N}(\mathbb{A})$ over $\mathbb{A}$ is Fig.1.

Obviously, the overall relation appears to be roughly linear over at least four orders of amplitude size, and data from more recent models seem to resume the trend of earlier, less complete models. Furthermore, there is no fundamental difference in this behaviour between all of the data and amplitudes of longperiodic, diurnal, semidiurnal, or terdiurnal tidal bands (as demonstrated for the Tamura model in Fig.1).

Amazingly, the overall trend of the log-log-relationship closely follows the simple equation

$$N = 4 \cdot \mathbb{A}^{-0.5} \quad . \qquad (1)$$

It is easily recognized that a relation with, for instance, 3 or 5 instead of 4 as coefficient in eq.(1), or with exponent -0.4 or -0.6 instead of -0.5, yields a much worse fit. The rather poor fit for big amplitude values could be a consequence of the low number of constituents having such big amplitudes. Given that the amplitude is the characteristic linear dimension of a harmonic constituent, the set of all constituents may be said to have a fractal distribution (Turcotte, 1989). The fractal dimension of that distribution is then close to 0.5.

If for any reason eq.(1) would be correct, several conclusions may be drawn:

- When for the refinement of some tidal model the level of amplitudes to be included shall be lowered by a factor of one hundred, the number of frequencies that have to be considered in the new model will be about ten times higher than in the old model.
- For a complete model of constituents, down to infinitely small amplitudes, the number of constituents will be infinite.
- Since the amplitude A_i of the i-th biggest constituent is on average $16/i^2$ (inversion of eq.(1)), the sum of all amplitudes, i.e. for i running from 1 to infinite, may be obtained by computing the sum of the respective infinite series. This sum is 26.3189451... or $16\,\pi^2/6$ (Bronstein & Semendjajew, 1970).
- Similarly, knowing the number of constituents included in some tidal model, the average sum of the corresponding amplitudes can be computed. Then, the residue with regard to a complete model, i.e. the sum of all the neglected amplitudes, can be estimated to be

$$\text{Residue} \approx 16 \cdot \left(\pi^2/6 - \sum_{i=1}^{N} 1/i^2 \right). \qquad (2)$$

The residues of the models cited above are, in percentage of the M_2-amplitude: 4.6% for Doodson's development (1921), 3.5% for the Cartwright et al. model (1971, 1973), 2.7% for the model of Büllesfeld (1985), 1.5% for that of Tamura (1987), and 0.61% for Xi Qinwen's model (1989). It has been assumed that all models are complete, meaning that no constituent with an amplitude bigger than the smallest one has been omitted. Correspondingly, about 16 000 constituents (different frequencies) have to be included in a model to reduce its residue to 0.11% of the M_2-amplitude, about 160 000 to reduce it to 0.011%, and so on.

So far the findings are purely empirical. In the search for a theoretical reasoning it may worthwhile to investigate whether **any** form of the frequency - magnitude relation of the harmonic development of tides could be justified, or if a fractal distribution reflects some intrinsic, natural aspect in the phenomenon of tides.

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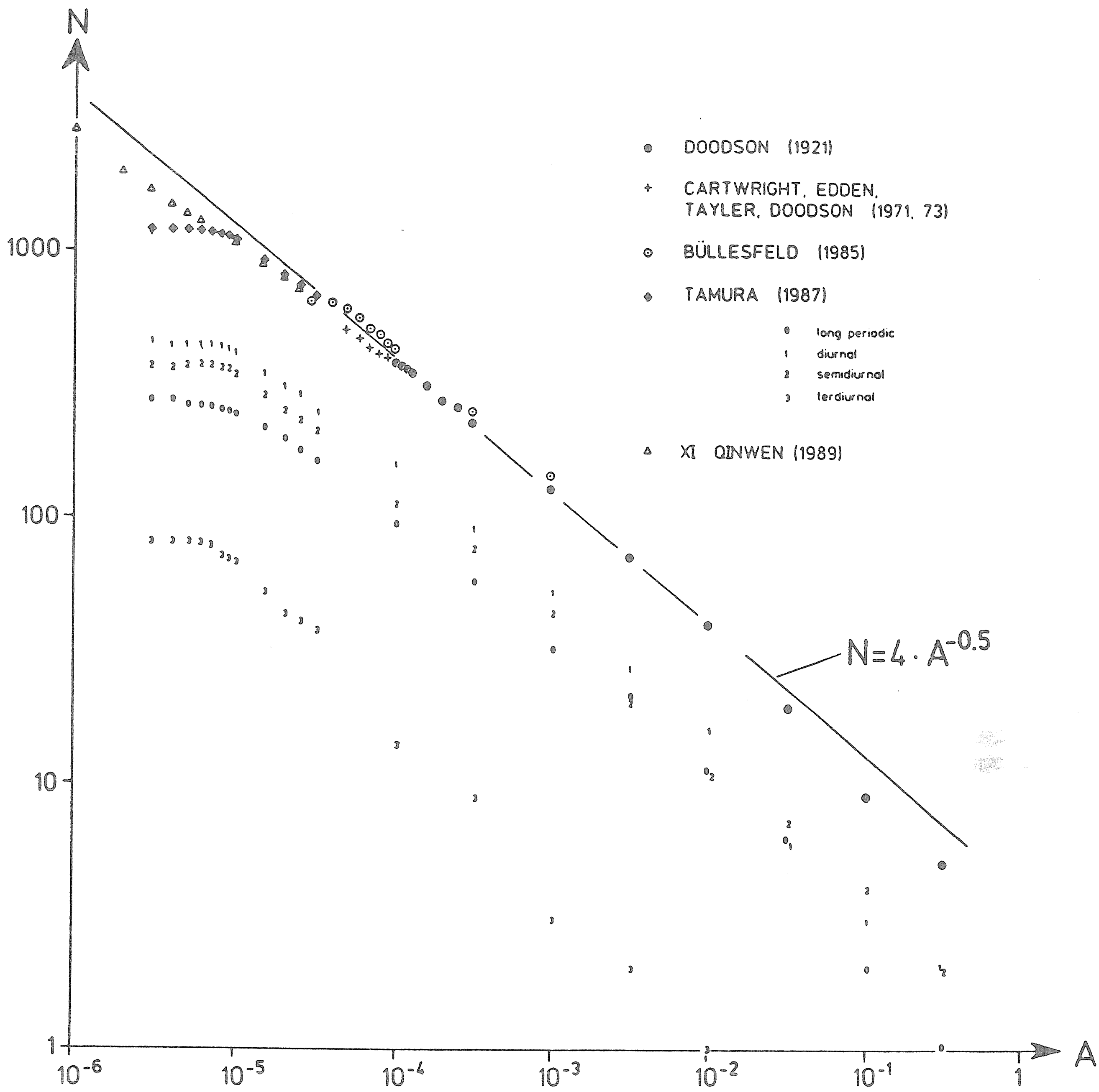

Figure 1: Log-log-plot of number **N** of harmonic constituents of amplitude equal or greater than some dimensionless amplitude **A** of the tidal potential, over **A**, displaying a 'frequency - magnitude relation' close to $N = 4 \cdot A^{-0.5}$. Tidal potential according to models of various authors, as indicated. Harmonic constituents of long periodic, diurnal, semidiurnal, and terdiurnal tidal bands for Tamura's model only. For big values of **A** two datapoints per amplitude-decade have been plotted, up to eight datapoints per decade for smaller values of **A**.

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On the comparison of the new developments of the tidal generating potential.

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1. Introduction

It is common knowledge that the standard tidal potential model CTED is not precise enough for analysis of precise gravity data, especially for analysis of superconducting gravimeter data. At the moment, two approaches to the development of a high precision tidal potential have been presented. One is obtained directly by an analytic method (Xi,1989); the other is obtained by a spectral method (Tamura,1987). The precision of the tidal potential was first discussed by Ducarme (Ducarme,1989); subsequently Friedrich & Zimmermann (Friedrich and Zimmermann,1989) and Hinderer, Crossley & Florsch (Hinderer, Crossley and Florsch,1991) discussed the same problem. In Ducarme's paper the data set is not precise enough as a base for evaluating the potentials. The two authors do not compare the precision between Xi's and Tamura's tidal potential. We have discussed the precision of the tidal potential developed by Xi (Xi,1989) and the standard data set established as a basis, but have not compared the precision with Tamura's potential. The working group on high precision tidal data processing has recommended a comparison of the precision of the two tidal potentials using the same astronomical and geophysical parameters.

2. Comparison

A basic or standard data set should therefore be adopted for tidal potential comparison. We continue to use the standard data set established by Xi several years ago (Xi,1991). This data set, the theoretical gravity tides in 1987, was done for a station at latitude 40.0 ° N, longitude 116.0 ° E and elevation 0.0 M. It includes the potential up to fourth degree for the moon and third degree for the sun, but does not include the corrections of the conversion from the plumb line to the normal line. In author's opinion, this conversion is only a transformation of the coordinate systems. Therefore one can adopt any system (plumb or normal) for the comparison.

At first the theoretical gravity tides corresponding to the station and the year above mentioned were calculated using Xi's and Tamura's tidal potential respectively. Then the residuals were obtained by subtracting the standard data set from the theoretical gravity tides.

In order to avoid the increase of phase error with time, an expression ($a\tau+bs+ch+dp+eN+fp_s$) was used instead of the angular velocity in calculation of the phases. Fig. 1 and Fig. 2 show the residuals of Xi's and Tamura's tidal potential. Fig. 3 and Fig. 4 show the respective power spectra.

The standard deviations are expressed as follows

$\sigma_{Xi} = \pm 5.1$ ngal

$\sigma_{Tamura} = \pm 6.2$ ngal

3. Conclusion

The standard deviations indicate that the error of Xi's tidal potential is lower than that of Tamura's. From Fig. 1 and Fig. 2, one can see that the residuals of Tamura's are generally greater than Xi's. The extreme values of the residuals are −27 ngal and 26 ngal for Tamura's and −18 ngal and 24 ngal for Xi's. From Fig. 3 and Fig. 4, one can see that the residual power is greater for Tamura's potential compared to Xi's at the high frequencies (over the frequency of the diurnal waves). Fig. 5 and Fig. 6 are the histograms of the residuals. The distribution in Fig. 5 is more symmetric and concentric than that in Fig. 6.

The relation between the precision and the number of components in Xi's tidal potential was investigated by using different values of the amplitude cut off (H> 1,5,6,7,8,9,10) and by evaluating respective errors. The results show in Table 1.

Table 1. The relation between the precision (m) and the number of components (N) in Xi's tidal potential

	1	2	3	4	5	6	7
H>	1	5	6	7	8	9	10
N	3070	1400	1302	1236	1181	1124	1079
m^{ngal}	± 5.1	± 6.4	± 6.8	± 7.1	± 7.9	± 8.5	± 9.3

Each column in Table 1 is corresponding to a subset of Xi's complete tidal potential, and it has N components and a computed precision m. In the first column, the precision is the highest as it corresponds to the complete tidal potential. If we take a precision of 10 ngal as a practical requirement, the seventh column is a sufficient choice with the least number of components. The second column is a good choice as it satisfies both a modest number of components and higher precision at the same time. In author's opinion, the second column is the most appropriate choice. It is clearly an advantage of Xi's tidal potential that one can construct different tidal potentials for the different requirement precision in use .

In view of the current availability of high–speed computers, it seems reasonable that the choice of a tidal potential for tidal computation should not depend on the number of components in a particular expansion. The precision of the tidal potential and the requirement in use are the important decisive factors.

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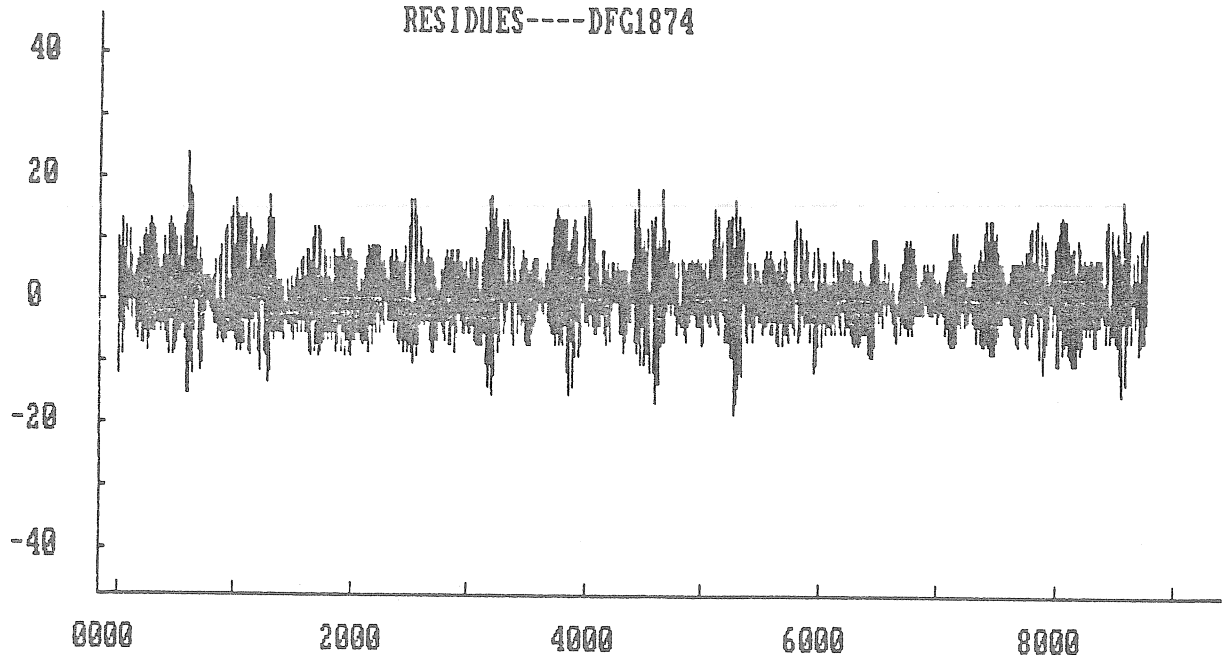

Fig. 1. The residuals of Xi's tidal potential

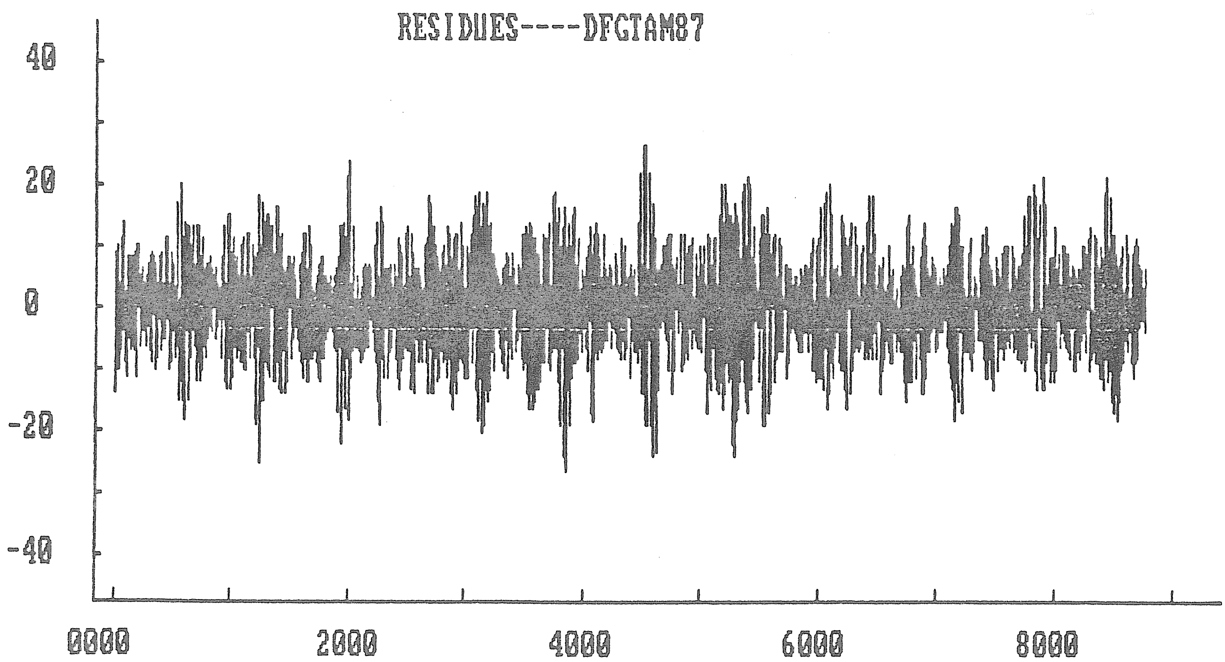

Fig. 2. The residuals of Tamura's tidal potential

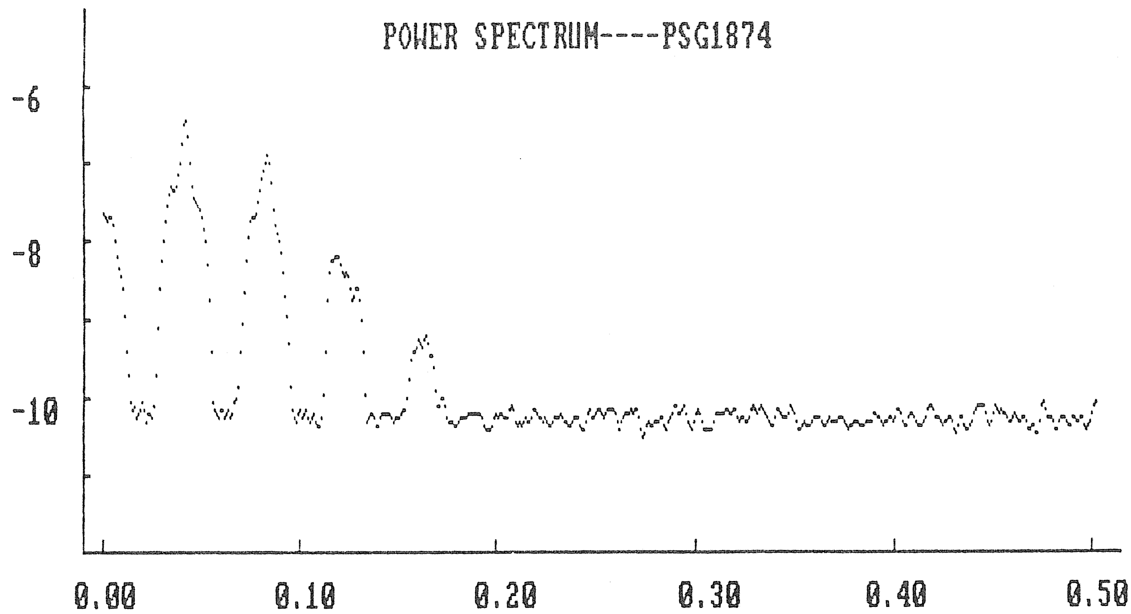

Fig. 3. The power spectra of Xi's tidal potential

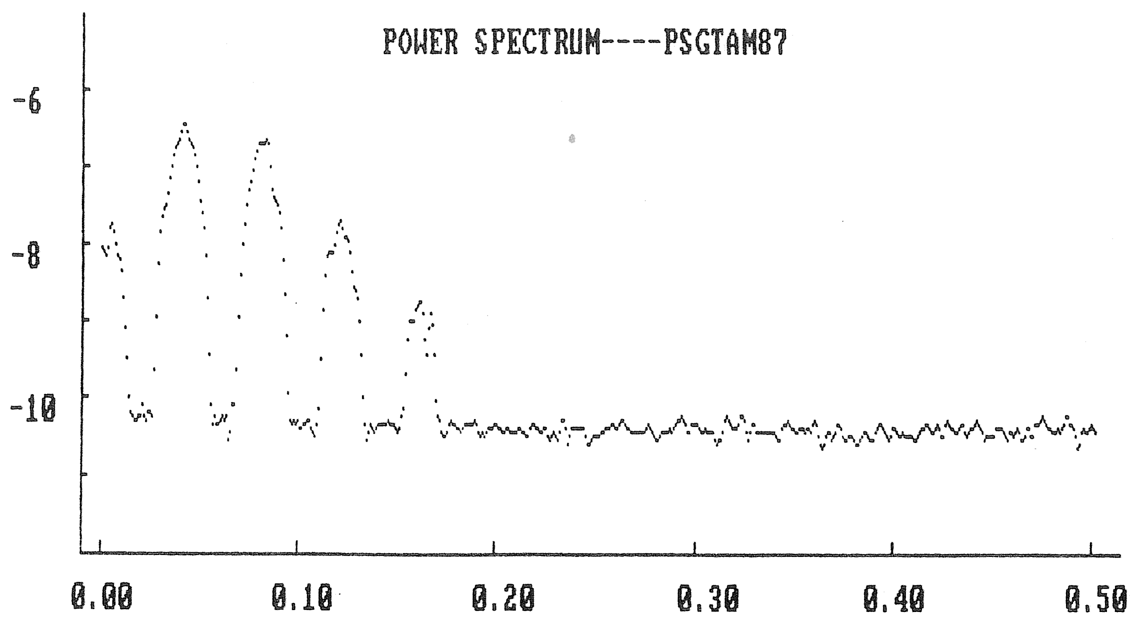

Fig. 4. The power spectra of Tamura's tidal potential

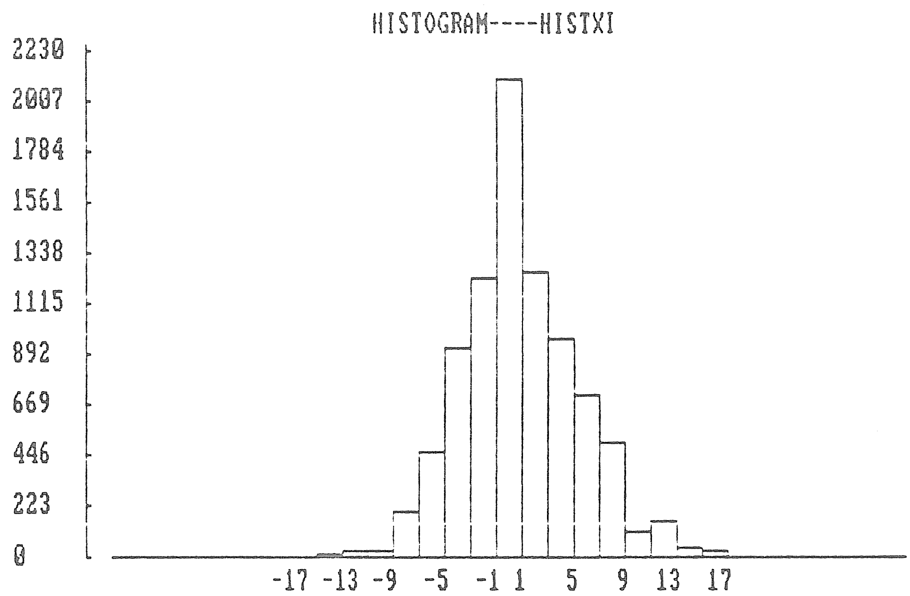

Fig. 5. The histogram of residuals of Xi's tidal potential

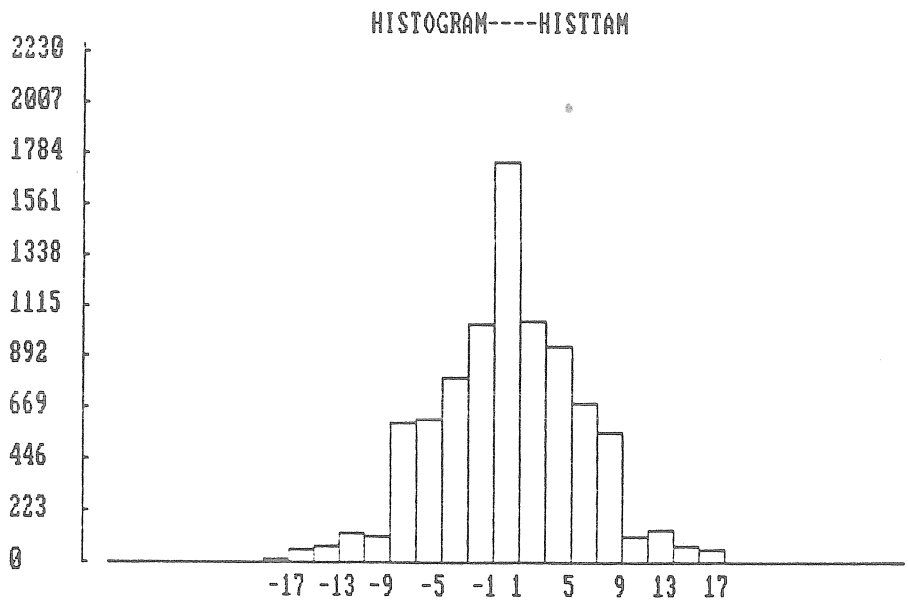

Fig. 6. The histogram of residuals of Tamura's tidal potential

Scaling tidal gravity records by means of an absolute gravimeter.

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1. Introduction

The precision of absolute gravimeters is sufficient to record tidal gravity changes (Niebauer & Faller, 1992). However it is generally not possible to obtain records long enough to perform conventional tidal analysis. On the other hand superconducting gravimeters have produced very long records of high quality but without calibration.

As soon as 1989 Ducarme & Van Ruymbeke proposed to use short continuous absolute gravity records to scale the tidal records obtained with the superconducting gravimeters.

An agreement was found with the Geodeettinen Laitos of Helsinki to operate the JILAG-5 absolute gravimeter at Brussels and Strasbourg next to the superconducting gravimeters. However the site of Brussels showed up too noisy to allow sufficient signal to noise ratio for tidal recording and it is only in 1990 that a very quiet site was found in Membach (East of Belgium) which is a fundamental station of the belgian seismic network. In the meantime the method was successfully applied in Strasbourg (Hinderer, 1991).

We present here a generalization of the principle, using synthetic tidal data based on modelized tidal factors and on records of the local atmospheric pressure variation. So it was possible to use not only absolute gravity records in Membach but also the records obtained in Ilomanci (Finland) during the solar eclipse of july 1990.

The results allow :

- to check the coherency between the Trans European Tidal Gravity Profiles 1971-1973 (Melchior & alii, 1976) and the Scandinavian network of the Geodeettinen Laitos (Kääriäinen & Ducarme, 1980);
- to confirm the correction to the so called Brussels system (Ducarme & Van Ruymbeke, 1991).
- to confirm the validity of the Wahr-Dehant model (Dehant & Ducarme, 1987).

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2. Absolute gravity observations

The JILAG-5 gravimeter is a free fall gravimeter made by Faller (Niebauer & Faller, 1991) which can be operated automatically following a preset scheme.

The scattering of individual measurements is high, ranging from 150 nms^{-2} to 300 nms^{-2} according to the site quality. It is a reason why the on line processor gives mean values for data sets of 25 to 50 drops while the individual values are saved. Additional parameters (pressure, temperature, residual vacuum) are only measured between the data sets. The spacing of the drops is also adjustable.

An other important parameter is the so called Laser color corresponding to two orthogonal polarisation modes of the He-Ne Laser. The two modes are called blue and red and do produce an offset of the measured values, the adopted value corresponding to the mean of the two series.

The technical settings of the gravimeter during the different experiments are summarized in table 1.

The observations in Ilomanci, which are covering more than 3 days, were interrupted during 30 minutes for an instrumental adjustment.
We have thus two data sets with a possible offset.

The observations in Membach covered a time span of three days in 1990 and only two days in 1991. In 1991 the automatic colour switching between the data sets was effectively used.

We tried to use the observations in Brussels taking into account a severe limitation of the site where only night observations are possible due to the industrial noise of the city. It is limiting the effective length of the observations to ten hours. It is thus not possible to observe two consecutive tidal extrema. Two data sets of september 1990 were tentatively used. The quality of the data sets is illustrated in table 2.

3. Tidal gravity data

We are synthesizing tidal gravity data using the tidal potential development of Cartwright-Tayler & Edden together with observed or modelized tidal gravity amplitude factors and phase differences. Given the high noise level (greater than 25 nms^{-2}) of the filtered data (table 2) it is useless to use a more accurate tidal development (Ducarme, 1989). The signal to noise ratio for tidal amplitudes comprised between 1.5 μms^{-1} and 2.0 μms^{-2} is slightly better than 35 db.

The relative precision of the synthetic tides will mainly depend from the accuracy of the ratios between the main tidal groups and from the accuracy of the phase lags.

For Brussels with have very precise tidal parameters obtained with the superconducting gravimeter scaled in the Brussels system ($\delta(O_1)$ = 1.161) (Ducarme, 1975).

For Ilomanci we used the tidal observations from Joensuu with the Geodynamics gravimeter GEO 761 (Ducarme & Kääriänen, 1980). The tidal observations in Joensuu were referred to the Brussels system as GEO 761 has been recording also at the Royal Observatory of Belgium.

For the Membach station we have only old registrations obtained with an old Askania gravimeter GS12 n° 175 at Liège (Cointe) some thirty kilometers away. We decided thus to use synthetic tidal factors based on Molodenskii model corrected for oceanic tidal effect computed from the Schwiderski cotidal maps (Schwiderski E.W., 1980) as it has been already shown that such a modelisation fits the observations in Belgium. As Schwiderski produced only oceanic cotidal maps for Q_1, O_1, P_1, K_1, N_2, M_2, S_2, K_2 and M_f we have to extrapolate the values to the smaller groups. For J_1 and 001 we know that we cannot extrapolate the tidal factors of the resonant K_1 and we use static values.

