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Acquisition, Preprocessing and Evaluation of GFZ Potsdam SCG Data

J. Neumeyer

GeoForschungsZentrum (GFZ), Telegrafenberg A17, D-14473 Potsdam
Germany

Summary

In preparation of the GGP-Project [1] the used data acquisition and monitoring system, the procedures of data processing and the performance concerning the drift of the GFZ Potsdam Superconducting Gravimeter is described. A proposal towards a standard for an acquisition system in hardware and software is made.

Regression coefficients between tide free output air pressure and ground water level variations are calculated, respectively. The tide free output is corrected with these coefficients. Polar motion data are used to calculate the variations of centrifugal acceleration. They are compared with the tide free output. A linear drift of 29nm/s^2 per year is determined. Further analysis results are published in [2] and [3].

Data acquisition and monitoring system DDAS1

The GWR company data acquisition system DDAS1 has 33 input channels. One of them has a resolution of 22bits. It is used as gravity channel. The other 32 channels have a resolution of 16bits. They are used as tide and mode channels, for recording of air pressure, special supervising parameters of the SCG and the room temperature.

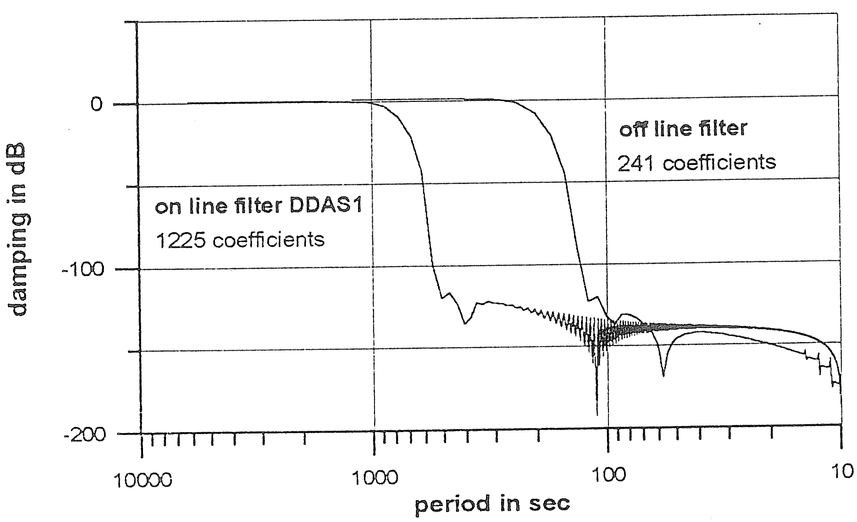

Fig. 1 Frequency response function of two digital zero phase shift filters

An ADC needs 1bit for the sign. Therefore, the resolution of the 22bits ADC is 2097152 digits. The input voltage range is ± 10V and the LSB (Least Significant Bit) is 5μV. The LSB corresponds to a resolution in gravity of 0.003nm/s^2. The resolution of the 16bits ADC is 32768 digits and the LSB of 0.305mV corresponds to a resolution in air pressure of 0.04hPa. For weak signals (e.g. Earth's Core Modes: 0.01nm/s^2) the resolution of the 22bits ADC is necessary. For supervising parameters of the SCG and meteorological data the 16bits ADC is sufficient.

An on line working digital zero phase shift filter produces two additional channels: gravity and air pressure. It filters and decimates data from 5 seconds to 1 minute. Figure 1 shows the frequency response functions of two digital filters. The corner period of the on line filter of DDAS1 is about 1000s. It has a length of 102 seconds. A second filter is used in off line filtering of data (filter coefficients from [6]). It has a corner period of about 300 seconds and a length of 20 minutes.

The data are stored in a ring buffer in binary format on a hard disk with a capacity of 30Mb. Depending on sampling rate data of several months can be stored. Access to the data is possible via floppy disk or modem. The time keeping is done by an Omega clock.

For preprocessing 5 second sampled data of gravity and air pressure and 1 minute filtered data of gravity and air pressure are available.

Data acquisition and monitoring system towards a standard

In general the idea of the GWR system is good, but one should have an acquisition system working on a standard PC with additional boards from the shelf, which easily can be duplicated. The software should run under the QNX real time operating system.