The factors effectively used to synthesize the tidal gravity values at one minute intervals are given in table 3a, b, c. The wave numbers refer to the Cartwright–Tayler–Edden development (505 waves). The amplitude factors do include the inertial correction (−0.0009 for O_1, −0.0038 for M_2) but this one is automatically removed by the program computing the theoretical tides.

The constant term M_0S_0 is introduced with a unit factor.

4. Observation equations

Each filtered observation of the absolute gravimeter, which is the mean of 25 or 50 drops, can be written under the form

$$g_i = g_0 + \alpha\, T_i + \beta\, (P_i - P_m) + \gamma\, K + \xi\, S_i + \varepsilon_i \text{ for } 1 \le i \le n$$

n : number of data
g_i : observed values of g
g_0 : constant term
T_i : synthetic tides
P_i : observed values of atmospheric pressure
P_m : mean atmospheric pressure during the experiment
K_i : laser colour switching
0 for Blue, 1 for Red
S_i : offset between consecutive data sets
0 for the first data set
1 for the second data set
ϵi : residuals

The unknowns have the following meanings

α scale factor of the tides

β pressure coefficient

γ gravity jump between the two laser colours

ξ offset between the different data sets

We have also to take into account the fact that the original sampling rate of our data is different. We decided thus to interpolate the tides (given every minute) and the pressure (given only between the data sets) at the moment of the raw observations. Later we apply the same operator to all the data to obtain the mean values of 25 or 50 raw data. It ensures that there will be no tidal attenuation between observed and computed tides. It is of course less important for the atmospheric pressure. It is not necessary to introduce temperature in the observation equations as no correlation was detected between the residues of the adjustment and the temperature data. (correlation coefficient < 0.1). A tentative regression between residuals and temperature gave coefficients with error bars greater than 90 %.

5. Results at Ilomanci

The tidal amplitude at Ilomanci (table 4) is very large for that latitude as the recording period did coincide with the solar eclipse.

We were not able to use the second data set alone as the tidal variation reaches only 350 nms^{-2}. On figure 1 one can see that a slight positive offset followed the interruption.

Looking at the adjustment results (table 5) we see that the tidal scale factor is very stable and is not influenced by the pressure. The difference between the solutions is lower than the RMS errors which are of the order of 0.2 %.

The pressure coefficient is well determined and the offset between the two data sets depends on pressure. It is due to the fact that the pressure variation changed abruptly after the interruption (figure 2). The standard deviation σ on the adjusted signal reaches 2.5 nms^{-2}.

6. Results at Membach

For Membach 91 we had to introduce a supplementary unknown taking into account the offset between the two Laser colors (γ in table 6).

The solutions with and without air pressure correction do agree within the RMS errors which are twice the RMS errors in Ilomanci. It is partly due to the fact that the data length is much shorter.

For what concerns atmospheric effects the low regression coefficient for Membach 90 is quite anomalous, but it is real as shown by the trial adjustment obtained after subtracting a pressure effect with the coefficient -3.5 nms^{-2}/hPa obtained in 1991. In this adjustment the scale factor of the tides is badly affected and the error increases significantly. As shown in figure 4 the measurements in Membach 90 coincides with a sudden decrease of pressure due to a cold front. As it is a local effect it can have an quite different impulse response compared with long term variations.

The results obtained with single colours for Membach 91 do not significantly differ from the global adjustment. However the pressure coefficient is slightly affected.

The standard deviation on the adjustments reaches 3 nms^{-2} for Membach 90 and 5 nms^{-2} for Membach 91. The higher error on Membach 91 is due to the shorter time interval (3000 minutes against 4000 minutes) and to systematic effects related to the Laser colour switching.

The best adjusted values for Membach 90 and Membach 91 are respectively 0.9972 and 0.9918 with associated errors of half a per cent.

7. Results at Brussels

A first glance on table 4 shows that the variation of the parameters is not always sufficiently large to ensure a correct determination of the associated unknowns. It is clear that the pressure variations are too small and that the tidal variation are very weak during the second experiment in Brussels.

On the other hand the noise level (table 2) is very high. It is a reason why no reasonable α value is obtained for Brussels 2. On the other hand the introduction of the pressure in the model is destroying the solution with a large increase of the error on the parameters.

The global solution without pressure adjustment is quite similar to the result obtained after subtraction of the pressure effects with a fixed parameter -3.5 nms^{-2}/HPa. The jumps between the Laser colours are quite different between the two experiments but seem to be very stable. The gravity jump is of the order of 40 ± 20 nms^{-2}.

It is clear that the scale factor for the tides is poorly determined.

8. Conclusions

For the tidal models scaled on the "Brussels System" the scale factors are of the order of 0.99. It confirms the results of previous experiment concerning the scale factor of the Brussels system (Ducarme & Van Ruymbeke, 1991). Table 8 give a summary of the results obtained so far for the amplitude factor of the tidal wave O_1. These results are compared with a modelisation using the Wahr-Dehant model and loading computations based on the Schwiderski maps.

At Brussels the different results agree with the modelisation to within a few tenth of a percent. A similar agreement is achieved in Ilomanci and in Dourbes.

The general conclusion is that the new results confirm that a decrease of the tidal factors inside the Brussels system is required. It is a reason why a general revision of the ICET data bank has been performed (Melchior, under press).

The scale factor of Membach reflects the fact that the Molodensky model is not correct at our latitude. With respect to the Wahr Dehant model it should be reduced by a factor 0.9945 in the Diurnal band and 0.9954 in the Semi-Diurnal band (Table 9). The agreement with the mean computed factor 0.9945 is excellent.

9. Acknowledgements

The authors are very indebted to Prof. J. Kakkuri, Director of the Geodeettinen Laitos who allowed the use of the absolute gravimeter JILAG 5 for tidal calibrations.

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Table 1

Absolute Gravity Measurements

data sets	begin	end	number	sampling	mean on	number of filtered values	Laser colours
ILOMANCI (data set 1)	90/07/20 23h46m59s	90/07/22 15h09m03s	19500	6s	50	390	1
ILOMANCI (data set 2)	90/07/22 15h40m18s	90/07/23 03h26m47s	5850	6s	50	117	1
MEMBACH 90	90/09/19 15h48m00s	90/09/22 11h48m00s	11500	20s	50	230	1
MEMBACH 91	91/04/30 16h45m00s	91/05/02 23h48m00s	4500	20s	25	180	2
BRUSSELS 1	90/09/08 19h30m00s	90/09/09 05h19m59s	2000	12s	25	80	2
BRUSSELS 2	90/09/15 21h30m00s	90/09/16 05h49m59s	1700	12s	25	68	2

Table 2

Noise Level

data sets	R.M.S. error on raw data (nms^{-2})	mean on	R.M.S. error on mean values (nms^{-2})
ILOMANCI (1)	173,3	50	28,2
ILOMANCI (1+ 2)	164,4	50	28,6
MEMBACH 90	175,6	50	27,3
MEMBACH 91	168,5	25	34,1
BRUSSELS 1	352,0	25	80,3
BRUSSELS 2	289,7	25	69,6

Table 4

Variation of the parameters during the observations

data set	Tidal Variation (nms^{-2})	Mean pressure (Hpa)	Pressure Variation (Hpa)
Ilomanci 1	1950	990,39	8
Ilomanci 1 + 2	1950	989,61	8
Membach 90	1600	975,87	17
Membach 91	2000	982,30	15
Brussels 1	1900	1012,60	2
Brussels 2	480	1013,17	1
Brussels 1 + 2	1900	1012,56	2

Table 3a

Parameters for Ilomanci

wave number in CTE	main wave	amplitude factor	phase difference
2–128	M_f	1.160	0.0
129–193	Q_1	1.133	1.96
194–219	O_1	1.1620	–0.26
220–241	NO_1	1.167	0.61
242–251	P_1	1.153	0.28
252–274	K_1	1.1346	–0.444
275–296	J_1	1.234	0.03
334–374	$2N_2$	1.276	–2.19
375–398	N_2	1.162	0.19
399–424	M_2	1.1826	0.27
425–438	L_2	0.933	–2.98
439–447	S_2	1.1638	–0.76
448–488	K_2	1.232	–0.85
489–505	M_3	1.014	8.5

Table 3b

Parameters for Membach

wave number in CTE	main wave	amplitude factor	phase difference
2–128	M_f*	1.16	0.0
129–193	Q_1	1.156	–0.26
194–241	O_1	1.155	0.06
242–251	P_1	1.155	0.22
252–274	K_1	1.140	0.21
275–296	J_1*	1.160	0.0
297–333	OO_1*	1.160	0.0
334–398	N_2	1.180	2.91
399–438	M_2	1.193	2.38
439–447	S_2	1.196	0.97
448–488	K_2	1.194	0.85
489–505	M_3*	1.070	0.0

* no indirect effect available

Table 3c

Parameters for Brussels

wave number in CTE	main wave	amplitude factor	phase difference
2-128	M_f	1.16	0.0
129-193	Q_1	1.162	-0.46
194-219	O_1	1.161	-0.06
220-241	NO_1	1.168	0.15
242-251	P_1	1.161	0.05
252-274	K_1	1.149	0.16
275-296	J_1	1.171	0.03
297-333	OO_1	1.173	0.06
334-374	$2N_2$	1.133	3.69
375-398	N_2	1.169	2.97
399-424	M_2	1.191	2.49
425-438	L_2	1.128	3.13
439-447	S_2	1.205	0.92
448-488	K_2	1.210	1.10
489-505	M_3	1.060	0.0

Table 5

Results at Ilomanci

	α	β (nms⁻²/hPa)	ξ (nms⁻²)	σ (nms⁻²)
data set 1	0.9891 ± 0.0024			
	0.9901 ± 0.0023	− 3.37 ± 0.52		2.47
data sets 1 & 2	0.9881 ± 0.0024		− 26.56 ± 3.48	
	0.9891 ± 0.0023	− 3.56 ± 0.52	− 39.32 ± 3.83	2.54

Table 6

Results at Membach

	α	β (nms⁻²/hPa)	γ (nms⁻²)	σ (nms⁻²)
Membach 90	0.9960 ± 0.0041			
	0.9972 ± 0.0041	− 1.17 ± 0.37		3.13
	(0.9922) ± 0.0050	[−3.5]*		
Membach 91	0.9980 ± 0.0047		1.699 ± 0.563	
	0.9918 ± 0.0043	− 3.53 ± 0.55	1.172 ± 0.508	5.08
blue	0.9950 ± 0.0064	− 4.39 ± 0.81		
red	0.9888 ± 0.0057	− 2.68 ± 0.73		

* fixed coefficient

Table 7

Results at Brussels

	α	β nms⁻²/hPa	γ (nms⁻²)	ξ (nms⁻²)	σ (nms⁻²)
Brussels 1	0.9982 ± 0.0159		57.55 ± 18.09		17.94
	0.9683 ± 0.0263	− 43.29 ± 30.41	55.20 ± 18.05		
Brussels 2	(0.9535) ± 0.0522		127.99 ± 17.01		
	0.8996 ± 0.0716	− 51.84 ± 47.24	128.50 ± 16.98		
Brussels 1 + 2	0.9889 ± 0.0156		(1) 54.39 ± 17.41 (2)132.29 ± 18.93	− 38.51 21.56	16.88
	0.9631 ± 0.0238	− 37.01 ± 25.94	(1) 52.59 ± 17.39 (2)131.43 ± 18.87	− 0.56 ± 34.19	
	0.9913 ± 0.0157	[−3.5]*	(1) 54.56 ± 17.43 (2)132.37 ± 18.96	− 42.11 ± 21.59	14.70

* fixed coefficient

Table 8

Comparison of recent direct and indirect determinations of the amplitude factor $\delta(O1)$ at Brussels

	initial value*	scale factor	final value	modelisation**	ratio
ILOMANCI	1.1629	0.9895	1.1506	1.1493	1.0012
BRUSSELS	1.1619	0.9913	1.1518	1.1499	1.0016
+ LCZ 3			1.1504	1.1499	1.0004
+ ET 13			1.1479	1.1499	0.9983
+ ASK 143 (Dourbes)			1.152	1.1492	1.0024

* inertial correction removed

** body tide according to Wahr-Dehant model plus loading effect according to Schwiderski maps.

\+ Ducarme & Van Ruymbeke, 1991.

Table 9

Comparison of the theoretical tidal factors at a 51° latitude

	Molodensky*	Wahr-Dehant	ratio
O_1	1.1604	1.1540	1.0055
M_2	1.1638	1.1585	1.0046

* inertial correction removed

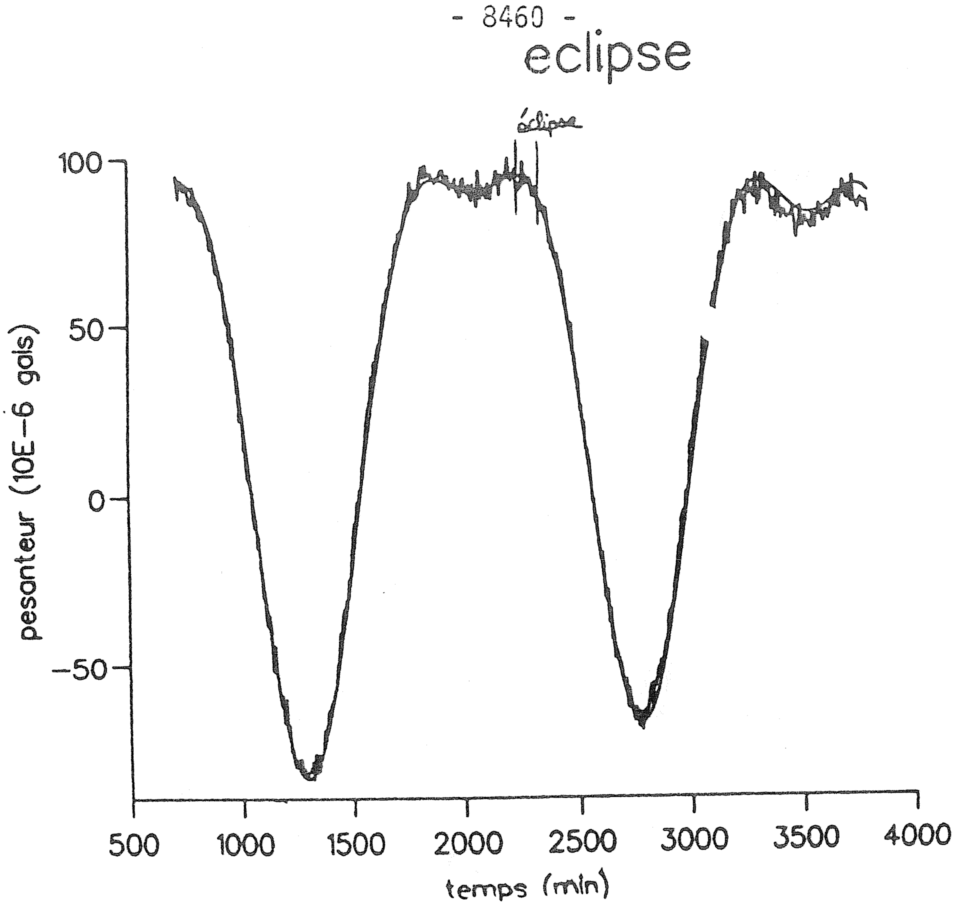


figure 1 : observed (thick line) and synthetic tidal variations at Ilomanci

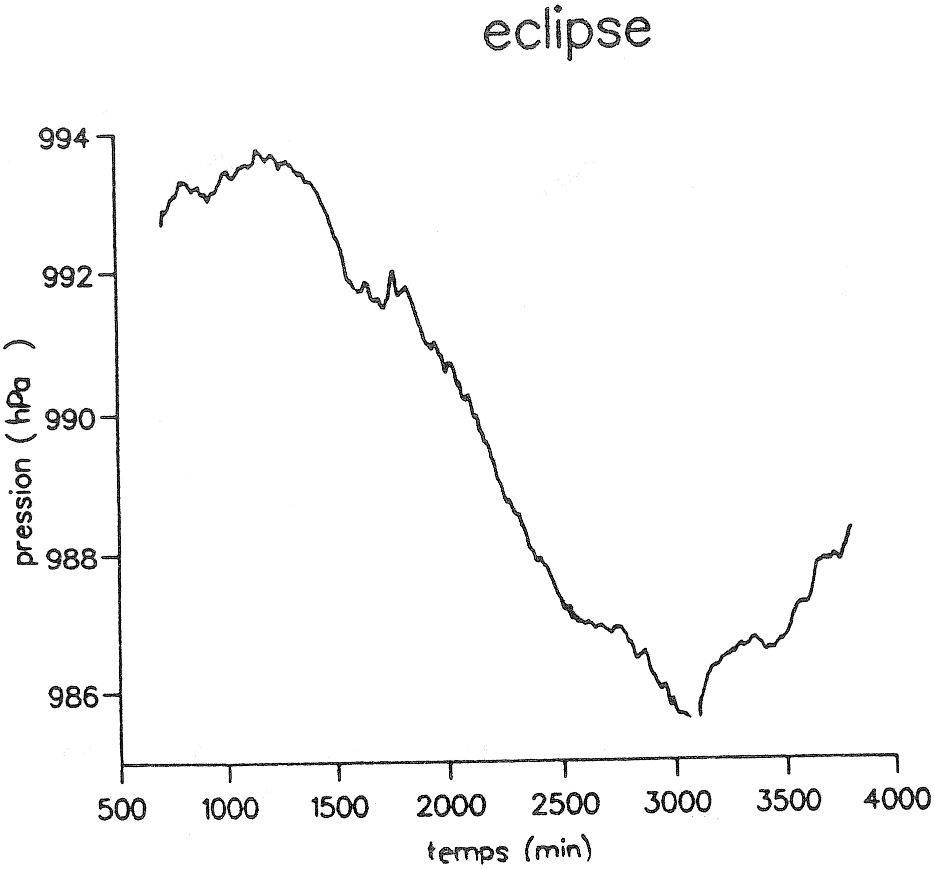
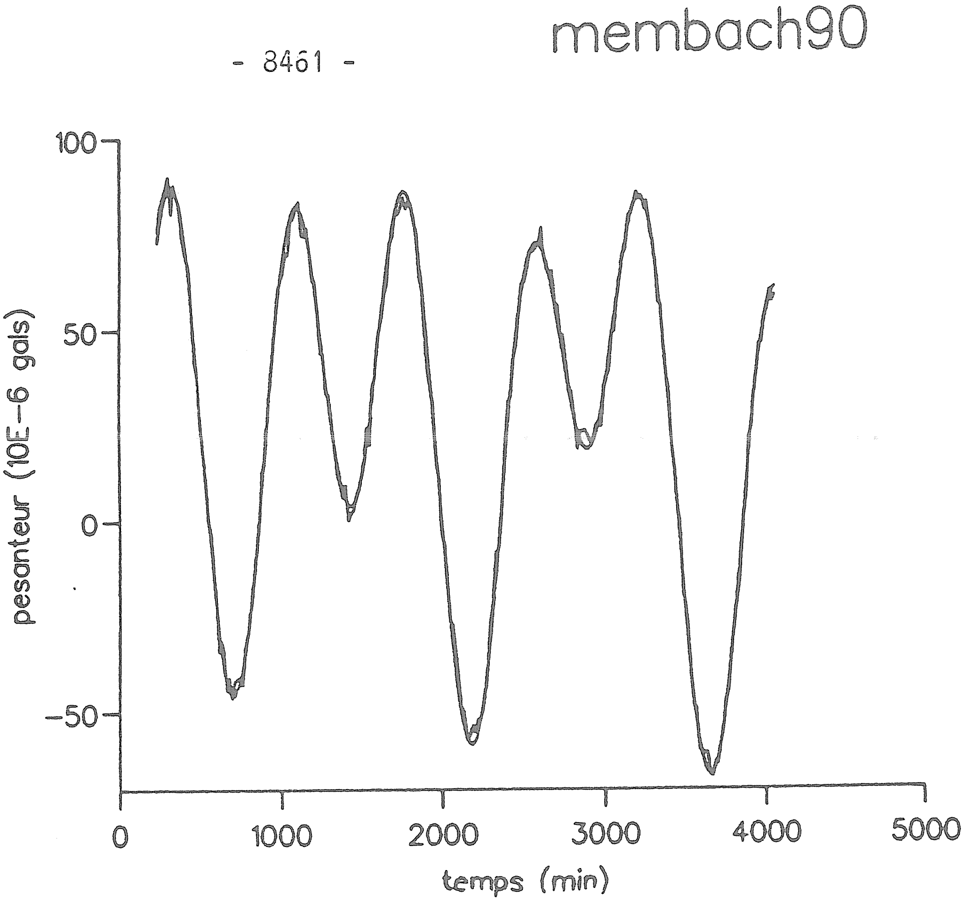


figure 2 : atmospheric pressure variations at Ilomanci



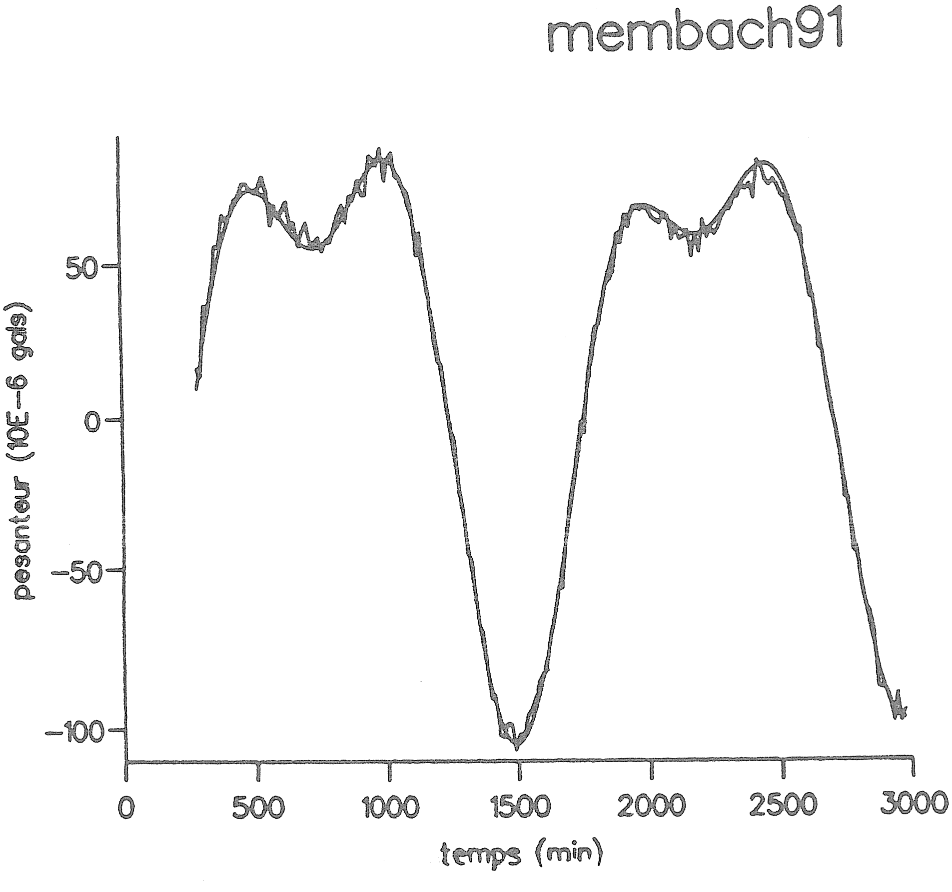
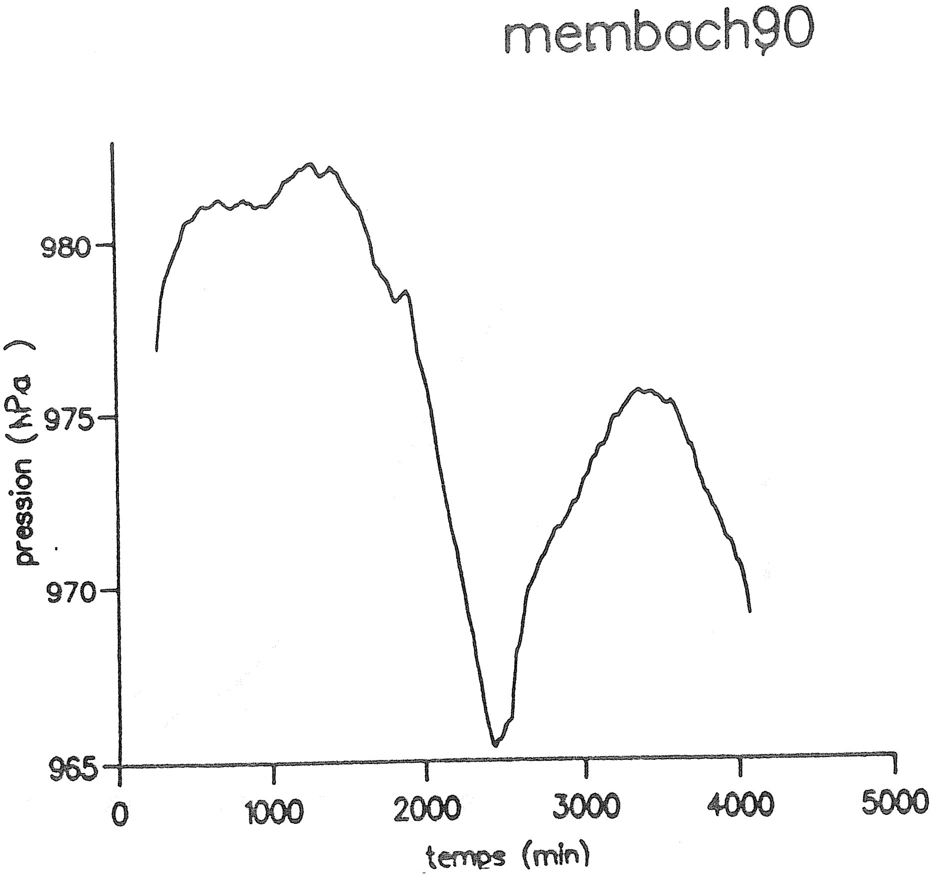


figure 3 : observed (thick line) and synthetic tidal variations during Membach 90 and Membach 91 experiments



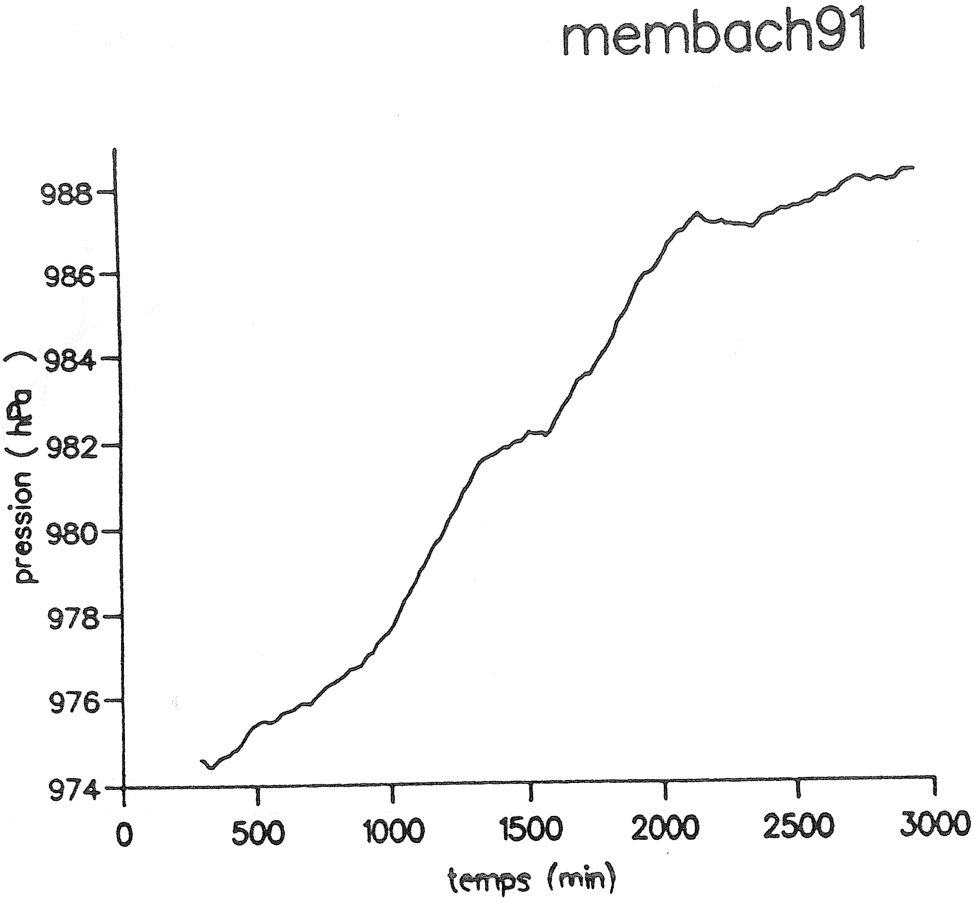
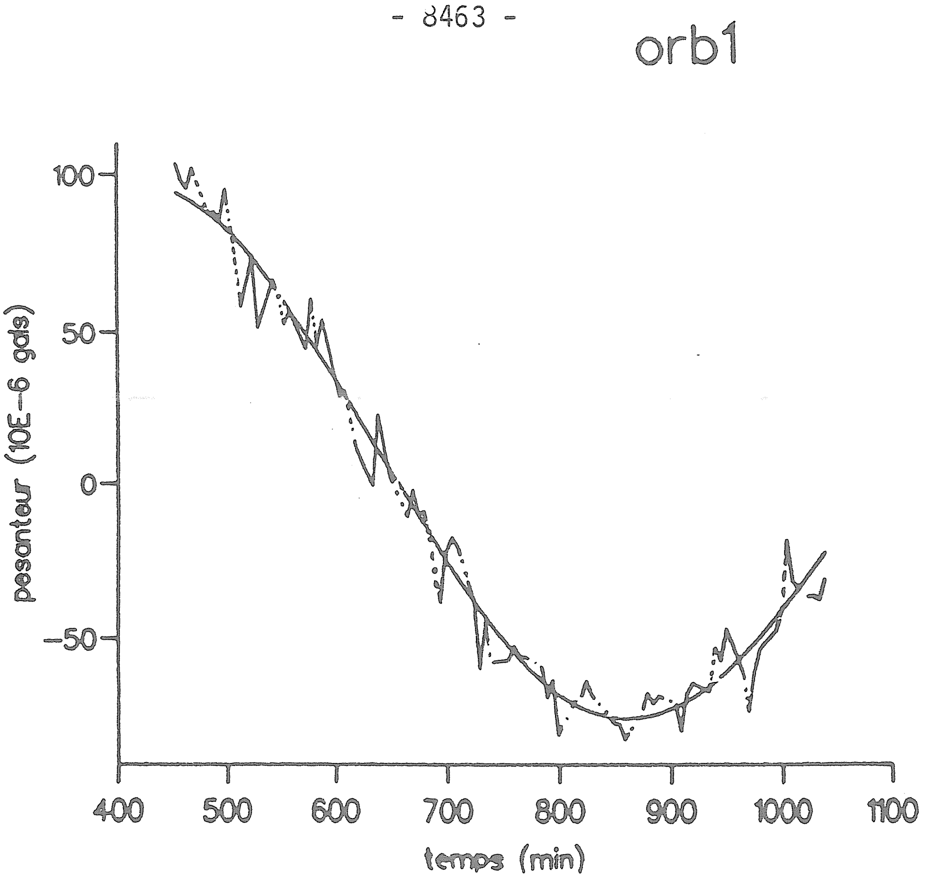


figure 4 : atmospheric pressure variations at Membach



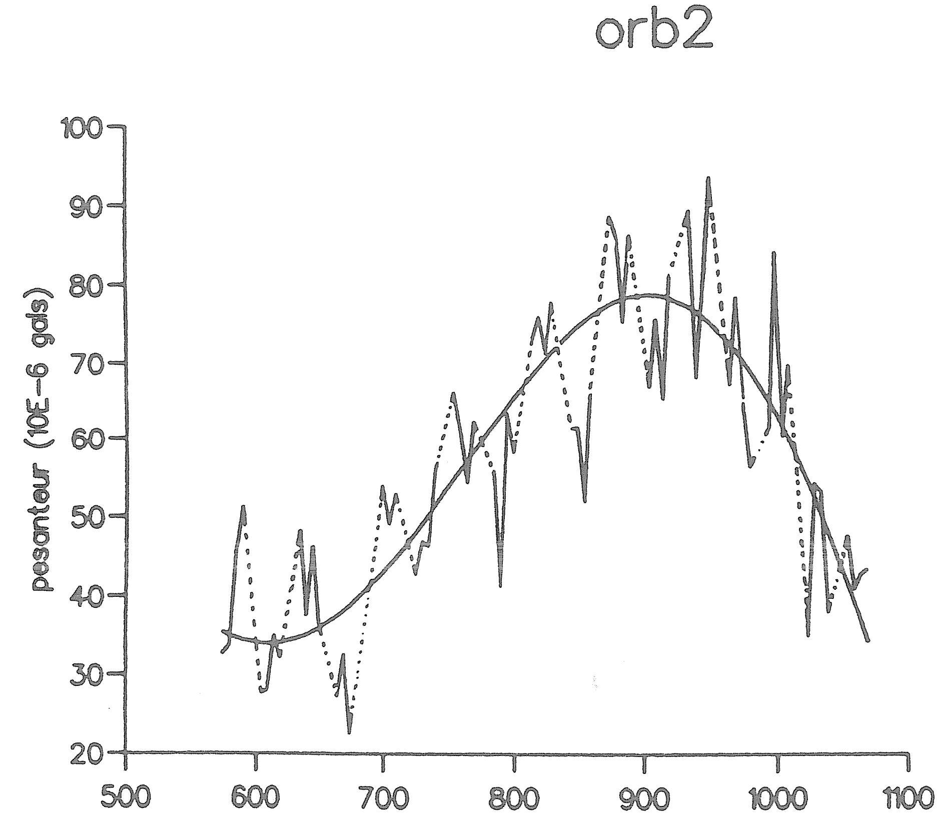


figure 5 : observed (interrupted line) and synthetic tidal variations at Brussels.
Note the offset between blue and red Laser colours.

Report on the Laboratory calibration activity in gravimetry at Budapest Geodynamical Observatory.

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It was reported earlier (Csapó et al., 1991) on the development of the following gravimeter calibration devices at the Budapest Geodynamical Observatory:

- underground calibration line with a range of 1300 microgal
- absolute calibration device with the use of a vertically moved heavy circular ring.

The underground calibration profile was designed by Csapó (1983). The basic idea was to calibrate the line without the use of gravimeters. As the tunnel used for the profile was it was scaled by a computer regulated Eötvös torsion balance.

The principle of the absolute calibration device was given and described in details by Varga(1989). The equipment is able to generate gravity differences of about 100 microgals with the use of a vertically moved circular ring. The positive features of calibration with the use of a heavy homogeneous circular ring are:

- the homogeneity of the generated gravity field at the extremums is very high. This circumstance was discovered by Barta (see e.g. Barta et al., 1986)
- the ring raised and lowered around the instrument does not load the ground around the meter
- the gravimeter remains stationary during the procedure, what is a required condition for sufficient control of the instrumental drift and to detect small gravity changes with high accuracy
- owing to technical reasons the gravity change brought about by the ring is greater than that caused by other geometrically regular shaped bodies.

The main design parameters of the absolute calibration device were determined by the author, the technical draft and the realization was done by the workshop of the Eötvös Loránd Geophysical Institute of Hungary. The mass of the ring (3200 kg) is composed of 18 units fixed together by three joining components.

The gravitational effect of a vertical cylindrical body is usually given for the axial symmetrical case. Due to the small distance between the mass of the instrument and the ring and also due to the assymetric position of the gravimeter's mass within the ring, gravity values outside of the axis of the symmetry are needed. In this case, however, complete elliptic integrals of the first and second order appear in the mathematical expression of the ring's generated gravity field. Therefore a numerical solution has been proposed by Hajósy (1988). This numerical integration is based on a linear combination of first and second kind Chebysev–Gauss quadratures. The important feature of this procedure is that it enables to determine the bound for error of the calculated values.

Many model experiments carried out by Hajósy proved that LCR type gravimeters can be calibrated by the calibration device in principle with an accuracy of 0.1%. In this case the position of the ring relative to the mass of the gravimeter is needed with an error of 1 cm, and the mass of the ring must be determined with a relative accuracy of $4 \cdot 10^{-5}$.

The first measurement series by the absolute calibration device was carried out during the summer of 1991 in close cooperation with the Technical University Darmstadt (Varga et al., 1991).

In the course of 1992 the detailed analysis of the measured gravity variations has shown that they, have an accuracy of 0.2% due to the lifting the ring over the gravimeter with a single raising and lowering the mass. It is probable that an automatization of the device, which allows to determine the scale of the gravimeter from many mass raising–lowering procedures would give an accuracy better than 0.2%. This development of the calibration device is in progress recently.

On the basis of the obtained results it can be concluded:

- the scale determination error is the main systematic error source of gravity earth tide observations. The record used table calibrated — on the basis of instrument comparison — with an accuracy 0.5%. With the use of the device reported here this error can be reduced significantly

- it was supposed on the basis of earlier experimental works that the gravity constant determined in laboratories differs from the values obtained with the use of big, geologic masses by 1%. Our experimental results show, however, that this difference cannot be bigger than 0.2%.

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Short remarks concerning the calibration of quartz tube extensometers.

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Abstract

The paper deals with the calibration problems of extensometers. In the last years a few extensometers have been installed in Hungary (Mentes). Their calibration is made by means of magnetostrictive coils or crapoudines. To ensure the high accuracy of the measurements it is desirable to check regularly the temporal stability of the calibration units. To solve this problem a high precision calibration instrument was developed in the Geodetic and Geophysical Research Institute and in the Institute of National Surveying and Engineering Geodesy.

Introduction

To check the linearity and the temporal stability of magnetostrictive coils and crapoudines built into the extensometers for the regular calibration, a very precise calibration instrument with high resolution is needed. The desired accuracy is higher than 1 nm. This accuracy cannot be achieved directly by laser interferometers. That was the reason why we have built a special calibration instrument for measurement of very small displacement. In the calibration unit we have combined the high absolute accuracy of a laser interferometer with the high resolution of a capacitive transducer.

The high precision calibration instrument

The principle of operation of the calibration unit can be seen in Figure 1. It consists of a precision vertical rotation axis fixed to a very rigid base board. A beam rotates around this axis. The position of the beam is sensed by means of two differential transducers placed at the extremities of the beam. The output signals of the capacitive transducers are subtracted from each other by means of a differential amplifier. This solution ensures that only the rotation angle of the beam is measured and the parallel shifts of the beam (due to the inevitable mechanical faults of the rotation axis) are eliminated. The differential solution minimizes the influences of the enviromental parameters (temperature, humidity and air pressure), too. The output signal of the differential transducer is digitized, digitally displayed and led into a computer.
The rotation angle of the beam can also be measured by means of a HP interferometer. The interferometer makes it possible to control the sensitivity of the capacitive transducer during the measurements. The high accuracy of the laser and the high linearity and resolution of the capacitive transducer ensures a high measurement accuracy of the calibration instrument.

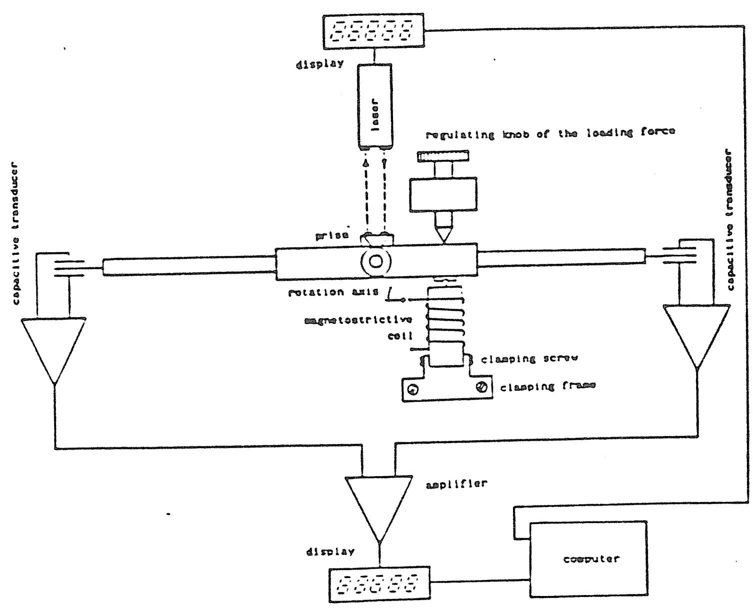

Fig. 1. The principle of the calibration instrument

The magnetostrictive coil or crapoudine to be measured is fixed to the base board by means of a mechanically very stable clamping unit. It actuates the beam near to the rotation axis. The movement of the beam is sensed at the extremities. So this solution ensures a mechanical leverage ratio of about 5 to increase sensitivity. A regulating device for setting the same loading force as acting on the calibration device during the operation in the extensometer is facing to the calibration device to be tested.
The calibration instrument is made horizontal (i.e. the beam rotates in a horizontal plane) because it can be used so directly to measure the linearity of extensometers if we connect it to the extremity of the latter.

Calibration of a crapoudine

The measurement is carried out as follows:
First the calibration instrument is calibrated by means of the laser interferometer. The measaured sensitivity of the instrument is: 96 mV/μm. The mercury vessel of the crapoudine is lifted up and then sunk down by 150 cm and the displacement of the membrane is measured by means of the calibration instrument. The calibration curves in both directions (above) and the linearity errors in each measuring point (below) can be seen in Figure 2.
The crapoudine has a hysteresis. The average slopes of the curves of the forward and backward measurements, i.e. the forward and backward sensitivities of the crapoudine are 0.352 nm/Hgcm and 0.329 nm/Hgcm, respectively. The measurement is repeated with different loading forces. The results show that the sensitivity of the crapoudine does not change vs the loading force in the range of 1...50 N, only the calibration curves are parallel shifted.

Calibration of a magnetostrictive coil

The calibration of the magnetostrictive coil is made similarly as the calibration of the crapoudine. The current of the coil is changed from 0 to 250 mA and the displacement is measured electrically by means of the calibration instrument.

The magnetostrictive coil has a hysteresis, too. The sensitivity of the coil i.e the slope of the regression line of the measured values is in the case of the tested magnetostrictive coil: 3 nm/mA. The results can be seen in Figure 3.

The magnetostrictive coil was also calibrated by different loding forces. The results for two loading forces are seen in Figure 4.

Conclusions

The calibration instrument has a very high accuracy and resolution. By means of it the calibration can be made with higher accuracy than by laser interferometers. It is able to carry out in-situ calibration of extensometers, too.

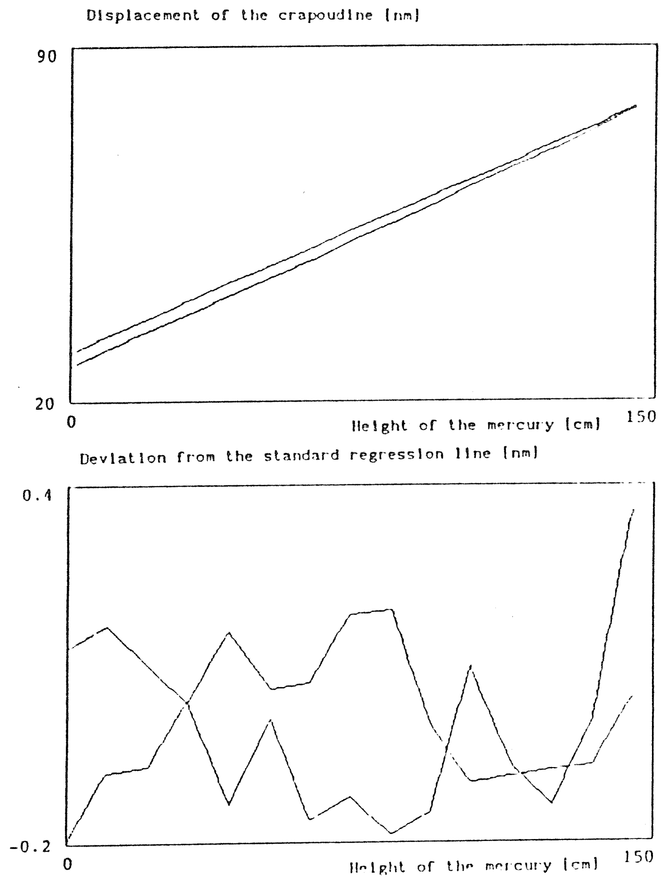

Fig. 2. The measuring results of the crapoudine calibration

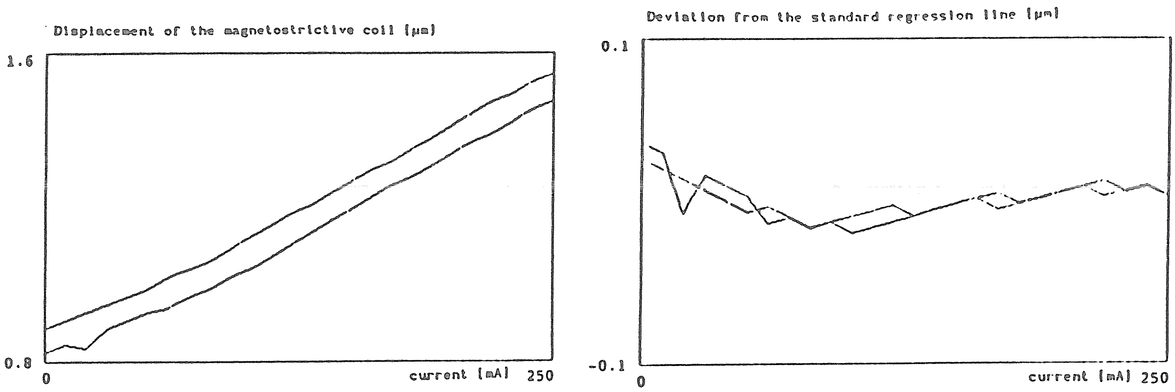

Fig. 3. The measuring results of the calibration of a magnetostrictive coil

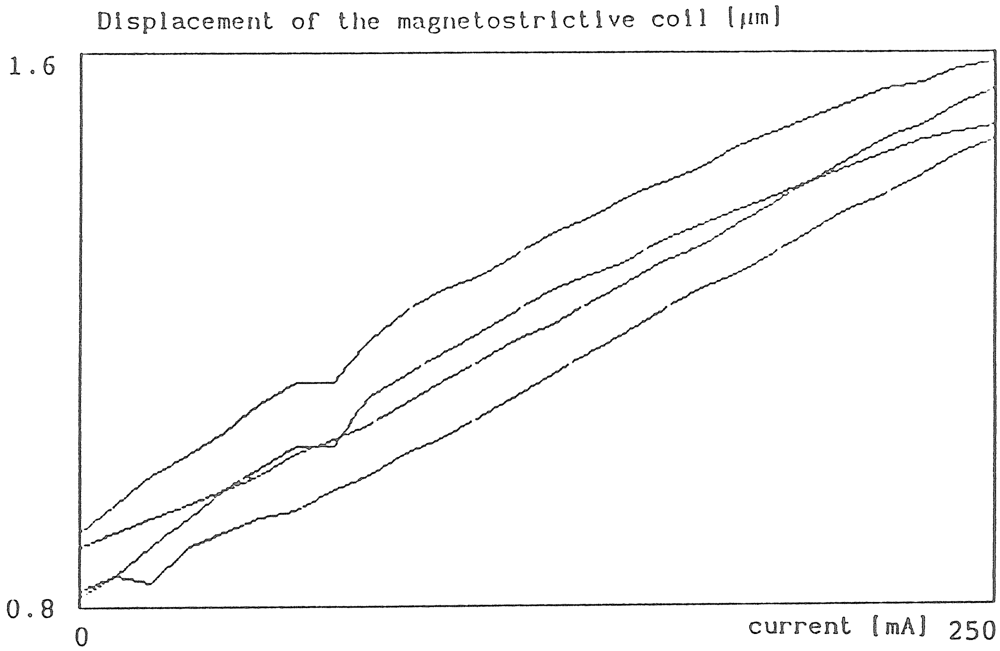

Fig. 4. The characteristics of a magnetostrictive coil in case of two loading forces

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Instrumental tests and calibration of the gravimeter LCR ET 18.

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1. Introduction

The gravimeter LCR ET 18 was first delivered with mechanical feedback in 1973, in 1983 it was transformed to electrostatic feedback. The gravimeter was calibrated in 1985, 1986, and 1987. From 1987 to 1991 the gravimeter was installed in Metsähovi/Finland. For not disturbing the recording no tests or calibration were carried out during that period. It was now time to recalibrate the meter to prove the results taken from earlier calibration runs.

The step response method was used for determination of the phase lag caused by the observation system to correct observed tidal phases for the main tidal waves. This is necessary because tidal measurements provide a precision of about 0.01° or less.

For the performance of these tests it is necessary to prove the meter setup to reduce instrumental faults.

2. Instrumental Test

In order to check the electronic of the meter and the agreement of the electronical and mechanical zero the allignment procedure given by the manufacturer (LARSON 1983) was carried out several times. No changes were required so that the meter can presumed to be stable. Only the electronic levels showed some drift so it is required to check them befofe leveling the meter. That is important because the meter is an astasized one, changes of tilt alter sensitivity and result in misbehaviour of the feedback system.

The last task of the allignment procedure is to determine the nonlinearity of the feedback. Therefore the spindulum is turned some multiple numbers of the transmission ratio in each direction to keep nonlinearities of the spindulum as small as possible, and the output (direct tide) is measured. Nonlinearity should always be smaller then 0.1%, otherwise the allignment procedure has to be repeated.

The sensitivity of the feedback is given in CU/mV by dividing the counter units by the measured output difference.

3. Determination of the instrumental phase lag using the step response method

Some of the following theory was taken from RICHTER & WENZEL (1991), because this was one of the most recently published papers.

An ideal system would transmit an input signal without any distortion or time shift:

$$y(t) = A(x,y)\,x(t)$$

with x(t): input signal, y(t): output signal, A(x,y): conversion-factor

The conversion-factor is only used to transform physical units and it determines the not time depending relation between the input and the output signal, so it can be neglected furthermore.

A real system differs in the way that any kind of inertia causes a phase lag. Presuming the system to be linear, time invariant and stable, the input - output relation is given by:

$$y(t) = \int_0^\infty h(\tau)x(t-\tau)d\tau$$

with $h(\tau)$: impulse response

Linear systems with constant parameters are not disturbed by frequency translation so that only phase and amplitude gain are influenced by the system

$$Y(\omega) = H(\omega)\,X(\omega)$$

with $H(\omega)$: complex frequency transfer function

The transfer function $H(\omega)$ is given by the Fourier-transformation of the impulse response $h(\tau)$

$$H(\omega) = \int_0^\infty h(\tau)e^{i\omega\tau}d\tau$$

which can be split into its real part and imaginary part

$$H(\omega) = p(\omega) + iq(\omega)$$

With known frequency transfer function the amplitude gain $G(\omega)$, the phase lag $\Psi(\omega)$ and the time lag $\Theta(\omega)$ of the observation system can be calculated

$$G(\omega) = \sqrt{p^2(\omega) + q^2(\omega)}$$

$$\psi(\omega) = \arctan\frac{q(\omega)}{p(\omega)}$$

$$\Theta(\omega) = \psi(\omega)\,T$$

with T: period

The step function can be applied to the gravimeter by turning the nulling dial or in case of electrostatic nulled systems by changing the electrostatic feedback force. Therefore a little circuit was built in to add about 2 Volts to one of the plates of the three-plate-capacitor to provide a rapid move of the beam.

The step response of the gravimeter was recorded digitally with a high sample rate of 0.1 seconds to approximate the differential dy/dt by the difference quotient. Figure 1 shows the digital record of the step response.

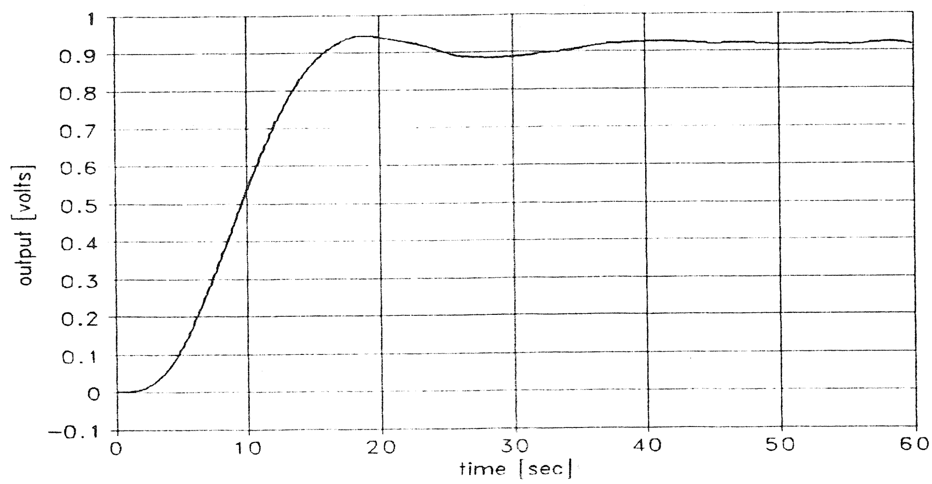

Figure 1: Step response ET 18 (step upwards). Sample rate is 0.1 sec.

The frequency transfer function is obtained by a discrete Fourier-transformation of the impulse response

$$p(\omega) = \sum_{i=1}^{n} h(\tau_i)\cos(\omega\tau_i)$$

$$q(\omega) = \sum_{i=1}^{n} h(\tau_i)\sin(\omega\tau_i)$$

These coefficients are computed for several frequencies and amplitude gain, phase lag and time lag are determined.

Because the Fourier-transformation allows no error estimation 25 step responses (up- and downwards) were carried out and computed to give an empiric error estimation (standard deviation).

The results are given in figure 2 (amplitude gain), figure 3 (phase lag) and figure 4 (time lag). Table 1 shows the results for the main tidal waves.

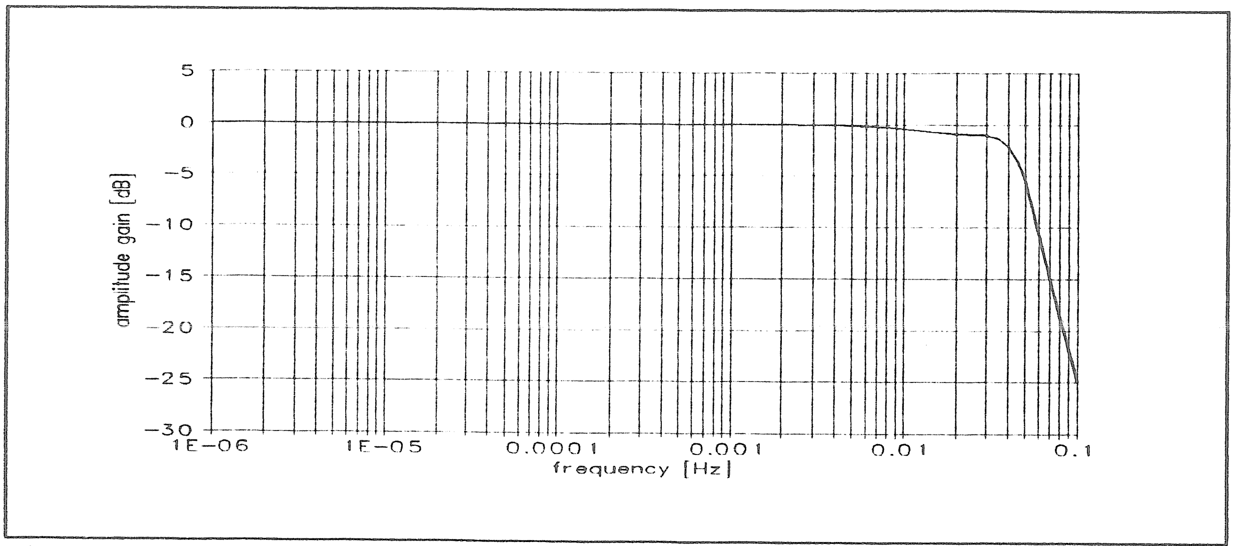

Figure 2: Amplitude gain versus frequency.

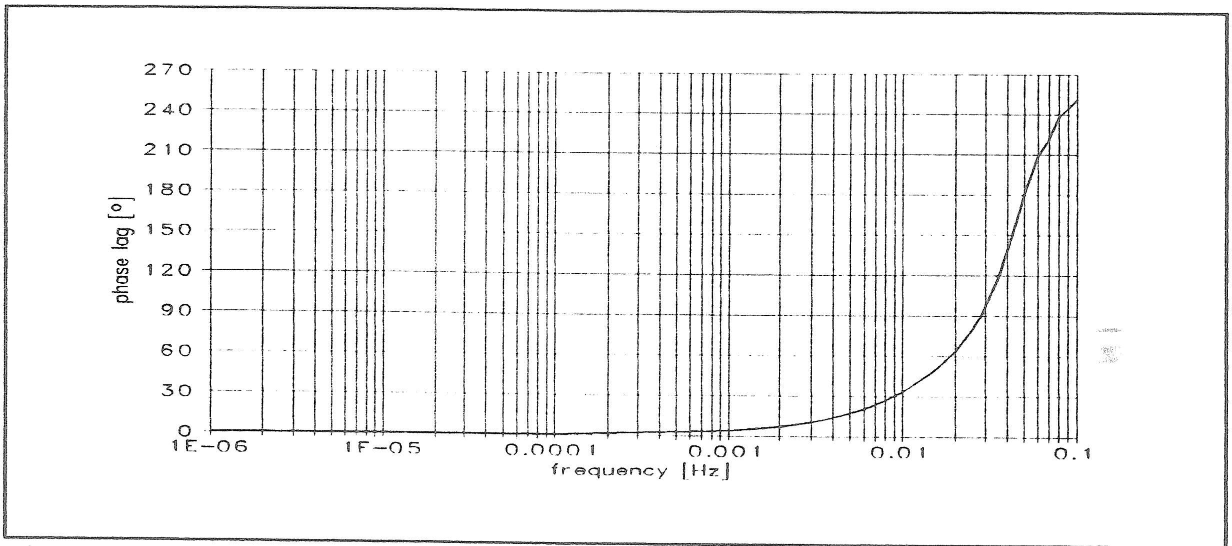

Figure 3: Phase lag versus frequency.