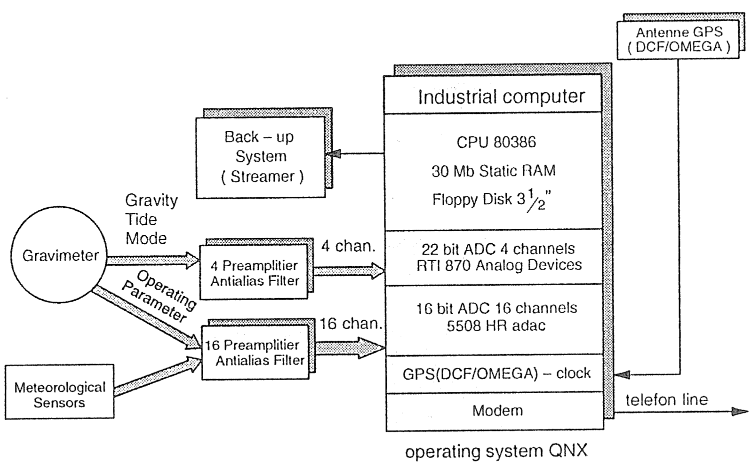

Fig.2 Hardware concept of the data acquisition and monitoring system

Figure 2 shows the hardware of the data acquisition system. The hardware consists of a standard PC better an industrial PC. In place of the hard disk a static RAM should be used. This has the advantage that no moving parts are in the acquisition system. The analog to digital conversion can be done with two ADC's the 22bits 24 channels ADC RTI 870 from company "Analog Devices" and the 16bits 16 channels ADC 5508HR from company "adac". Time keeping should be done with a GPS clock. DCF or OMEGA clocks may be optional. A built-in modem makes it possible to talk with a remote computer. Preamplifier and antialiasing filter are necessary. We don't forget a back-up-system to save the data from time to time. It can be done with a streamer tape.

The software routine of the data acquisition and monitoring system should contain the following subroutines:

- Read 22bits ADC
  Reading of the ADC input data of each channel and storing on RAM according to selected sampling frequency.
- Read 16bits ADC
  Reading of the ADC input data of each channel and storing on RAM according to selected sampling frequency.
- Generating of GPS-time
  According to GPS-time is set the sampling frequency of each channel, the data are stored with time information.
- Storing of data in associated files in a ring buffer on static RAM or hard disk
- Copying of data to floppy disk
  The data can be purged after copying only.
- Data transfer to a remote computer
  All functions of the program are selectable including data transfer of each channel to the remote computer.
- Auto zero of the ADC's
- Back up routine

The menu should contain the following options:

- Setting of the sampling frequency of each channel (selectable from 1s to 10 min).
- Setting of the preamplifier gain (selectable from 1 to 16).
- Plotting of the GPS-time.
- Plotting of the available disk space and the size of the recorded data files.
- File transfer to a remote computer.
- Copying data files to floppy disk.
- Setting of the program parameters by remote computer.
- Graphical view of the recorded data for selectable channels.
- Start and stop of the data acquisition for each channel.
- Start and stop of the program.
- On screen error plotting.

program **ALPHAsq**

* input: 5sec gravity and 5sec air pressure data
* sequence correction of data
* data gap detection and marking
* screen plotting of data
* output for ALPHAed

BETAsq

* input: 1min gravity and 1min air pressure data
* sequence correction of data
* data gap detection and marking
* screen plotting of data
* output for BETAed

program **ALPHAed**

* input from ALPHAsq
* digital filtering with zero phase shift filter, decimation of data from 5sec to 1min
* graphical editor (gaps) of gravity and air pressure data
* calculation of tide free output
* screen plotting of data
* output for PRETERNA (format RAW)

BETAed

* input from BETAsq
* graphical editor (gaps) of gravity and air pressure data
* screen plotting of data
* output for PRETERNA (format RAW)

program **PRETERNA**

* input from BETAed/ALPHAed
* calibration of data (gravity and air pressure)
* despiking of gravity data, limit (2-4)nm/s^2
* destepping of gravity data, limit (5-8)nm/s^2
* degapping of data, limit 48 hours and 50 gaps per file, fill in of gaps by theoretical values
* output for ETERNA

program **ETERNA**

* input from PRETERNA
* determination of tidal parameters
* zero phase shift filtering of data (8 different filters)
* 4 different tidal developments may be used
* drift modelling
* error estimation from residuals
* up to 5 additional (meteorological) parameters my be used
* determination of air pressure regression coefficient

Fig. 3 Processing and evaluation of GFZ Potsdam SCG data

Preprocessing and evaluation of SCG data

Figure 3 shows the standard processing and evaluation chain of GFZ Potsdam SCG data. It consists of 4 programs ALPHA [5], BETA [5], PRETERNA [6] and ETERNA [7]. The programs ALPHA, BETA and PRETERNA are used for preprocessing and the program ETERNA for tidal analysis.