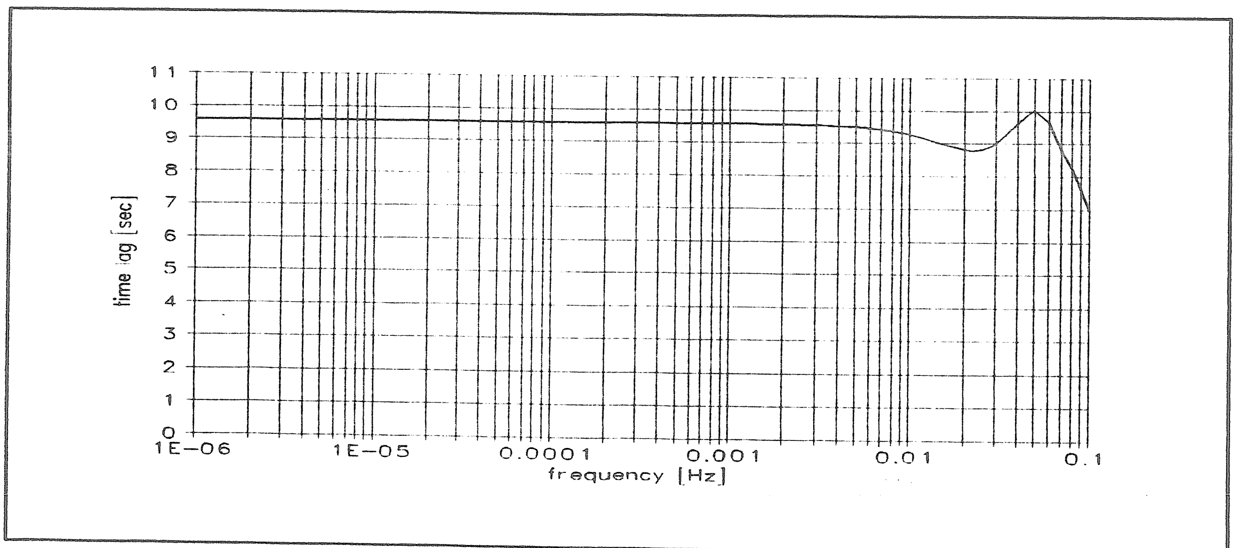

Figure 4: Time lag versus frequency.

Table 1: Phase lag and time lag of the main tidal waves

wave	frequency [10^{-5} Hz]	phase lag [°]	stdv [°]	time lag [sec]	stdv [sec]
Q1	1.03385	0.03567	0.00162	9.58	0.43
O1	1.07585	0.03712	0.00168	9.58	0.43
M1	1.11857	0.03859	0.00175	9.58	0.43
P1	1.15424	0.03982	0.00181	9.58	0.43
S1	1.15741	0.03993	0.00181	9.58	0.43
K1	1.16058	0.04004	0.00182	9.58	0.43
N2	2.19442	0.07571	0.00343	9.58	0.43
M2	2.22364	0.07716	0.00350	9.58	0.43
S2	2.31482	0.07987	0.00362	9.58	0.43
K2	2.32115	0.08008	0.00363	9.58	0.43
M3	3.35464	0.11574	0.00524	9.58	0.43

3.1 Discussion of results

There is a remarkable high standard deviation of about 4.5%. If only steps of one direction are computed the error would be smaller which could be explained by assuming an non-linear behaviour of the feedback circuit, in particular of the feedback three-plate-capacitor.

In case of our interest of frequencies lower than 0.005 Hz (period greater than 200 sec) amplitude gain is near 0 dB and time lag is nearly constant. That means that the phase lag increases linear with frequency, because time lag is the product of phase lag and period.

However, observed signals need not to be corrected in amplitude but in phase.

4. Calibration

After the conversion to electrostatic feedback the gravimeter was calibrated at the vertical base-line in Hannover in 1985, 1986 and 1987 (JENTZSCH & MELZER 1989). The total range of the spindulum of the gravimeter covers a little less than 8 mgal , so we used the points 190, 220 and 250 of the staircase with an applicable gravity difference of 6.14 mgal (KANNGIESER & TORGE 1981). These points were in use earlier, too. Seventeen measurements were taken according the scheme 220,250,220,190 and so on.

Moreover, we measured the local air-pressure to prove some compensation.

Each measurement was taken at full five minutes at least five minutes after completing the setup in order to use the theoretical tides computed before in five minute sample rate for correction.

The scale factor [mgal/CU] is obtained as difference quotient of two neighbouring gravity values and their scale units. For computation of the calibration factor [mgal/mV] the sensitivity is required which was determined in the linearity-test to be 1.0226 CU/mV. Table 2 gives the results of the four calibration campaigns at Hannover and compares the scale factor with the value given by LCR in 1973.

Table 2: Results of calibration campaigns

period	n	sensitivity [CU/mV]	scale factor [10^{-5} mgal/CU]	difference LCR [%]	calibrationfactor [10^{-5} mgal/mV]
May 1985	7	1.0017	7.8002±0.7%	+0.24	7.893
Nov 1986	12	1.0219	7.7798±0.4%	-0.01	7.950
Mar 1987	18	1.0178	7.7985±0.3%	+0.23	7.937
Apr 1992	16	1.0226	7.7726±0.3%	-0.11	7.948
weighted mean	---	---	7.7867±0.3%	+0.07	7.938

4.1 Discussion of the results

The error intervals of all calibration values overlap and are in good agreement with LCR. That means that the behaviour of the meter did not change with time. On the contrary to other authors, who found the calibration carried out by LCR being incorrect within 0.5% to 1%, our results show a difference (in weighted mean) of only 0.07%.

The reconsideration of the influence of air-pressure was not successfull. Supposing a regression coefficient of 0.35 μgal/hPa the influence is neglectible small, the calibration factor only differs of about 0.02%. That is one tenth of error interval.

A disadvantage of this calibration method is that we added up the errors caused by spindulum and feedback system, although we do not use the spindulum during long period recordings. Now our aim is to calibrate the feedback system directly, without using the spindulum.

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Calibration of Askania gravimeter records.

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1. Introduction

If we want to check a model of the Earth tides by measurements, especial care must be paid to the record calibration.

At the tidal station Pecný merely Askania gravimeters are being used. According to our experience, with this type of gravimeters it is possible to achieve a real accuracy 0.1-0.2% in δ factors of the main waves from measurements lasting three or more years and no comparative measurements at a fundamental station are needed. This experience can justify our opinion that it may still be worthwhile to use Askania gravimeters provided that an appropriate measuring technique is employed. In the following we briefly describe the way of solving the calibration problem at our tidal station. More detailed information with examples is given in (Dittfeld et al. 1990).

The scale value of Askania gravimeter record changes with time. Therefore, we must frequently calibrate the record, e. g. every 10 days, and approximate the results by a smooth curve. For this current calibration the electromagnetic calibration device is used, if the gravimeter has such an equipment. However the basic calibration method, also used for determination of the constant of electromagnetic device, is the calibration with measuring screw.

This method supposes that the scale of the measuring screw is precisely calibrated. This can easily be done with an accuracy better than 1×10^{-3} if we determine the course of the scale value by the "ball calibration" on several places of the scale and measure the gravimetric base line with the gravity difference of at least 100 mGal.

The glass-scale proper is equidistant with a sufficient accuracy of 0.1% as a rule, which can be proved by the optical micrometer of the gravimeter. However we can find, that the mean scale division does not exactly correspond to 100 but to m micrometer scale divisions. This run error of the micrometer must absolutely be corrected by the record calibration. Each micrometer reading μ must be multiplied by the ratio $100/m$, or, the correction

$$r(\mu) = \mu(100-m)/100 \qquad (1)$$

must be applied. The reading of the gravimeter is then $z=n+\mu/100$ where n denotes the main scale reading.

The main problem of the record calibration lies in the fact, that the optical micrometer does not ensure a linear subdivision of the calibrated main scale. The micrometer non-linearity is discussed in Chapt. 2.

Besides, as with all other methods of record calibration, we must suppose that the transducer of the gravimeter beam position and the registration device work linearly, or, that it is possible to determine and to correct their non-linearity. The check of the trancducer linearity is solved in Chapt. 3.

For record calibration we then use the maximum change of the gravimeter reading allowed by the range and linearity of the device in order to reach the maximum relative accuracy of the record scale value *k* (μGal/reg. unit). If only the record range is too small, then it is possible to compensate the gravimeter signal by an exactly measured voltage or to use a digital voltmeter with sufficient range instead of our registration device. But we must determine a corresponding coefficient to be able to recalculate the measured values in the recording units. Another possibility may be to switch the recording device to a lower sensitivity.

We use the double shift method for the record calibration: first the measuring screw is set to the first extreme position, then to the second and then back to the first one. The readings of the gravimeter measuring scale are z_1, z_2, z_3, corresponding ordinates y_1, y_2, y_3 (positive in the direction of the beam movement downward). Let us now denote by $f(z)$ the value of one division of the measuring scale. Then the record scale value is

$$k = -f(z)\frac{(z_1+z_3)/2 - z_2}{(y_1+y_3)/2 - y_2} . \qquad (2)$$

If the ordinates are read evenly in time, the linear parts of the drift and the tides are eliminated. The values of z and y must be corrected for the run error and for all non-linearities.

The ordinates should be read immediately after reseting the measuring screw as soon as the transition process has been finished. Therefore, a great instrumental damping is disadvantageous for record calibration. The possible influence of the damping on resulting record scale value may be estimated if the results of usual calibration "from inside" are compared with the results of the modified calibration method "from outside" (Šimon & Brož 1991).

2. Micrometer Non-linearity

Non-linearity of optical micrometers with Askania gravimeters may reach up to several per cent and that is the main cause of systematic errors in the resulting values of the gravimetric factors δ.

A check of the micrometer function we perform by multiple exact calibration with the measuring screw using different parts of the micrometer scale. For single calibrations we set the measuring screw in such positions, that the mean micrometer readings cover as equally the micrometer scale as possible. At bigger deviations of the beam from zero position the range of the registration device may not be sufficient and we must compensate the gravimeter signal. Besides, we must usually apply the corrections for transducer non-linearity.

If the record scale values $k(\bar{\mu})$ determined for single mean micrometer readings $\bar{\mu}$ are different, the micrometer is non-linear. An ideal linear micrometer would show a constant scale value k.

Now, we replace the measured discrete values $k(\bar{\mu})$ by a continuous function $k(\mu)$ and call the ratio $a(\mu)=k(\mu)/k$ the coefficient of the micrometer non-linearity. By dividing the result of the record calibration by this coefficient we get the correct value k. But more suitable is to add a correction $c(\mu)$ to each micrometer reading μ. With respect to Eq.(2) it must hold

$$\mu + c(\mu) = \int_0^{\mu} \frac{d\mu}{a(\mu)} \quad . \tag{3}$$

Because $a(\mu)$ is always close to 1, it holds

$$\frac{1}{a(\mu)} = \frac{1}{1-[1-a(\mu)]} = 1+[1-a(\mu)]$$

and after substituting it in Eq. (3) we obtain

$$c(\mu) = \int_0^{\mu} [1-a(\mu)]\,d\mu \,. \tag{4}$$

For $\mu=100$ (and also for $\mu=0$) the correction $c(\mu)$ must be zero, so that

$$\int_0^{100} [1-a(\mu)]\,d\mu = 0 \,.$$

The scale value of the linear micrometer is then

$$k = \frac{1}{100} \int_0^{100} k(\mu)\,d\mu \,. \tag{5}$$

With this value we can evaluate the coefficients $a(\mu)$ and corections $c(\mu)$.

The method requires that the record scale value does not change during the experimet or, if it is not the case, that measured values $k(\bar{\mu})$ are corrected for this effect.

The method is complicated by the necessity to determine and to introduce the corrections for transducer non-linearity. If the gravimeter has an electromagnetic calibration device, it is possible to use it and to keep the beam close to the zero position in each of calibrations. Then this corrections need not be applied, but the heating of the device may disturb the drift of the instrument.

It is also possible to put the beam back to the zero position by tilting the gravimeter in the plane of the beam rotation axis. By tilting the gravimeter in this direction, the sensitivity of the gravimeter should theoretically not change. This property of the measurig system must be tested with each gravimeter in such a way that we calibrate the record using the same part of the micrometer scale in three gravimeter positions: leveled instrument and instrument tilted in both directions so that its reading diminishes by one division of the main scale. The results must coincide within the limits of measuring accuracy.

The simpliest method of micrometer linearity checking could be used if we make an additional line on the main scale close to one of its lines. In such a case we could measure the distance of these lines by the micrometer using different parts of its scale. If we use to this aim the width of some cipher of the scale, we should not necessarily obtain the correct result (Šimon & Brož 1989).

3. Non-linearity of Transducer of the Beam Position

The range of the linear function of the transducer of the beam position may be very narrov. To check this linearity we calibrate the record at different declinations of the beam from its zero position. The calibrations must be at most accurate and the influence of the micrometer non-linearity must be eliminated. As a rule, the gravimeter signal must be compensated by exactly measured voltage to save it within the range of the registration device. The simpliest way to do it is to use an electromagnetic calibration device, if the gravimeter is equiped with it. The resulting record scale values k_e(mV/reg. unit) are

$$k_e(\bar{x}) = -\frac{(U_{e1}+U_{e3})/2 - U_{e2}}{(y_1 + y_3)/2 - y_2}, \qquad (6)$$

where

x is the mean declination of the beam from its zero position (in micrometer units), positive if the beam is above the horizon;

U_e is the voltage (in mV) measured on the electromagnetic calibration device, positive if it moves the beam upward.

The deviation x of the beam is given by the equation

$$x = (U_k/k_k - y + N)/d, \qquad (7)$$

where

U_k is the compensating voltage (in mV), positive if it moves the beam downward, constant with certain calibration;

k_k is the record scale value with respect to the compensating voltage (in mV/reg. unit);

N is the ordinate of zero position of the beam;

d is the value of one micrometer scale division in units of the record.

Let us again replace the measured discrete values $k_e(\bar{x})$ by a continuous function $k_e(x)$ and call the ratio $a(x)=k_e(x)/k_e(0)$ the coefficient of the transducer non-linearity. By dividing the result of the record calibration carried out at the mean deviation x of the beam by $a(x)$ we get the correct scale value. The transducer non-linearity may also be corrected by adding the correction

$$c(x) = \int_0^x [1 - a(x)]\, dx \qquad (8)$$

to each micrometer reading.

If the gravimeter has no electromagnetic calibration device we must use the measuring screw for the control calibrations. All calibrations must be done using the same part of the micrometer scale to eliminate the influence of its non-linearity. In this case we may attain the deviation x of the beam by tilting the gravimeter in the plane of the beam rotation axis, see Chapt. 2.

4. Record Calibration without Using the Micrometer

If the micrometer of the gravimeter does not work linearly and, especially, if its non-linearity changes with time, it is better to calibrate the record without using the micrometer. In this case we reset the measuring screw by one division of the main scale so that the beam moves between two positions symmetrically to the zero position.

Again the gravimeter signal must be compensated by the voltage U_k and/or the electromagnetic calibration device (voltage U_e) is used to move the beam back to the zero position. The record scale value is

$$k = -f(z)\frac{(z_1+z_3)/2 - z_2}{[(y_1+y_3)/2-y_2] - \frac{1}{k_k}[(U_{k1}+U_{k3})/2-U_{k2}] + \frac{1}{k_e}[(U_{e1}+U_{e3})/2-U_{e2}]} \quad (9)$$

The readings of the gravimeter z must be corrected for the transducer non-linearity. The run correction $r(\mu)$ need not be applied.

5. Back Lost of the Recorder

Compensating recorder used for analogue recording may have a back lost - its pen stops in different places as it moves to the equilibrium position from the left or right side. If we calibrate the record, this effect may diminish the measured difference Δy. The resulting increase of the scale value k may reach up to several tenths of per cent. It may either be corrected numerically or eliminated if we re-set the measuring screw so that the pen moves to both extreme calibration positions from one side only.

The back lost has practically no influence on the measured amplitudes of tidal waves, but it shifts the recorded curve in time and increases the measured phase lags.

6. Concluding Remark

All these complicated methods would not be necessary if we had a digital recording device and a gravimeter equipped with a feedback system, both devices linear and with a range which enables us to make the record calibration by shifting the measuring screw by one division of the main scale.

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Comparison of ET16 Parallel Recording at Sites in Europe and China.

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Abstract

The LaCoste Earth-Tide meter ET16 was modified by installing the Harrison/Sato type electrostatic feedback in 1984 and has been used for tidal recording at Wuhan and Shanghai in China from 1985 to 1989. After its return to Germany it was installed at the Geodetic Institute Potsdam for about 9 month. This paper gives the results of the tidal analysis for the three sites and compares the calibration as found from a staircase calibration line and from intercomparison to other gravimeters recording in parallel.

1. Introduction

In the seventies ET16 was used for tidal recording at various sites in Europe, see e.g. (Gerstenecker and Groten, 1976). With increasing age of the instrument two deficiencies became obvious. The mechanical feedback suffered from a severe backlash resulting in distorted values for instrumental phase lag corrections. The application of sophisticated approaches for modelling the effects did not improve the results to a satisfactory limit, see (Gerstenekker, Schüller, 1983). The second problem arose with the heavy drift of the instrument which was somehow related to environmental parameters but could not be finally explained (Gerstenecker, Schüller, 1983).

In order to eliminate the backlash problem of the mechanical feedback it was replaced by the electrostatic feedback of Harrison and Sato (1983).

In a cooperation with the Chinese Academy of Sciences, Prof. Hsu, ET16 was then installed at Wuhan Underground Station in China and later in Shanghai Observatory. Results published in (Xu, et al., 1988) showed that the backlash problem indeed had been solved, nevertheless a difference in calibration became obvious and the large nonlinear drift still remained in the records.

In this paper we will analyze the calibration factor of ET16 based on comparisons with other instruments recording in parallel and on calibration line measurements. An explanation of the drift-behaviour based on data and tests conducted at the Geodetic Institute Potsdam, now GeoforschungsZentrum Potsdam, will be given.

Table 1. History of ET16 Recordings

Epoch	Place
1972 - 1983	Recording at: Kiel, Braunschweig, Berlin, Münster, Frankfurt, Darmstadt, Würzburg, Wolfstein, Paris, Obrigheim, Stuttgart, München, Berchtesgaden, Zürich, Tihany
1984	Conversion to Electrostatic Feedback
1985 - 1989.1	Recording in Wuhan Underground Laboratory, Institute of Geodesy and Geophysics
1989.1 - 1989.12	Recording in She-Shan Station of the Shanghai Astronomical Observatory
1990.8 - 1991.4	Recording in Potsdam Gravimetric Observatory, Geodetic Institute
1990.6 - 1992.1	Repair at LaCoste and Romberg USA
1992.8 -	Recording at Lanzhou Seismological Observatory of the State Seismological Institute

2. Calibration of ET16

It is well established, that the manufacturers scale factor values for LaCoste gravity meters are only accurate to about 1 %, see e.g. (Baker et al., 1981). This is mainly due to the procedures and the reference values used by LaCoste and Romberg for calibrating the measuring screw.

However, in electrostatically feedback instruments there is another error source, namely the determination of the feedback calibration function. this is especially important as, in contrast to the screw calibration itself, this calibration function may change with time due to ageing of the electronic parts of both capacitive position indicator and feedback and due to various other parameters.

The calibration of the measuring screw is usually done on calibration lines using gravity differences precisely determined by a multitude of well calibrated LaCoste and Romberg Model G and Model D meters.

Although inherently nonlinear and furthermore superposed by periodical errors (Valliant, 1991), the calibration function of the Model ET gravity meters can be taken as a single constant factor as both nonlinearities and periodical errors of screw, lever-system and gearbox should be reduced below the detectable level due to selection and precise adjustment of the meter. (LaCoste, 1986, pers. Com.).

Calibration of ET16 was made at the staircase calibration lines in Darmstadt (Becker et al., 1987) and in Wuhan, China (Hsu et al., 1991). For the gravity range of the ET-meter of about 60 μms^{-2} a precision of about 20 nms^{-2} or about 0,03 % can be obtained. Table 2 gives the results.

Tab. 2 Measuring Screw Calibration of ET16

Source	Date	Factor	Error
LaCoste and Romberg,	1971	0,60587 µm/c.u.	-
Wuhan	1989	0,60671 µm/c.u.	0,000015
Wuhan	1989	0,60682 µm/c.u.	0,000016
Darmstadt	1990	0,60901 µm/c.u.	0,00038
Weighted Mean		0,606767 µm/c.u.	0,00002

Due to problems in installing the relatively large ET16 at the Darmstadt staircase points and to additional errors introduced by the vertical gravity gradient required for the reduction this value has a larger error. Looking at the weighted mean value the manufacturer's factor was too small by about 0.15 % only.

Tab. 3 Adjusted Scale function for ET16 Feedback Voltages

Place	Time	Linear Factor nm/Volt	Quadratic Factor $nm/Volt^2$
Darmstadt, Wuhan, Shanghai	1984 - -1990	416,967 ± 1,83	0,1108 ± 0,024
Potsdam (only 2400 nm/s**2)	1991	414.596 ± 0.60	-- --
Lanzhou (after repair of ET16)	1992	410.600 ± 0.03	1.1236 ± 0,010

Using the new calibration factor of the screw all calibrations of the electrostatic feedback against the screw were re-computed and the final result is given in Tab. 3. No significant time-dependend changes in the factors could be detected over the interval from 1985 to 1990. The calibration factor determined during the installation in Potsdam was measured using only a range of 2400 nm/s**2. Probably due to this small range beeing only one fifth of the total range of the feedback it turned out in the analysis to be too small and not reliable, so the factor determined in China and Darmstadt using the whole range of the feedback was used in the tidal analysis of the Potsdam record.

After return from Potsdam in 1991 ET16 was sent for a checkout to LaCoste and Romberg. After return from the manufacturer the feedback calibration changed due to mechanical adjustments. The new values are given in Tab. 3.

The instrumental phase lag was determined experimentally by use of the step-response method (Richter and Wenzel, 1991) during the stay at the Potsdam Geodetic Institute. The time constant was determined as T = 22,53 sec, leading to a lag of 0.087 degree for O1 and 0.181 degree for M2.

3. Tidal Recording in Potsdam

In the period from August 7th, 1990 to April 10th, 1991 ET16 was installed at the Geodetic Institute Potsdam for a series of parallel recording with Askania GS15 Gravimeter No. 222. Details about the Potsdam earth tide station and previous results can be found in (Dittfeld, 1991). Procedures and installation of ET16 are as described in (Xu et.al.,1990). Table 4 lists the relation between the results for the analysis of ET16 and A222 data over the same interval in time and using the same block-gap structure for both sets of data. Analysis was computed with the program ETERNA. The complete listing of the output and the tidal factors are given in Appendix A: and B. Results of ET 16 are scaled using the values given in table 3 for Darmstadt and China, see section 2.

Tab 4. Comparison of Observed Tidal Parameters in Potsdam: A222 - ET16

No.	Wave	Delta	Kappa
1	Q1	0.00147	0.2101
2	O1	0.00502	-0.1017
3	M1	0.00191	-1.4594
4	K1	0.00307	-0.0241
5	J1	0.00758	0.3505
6	001	0.00364	-0.8114
7	2N2	0.00727	0.5124
8	N2	0.00496	-0.0956
9	M2	0.00299	-0.0665
10	L2	0.01165	1.2308
11	S2	0.00555	0.2423
12	M3	-0.02058	0.8493

4. Comparison of Tidal Recordings in China

The Wuhan Tidal Gravity Station has been used for recordings with a number of different instruments in the last decade, see (Hsu et.al, 1992). After recomputation considering the proper calibration factors table 5 shows the comparison of ET15 and ET16. The results of ET16 come closer to the results of the other instruments, but is still about 0.2% low in the tidal factors. The phases agree well. Complete results for Wuhan are given in appendix C.

Table 6 compares the newly calibrated results for Shanghai She-Shan Observatory with earlier ones of Melchior et. al., 1985. Considering the different data basis and ways of analysis there is a rather good correspondence with differences of less than 0.3 % in the delta factors. Complete results for Shanghai are given in appendix D.

Tab. 5. Comparison of Observed Tidal Parameters in Wuhan ET15 - ET16

No.	Wave	Delta	Kappa
1	O1	0.0022	-0.02
2	K1	0.0025	-0.12
3	M2	0.0022	-0.09
4	S2	-0.0006	-0.15

Tab. 6 Comparison of Observed Tidal Parameters in Shanghai, Melchior et. al (1985) - ET16

No.	Tide	Delta	Kappa
1	K1	0.0003	-0.44
2	P1	0.0084	0.23
3	O1	-0.0034	-0.29
4	Q1	0.0240	-0.695
5	M2	0.0009	-0.24
6	N2	0.0111	0.13
7	S2	-0.0019	0.11
8	K2	0.0079	-1.34

5. Humidity Experiment in Potsdam

During the recording in China and in Potsdam the ET16 showed a large non-linear drift behaviour. According to earlier investigations (Gerstenecker ,Schüller, 1983) a correlation to temperature was supposed.

On the other hand the investigations of Bastien (1989) showed the strong influence of humidity changes on the drift of an ET-meter. Although not explained fully theoretically the practical experience with ET-12 revealed that the drift lags humidity-changes by 20 to 100 days. To test the response of ET16 the Potsdam installation gave the possibility to record and vary humidity in the observation chamber. Fig. 1 shows the humidity slowly decreasing by about 1% and the drift of A222 and ET16 over the 8 month interval. At the end of the recording period a step-like change was conducted in addittion to confirm the effect.

A cross-correlation computation excluding the step experiment revealed a 23 days lag of the drift of ET16 behind the humidity changes. The amount of drift depends on the amplitude as well as on the frequency of the humidity changes and a correction is hard to compute.

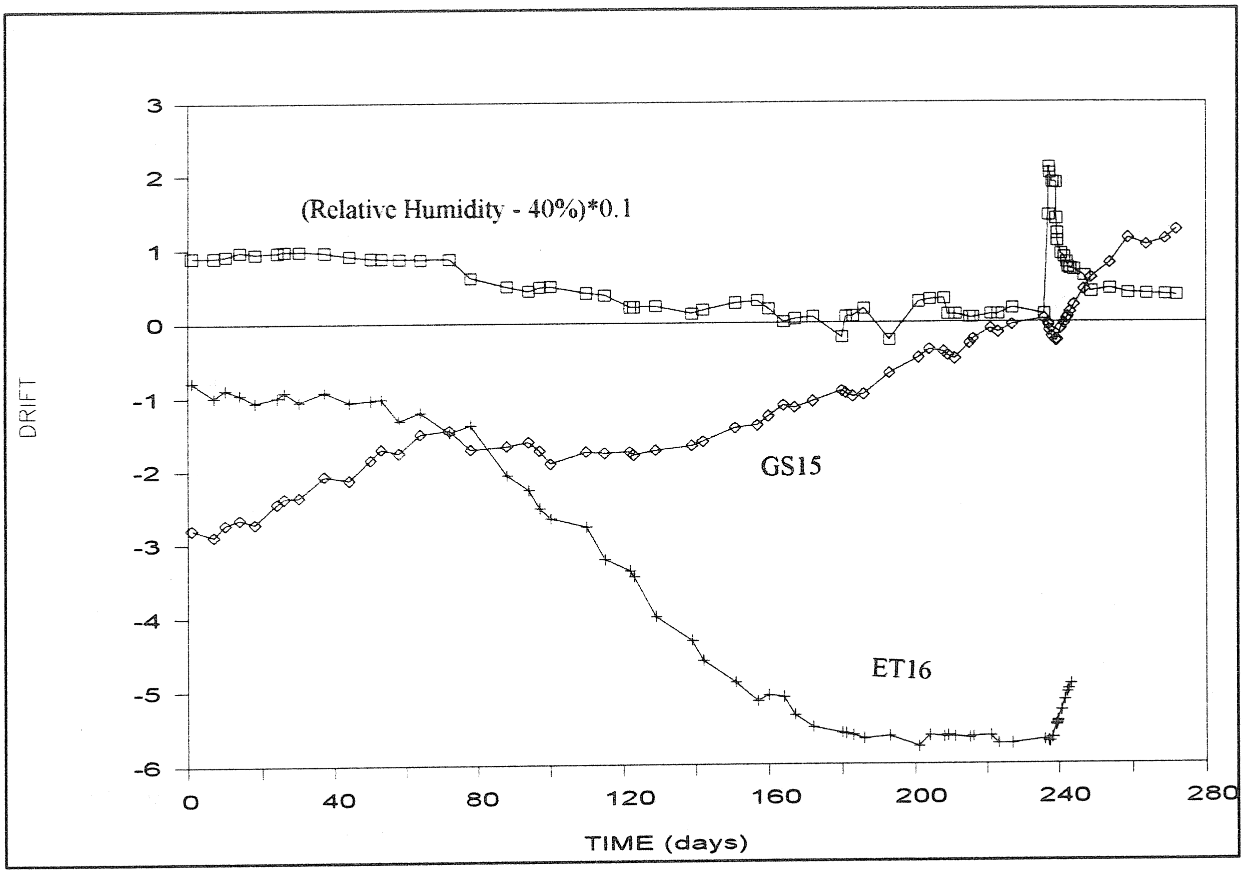
The best way of reducing the drift is the replacement of the seals of the gravity meter in intervals of less than about 5 years. After this procedure the drift of ET16 decreased by a factor of about 5 to 10.