According to the 5 second sampled or 1 minute filtered input data the programs ALPHA or BETA can be used. The input file format created by GWR company is an ASCII series of data with time information every hour. The input files are generated by the DDAS1 acquisition system. Other input files for the programs are possible. They need a conversion program.

Raw data generated by the acquisition system sometimes have missing samples, data gaps and incorrect time information. The correction and marking of these errors are carried out by ALPHAsq and BETAsq. Missing samples are detected and filled with the last real sample. This is allowed for a few samples only. More than a few missing samples must be handled like a data gap. Data gaps are marked and later in the PRETERNA program replaced by theoretical values. Incorrect time informations are replaced by interpolated values. The programs ALPHAed and BETAed are graphical editors. One has the possibility to edit bad data segments. These segments are marked and processed like a data gap. BETAsq and BETAed have reduced features and 1 minute input files. The reduced features are no filtering and no calculation and plotting of tide free output.

For further preprocessing the program PRETERNA is used with its steps calibration, despiking, destepping, degapping and reduction to hourly data samples by filtering.
The program ETERNA is used for evaluation of gravity data and determination of tidal parameters.

With these four programs a relatively easy and quickly preprocessing and standard evaluation of SCG data can be performed. Further evaluation can be done with available special programs.

For exchange of SCG data it is recommended to use the RAW-file-format created by Wenzel [6] shown in figure 4. The sampling interval should be 1 minute for gravity and air pressure data. The same format can be used for additional parameters as ground water level variations, temperature etc. The sampling interval can be greater than 1 minute up to some days. Additional informations in the header of the data are possible. This format can also be used for non-equidistant data.

```
header information
(e.g. station parameters, comments and parameters of the data acquisition)
   date            time         gravity       air pressure
C*****************************************
 yyyymmdd       hhmmss      g.gggggg       b.bbbbbb
```

Fig. 4 Recommended data file format for gravity data exchange

Drift behaviour of the instrument and recording of polar motion

Recording of long term gravity variations with an SCG is strongly influenced by the drift of the instrument. This arises the question whether these variations are due to real physical effects or due to imperfections of the instrument? Therefore, the drift should be small and linear. To determine the drift the tide free output must be corrected for non-tidal gravitational effects. According to the available data base this can be carried out for air pressure, ground water level and polar motion.

Available data base:

- SCG gravity data processed at GFZ by H.-J. Dittfeld with BETA and PRETERNA
- air pressure data (recorded at the SCG site)
- ground water level data (recorded in a distance of about 150m of the SCG site)
- polar motion data (from International Earth Rotation Service (IERS) Paris)

The interval of all data is 468 days (July 92 to October 93).

Processing steps:

1. Calculation of changes of centrifugal acceleration caused by polar motion (used delta factor = 1.16).
2. Calculation of tide free output (calibrated gravity minus model values).
3. Correction of tide free output for polar motion.
4. Calculation of linear regression coefficient for air pressure. For a time scale of 468 days the value is -2.77nm/s^2 per hPa.
5. Calculation of the linear regression coefficient for ground water level variations. For the time scale of 468 days the value is 71nm/s^2 per m.

Figure 5 shows the results. The upper curve is the tide free output with air pressure and polar motion corrected. The best fitted line yields a drift of 36nm/s^2 per year.
The lower curve shows the additional correction of the variations of ground water level. It remains a drift of 29nm/s^2 per year. This is a very good result for a Superconducting Gravimeter and it is within the system requirements of GWR company.

On the other hand the so corrected tide free output can be used to determine the amplitude and period of the polar motion. Figure 6 depicts the air pressure, ground water level and drift corrected tide free output and the polar motion calculated from IERS - data. One can see that the tide free output and the polar motion curves fit well. The determination of the amplitude and period of polar motion should be possible with a longer observation period (2 or 3 Chandler Wobble), if the drift is as small and linear as before.

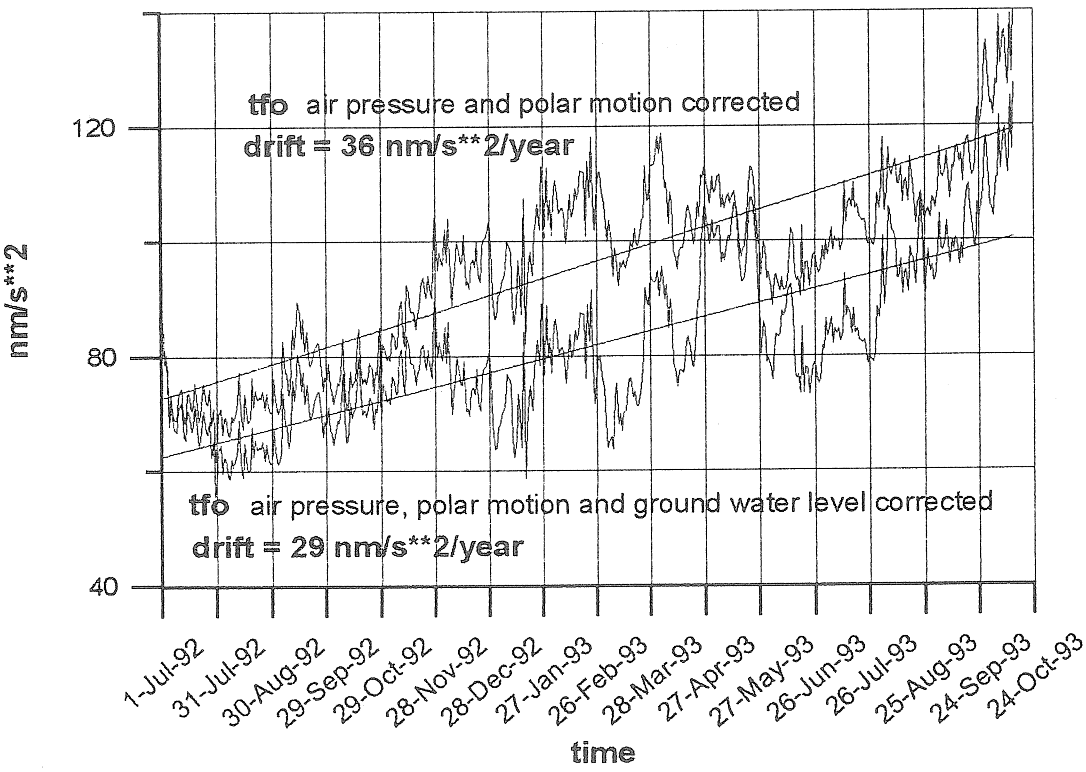

Fig. 5 Tide free output with corrections of air pressure, polar motion and ground water level