6. Future Works:

After refurbishing ET16 at LaCoste and modification of datalogging for conversion to PC-Basis ET16 a new co-operation with the Seismological Institute Lanzhou of the State Seismological Bureau (SSB) of China was started in 1992. Since september 1992 ET16 is recording in parallel to the Askania GS15 No.150 (modified by SSB Wuhan) in the underground site of Liu Ja Ping Observatory in Lanzhou, China. Monthly tidal analysis is computed in China and Germany on a regular basis.

The topic of the research is earthquake prediction by analysing and comparing variations in drift rate and variations of observed tidal parameters of two instruments running in parallel. Tidal observations by tilt- and strain-meters and geodetic observations are further parts of the earthquake prediction program of the SSB. The Gansu Province has high seismic risk and chinese scientists expect larger earthquakes within the next decade in the region of Lanzhou.

Fig. 1 Changes in Humidty ((Relative Humidity -40%)*0.1) and Drift (micrometer/s**2)



7. Conclusions

The unified analysis with updated calibration values revealed new results for the tidal registrations of ET16 in Wuhan, Shanghai and Potsdam. In Wuhan ET15, ET21 and GWR TT70 compare well to ET16 with a small systematic difference of ET16 tidal factors being too small by 0.2%. In Shanghai results agree within 0.3% to results of Melchior et. al., 1985.

In Potsdam the new calibration of the feedback did result in rather small tidal factors with a difference of 0.57% against the Askania GS15 No 222. With the old factors determined in Darmstadt and China about the same difference of ET16 with factors too small by about 0.3% as compared to GS15 is observed.

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Appendix A : Results of Askania GS15/222 Recording in Potsdam

GRAVIMETRIC OBSERVATORY, GEOFORSCHUNGSZENTRUM POTSDAM No.764
52.3806N 13.0682E H 81M P 1M VERTICALCOMPONENT

GRAVIMETER ASKANIA GS 15 NO. 222 ELECTROMAGNETIC CALIBRATION

1990/91 - congruent to ET16

INSTRUMENTAL LAG CORRECTED FOR 0.421 DEG O1 AND 0.876 DEG M2

NUMBER OF RECORDED DAYS IN TOTAL : 242.0

CTED 1973 TIDAL POTENTIAL USED.
WAHR-DEHANT-ZSCHAU INELASTIC EARTH MODEL USED FOR A PRIORI AMPLITUDES.

NUMERICAL FILTER IS PERTZEV 1959 WITH 51 COEFFICIENTS.

ESTIMATION OF NOISE BY FOURIER-SPECTRUM OF RESIDUALS

0.1 CPD BAND 9999.99 NM/S**2
1.0 CPD BAND .3135 NM/S**2
2.0 CPD BAND .1542 NM/S**2
3.0 CPD BAND .1293 NM/S**2
4.0 CPD BAND .0804 NM/S**2

ADJUSTED TIDAL PARAMETERS :

WAVE	OBS.AMPL. NM/S**2	SIGNAL/ NOISE	AMPL.FAC.	STDV.	PHASE LAG DEGREE	STDV. DEGREE
Q1	66.102	210.8	1.14896	.00545	-.0081	.2718
O1	346.405	1104.8	1.15274	.00104	.0673	.0519
M1	27.063	86.3	1.14524	.01327	-1.1443	.6638
K1	481.251	1534.9	1.13867	.00074	.1763	.0373
J1	27.498	87.7	1.16398	.01327	.4490	.6533
OO1	14.998	47.8	1.15902	.02423	-.6209	1.1978
2N2	10.091	65.4	1.17880	.01801	2.5424	.8756
N2	63.253	410.2	1.17968	.00288	1.7010	.1397
M2	332.564	2156.6	1.18753	.00055	1.3202	.0266
L2	9.686	62.8	1.22358	.01948	2.8789	.9122
S2	154.874	1004.3	1.18870	.00118	.5637	.0570
M3	3.589	27.8	1.06731	.03845	.9016	2.0638

STANDARD DEVIATION 4.467 NM/S**2 DEGREE OF FREEDOM 5533

ADJUSTED AIR PRRESSURE PARAMETERS :

REGR.COEFF.	STDV.	
.05266	.00069	AIRPRES.PASCAL

Appendix B: Results of LCR ET16 Recording in Potsdam

GRAVIMETRIC OBSERVATORY GEOFORSCHUNGSZENTRUM POTSDAM No.764
52.3806N 13.0682E H 81M P 1M VERTICALCOMPONENT

GRAVIMETER LaCoste-Romberg ET16, FEEDBACK

1990.08.07 - 1991.04.10

INSTRUMENTAL LAG CORRECTED FOR 0.087 DEG O1 AND 0.181 DEG M2

NUMBER OF RECORDED DAYS IN TOTAL : 242.0

CTED 1973 TIDAL POTENTIAL USED.
WAHR-DEHANT-ZSCHAU INELASTIC EARTH MODEL USED FOR A PRIORI AMPLITUDES.

NUMERICAL FILTER IS PERTZEV 1959 WITH 51 COEFFICIENTS.

ESTIMATION OF NOISE BY FOURIER-SPECTRUM OF RESIDUALS

0.1 CPD BAND 9999.99 NM/S**2 1.0 CPD BAND .1442 NM/S**2
2.0 CPD BAND .0699 NM/S**2 3.0 CPD BAND .0718 NM/S**2
4.0 CPD BAND .0490 NM/S**2

ADJUSTED TIDAL PARAMETERS :

WAVE	OBS.AMPL NM/S**2	SIGNAL/ NOISE	AMPL.FAC.	STDV.	PHASE LAG DEGREE	STDV. DEGREE
Q1	66.017	454.2	1.14749	.00251	-.2182	. 1261
O1	344.879	2372.9	1.14772	.00048	.1690	. 0241
M1	27.018	185.9	1.14333	.00610	.3151	. 3082
K1	479.954	3302.1	1.13560	.00034	.2004	. 0174
J1	27.319	188.0	1.15640	.00610	.0985	. 3048
OO1	14.951	102.9	1.15538	.01114	.1905	.5570
2N2	10.029	142.3	1.17153	.00817	2.0300	.4025
N2	62.987	894.0	1.17472	.00130	1.7966	.0641
M2	331.727	4708.5	1.18454	.00025	1.3867	.0122
L2	9.593	136.2	1.21193	.00883	1.6481	.4208
S2	154.151	2188.0	1.18315	.00054	.3214	.0262
M3	3.658	50.6	1.09789	.02135	.0523	1.1331

STANDARD DEVIATION 1.917 NM/S**2 DEGREE OF FREEDOM 5533

ADJUSTED AIRPRESSURE PARAMETER :

REGR.COEFF.	STDV.	PARAMETER
-.03037	.00030	AIRPRES.PASCAL

Appendix C: Final Results from Hycon Data Processing for ET16 in Wuhan

No.	Tide	Delta	RMS	Kappa	RMS
1	STQ1	1.2164	0.1029	-0.40	4.88
2	SIG1	1.1912	0.0216	0.21	1.05
3	Q1	1.1810	0.0044	-0.26	0.22
4	O1	1.1752	0.0008	-0.41	0.04
5	M1	1.1739	0.0107	-0.06	0.52
6	P1	1.1519	0.0021	-0.53	0.11
7	K1	1.1491	0.0007	-0.52	0.03
8	J1	1.1547	0.0109	-0.90	0.54
9	001	1.1619	0.0128	-0.71	0.64
10	V1	1.1500	0.0680	0.37	3.41
11	EPS2	1.1491	0.0516	0.65	2.59
12	2N2	1.1773	0.0107	-0.415	0.53
13	N2	1.1777	0.0022	-0.36	0.11
14	M2	1.1720	0.0004	-0.32	0.02
15	L2	1.1615	0.0091	-0.35	0.45
16	S2	1.1722	0.0008	0.01	0.04
17	K2	1.1673	0.0024	-0.042	0.12
18	ETA2	1.1629	0.0383	-0.71	1.90
19	M3	1.0717	0.0129	0.12	0.69

Appendix D: Final Results for Hycon Data Processing in Shanghai

No.	Tide	Delta	RMS	Kappa	RMS
1	STQ1	1.3220	0.1200	4.09	5.10
2	SIG1	1.2210	0.0250	1.21	1.17
3	Q1	1.1980	0.0050	0.085	0.26
4	O1	1.1987	0.0010	-0.24	0.05
5	M1	1.1920	0.0100	-1.13	0.50
6	P1	1.1716	0.0030	-0.91	0.14
7	K1	1.1730	0.0009	-0.92	0.04
8	J1	1.1790	0.0140	-2.13	0.66
9	001	1.1700	0.0160	-2.07	0.76
10	V1	1.1920	0.0780	1.15	3.74
11	EPS2	1.1920	0.0380	-1.71	1.79
12	2N2	1.1820	0.0080	-1.20	0.39
13	N2	1.1609	0.0017	-2.09	0.09
14	M2	1.1524	0.0004	-1.85	0.02
15	L2	1.0812	0.0176	-3.29	0.93
16	S2	1.1429	0.0008	-0.63	0.04
17	K2	1.1471	0.0023	-0.72	0.11
18	ETA2	1.1110	0.0300	-2.02	1.52
19	M3	1.0870	0.0110	1.323	0.60

Comparison of Tilt Measurements at Neighbouring Stations.

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1. Introduction

In southern Finland two tilt stations were in operation in parallel between autumn 1986 and autumn 1991. These are the underground observatory in the limestone mine of Lohja and the observatory of Metsähovi, about 30 and 15 km west of Helsinki, respectively (see fig. 1).

In 1975 the first 177 m long water tube was installed in Lohja at a depth 166 m below the surface (in E-W direction); the second tube of a lenght of 50 m was installed in N-S direction in 1983 (Kääriäinen, 1979; Kääriäinen & Ruotsalainen, 1989). In Metsähovi an ASKANIA biaxial borehole tiltmeter (no. P7) was installed in a borehole of a depth of 63 meter (Asch & Jentzsch, 1986; Alms et al., 1990; 1991).

In the following, a comparison of the tidal analysis of both records is discussed with respect to their coherence.

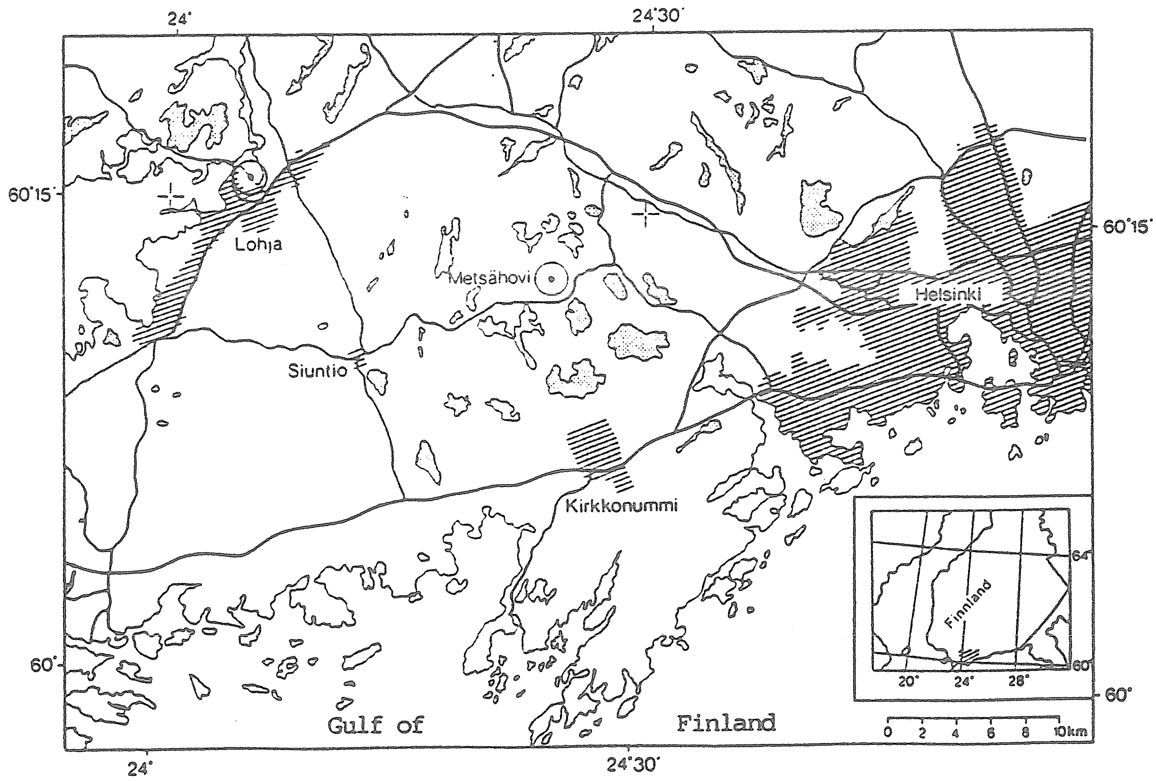

Fig. 1: Map of the area west of Helsinki showing the tilt stations Lohja and Metsähovi.

2. Data from Lohja and Metsähovi

All available data from the water tubes were analysed with respect to the tides: Due to interruptions for the North-South component 1021 days were available (within the period April 27, 1983, to January 28, 1992), and in East-West direction 887 days (period June 2, 1977 to October 3, 1991). For the vertical pendulum at Metsähovi nearly 700 days were used during the period December 3, 1986, until August 3, 1989.

Because of the interruptions only short parts of the records of both water tubes were in parallel during the common recording periods of these tubes and the borehole tiltmeter. Furthermore, another result of these gaps is that the long-term behaviour of the water tubes cannot be compared to the ASKANIA tiltmeter.

In August 1989 the ASKANIA tiltmeter P7 was exchanged to the tiltmeter P2 which recorded until autumn 1991. This data is not included here.

The analyses were carried out by Weise (1992). A comprehensiv publication on the work carried out in Metsähovi is in preparation as a volume of the 'Publications of the Finnish Geodetic Institute'. It includes a description of the experiment, the data obtained, as well as a detailed analysis. In addition, all the non-tidal effects are also discussed.

3. Comparison of the results from Lohja and Metsähovi

In tab. 1 the results for the main tidal waves are compared. Here, only the amplitudes, and the tidal parameters are given (*gamma* and *alpha*). These results are corrected for ocean loading. Fig. 2 gives the gamma-values including the error bars.

As we can see, both sets of parameters are very coherent. Only for M2 (N-S) we find error bars which do not overlap (because they are very small). Waves of small amplitudes like Q1 and K2 also have larger error bars. In the case of the diurnal waves in N-S direction both data sets show a significant anomaly from the 'normal' value of about 0.7.

4. Discussion and conclusions

Since many years tilt measurements are considered as being only of local value (comp. Lennon & Baker, 1973; Harrison, 1976; as well as many papers presented during the Earth Tides Symposia). All the presented results of tilt recordings showed strong anomalies which were due to the local installation (mainly in mines), introduced by Harrison as effects due to the local cavity, geology and topography.

Therefore, the results from the watertubes were disappointing at the beginning, because the parallel recordings of horizontal pendulums in the same gallery provided different results. The same was true for the ASKANIA borehole tiltmeters which were mainly installed in shallow boreholes first.

These local effects are mainly due to tidal strain which is different in both components. Further, the N-S strain is large for the semi-diurnal waves and nearly zero in E-W, whereas for the diurnal waves the ratio between N-S and E-W strains is about 0.26.

Table 1: Comparison of the results for the main tidal waves for the water tubes at Lohja and the ASKANIA borehole tiltmeter at Metsähovi; given are amplitudes, gamma-values and phases (corrected for ocean loading).

	Metsähovi			Lohja		
Tide	A	g	α	A	g	α
			N-S component			
Q1	0.475	0.755	6.8	0.451	0.714	-3.4
O1	2.456	0.747	1.6	2.527	0.767	-3.1
P1	1.166	0.763	-3.9	1.176	0.767	-5.6
K1	3.491	0.755	3.5	3.576	0.772	-3.6
N2	0.846	0.649	4.5	0.879	0.675	-3.1
M2	4.482	0.658	5.6	4.565	0.672	-1.8
S2	2.160	0.682	7.2	2.152	0.680	0.4
K2	0.530	0.615	1.6	0.575	0.668	-1.2
			E-W component			
Q1	0.712	0.658	-0.5	0.664	0.614	-2.5
O1	3.883	0.687	-3.2	3.828	0.678	-0.9
P1	1.863	0.709	-0.9	1.894	0.720	0.0
K1	5.831	0.734	-0.9	5.755	0.724	-1.6
N2	1.007	0.671	1.1	0.948	0.632	-2.2
M2	5.053	0.644	0.5	5.132	0.655	-2.6
S2	2.456	0.673	-0.2	2.487	0.682	-2.0
K2	0.668	0.674	-1.3	0.647	0.653	-4.3

This means that the anomaly of the diurnal tides in N-S cannot be allocated to strain induced effects due to local conditions. If tidal strain would effect our results in the N-S direction the semi-diurnal constituents would be the best candidate for such an effect; but here the results are 'normal'. On the other hand we would expect a disturbance due to tidal strain in the E-W component of the diurnal constituents; but again, the results are 'normal'.

Compared to the amplitudes the phases are less coherent. All phases from Metsähovi seem to be delayed systematically by some degrees. But this result is not significant, because the error bars vary between ± 0.5° and ± 4.0° for the six biggest and up to ± 11.2° for the smaller constituents. Therefore, most of these error bars overlap. Thus, we can conclude that our comparison shows a very good coherence in the tidal bands. This means that the results are not confined to the very local properties like installation and local geology. Further, the anomaly in the N-S direction of the diurnal constituents is due to a (at least) regional unisotropy of yet unknown reason.

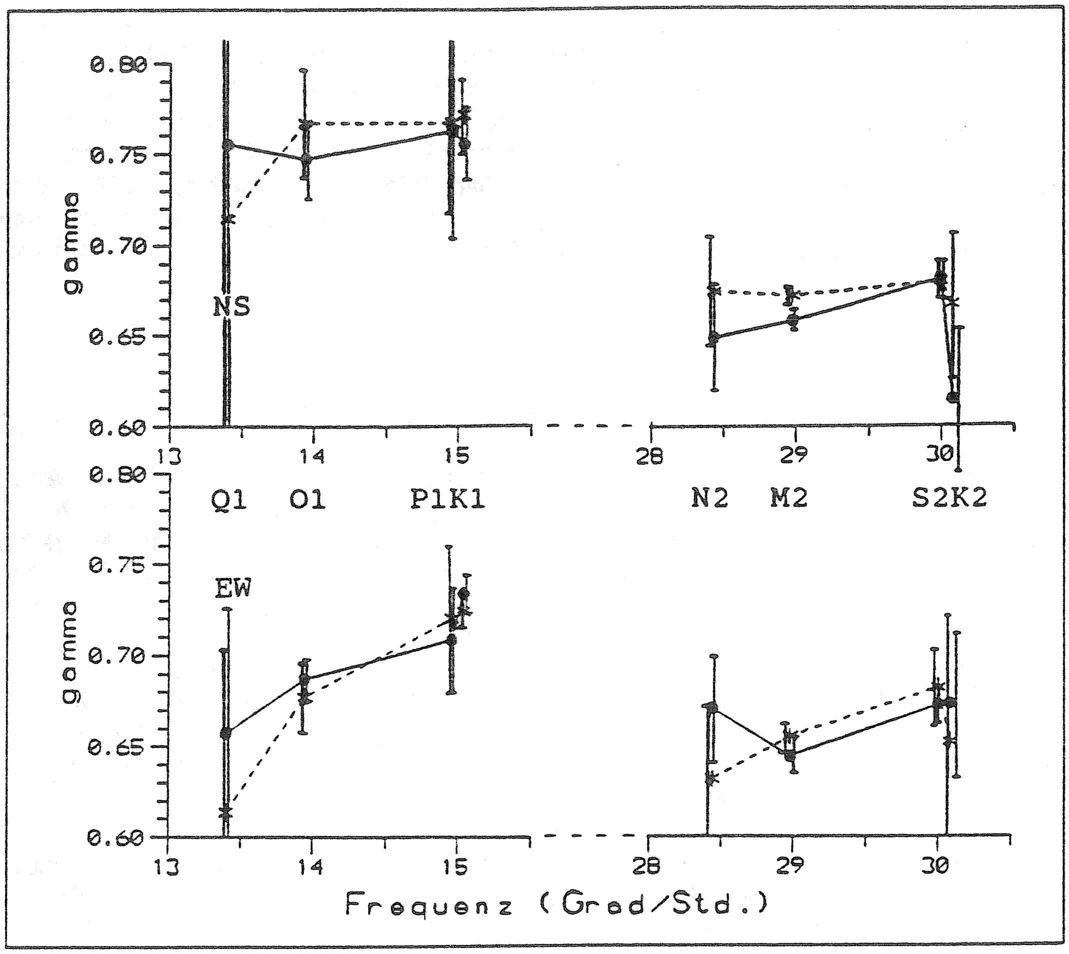

Figure 2: Comparison of the amplitude factors for Metsähovi (——•——•——) and Lohja (----*----*----); above: North-South; below: East-West components; noise level from Fourier spectrum is given as error bars.

Although there are still many effects which are typical for both places and not at all representative for the whole region (mainly due to ground water) we are encouraged from these results to continue our efforts to increase the depth of installation of the borehole tiltmeter in future. Thus, we hope not only to improve the signal-to-noise ratios in the tidal bands but also to improve the detectability of small signals like free oscillations of the earth.

Furthermore, the long-term stability should be much better in an environment which is far away from the ground water and meteorological influences. But the installation of the tiltmeter in boreholes of a depth of more than 60 meters (maybe 200 m to 600 m) requires much bigger efforts for the experiment. Especially the construction of the tiltmeter itself has to be changed as well as the method of determination of the azimuth which up to now is done optically (comp. Jentzsch et al., 1993, this issue).

5. Acknowledgements

During the first part of this work from 1984 until 1987 the first author was at the Institute of Geophysical Sciences at the Free University of Berlin. There, funds were available for basic developments regarding the experimental realization. Dr. G. Asch did most of the experimental work during this period. The 'Bayerische Kommission für die Internationale Erdmessung' of the Bavarian Academy of Sciences provided the tiltmeter P7. From the German side this research was supported by the German Research Soc. (Deutsche Forschungsgemeinschaft). All this is gratefully acknowledged.

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Deep Boreholes for High Resolution Tilt Recording.

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1. Introduction

At the Geodetic Observatory Metsähovi in southern Finland (about 15 km west of Helsinki) two borehole tiltmeters were in operation between autumn 1986 and autumn 1991. These biaxial tiltmeters are of the ASKANIA type. They were installed in one borehole of a depth of 63 meters (Asch & Jentzsch, 1986; Alms et al., 1990; 1991). The meter no. P7 was recording until August 1989; then it was exchanged to the tiltmeter P2 which recorded until autumn 1991. In the following, some examples are presented which show the high resolution of the tiltmeters as well as local influences from groundwater and meteorology. Proposals for an improvement of the system are derived from these results.

The data analyses were carried out by Weise (1992). The small scale groundwater effects were already discussed with respect to rock properties (Weise, 1991). A comprehensive publication concerning all the work at the 3-component station Metsähovi (including the gravimeter LCR-ET 18) is in preparation as a volume of the 'Publications of the Finnish Geodetic Institute'. It includes a description of the experiment, the data obtained, as well as a detailed analysis. In the present work, some non-tidal effects are discussed. A comparison of the tidal results to the results from the tilt station Lohja (about 15 km away) is given by Jentzsch et al. (1993, this issue).

2. Ground water effects on tilt - small scale

Fig. 1 contains a sketch of the local situation derived from a geophysical study as well as from wells in the vicinity. A water bearing layer of some 1 to 2 meters thickness is in a depth of about 43 meters inclining to north-west. The aquifer is confined, and the water in the well is raising up until about 6 meters below the surface.

The depth of the tiltmeter borehole was chosen to 63 meters in order to avoid this aquifer by at least 20 meters. The rock is granite, and the aquifer seems to be due to an overthrust. The observatory as well as other buildings in the vicinity are equipped with a water pump. This building was not used very often at the beginning of our measurements, but later it was used more frequently. This resulted in an increase of activities of the pump. Although our tiltmeter is well below the aquifer lots of disturbances could be allocated to these pumping activities.

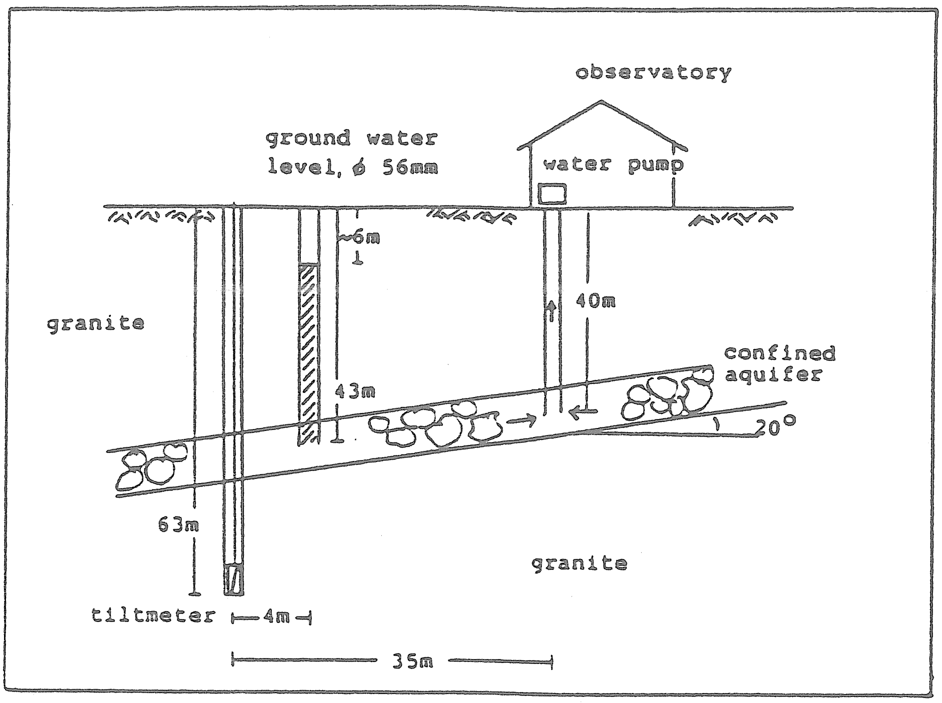

Fig. 1. Sketch of the local underground situation of the observatory Metsähovi: The tiltmeter is installed at a depth of 63 meters; the distance to the pump is about 35 meters.

Fig. 2 shows the record of seven days, channel X, the residual curve (tides removed), and the water level. It can be seen clearly that the changes of the water level in the well caused by pore pressure changes also disturb the tilt record.

Further, combining both channels to a vector plot the movements of the pendulum show a characteristic behaviour (see fig. 3): The curves always start with a flat circle south-east to east getting linear to about 45° N (corresponding to the direction of clefts (?) and to a swamp. After 80 to 100 minutes there is a strong change in the direction correlating with the end of the pumping. The direction now is about 300° N corresponding to the inclination of the aquifer. About one hour after the minimum of the water level the tiltmeter tends to move back to the starting position. The correlation between the movement of the pendulum and the change of the water level is very high: Looking at several events the paths of the pendulum until the first changes in direction provide a regression coefficient of 11.5 ± 0.3 msec/m of total amount of water level drop.

According to the geology we rather have a change in pore pressure than a change in ground water level. Therefore the effect of the pumping is seen 10 to 20 minutes earlier in the tilt record than in the water level of the well.

Similar signals of very small amplitudes (< 0.5 msec) are found in the tilt records as well without any corresponding changes in the water level (see fig. 4). But, according to the findings for large signals we must assume that they are due to pore pressure variations caused by pumping at other, more distant places in the vicinity.

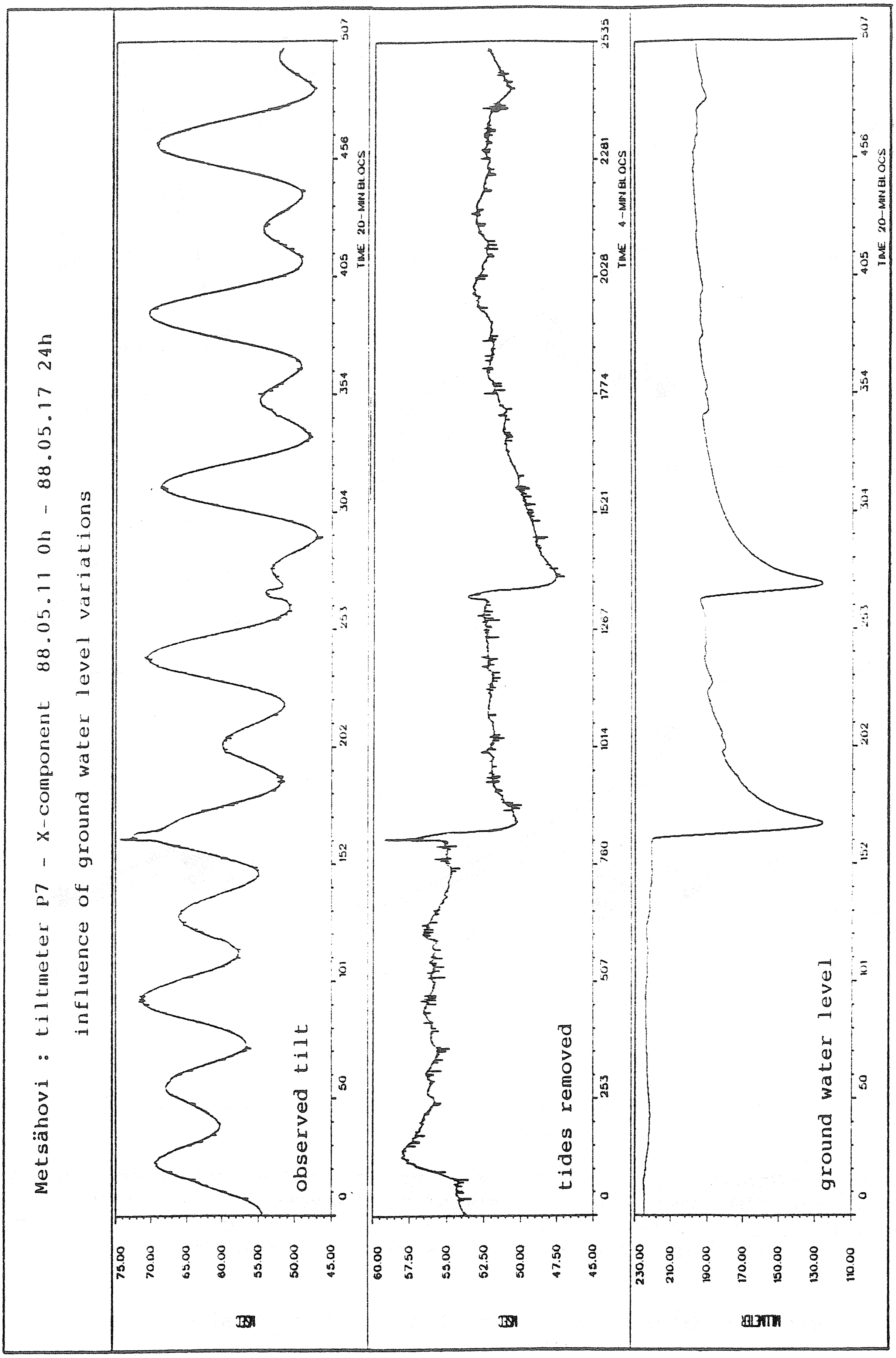

Fig. 2: Tilt record of channel X covering a period of seven days; below the residual curve (tides removed) and the water level changes measured in the well four meters away are given.

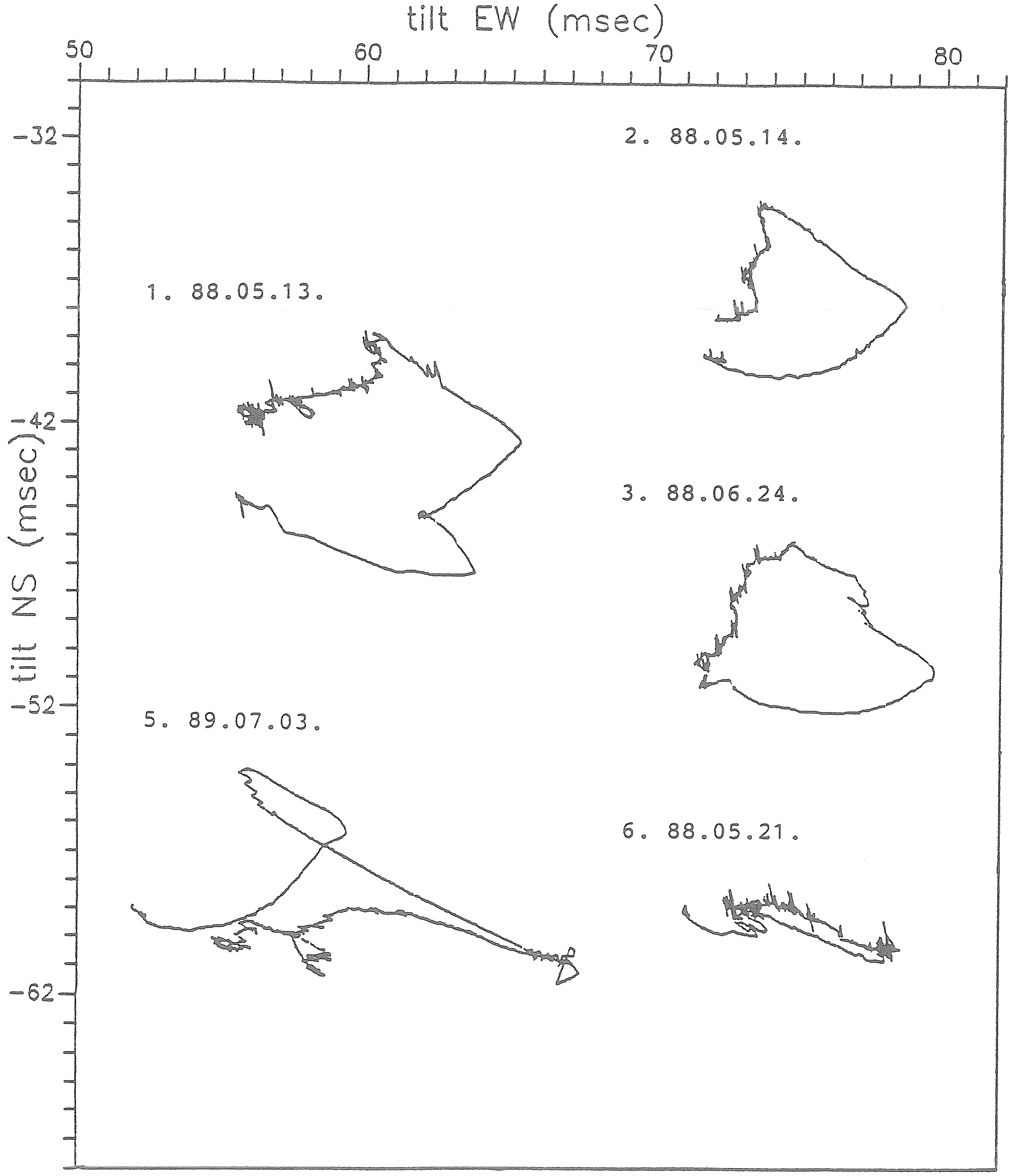

Fig. 3: Phasor plots of the movements of the pendulum due to pore pressure changes: The corresponding changes of the water level in the well are 94.6 cm (1), 67.6 cm (2), 65.6 cm (3), 92.7 cm (5), 19.5 cm (6); note that no. (4) is not included here.

3. Meteorological effects on tilt - large scale

The seasonal tilt changes (tides removed, see fig. 5) show a very distinct behaviour: During winter time, esp. during periods with temperatures below 0°C we find a nearly eastward movement which is repeated the next year. During periods with temperatures

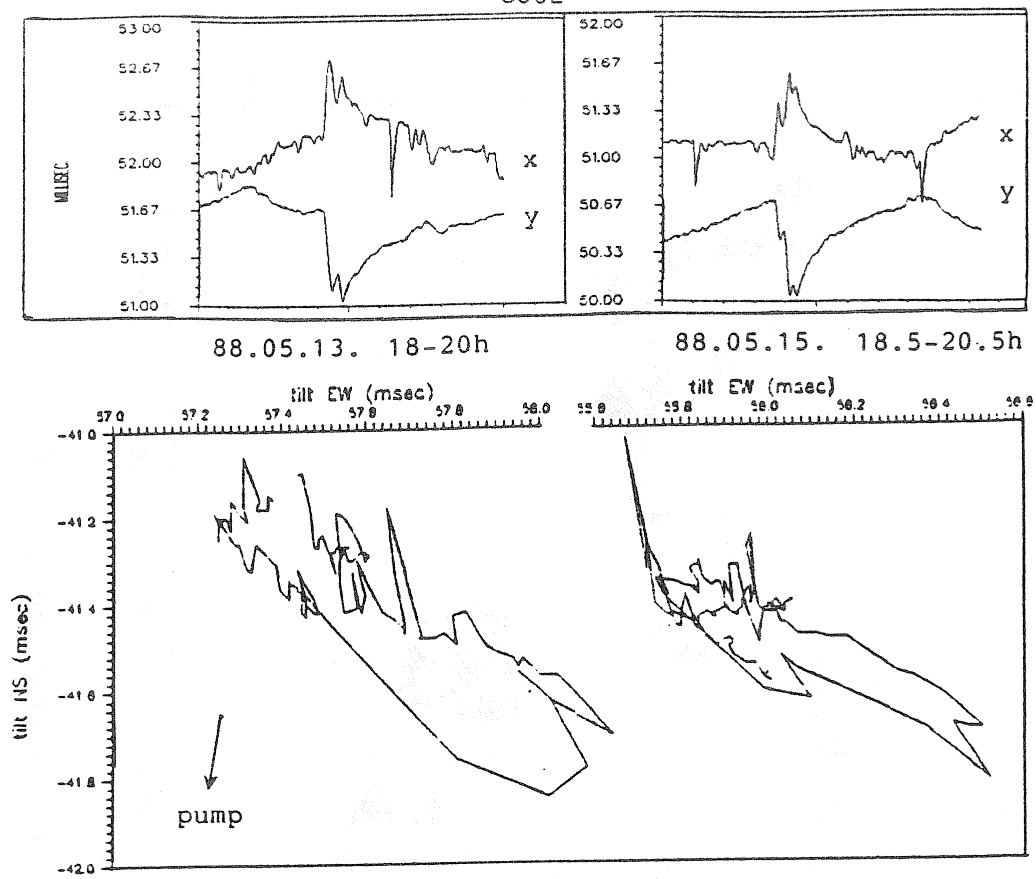

Fig. 4: Very small disturbances due to pore pressure changes: In tilt (X and Y components) and as phasor plots.

above 0°C we find movements in about 230° N and opposite. These seasonal trends do not correlate with the pore pressure changes indicated by the water level in the well.

On the other hand, the movements of the pendulum in about 150° lasting up to some days are strongly coherent with the air pressure field (local pressure as well as differential pressure between stations in southern Finland). These signals are also observed by the water tubes in Lohja (Kääriäinen & Ruotsalainen, 1989; comp. Jentzsch et al., 1993, this issue)

4. Necessary improvents of the tiltmeter for the installation in deep boreholes

Up to now according to the construction of the ASKANIA borehole tiltmeter there were two basic requirements to the borehole: First, the borehole must be cased and dry, which means that the tiltmeter should not be operated below a water surface. Second, the borehole must be straight such that the tiltmeter is visible in order to determine its orientation. This is carried out optically by observing the azimuth of an illuminated slit. Further, the borehole should not be inclined by more than three degrees; otherwise the pendulum is not adjustable.

In the meantime the BODENSEEWERKE (1979) improved the water tightness of the tube and the plugs to make it operational down to 50 meters below water. But, since the determination of the azimuth was not changed these improvements are only provisional means in case the borehole was flooded after installation. Thus, there was in fact no improvement related to deeper installations.

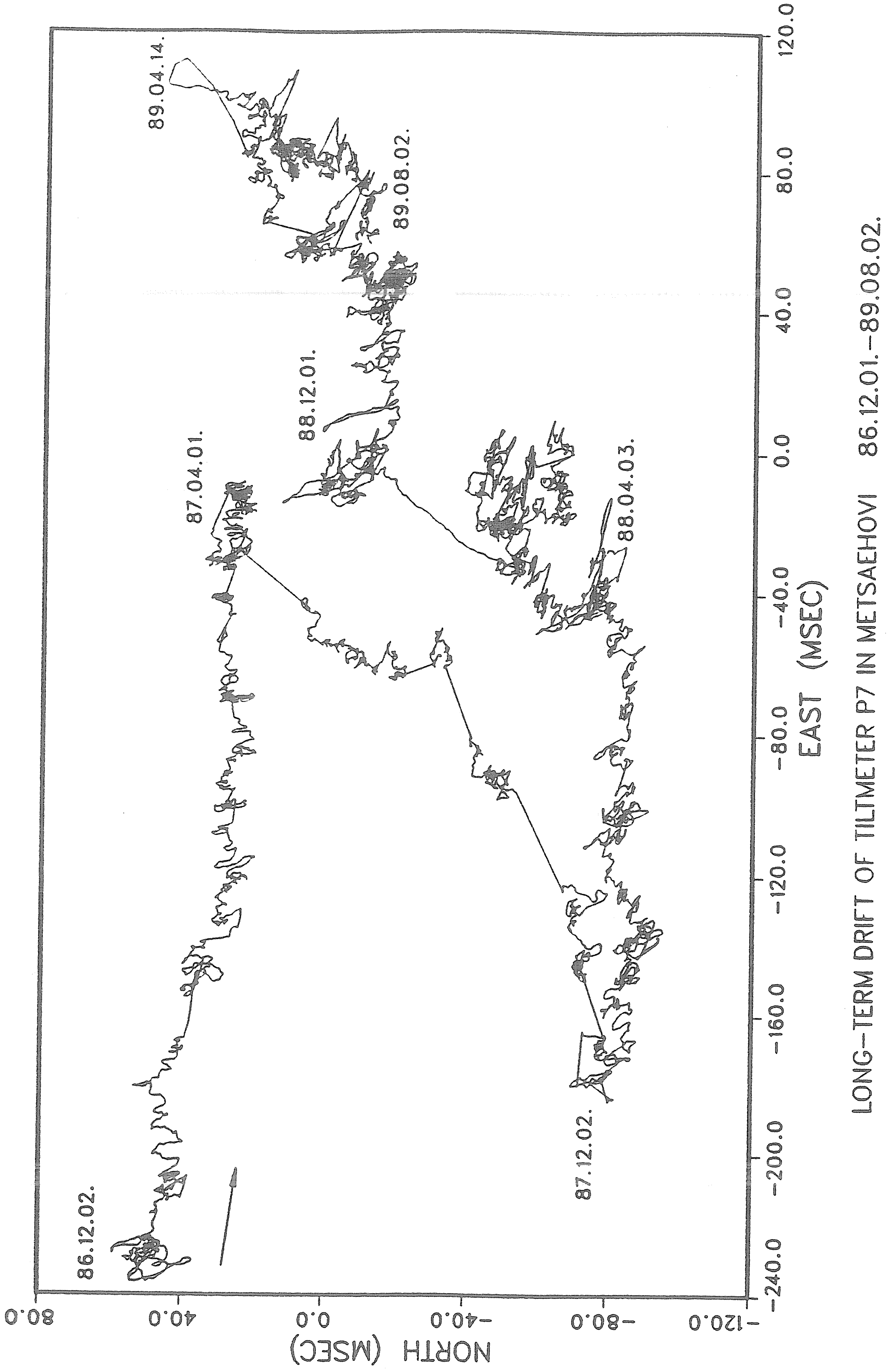

Fig. 5: Phasor plot of seasonal tilt changes: In winter time the main direction is about east, in summer time about 50° north to east and opposite, respectively. Many of the variations in about 150° N are due to the air pressure field. The orientation of the tiltmeter was changed twice.

Tab. 1: Instrumental modifications of the ASKANIA borehole tiltmeter for installation in deep boreholes.

Problem	necessary means
high water pressure	* construction of a new strong pendulum casing including the adjustment and clamping devices for the pendulum carrier; * modification of the clamping mechanism due to integrated cable and steel wire;
electronics	* microprocessor-control of main instrumental functions (adjustments, calibration, reset); * miniaturization of new capacitive transducer system; * implementation of a high resolution A/D-converter; * digital data transfer via RS-232 or RS-485 between instrument and surface;
azimuth determination	* development of an appropriate system on the basis of existing gyro-supplied navigation systems; * installation inside the pendulum tube;
further modifications necessary	* drastical reduction of the number of wires for power supply, adjustment and data transfer; * usage of a new all-in-one transfer- and carrying cable; * application of a motor winder for installation

The only attempt to install the tiltmeter at greater depths (110 meters) was made by Peters & Beaumont (1985) who attached a pin to the lower end of the tilmeter tube to fit into a 'horse shoe' at the bottom of the casing of the borehole. But here, the orientation of this horse shoe had to be known with the appropriate accuracy (we recommend less than $\pm$ 0.5°!).

There are mainly four improvements necessary before an installation in boreholes of 200 to 600 meters is possible. In such a depth also cased boreholes must be filled with water in order to balance the pressure. Further, in addition to problems due to high water pressure and azimuth determination the distance to the recording equipment is too far to use the now existing analog data transfer. The resulting requirements for a new design of the ASKANIA borehole tiltmeter are summed up in tab. 1.

Basically, these requirements are more or less independant from the ASKANIA tiltmeter; they also apply for the construction of a sonde for other sensors like the small horizontal pendulums developed by Levine, Harrison, Meertens (1983).

Regarding the determination of the azimuth a gyro-supplied navigation system is already under consideration. It is based on the gyro of the company LITEF (1989) which is supplementary equipped with two horizontal accelerometers for the correction of misadjustments due to tilt. A first test on the surface was very promissing, but further tests are necessary to reach the required accuracy of $< \pm 0.5^\circ$.

5. Discussion and conclusions

The results presented here show the high resolution of the ASKANIA borehole tiltmeter and its long-term stability. Although the study of ground water and meteorological effects were not the original goal of our research these effects provided interesting test signals to study the properties of our instrument. Referring to the conclusions drawn by Jentzsch et al. (1993, this issue) we may conclude that the ASKANIA borehole tiltmeter has excellent instrumental properties and it is a suitable instrument to measure stable tilt changes at high resolution over a wide span of periods starting at the periods of the free oscillations of the earth up to long-term trends.

But, to make the best use of these properties the tiltmeter must be installed in boreholes deeper than 200 meters, better 500 meters. There, we can avoid the influences of the surface due to ground water and meteorology to a high degree. In such boreholes we can expect that due to the low noise level tilt measurements can provide much better results covering short as well as long periods. Thus, tidal research with tiltmeters could have a totally new start!

On the other hand, tilt measurements in earthquake research are dependant on the detection of long-term tilt changes not effected by local influences. To make use of the properties of this and other tilt sensors as well the installation in deep boreholes is cruxial.

6. Acknowledgements

During the first part of this work from 1984 until 1987 the first author was at the Institute of Geophysical Sciences at the Free University of Berlin. There, funds were available for basic developments regarding the experimental realization. Dr. G. Asch did most of the experimental work during this period. The 'Bayerische Kommission für die Internationale Erdmessung' of the Bavarian Academy of Sciences, Munich, provided the tiltmeter P7. The Finnish Geodetic Institute arranged the borehole in Metsähovi as well as the careful maintenance of the tiltmeters. From the German side this research was supported by the German Research Soc. (Deutsche Forschungsgemeinschaft). All this is gratefully acknowledged.

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A Combined High Resolution Vertical Tilt and Strainmeter for Geodynamical and Technical Applications.

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1. Objectives of tilt and strain measurements

Observations of tilt and strain within tidal resolution range have in the past decades lost a certain scientific interest as the yield of the observed data is partly questioned. One of the reasons is that indeed such data are difficult to interpret as far as for instance global geophysical problems are concerned; this is due to the fact, that tilt and strain signals contain a more or less pronounced portion of local and regional effects which are at least difficult to eliminate. The main local signals result from cavity–, geology– and topography–effects, but also effects of hydrology, atmospheric pressure and temperature may reach a considerable amount.

But it is just the sensitivity of tilt and strain measurements to local and regional parameters and processes which offer a wide field of application – if those parameters and processes are subject of investigation. And they must or should be investigated within the context of many geoscientific and engineering problems: such as stability of edifices containing a relevant risk potential, processes in subsoil and foundation, control of underground cavities for the storage of perilous material; within the system of manifold tectonical questions earthquake prediction research has specially to be mentioned: if the stress accumulation of relevant geological volumes lead to non–linear stress–strain relations, the time variation of tidal responses may give information about the ongoing underground processes, and their possible risk development. And one should not forget the information potential of non–tidal signals which are within a tidal analysis determined as the "drift" of the time series.

It is a common objective of the applied geomechanic research to determine such precursory phenomena which inform as early as possible about the formation of critical states; and due to their high sensitivity to local effects and processes tilt and strain observations are predestinated means for such sort of investigations. On the other hand it is just the relative unsensitivity of gravimeter measurements to local features which make them appropriate for research of more global scale.

2. The principal problem of measuring high resolution tilt

Observations with a signal scattering of 10^{-3} " or better shall be understood as high resolution tilt–measurements.This scattering is controlled mainly by the instrumental properties of the tilt sensor and the effect of its coupling to the volume element of the Earth. Even if one does not underestimate the instrumental component it can be stated, that with modern technology the construction of a high resolution tilt sensor is at present no more the major part of the problem.

One has generally to distinguish between two types of instruments: those which contain a mechanical element representing the local and instantaneous horizontal (hydrostatic systems) and those representing the vertical (pendulum systems), corresponding to horizontal and vertical instrumental coupling as "natural" coupling directions. The choose of the appropriate coupling direction depends on the particular geophysical problem: relative vertical displacements in horizontal extension need a horizontal reference for mechanical signal transmission from one point to the other, relative horizontal displacements along the vertical direction need a vertical reference. If the length of the reference vector is 1 m the perpendicular displacement is 5 nm for an angle of 10^{-3}" or 0.5 nm for 10^{-4}".

It is the extremely small amount of relative displacement to be reproducibly measured which makes it complicated to establish a stable state of coupling between sensor and observation object. It has to be achieved, that the measured tilt signals do not contain any time or space variable coupling component and that the installation of the measuring instrument itself does not at all anyhow influence the tilt processes of the object. This is the principal and crucial problem!

The problem can briefly be demonstrated by the example of present–day vertical borehole tilt–measurements: The objective–quantities are the relative horizontal displacements of two points quasi–vertically positioned inside of a volume element of the Earth; the instantaneous relative position of the points shall be transmitted from one level to the other by the plumbline. Now, the drilled hole disturbes the natural stress field inside of the volume; the installation of a solid tube changes the stratigraphic coupling of the volume layers in the vicinity of the hole; hydrostatic and hydrodynamic pressure variations influence the geometry of the borehole tube; the tiltmeter is clamped to the tube effectively in a space mode instead of a double–point mode. Nevertheless the borehole technique is a very efficient and flexible variant of high resolution tilt observations, but one has to be aware of potential sources of systematical effects even when only interpreting results. Obviously the effect of coupling can at least partly be reduced by enlarging the coupling basis, however, for borehole tilt–measurements the individual base length is defined by the utilized instrument. So thoroughly appreciating the present state of the art concerning the performance of present high resolution borehole tilt–measurements one has nevertheless to recognize the existance of some serious metrological problems which have to be overcome by appropriate technical alternatives.

3. Present instrumental solutions for tilt measuremtents in quasi–vertical boreholes

The first successful high resolution borehole tiltmeter has been constructed by Prof. A. Graf about 35 years ago, which was lateron known as the Askania–tiltmeter. The sensor is a vertical pendulum which can be in–situ calibrated (ball calibration) and which can within limits be compensated for the inclination of the borehole. Although the performance of the instrument has been manifoldly proved some critical features should be mentioned: the weight of the device and, as a consequence of it, strong clamping forces; difficulties of measuring the orientation inside of the borehole; crossband suspension of the pendulum, which is not really an omnidirectional one, as one band is charged perpendicular to the direction of the minimum moment of inertia (problem of the definition of the "point" of rotation); high price as a consequence of the quantity of high quality mechanical elements. The instrumental performance of the Askania–boreholetiltmeter is still unsurpassed.

Recent constructions base on the combination of two small (!) horizontal pendulums inside of a vertically extended instrumental casing. Due to the pendulum dimensions and the problem of astatisation certain problems occur concerning mechanical stability and accuracy. As in quasi–vertical boreholes vertical space is in general sufficiently available, the application of a vertical pendulum seem nevertheless to be the more simple technical solution.

Some additional individual experiments were performed in recent times but did not lead to a small series production. Exemplarily shall be mentioned the experiment with a servo controlled Hughes tiltmeter installed in a borehole by C. Gerstenecker, Darmstadt.

4. Aspects for the construction and installation of a broad band borehole tiltmeter

In the following only vertical or approximately vertical (quasi–vertical) boreholes are considered. Such boreholes offer a maximum flexibility concerning the site of tilt observations, but of course only such processes can be investigated which are satisfied by a vertical coupling basis.

To minimize feedback effects of the borehole itself the borehole tube should be as weak as possible to avoid force transmissions of the surrounding material from one level to the other by the tube.

For the reason of stability the borehole should be filled with a liquid, which compensates partly by its hydrostatic pressure the acting outside stress.

To minimize the quantity of mechanical elements the borehole tube should be used as part of the tiltmeter system.

The length of the coupling basis has to be variable without changing the observation principle.

Observations close to the Earth's surface ought to be possible.

In terms of construction theory it must be distinguished between the mechanical element which represents the instantaneous direction of the vertical (pendulum) and those components which define the crust–fixed geometrical baseline; that baseline should as rigorously as possible be mechanically represented by two reference–points.

The plumbline sensor should be a wire pendulum as a good approximation to the mathematical pendulum sensor; by simply changing the length of the wire the length of the sensor device is changed without varying anything else. The clamping point of the wire represents mechanically the crustfixed point P_1 of the geometrical baseline.

The transducer device which monitors the relative motion of the pendulum body has to represent the crustfixed point P_2 of the geometrical baseline; as this device contains some other components too it will in the following be called "tastkopf". The coupling of the tastkopf to the crust has to be realized in such a way that it approximates the one–point–fixing.

The sensitivity of the transducer must be variable within an extended range; this permits starting the measurements without a–priori–information about size and structure of the signal to be investigated and enables the empirical adjustment of the device to the appropriate sensitivity.

The plumbline sensor should be adjustable to the particular investigated problem, the tastkopf should be standardized.

The temperature sensitivity of the instrumental device has to be minimized by rotation symmetrical construction of the relevant mechanical elements.

Instrumental effects due to atmospheric pressure variations must be minimized, mainly by avoiding buoyancy effects to the pendulum body.

In–situ–calibration facility is obligatory.

By a mechanical centering device the instrument should be applicable for the determination of long term processes and electronical drift determination.

The price of the equipment ought to be moderate; this offers the chance to perform observations in a quantity of sites spread over the region of investigation instead of measuring just in one site only (due to the price of a sophisticated instrument and the limited financial resources).

5. The double–pendulum tiltmeter

One of the major problems which occur when taking a long vertical wire pendulum as plumbline sensor is the accessibility to the pendulum body from upside the borehole. The problem can be solved by utilizing an inverse vertical pendulum using the buoyancy of an appropriate pendulum body in a liquid which fills the borehole; the body is suspended by a wire which is fixed at the bottom of the borehole. Simply by changing the level of the liquid one can optimize the wire–tension. By the form of the body and the viscosity of the liquid the mechanical damping of the system can be controlled. The lower clamping point of the wire forms a nearly ideal one–point–suspension. To exhaust the potential of the construction the wire will be chosen as thin as possible with regard to the necessary strength. But this may in function of the length of the wire lead to an unsufficient torsion stability of the buoyancy body; keeping the instrumental advantage of a thin wire the problem can principally be solved by interposition of a sufficiently long double wire component with appropriate wire distance.

At the upper part of the borehole the transducer for monitoring the relative movements of the buoyancy body is installed; due to the necessary lateral dimensions of the transducer a one–point–installation can not strictly be realized, but an approximate solution can be achieved by using a second wire pendulum, dipping into the buoyancy body; by two differential capacity units, integrated in the tastkopf, the relative motions of the two pendula are transformed into electrical DC–signals; the sensitivity is adjustable by lateral changes of the position of capacitive electrodes attached on the transducer pendulum body. It is important specially for the upper part of the mechanical device that the wires minimize the thermal conductivity. The upper point of suspension for the transducer pendulum forms the second point P_2 of the geometrical reference basis. Nevertheless this point is part of a more or less laterally extended mechanical element which has to be fixed to the object of investigation in a space or multipoint mode. But, as the upper part of the installation (for the described variant) is accessible it is possible to optimize the coupling empirically, depending on the local conditions. Best results have been achieved when using a three–point–fixing in connection with a strictly radial–symmetrical design of the suspension unit. The principle of the construction is demonstrated in the figure.

It has to be recognized that different from fixed mounted transducer systems an inclination of the tiltmeter system only produces translateral displacements between the plumbline sensor and the transducer pendulum.