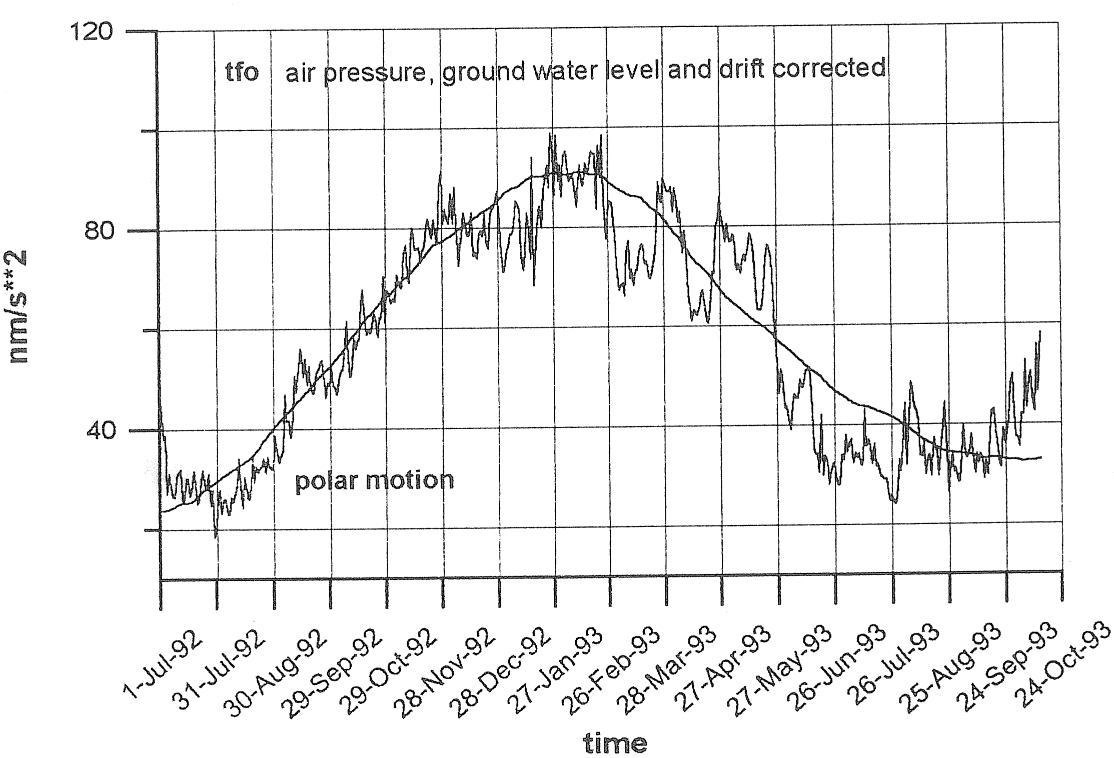

Fig: 6 Tide free output and polar motion

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Traduction

OBSERVED RESULTS OF GRAVITY EARTH TIDE IN KUNMING REGION

TANG Buo-Xiong, WU Kang-Sen, ZHOU Zhi,
ZHANG Li-Fen, YANG Sheng-Mei.

(Seismological Bureau of Yunnan Province).
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Abstract

The optimum values of the gravity tidal factors at Kunming are given here, based upon the observations made in 1975-1983. The results for the three main tidal waves are as follows:

$\delta(O_1) = 1.164 \pm 0.005$ $\alpha(O_1) = -0.58° \pm 0.28$

$\delta(K_1) = 1.140 \pm 0.003$ $\alpha(K_1) = -0.36° \pm 0.18$

$$\delta(O_1) - \delta(K_1) = 0.024$$

$\delta(M_2) = 1.166 \pm 0.001$ $\alpha(M_2) = -0.37° \pm 0.06$

1. Introduction

In the period 1975 - 1981, five gravimeters GS-15, LaCoste and CG-2 (made in Canada) were installed at Kunming Tidal Gravity Station. The gravity tidal factors and phase lags of main tidal waves observed with these gravimeters are listed in table 1. Taking M_2 as an example, the amplitude factors obtained by different instruments vary from 1.135 to 1.182, a discrepancy which is out of tolerance range of the errors. For astronomical and geophysical research purposes, it is difficult to use these observed tidal factors because of their too large dispersion.

For one station and a certain period, the tidal factors, which mainly reflect the structure and elastic properties of the Earth's interior, should be stable. Therefore it is interesting to investigate why the different instrument (GS-15 n° 211 and GS-15 n° 231) give different results. It is also our purpose since 1980 to know what are the optimized values of the tidal gravity factors in the Kunming region.

2. Observations

The general conditions of the Kunming station have been described in ref. 1. In order to study the reliability of the results obtained by GS-15 n° 211 (see table 1) and find out what are the true gravity tidal factors in Kunming region, four improvements have been introduced in our observations:

(1) Delay time

Trying to reduce the effect of the delay time on calibration and recordings, the delay time of the instrument and its recorder is modified from original 12 min to 1 min by replacing RC filter components and active filters with smaller time constant (100 sec). Such value agrees with the GS-15 gravimeter which is equipped with a magnetic calibration device and a continuously controlling temperature device.

(2) Hourly time marks

Hoping to improve the accuracy of the measured phase lag, we replace the previous mechanical clock with a quartz clock (drift less than 2 sec/week) to give the time mark signal. We also increase the paper speed to 6 cm/h.

(3) Calibration

In order to increase the number of effective digits in the calibration determination, we move the spring by 100 divisions of the micrometer instead of the previous 4 to 5 divisions. Effective digits of the calibration value raise therefore from 3 digits to now 4 digits. For instance, the former value was 2.01, now it becomes 1.501 μgal/mm. The difference between two successive calibrations, is generally no more than 1%. Calibration interval is once per 1 to 2 months.

(4) Increasing map scaling precision

After removing the inner temperature control device and keeping only the outer temperature control device, the width of the recording line was reduced from 4 mm to 1 mm. This increases map scaling precision.

After the above-mentioned four improvements, the precision increased from 1 μgal to 0,1 μgal. The standard deviation on diurnal and semi-diurnal waves is bellow 3 μgal which is 1.5 μgal smaller than the previous results (see table 2). Delay time effect on calibration is evidently also reduced. The photographic recording was used from october 1977 to december 1978, so the tidal factors are smaller than those of in normal condition due to the bad delay time treating. These data will not be included for later discussion.