If pure water is used as buoyancy liquid (for the reason of environmental restrictions for instance) one has to protect the system against evaporation; this can be achieved by covering the watersurface with an appropriate liquid of very low vapour pressure.

Compared with air the viscosity of any liquid is such that the restoring forces of the buoyancy pendulum more or less close to its vertical position may be compensated by the viscous resistance of the surrounding medium. This problem is of course partly depending on the viscosity; it has been proved that using a liquid with 1 cP viscosity and having adjusted an appropriate buoyancy force a pendulum of 1 m in length reproduces its zeroposition better than some $10^{-4''}$ (limit of the resolution of the test device). On the other hand just due to the viscosity of the liquid the sensor can efficiently be damped which diminishes some serious problems of signal filtering. In general the damping of the transducer pendulum is of minor importance due to the relatively short period of its proper motion (an effect of its limited length) and due to the relatively small lateral displacement per angle deflection.

Finally it should be mentioned that even the ratio between the lengths of the two pendula may be changed according to the particular problem under consideration. Thus the principle can also be applied for monitoring ceiling stabilities of underground cavities for instance. In such cases the downward hanging pendulum might be damped by a liquid volume inside of the buoyancy body of the upward pendulum.

6. The calibration and centering device

In the high resolution mode the tiltmeter is calibrated by lateral electrostatic forces; the corresponding vertical electrodes are part of the tastkopf and operate from outside of the buoyancy body which has a quadratic horizontal cross–section. Critical parameters are the actual distances between the electrostatic plates; these distances can be determined experimentally by bringing the transducer pendulum in the central position, which is that postion where equal voltages on opposite plates do nor more produce a deflection; knowing the geometrical dimensions of the relevant mechanical elements the plate distances can be calculated from dimension differences. This procedure of centering allows the mechanical determination of long term processes as well as the determination of the electronical drift.

7. The vertical extensometer

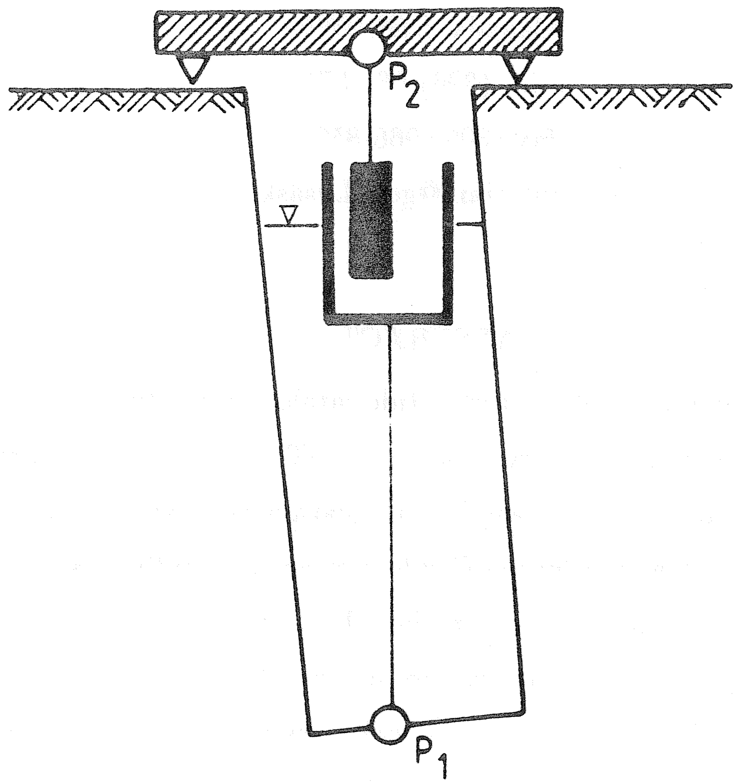
The construction can be used as a vertical extensometer too if a borehole tube of weak (deformable) material is used. In that case the vertical distance differences between buoyancy body and transducer pendulum have to be measured in a corresponding way as described before. Special attention has to be drawn to the material of the wires, which must have a very small temperature extension coefficient. In the high resolution mode the vertical extensometer is calibrated by an appropriate piezzo element at point P_2 of the suspension of the transducer pendulum.

8. The test device for the determination of systematical instrumental effects

As the tiltmeter system should be able to operate close to the Earth's surface too it is necessary to know the instrumental response to external parameter variations, mainly such of meteorological origin. Correspondingly a fixed relative position of buoyancy body and transducer pendulum has to be realized. This mechanical problem is solved in the following way: The downward suspension point P_1 of the plumbline sensor wire is integrated in an anchor element, normally sitting by its weight on the horizontal bottomplate of the borehole. By an appropriate system of wires it can be slightly liftet such that the anchor acts as a pendulum too. In that mode there is nor more any tilt signal (within mechanically defined limits) which means that non–clinometric, instrumental effects can be quantified and later on as corrections be eliminated from the tilt observations.

9. State of realisation

Since more than eight years different prototypes of the described tiltmeter and extensometer system have been developed and applied within different geomechanical and engineering problems. One instrument is running since five years without any perturbation. The maximum base length ($\overline{P_1P_2}$) has been 30 m so far. The system is operational. A geodynamical station for tidal observations too is in preparation.



The principle of the double-pendulum tiltmeter

A COMPARISON OF RECENT TIDE CATALOGUES

AND THE

CONSEQUENCES OF CATALOGUE ERROR FOR TIDAL ANALYSIS

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ABSTRACT

The gravity tide predictions of two recent tide catalogues are tested by comparing them with a benchmark series over an eleven year period. They are found to have a maximum error of several tens of ngal. It is shown that the catalogues have no false inclusions, nor omissions, greater than a few *ngal* in amplitude, nor are any individual entries in error by more than a few *ngal* in amplitude. This implies that using these catalogues as a basis for tidal analysis will result in gravimetric factors in error by no more than about 1/10,000 due to errors in the catalogues. Using the benchmark tidal ephemeris program, specific luni-solar and planetary effects in the tidal record are isolated, and errors in the catalogues are traced. Known errors in one catalogue, that is, the omission of the lunar inequality, nutation, and planetary effects, account for some of the error in that catalogues predictions, but most of the error in both catalogues originates from errors at luni-solar frequencies distributed throughout the tidal band. The consequences of using an incomplete catalogue for tidal analysis are shown, and it is demonstrated that both catalogues are adequate for most work.

INTRODUCTION

Superconducting gravimeters have a nominal sensitivity of about a *ngal* ($10^{-11} m\, s^{-2}$). Indeed, Richter(1987) has shown from the parallel registration of two supercondcuting gravimeters that they respond to ngal level signals, and Merriam(1993) has shown that known signals from atmospheric pressure of a ngal or less in amplitude are faithfully recorded. Core oscillations are expected to be about this amplitude, but if they lie in the tidal band, as some theoretical work suggests, their presence will be masked by the much larger Earth tide. As a result, there is a need for accurate tide predictions which can then be used to remove the tide from a record. The determination and elimination of the instrumental drift, including tares, and the repair of segments of the data corrupted by free oscillations or equipment malfunctions, all depend on an accurate, spectrally correct tidal prediction. Errors in calibration, and in Earth response, are much larger than any of the catalogue errors discussed here, but it is still important to have a catalogue that matches the sensitivity of the gravimeter, so that variations of the gravimetric factor with time, or across the tidal band, cannot be attributed to errors in the catalogue. I show below that only two tidal catalogues, those due to Tamura(1987) and Xi(1987,1989), are sufficiently accurate to be used with the best data. Using these two catalogues and an older catalogue I show the consequences of catalogue error on the measurement of tidal amplitudes and admittances.

Doodson's (1921) original development of 359 partial tides was accurate to about 500 *ngal*, in the direct attraction of the Sun and moon. Cartwright and Tayler's (1971) development (see also Cartwright and Edden, 1973) added a further hundred and fifty partial tides, and improved accuracy to about 250*ngal*. From this it can be seen that the tidal series converges so slowly that large increases in the number of partial tides are required to achieve modest increases in accuracy. As a rough rule, the maximum error in a tidal prediction is about fifty times the largest partial tide omitted from the summation. Recently, several new catalogues have appeared: Bullesfeld(1985) 656 terms, Xi(1987,1989), 3070 terms, and Tamura (1987), 1200 terms. Ducarme (1989) has compared these three catalogues with each other, and against a benchmark series for Hannover. Discrepancies of several tens of *ngals* were found between the predictions of the Xi and Tamura catalogues, and the benchmark series. The Bullesfeld catalogue was found to be in error by over a hundred ngal. However, the benchmark series was itself accurate to only 10*ngal*, so that Ducarme was unable to fully test the Xi and Tamura catalogues, nor was he able explain the source of errors. By using a more accurate benchmark tidal series Wenzel(1992), came to similar conclusions, and recommended that only the Xi and Tamura catalogues be used for precise work.

In this paper I compare the predictions of the Xi and Tamura catalogues with a benchmark series of eleven years duration, which has itself been verified to about a *ngal*, and I trace some of the errors in the Xi catalogue to known omissions from that catalogue. By examining the amplitude spectra of the differences between the benchmark sequence and the predictions of the catalogues, I show that no individual wave in either catalogue is in error by more than a few *ngal*, and that there are no spurious inclusions, or omissions, greater than a few *ngal* in amplitude. In the case of the Xi catalogue, the differences are shown to be due partly to known deficiencies in the catalogue, namely the lunar inequality, nutation, and planetary effects, and partly to truncation of the catalogue and other unknown causes. Finally, I show the consequences of using a truncated catalogue, such as Cartwright, in a tidal analysis.

THE FORCING FUNCTION

The tidal catalogue of Xi (1988) is the most extensive available. It contains 3070 separate tidal lines, each of which makes a contribution to gravity on the rigid sphere at colatitude θ, and east longitude λ, of the form

$$AMP = \frac{XAMP \times XL \times D \times n}{a} P_n^m(cos\theta)cos(\phi)$$
$$\phi = nh \times h + \tau \times R + (ns + \tau) \times s + np \times p - nn \times \Omega + ns \times p_s + m \times \lambda \qquad (1)$$

where h is the geometric mean longitude of the Sun, s that of the moon, p_s the mean perigee of the Sun, p the mean perigee of the moon, Ω the argument of the mean lunar node, and R the right ascension of the fictitious mean Sun, measured from the equinox of date. XAMP is the catalogued amplitude, and XL is a scale factor (following Doodson(1921), that depends on the degree number. Doodson's constant, D, has been redefined by Xi, so that gravity predictions are made at the equatorial radius, $a = 6378.140km$, rather than the mean radius of the Earth.

$$D = 26335.838m^2 s^{-2}$$

The phase, ϕ, needs to be retarded by 90^o for all waves for which the sum of the degree number n, and the order number m, is odd.

The astronomical argument formed from each unique combination of the integers nh, ns, np, nn, τ advances at a unique rate, and defines a separate tidal frequency. The mean elements do not change at a constant rate, but exhibit secular and harmonic perturbations, so that each combination of integers can only be said to represent an approximate frequency, over a given period of time. For example, the acceleration in the argument of lunar perigee is $0^o.01\,cy^{-2}$. After ten years the lunar perigee has advanced $0^o.001$ more than the linear rate would suggest, which would produce several ngal difference in the tide. Thus, the luni-solar part of the catalogue can only be considerd to be harmonic at the ngal level for epochs of less than ten years. Accepting that each combination of integers represents a separate tidal frequency, the above equation can be rewritten

$$AMP = \frac{XAMP \times XL \times D \times n}{a} P_n^m(cos\theta)cos(\omega t + \phi_o) \qquad (2)$$

where ω is the frequency, t is the elapsed time from some arbitrary time, t_o and ϕ_o is the phase of the tide at t_o. Thus the frequency and time carry the phase forward at a rate defined by the mean elements. The Tamura catalogue contains explicit secular terms for the largest waves. As written, (2) gives the amplitude of the tide on a rigid sphere of radius a. Tidal gravity by definition is measured normal to the ellipsoid of an elastic earth, and includes a poorly characterized nearly diurnal free wobble response, as well as ocean tide loading, but for the purpose of comparing catalogues (2) is adequate. In fact, since the earth response cannot be computed to the ngal level, the use of (2) is necessary in the context of this paper, so that one can be sure that any discrepancy between predictions can be traced to error in the catalogues, with complete assurance that differences in how earth response is computed are not responsible.

The Xi catalogue is strictly a lunisolar catalogue in that only the direct attraction of the Sun and moon are accounted for, and the argument of the tide is described by luni-solar arguments only. Tamura includes eight planetary tides. Planetary tides are raised in two ways: by the direct attraction of the planets on the Earth, and by perturbing the position of the Sun and moon, thus giving rise to an indirect effect on the luni-solar tide. Merriam(1992) has shown that indirect tides are generally larger than direct tides, and that planetary effects, mostly due to Venus and Jupiter, can reach almost 100 ngal, although during the eleven year period of the test, planetary effects are much smaller than this. The Xi catalogue contains no direct planetary tides, but its author suggests that the indirect effect of planets, (ie the perturbation of luni-solar coordinates by the planets), may be introduced by adding known harmonic perturbations (due to the planets) to the mean longitude of the Sun. This amounts to a small time-dependent adjustment to the phase of all those partial tides that include the mean longitude of the Sun in their astronomical argument. Because any partial tide may have contributions from variations in longitude, latitude and parallax, this scheme is incomplete and approximate. By adding planetary perturbations of solar longitude to the argument of any partial tide, one is adjusting its argument assuming that the partial tide is entirely due the variation in solar longitude. Planetary perturbations to latitude and parallax, which are only of slightly less consequence than those in longitude, are ignored. The largest planetary perturbations of the Sun's longitude are:

$$\begin{aligned} &0^{\circ}.00134 cos(-8^{\circ}.49 + 22518^{\circ}.44 T_J) \quad \text{Venus} \\ &0^{\circ}.00154 cos(253^{\circ}.14 + 45036^{\circ}.89 T_J) \quad \text{Venus} \\ &0^{\circ}.00200 cos(157^{\circ}.21 + 32964^{\circ}.47 T_J) \quad \text{Jupiter} \end{aligned} \tag{3}$$

where T_J is the time in Julian centuries from 12 hrs UT Jan 1 2000. Each of these acts to split any lunisolar tidal harmonic with the Sun's longitude in its argument by plus and minus the above frequencies. The largest tides affected are S_2 and P_1, and waves of about half a ngal are split from each. The neglected terms in the sequence of which (3) are the leading terms, can result in net perturbations of about 10 ngal to the mid-latitude tide, during the test period. Planetary perturbations of the moon's mean longitude, although generally smaller than those of the Sun, should be included as well.

Similarly, terms in nutation, the lunar inequality, and a secular term in the longitude of the Sun, produced by the evolution of the eccentricity, are not explicitly included in the Xi catalogue. The lunar inequality in the Sun's longitude is

$$0^{\circ}.00178 cos(s - h) \tag{4}$$

and this should be added to the geometric mean longitude of the Sun. The principal effect is to split P_1 and S_2 by plus and minus $s - h$.

The nutation in longitude, of which the leading term is:

$$(-0^o.00477 - 0^o.000048T_J)sin(\Omega) \quad (5)$$

must be added to all of the fundamental arguments in (1). Its principal effect is to split O_1, P_1, K_1, and K_2 by plus and minus a nodal cycle. Finally, a secular term in the eccentricity of the Sun's orbit results in a perturbation to the Sun's mean longitude of

$$-0^o.00232T_J(1 + 0.003T_J)sin(h - p_s) \quad (6)$$

which acts principally to split S_2. The terms in (4), (5), and (6), as well as the planetary perturbations in (3), are all omitted from the Xi catalogue, but Xi suggests that they may be included as a first order approximation by simply adding them to the appropriate argument, but the nutation in obliquity, the lunar inequality in latitude and parallax, and planetary terms in latitude and parallax cannot. Indeed, to include the above terms in the manner suggested by Xi produces only marginal improvement in the comparison with the benchmark sequence. To retain the purely harmonic structure of the catalogue, the correction terms described above are not used here, and the sequence produced from the terms in the XI catalogue, excluding the perturbations discussed above, is called the Xi sequence.

TEST PROCEDURE

Merriam (1992) has described a benchmark program, GTIDE, the precision of which has been tested by comparing its computed ephemeris with published values over a ten year period, and by comparing its predictions against those of another benchmark program (Wenzel,1992). GTIDE has been confirmed to about a ngal, (but see Wenzel, 1992, and Dahlen, 1993) in the attraction on a rigid sphere, so that any discrepancy with catalogue predictions can be attributed to a deficiency in the catalogue, that is, in the amplitude or astronomical phase of particular partial tides, omissions from the tidal catalogue, or spurious inclusions in the tidal catalogue. Furthermore, a spectral analysis of the differences between the two benchmark series reveals that at any single frequency GTIDE is in error by no more than a few tenths of a ngal. GTIDE also includes direct planetary tides which are not included in the Xi catalogue, and are truncated in the Tamura catalogue. They are, in any case, small throughout the eleven year period, reaching a maximum of only a few *ngal*.

Figure 1a shows the difference between the predictions of the Xi catalogue, and the benchmark series, over an eleven year period 1989-2000. The mean difference between the two series is only 0.2 *ngal*, and the standard deviation 7.5 *ngal*. The maximum error, which must be nearly all error in the Xi catalogue, is 48.7 *ngal*. Note that the largest excursions have an annual and semiannual modulation, and that the variance increases with time, as the purely harmonic signal of the catalogue drifts out of phase with GTIDE. This can be remedied in part by calculating the phase with (1) instead of (2). The errors in the predictions of the Tamura catalogue, (Figure 1b) are similar in mean and standard deviation, but reach 60 ngal in maximum deviation. The secular terms in the catalogue keep the Tamura predictions in phase with the GTIDE predictions throughout the eleven year period, so that there is no growth in the variance of the errors with time.

Figure 2a and 2b show the amplitude spectra of the two error sequences shown in Fig 1, for the first three years. The largest amplitude in the spectrum of differences is at, or very near, K_1 in both cases, and is 2.8 ngal for Xi, and 3.6 ngal for Tamura. Since the K_1 wave is 50,000 ngal at midlatitudes, K_1 is correctly expressed in both catalogues to better than 1/10,000, as are all of the principal waves. This is slightly greater than the formal error on the determination of tidal admittance from the best gravity data, so that both of these catalogues are adequate for precise tidal gravity processing. A cross spectrum between GTIDE and the Xi predictions indicates that in general, diurnals are underestimated and semi-diurnals overestimated by the catalogue during this period. In general the phase of the principal waves in the catalogue is ahead of GTIDE by $10^{-5} rad$.

GTIDE explicitly includes several hundred planetary perturbations to solar longitude, latitude and parallax, as well as seventeen terms in the nutation in longitude and twenty in obliquity. The lunar inequality in longitude, latitude and parallax is included, as well as the secular term in eccentricity. Because of the structure of GTIDE, the effect of any of these in tidal gravity can easily be isolated for study. Fig 3a is the planetary tide sequence (direct plus indirect) for the eleven year period, and Fig 3b is the semidiurnal part of the amplitude spectrum of the combined direct and indirect planetary tides. The vertical dashed lines are the expected indirect planetary tides produced by perturbing the Sun's longitude by (3) in the manner described above, and the asterisks are the amplitudes of the four planetary tides in the semidiurnal band of the Tamura catalogue. All of the frequencies predicted by perturbing the Sun's longitude are present, and in approximately the correct amplitude, but the actual spectrum is evidently much more complex than the longitude perturbation suggests. The failure of the longitude perturbations to reproduce the correct spectrum is due to the truncation of the sequence (3) and the neglect of effects on latitude and parallax.

Similarly, the effect of nutation (in obliquity and longitude), the lunar inequality (in longitude, parallax and latitude) and the secular term in eccentricity, can be isolated from the GTIDE sequence. Fig 4a shows the sum of all of these effects, and Fig 4b shows the diurnal part of the spectrum. The vertical dashed lines are the anticipated spectrum from (4), (5), and (6). Once again the procedure of perturbing the Sun's longitude makes a reasonable account of the largest effects, but fails to completely account for the spectrum. The effect of the lunar inequality (the dashed lines near $14^o.5/hr$ and $15^o.5/hr$ is not reflected in the difference spectrum. Therefore, either the lunar inequality is built into the Xi catalogue, contrary to the claim of its author (Xi,1989), or the effect of the lunar inequality on latitude and parallax effectively cancel its effect on longitude.

The tide sequence shown in Fig 3a (due to planetary effects) and the tidal sequence shown in Fig 4a (due to the terms in equations (4-6)) only explain about half of the errors in the Xi sequence (Figure 1a and Figure 2a). Evidently, there are errors in the Xi catalogue other than from the omission of planetary effects, nutation, the lunar inequality, and the secular term in eccentricity. By subtracting the sequences shown in Figure 3a, and Figure 4a from the sequence in Figure 1, the remaining errors in the Xi catalogue (which must be luni solar) may be isolated. These are shown as an amplitude spectrum in the semidurnal band in Figure 5. In comparison with the spectra of the planetary tides and the terms in equations (4-6) which are dominated by a few peaks, this spectrum is much more complex, and suggests the remaining errors in the Xi catalogue are distributed rather uniformly throughout the tidal band. There are no explicit omissions from the ephemeris used to calculate the Tamura catalogue, so the situation is not as clear cut as it is for the Xi catalogue. However, a similar analysis indicates that the errors are spread throughout the tidal band.

The Xi catalogue, and the Tamura catalogue, are known to be in error by about 50 ngal over a several year period, and it has been shown here that at any individual frequency they are in error by no more than a few ngal. In this section I demonstrate the consequences of using a truncated catalogue. GTIDE was used to generate several one year long records of hourly samples of the tide at station Cantley, Quebec. Each of these one year records was then analyzed for the gravimetric factors of a suite of diurnal and semidiurnal tides, using the Cartwright, Tamura and Xi catalogues as a basis. The gravimetric factors were compared with each other, and with the known gravimetric factor in GTIDE. The Xi and Tamura catalogues were found to be clearly superior to the Cartwright catalogue, at every partial tide tested. At M_2, the Tamura catalogue seems to be superior to the Xi catalogue, in that the mean value for the eleven year period was in better agreement with the known gravimetric factor in GTIDE. Also, the year to year variations in the amplitude of the M_2 gravimetric factor were slightly smaller when the Tamura catalogue was used as a basis compared to when the XI catalogue was used. Figure 6 shows the fractional error in the measured M_2 gravimetric factor as a function of epoch, for each of the three catalogues. The year to year fluctuations in the measured gravimetric factors are caused by a combination of errors, omissions, and possibly false inclusions in the tidal catalogue used as a basis. They are the sum of errors in the frequency band centered on M_2 and plus or minus 1 cycle/ year wide. The error bars for each are set at the equivalent of one ngal, which is the nominal sensitivity of a superconducting gravimeter. Thus, the Cartwright-Tayler catalogue is clearly inadequate for tidal processing of superconducting gravimeter data, and only the very best data will require more than the sophistication of the Xi and Tamura catalogues. The variations in the fractional error in δ suggests that the Xi and Tamura catalogues are in error in the M_2 ($\pm$ 1 cy/yr) band by about 1 ngal, consistent with the results in Figures 2a,2b. The Cartwright catalogue is in error by about 7 ngal, at $M_2 \pm$ 1 cy/yr. Generally, the Xi catalogue serves as a better basis, but the Tamura catalogue is sometimes superior, as it is at M_2.

It has been amply demonstrated above that the Xi and Tamura catalogues are in error at any tide frequency by no more than a few ngal. The question remains as to whether this difference is important when doing a tidal analysis with real data. Can a gravimeter detect the difference between the Xi, Tamura and Cartwright catalogues? Merriam (1993) has shown that superconducting gravimeters can accurately record signals smaller than a ngal, so that in principle they should be able to distinguish between even the Xi and

Tamura catalogues, which disagree by about 3 ngal at any individual wave. Table 1 shows some diurnal gravimetric factors determined from three years data of the superconducting gravimeter at Cantley, Quebec. There is clear agreement in amplitude and in phase with measurements made using the Xi and Tamura catalogues as a basis, but the measurements made using the Cartwright catalogue disagree with the other two by at least one formal error in amplitude (equivalent to about 2 ngal) and often much more in phase. Thus, it appears that the superconducting gravimeter is unable to distinguish between the Xi and Tamura catalogues, at least for this combination of data and waves, and that the Cartwright catalogue cannot meet the standard required by the best gravimeter data.

The study of the Earth's Nearly Diurnal Free Wobble (NDFW) requires precise information on tidal spectroscopy for accurate results. For the three years of the Cantley data, the analysis based on the Xi and Tamura catalogues produces results for the NDFW parameters (resonance frequency, real part of oscillator strength, imaginary part of the oscillator strength and Q) that agree with each other to within one formal error. The Cartwright catalogue, however, produces NDFW parameters that are not in agreement with those found using the other two catalogues as a basis. In particular, the resonance strength is more than a formal error different, and the solution Q is very high, 30,000. From the results shown above, where the gravimetric factors derived using the Cartwright catalogue as a basis are shown to vary with epoch, it can be concluded that the NDFW parameters derived using the Cartwright catalogue as basis, may also show substantial variation with epoch, and that therefore the Cartwright catalogue may well lead to anomalously low Q at other epochs. Earlier estimates of the FCN parameters that have a low Q (Richter and Zurn, 1988), Neuberg et al, 1987) may thus be due to the truncation of the Cartwright catalogue.

SUMMARY

The Xi and Tamura tide catalogues differ from each other by no more than a few ngal at any individual frequency, but the sum of all differences can sometimes amount to fifty or sixty ngal. Some of the errors in the Xi catalogue are due to known omissions from the ephemeris used to construct that catalogue. The remaining errors are more-or-less uniformly distributed throughout the tidal band. The Tamura catalogue has no known

omissions, and its errors are also rather evenly distributed throughout the tidal band. The demonstrated ngal resolution of the superconducting gravimeter suggests that it should matter whether one uses the Xi or Tamura catalogue as a basis for tidal analysis, but this seems to be unfounded. A suite of gravimetric factors measured in data from the superconducting gravimeter at Cantley, Quebec, using both catalogues as a basis, yields gravimetric factors that agree with each other to within one standard deviation, so that at least for this combination of waves and epoch, the data cannot distinguish between these two catalogues.

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WAVE	XI AMP	XI PHASE deg	TAMURA AMP	TAMURA PHASE deg	CARTWRIGHT AMP	CARTWRIGHT PHASE deg
O_1	1.166451	0.5450	1.166444	0.5451	1.166314	0.5491
	(0.000059)	(0.0029)	(0.000059)	(0.0029)	(0.000059)	(0.0029)
P_1	1.161791	0.4830	1.161728	0.4710	1.161871	0.4880
	(0.000145)	(0.0070)	(0.000145)	(0.0070)	(0.000148)	(0.0072)
K_1	1.148300	0.5873	1.148280	0.5840	1.148359	0.5923
	(0.000045)	(0.0022)	(0.000045)	(0.0022)	(0.000046)	(0.0023)
Ψ_1	1.275229	0.5375	1.282730	0.6293	1.282503	0.2877
	(0.005941)	(0.2620)	(0.005983)	(0.2615)	(0.006069)	(0.2684)

Table 1 Gravimetric factors, phases, and one sigma formal errors (in brackets) for four diurnal waves measured in three years of data from the superconducting gravimeter at Cantley, Quebec, using the Xi, Tamura, and Cartwright catalogues as a basis. The Xi and Tamura catalogues yield admittances which are in agreement with each other to within much better than a formal error, whereas the Cartwright catalogue yields results which for some waves disagrees with the others by more than one formal error. These four waves are the principal source of information on the parameters of the NDFW, so that, the use of teh Xi and Tamura catalogues will result in essentially the same NDFW parameters. The Cartwright catalogue will result in biased parameters, that will be seen to vary with epoch.

Figure 1 a,b. Figure 1(a) shows eleven years of residuals GTIDE - Xi, at latitude 45° on a rigid sphere. Figure 1(b) shows the GTIDE - Tamura residuals. Note that variance increases with time in Figure 1(a), as the phase of the purely harmonic Xi catalogue drifts with respect to the phase of GTIDE. The Tamura catalogue includes secular terms for the largets waves, so that, the variance in Figure 1(b) is unchanged with time.