3. Observed results

Tables 3, 4 and 5 provide the results obtained with the Venedikov method (363 tidal waves) and Cartwright development. Since our purpose is to compare the observed results of different kinds of gravimeters and to study the variation of tidal factors with time and as the present cotidal maps are not accurate enough, *no ocean loading correction and inertia correction have been applied.*

4. Discussion

(1) Results of the observations with the GS-15 n° 211 gravimeter

According to table 2, the $\delta(M_2)$ values are comprised between 1.111 to 1.141, 1.155, and between 1.162 to 1.168 when the delay time is respectively more than 12 min, 4 min and 1 min. This means that the gravity tidal factors are inversely proportional to the delay time.
In the observing conditions at Kunming station, the effect of the delay time on tidal factors is mainly through the calibration value.
There are four reasons:

(1) Time marks on the recording paper are already slower than Beijing time. The difference is nearly equal to the delay time. This means that the delay correction has been already done when reading the data on the recording paper.

(2) The delay time measured for GS-15 n° 211 gravimeter is 12 min (this value is reliable, because the delay time of gravimeters which have the same construction as GS-15 n° 211 and without magnetic calibration device is also about 12 min). According to the analysis for GS-15 gravimeter data in ref [4] based upon a rheologic model - combination of a Hooke body and a Kelvin body, the tidal gravity factor can be corrected from 1.141 to 1.167 only when the total delay time of the gravimeter and the recorder reaches 24.5 min. This seems contradictory with our measured delay time (12 min) and with the present working situation (delay correction is done when reading data).

(3) The phase lag jumps from 0.83° to 2.78° if we correct the data according to delay time of 24.5 min. The difference between the corrected value (2.78°) and the optimized value (- 0.37°) is much larger than the former difference between the uncorrected value (0.83°) and optimized value (- 0.37°). This proves that the variation of the gravity tidal factors between 1.141 and 1.167 are not caused by the 24.5 min delay time, because it does not correlate both amplitude factor and phase lag.

(4) During the interval 7/5/1977 to 4/7/1977 the delay time was 12 min. It had been considered when scaling the recording paper, i.e. the time mark on it was 12 min slower than universal time. The analysis results are:

$$\delta(K_1) = 1.115,\ \delta(O_1) = 1.136,\ \delta(M_2) = 1.143.$$

If we still take 12 min delay time, but the time mark is that of universal time the corresponding results are:

$$\delta(K_1) = 1.125,\ \delta(O_1) = 1.134,\ \delta(M_2) = 1.144.$$

These two results do not differ very much. It means that the influence of the time delay on the tidal factors is not so large when the calibration is correct. Therefore, our opinion is that the phenomena of the inversely proportionality of the time delay to tidal gravity tidal factors depends mainly on the incorrect calibration value when under the existence of the delay time, the longer the delay time is, the longer the discrepancy would be.

Since 1980, the recording quality has been much improved by a series of actions:

- delay time was modified from 12 min to 1 min;
- scaling precision increased from 2 to 3% to 0.4%;
- time accuracy improved from 1 to 2 min/day to 0.1 to 0.25 min/day;
- paper speed increased from 1 cm/h to 6 cm/h;
- the width of recording line decreased from 4 mm to 1 mm.

The results of every year for the latest four years are:

$$\delta(M_2) = 1.162/1.168/1.165/1.168$$

$$\delta(O_1) = 1.164/1.167/1.164/1.162$$

They seem quite stable, and their deviation is random and less than 0.3%. Consequently, we conclude that the reasonable result of GS-15 n° 211 gravimeter at Kunming station should be the result after july 1980 (delay time modified to 1 min), i.e.

$$\delta(O_1) = 1.164 \pm 0.005 \qquad \alpha(O_1) = -0.58° \pm 0.26°$$

$$\delta(K_1) = 1.140 \pm 0.003 \qquad \alpha(K_1) = -0.36° \pm 0.18°$$

$$\delta(O_1) - \delta(K_1) = 0.024$$

$$\delta(M_2) = 1.166 \pm 0.001 \qquad \alpha(M_2) = -0.37° \pm 0.06°$$

(2) Gravity tidal factor in Kunming region

The four gravimeters listed in table 6, installed at Kunming station belong to two kinds: GS-15 is a relatively stable and static gravimeter, CG-2 and LaCoste are astatized gravimeters. The results obtained by two GS-15 gravimeters are similar (see table 6), while the results of two astatized gravimeters are also rather close, but the tidal factors are 1 to 1.5% larger than those of GS-15. What is the real value for gravity tidal factor in Kunming region ? Should we take the average value of there two kinds of gravimeters, or just take one of them as standard value ? We think it is better to take the result obtained from GS-15 gravimeter as the reference values. There are three reasons:

(1) The rheologic model for an astatized gravimeter is quite complicate and the error could be large as we have not performed any accurate measurement on it at Kunming station.

(2) The precision of the result obtained by GS-15 gravimeter is relatively high because stable and reliable data have been obtained for three years.

(3) The International Standard Earth Tide Station in Bruxelles also takes the data of GS-15 as standard, but not the data of astatized gravimeter, such as LaCoste Romberg instruments. In accordance with the international reference we think it is better to take the results

obtained with GS-15 as the standard in Kunming region.

(3) Variation of tidal gravity factor with time

It was already discussed in ref. [1] for the GS-15 n° 211 gravimeter in 1976. Is this variation true since we have confirmed now that the result after 1980 is the reasonable result ? Our opinion is that the time variation of tidal factor did exist in 1976, because:

(1) during 10/1975 - 9/1977, no change was made for delay time, recording method, accuracy of time service and way of scaling (see table 3). Therefore the relative change (see fig. 1) is real.

(2) It is demonstrated that the recording of GS-15 n° 211 in 1976 is reliable because, after comparing the drift curves obtained by GS-15 n° 211 and LaCoste gravimeters, no concordance has been found while gravity tidal factors derived from GS-15 n° 211 and n° 231 agree also very well. Therefore we could say the instrument was stable and the observations are reliable even if GS-15 n° 211 was the only gravimeter working at Kunming station in 10/1975-10/1977 (more gravimeters installed after 8/1977).

5. Conclusion

After four years of continuous observations, we can confirm that, just as mentioned in ref. [1], there is a systematic error existing in the previous observations (1975-1979) at Kunming station due to the incorrect calibration value which was affected by a wrong delay time.

The observations are reliable if GS-15 gravimeter is operated properly when the measured delay time is less than 1 min. For astatized gravimeters, e.g. LaCoste, CG-2 etc; there could be a relatively large systematic error in the results if they have not been precisely calibrated for the parameters of their complicate rheologic model. This may be the reason why there is a difference between the tidal factors obtained by both GS-15 and LaCoste astatized gravimeters at Kunming station.

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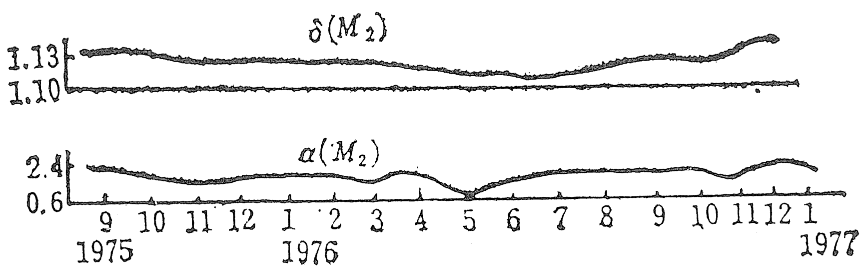

Variation of the tidal gravimetric factors with time

Table 1

Tidal gravimetric factors of Kunming with GS-15, LaCoste, CG-2 gravimeter during 1975-1981

Instrument	Epoch	δ(01)	δ(K1)	δ(01)-δ(K1)	δ(M2)	α(01)	α(K1)	α(M2)
GS-15 N°211	1975.4-1979.2	1.144	1.117	0.027	1.135	-0.4°	-0.2°	-0.2°
GS-15 N°231	1980.1-1980.12	1.167	1.133	0.034	1.167	-0.8°	-0.3°	-0.77°
CG-2 N°317	1977.8-1977.10	1.185	1.152	0.033	1.182	-1.65°	-2.55°	-0.35°
LaCoste N°402	1980-1981.5	1.190	1.158	0.032	1.177	-1.50°	-1.12°	-0.73°

Table 2

Tidal gravimetric factors of Kunming with GS-152 n° 11 gravimeter under different conditions