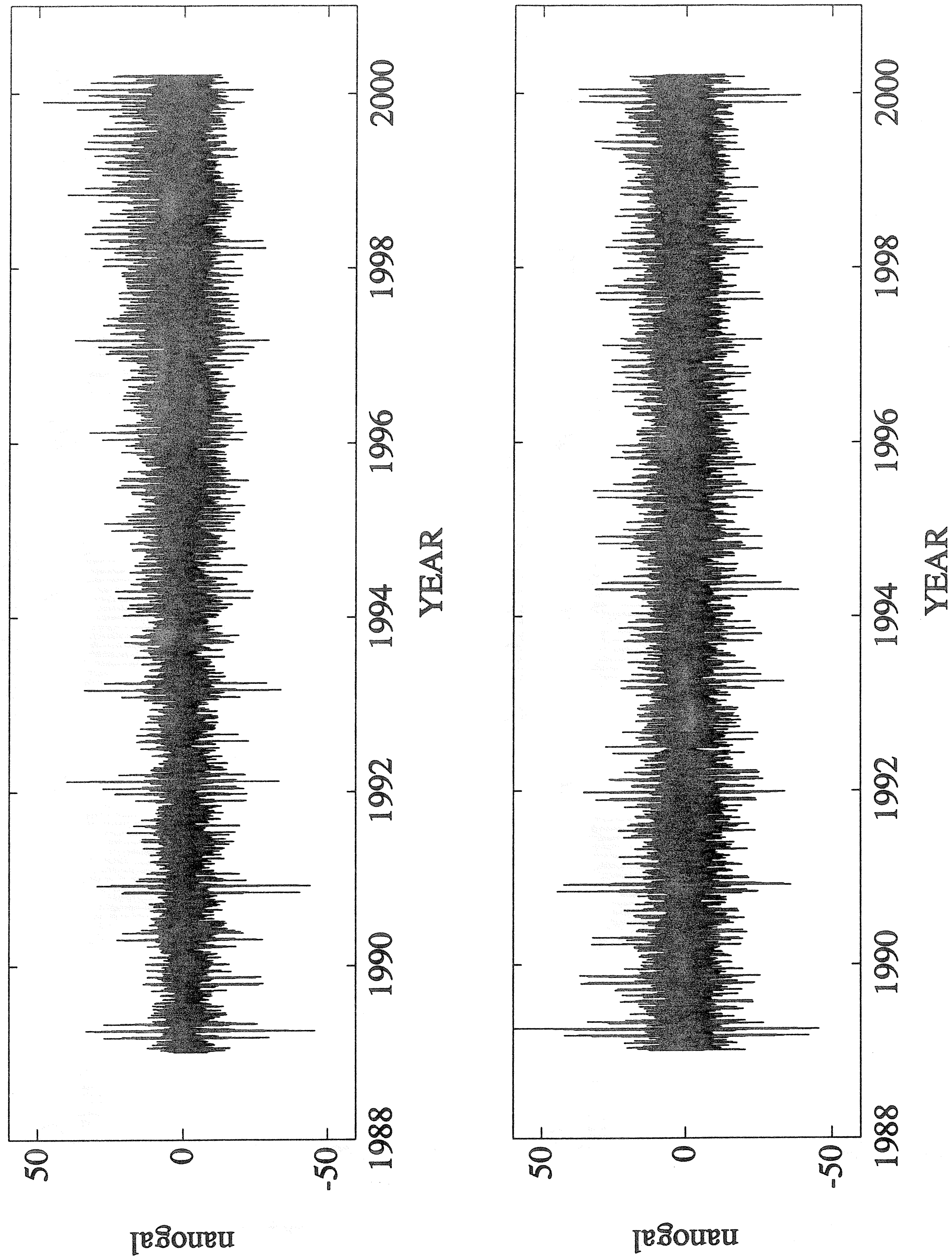
Figure 2 a,b. The amplitude spectra for the first three years of the data shown in Figure 1a,b. Figure 2a GTIDE-Xi, Figure 2b GTIDE - Tamura. Similar results are obtained for other subintervals of the eleven years. Both the Xi and Tamura catalogues are good to about 3 ngal at any frequency. The largest residuals are at. or near, K_1 in both cases.

Figure 3 a,b. Figure 3(a) shows the sum of indirect and direct planetary tides in GTIDE during the eleven year period. During this period indirect tides are well below their maximum, but are still larger than direct tides. Figure 3(b) shows the amplitude spectrum in part of the semidiurnal band. The continuous spectrum is the sum of all planetary effects in GTIDE. The vertical dashed lines forming a discrete spectrum are the principal indirect planetary tides resulting from first order perturbations of the Sun's longitude by Jupiter and Venus. Indirect planetary effects arising through the Sun's latitude and parallax are included in the continuous spectrum, but cannot be included in the discrete spectrum. The asterisks are the amplitudes of the four planetary tides in the semi-diurnal band of the Tamura catalogue.

Figure 4 a,b. Figure 4a shows the effect of the lunar inequality, nutation, and a secular term in the eccentricity of the Earth's orbit (these are known omissions from the Xi catalogue). Figure 4(b) the spectrum of the above in the diurnal band. The vertical dashed lines are the result of pertrubations to the longitude of the Sun by the largest of the above terms, and the continuous spectrum is the spectrum of the above effects extracted from GTIDE. The effect of the nutation in obliquity, and of the lunar inequality in the Sun's latitude and parallax are included in the continuous spectrum, but cannot be included in the discrete spectrum. The lunar inequality (the vertical dashed lines near 14.5 and 15.5 deg/hr is not noticeable in the continuous spectrum, which suggests that either the lunar inequality is in the Xi catalogue, or the effect from latitude and parallax must nearly cancel the effect from longitude.

Figure 5 The remaining errors in the Xi catalogue ie other than those due to the neglect of planetary effects, the lunar inequality, nutation, and a secular term in eccentricity in the semi-diurnal band. Note that these errors are much more uniformly distributed across the tidal band than are the errors shown in Figures 3 and 4.

Figure 6. The fractional error in the measured gravimetric factor of the M2 wave, using the tide catalogues of Cartwright and Tayler, Xi and Tamura as a basis. Each measurement was made with one year of hourly GTIDE predictions at midlatitude. The errorbars that would result from a one nanogal uncertainty (the nominal sensitivity of a superconducting gravimeter) are also shown. The estimate of δ_{M_2} using the Cartwright catalogue as a basis depends on epoch, and fluctuates by what amounts to a several ngal uncertainty in M_2. The amplitudes of M_2 found using the Xi and Tamura catalogues are always within a ngal of each other, and therefore only the very best superconducting gravimeter data could possibly distinguish between the Xi and Tamura catalogues.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-50
1988
1990
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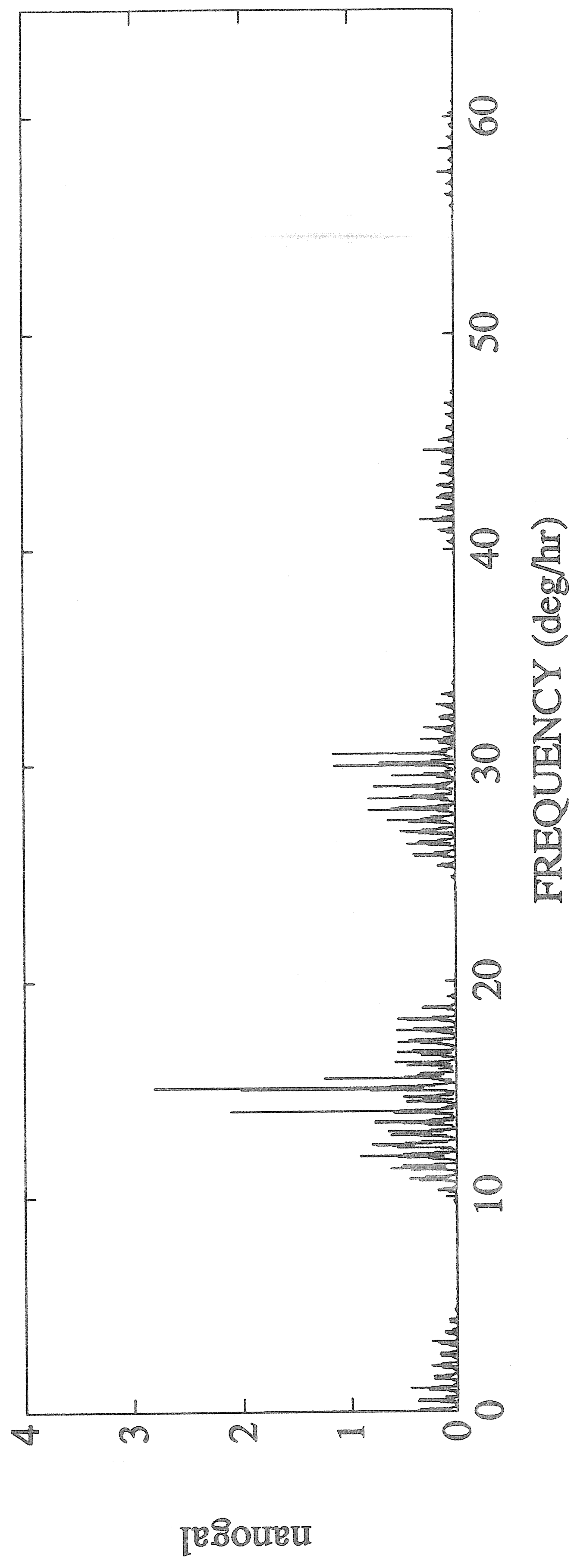
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40
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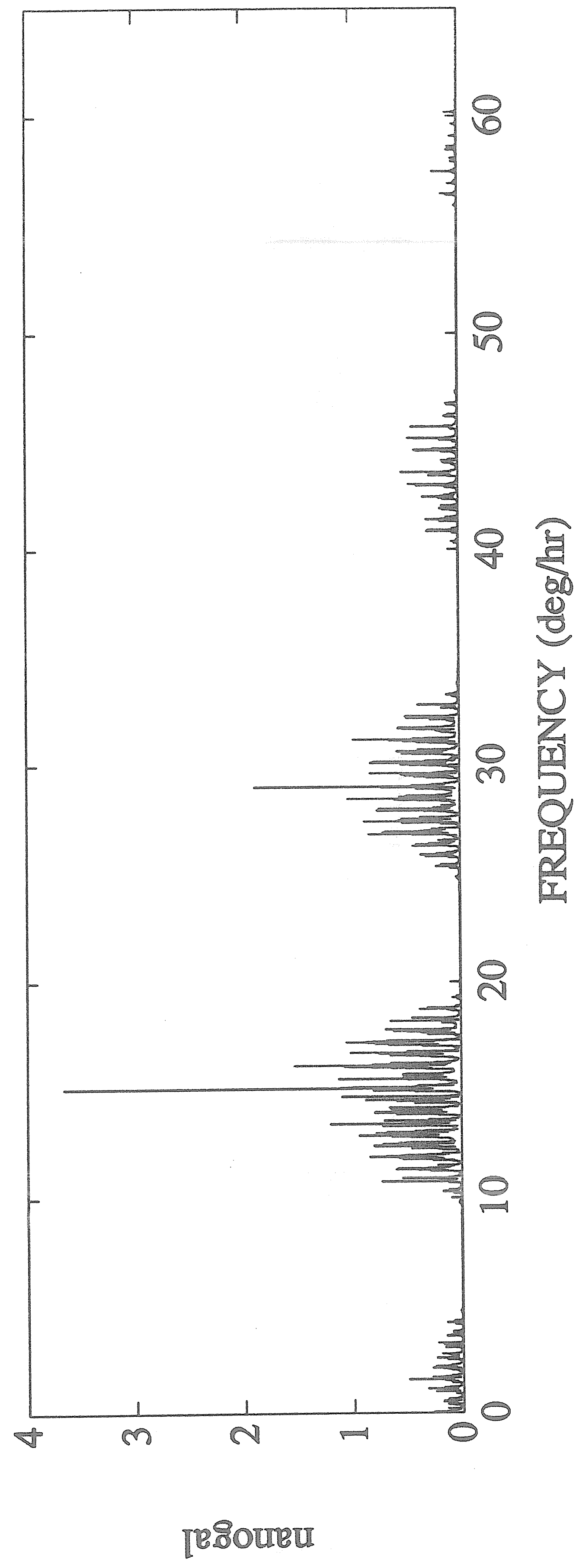
60
FREQUENCY (deg/hr)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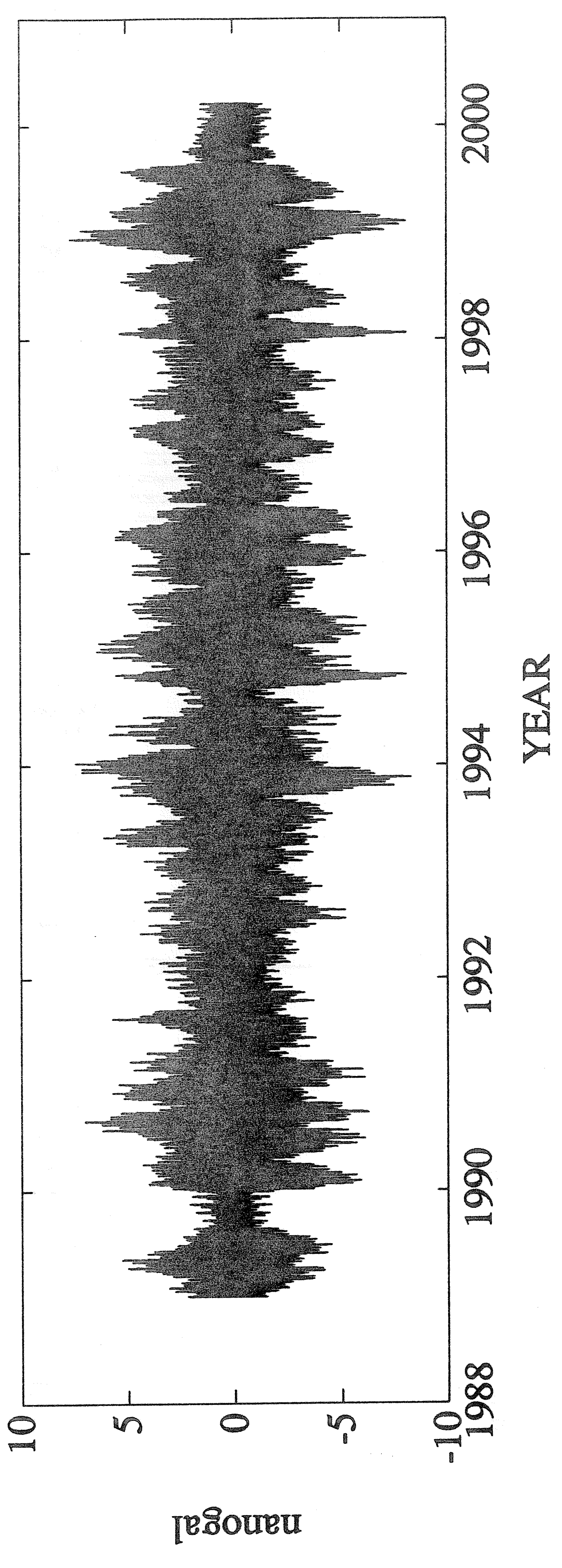
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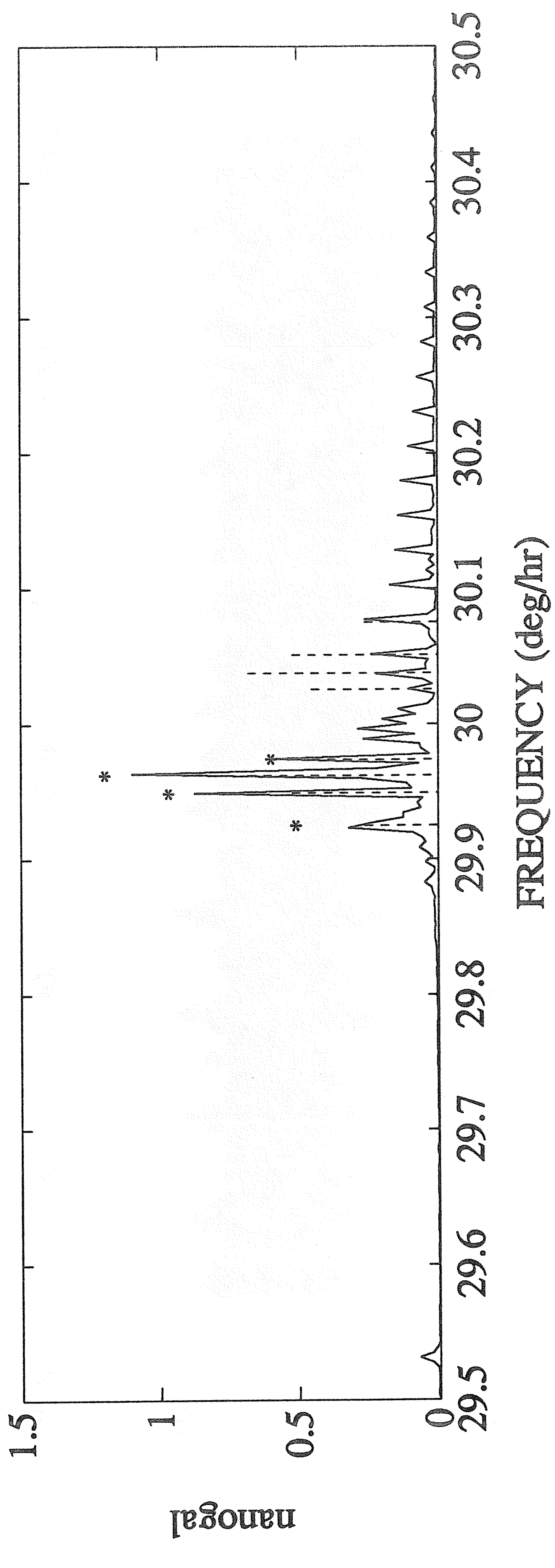
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0.5
0
29.5
29.6
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29.8
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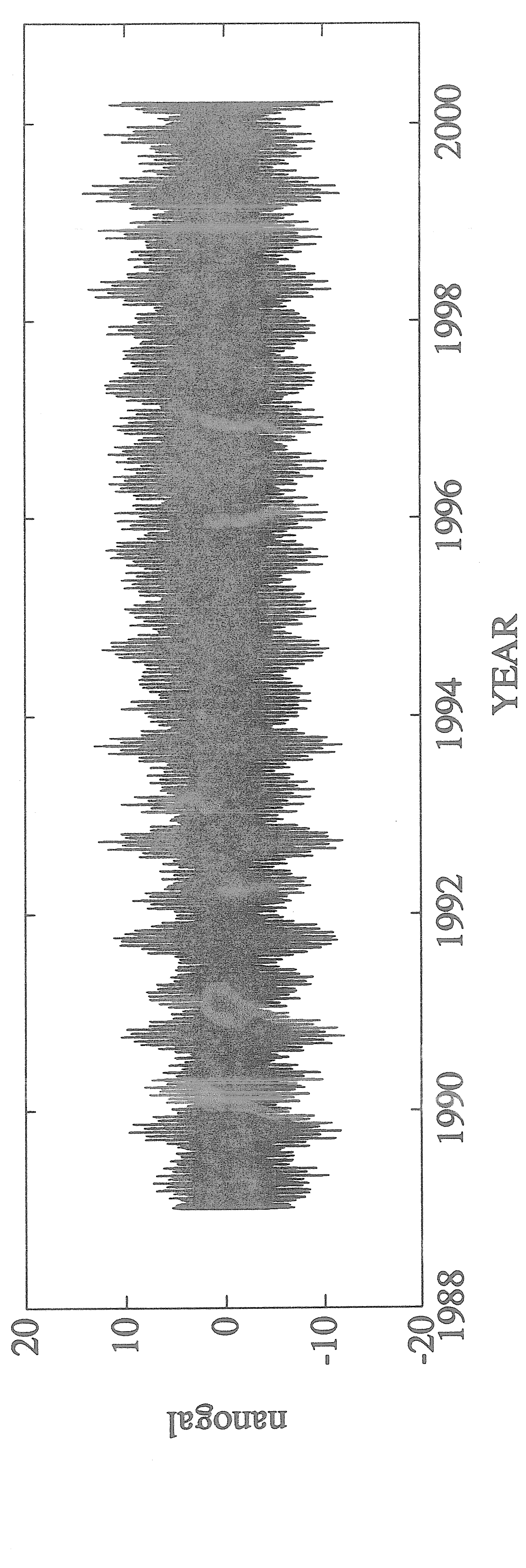
30
30.1
30.2
30.3
30.4
30.5
FREQUENCY (deg/hr)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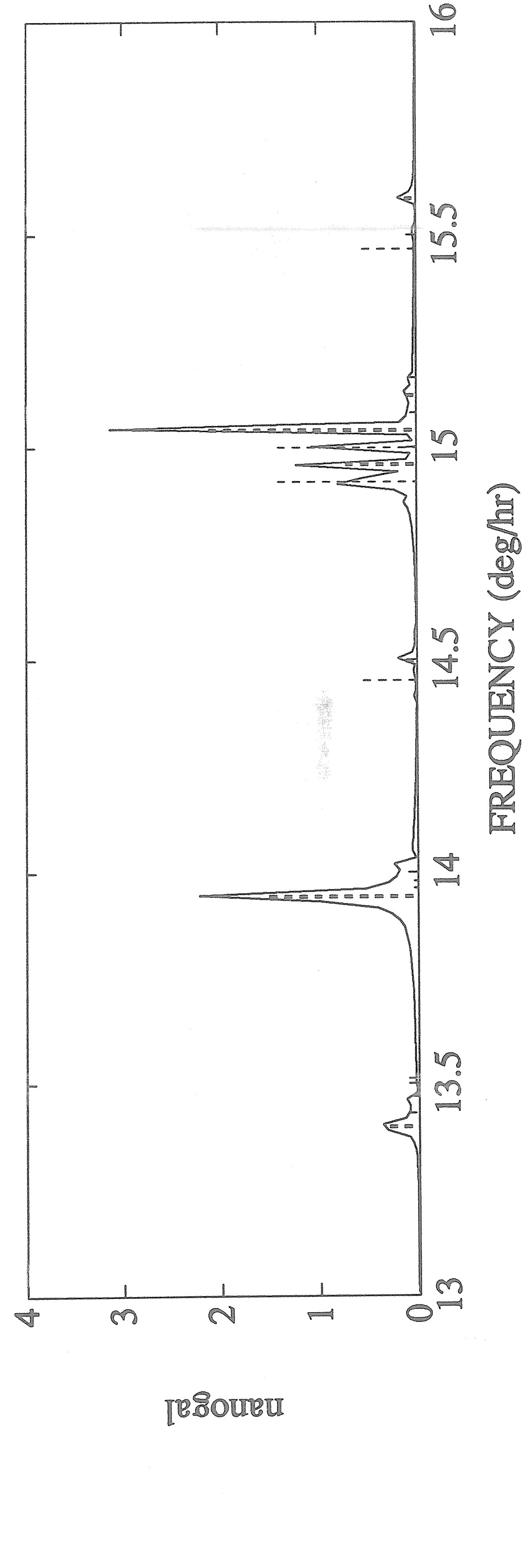
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FREQUENCY (deg/hr)
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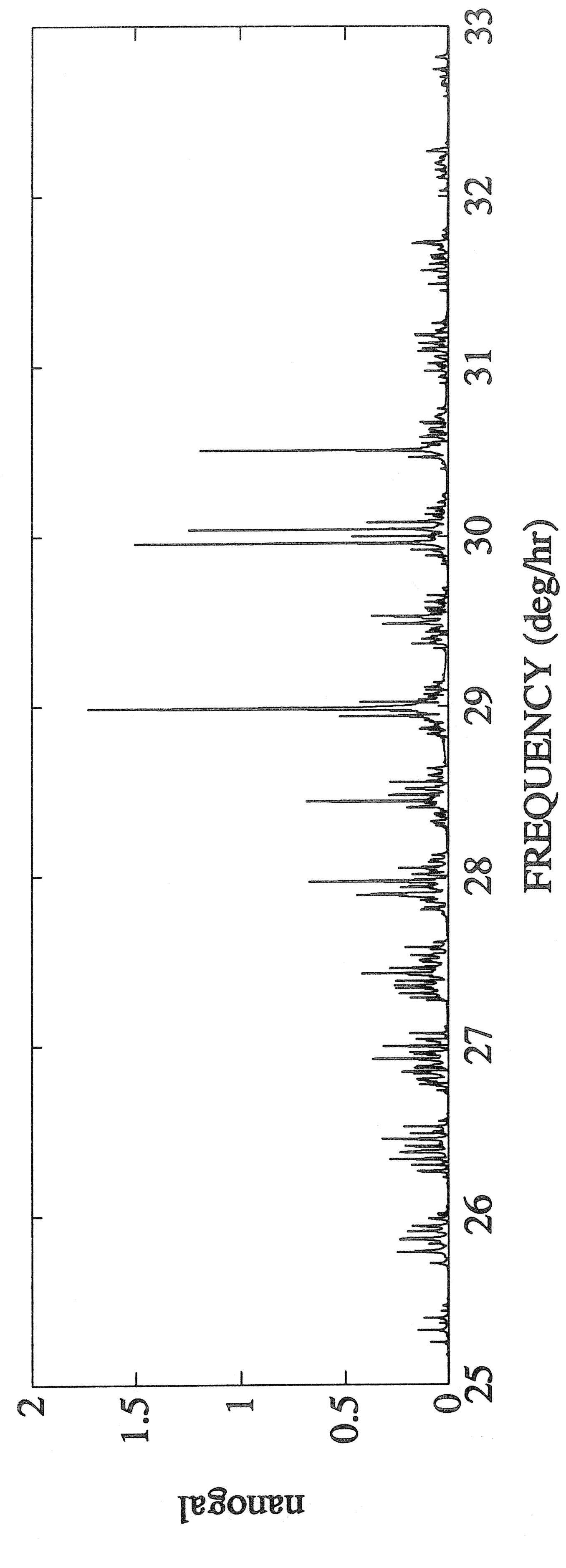
13.5
14
14.5
15
15.5
16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25
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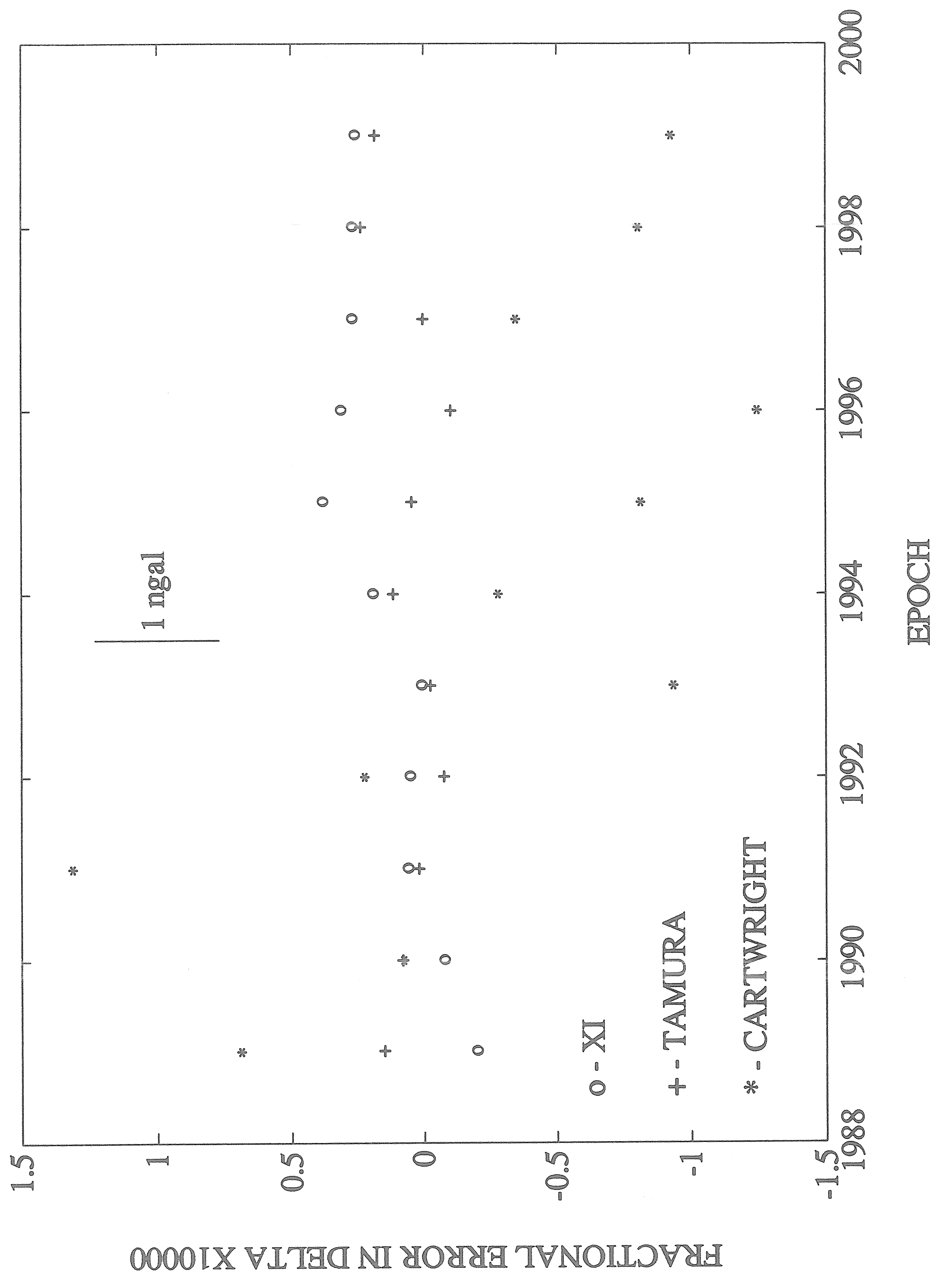
30
31
32
33
FREQUENCY (deg/hr)


1 ngal
o - XI
+ - TAMURA
* - CARTWRIGHT
1988
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1992
1994
1996
1998
2000
EPOCH
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0
-0.5
-1
-1.5
FRACTIONAL ERROR IN DELTA X10000