Date	Days	Delay Time	Recording Method	Time Service	Calibration Effective Digits	δ(01)	δ(K1)	δ(01) δ(K1)	σ δ1	δ(M2)	σ δ2	α(01)	α(K1)	α(M2)
1975.10-1976.10	386	12	visual	clock	3	1.116	1.089	0.027	3.6	1.111	4.2	0.02	0.16	1.31
1977.01-1977.09	252	12	visual	clock	3	1.140	1.117	0.023	3.2	1.141	4.0	0.28	0.34	0.83
1977.10-1978.12	446	1	visual	clock	3	1.124	1.109	0.015	3.9	1.123	5.1	-0.71	-0.36	-0.38
1980.03-1980.07	128	4	photo	quartz clock	4	1.159	1.131	0.028	2.4	1.155	1.6	-0.34	0.22	0.72
1980.07-1981.05	304	1	visual	clock	4	1.164	1.134	0.030	2.7	1.162	2.9	-0.43	-0.45	-0.19
1981.07-1982.01	190	1	visual	clock	4	1.167	1.143	0.024	2.3	1.168	2.2	-0.49	-0.32	-0.08
1982.02-1983.04	438	1	visual	clock	4	1.164	1.139	0.025	5.4	1.165	2.2	-0.71	-0.24	-0.58
1983.04-1983.08	108	1	visual	clock	4	1.162	1.145	0.017	2.8	1.168	1.5	-0.71	-0.43	-0.63

Table 3

Example of variation of tidal gravimetric factor with time

Epoch	Days	δ(M2)
1975.10-1975.12	80	1.129
1975.12-1976.2	70	1.121
1976.3-1976.5	80	1.107
1976.5-1976.8	80	1.096
1976.8-1976.10	76	1.110
1977.1-1977.4	80	1.146
1977.4-1977.6	80	1.139
1977.7-1977.9	92	1.137

Time delay 12 min.
Visual recording
Time : Clock
Calibration : 3 digits

Table 4

Some major tidal gravimetric amplitude factors of Kunming region

Epoch	Days	Q1	O1	M1	P1S1K1	J1	OO1	2N2	N2	M2	L2	S2K2	M3
1980.7-1981.5	304	1.194±0.019	1.163±0.004	1.144±0.033	1.134±0.002	1.180±0.044	1.179±0.089	1.193±0.033	1.166±0.007	1.162±0.001	1.106±0.053	1.171±0.003	1.072±0.028
1981.7-1982.1	190	1.192±0.019	1.167±0.004	1.147±0.043	1.143±0.002	1.162±0.045	1.173±0.097	1.135±0.032	1.164±0.006	1.168±0.001	1.180±0.051	1.175±0.003	1.092±0.044
1982.2-1983.4	428	1.179±0.027	1.164±0.005	1.220±0.085	1.139±0.004	1.158±0.065	1.155±0.131	1.164±0.021	1.162±0.004	1.165±0.001	1.198±0.031	1.180±0.002	1.094±0.036
1982.5-1983.8	446	1.183±0.024	1.163±0.005	1.247±0.076	1.137±0.003	1.178±0.058	1.144±0.119	1.171±0.019	1.164±0.004	1.166±0.001	1.174±0.029	1.181±0.002	1.099±0.034

Table 5

Some major tidal gravimetric phase lags (degree) of Kunming region

Epoch	Days	Q1	O1	M1	P1S1K1	J1	OO1	2N2	N2	M2	L2	S2K2	M3
1980.7-1981.5	304	-0.04±0.89	-0.43±0.18	-0.82±1.66	-0.45±0.12	-0.24±2.11	2.94±4.32	-1.20±1.59	-0.51±0.33	-0.19±0.06	-0.52±2.76	0.17±0.13	-0.79±1.49
1981.7-1982.1	190	-0.08±0.92	-0.49±0.18	-1.69±2.14	-0.32±0.12	-1.64±2.21	1.92±4.74	0.94±1.60	0.25±0.31	-0.08±0.06	-0.55±2.50	0.27±0.13	3.23±2.30
1982.2-1983.4	428	-0.11±1.33	-0.71±0.26	0.96±4.00	-0.24±0.18	-0.41±3.23	3.16±6.52	-0.56±1.03	-0.36±0.20	-0.58±0.04	-1.97±1.50	-0.66±0.08	-0.07±1.90
1982.5-1983.8	446	-0.12±1.18	-0.71±0.23	3.11±3.51	-0.23±0.16	-0.27±2.83	1.27±5.95	-0.38±0.92	-0.48±0.19	-0.63±0.04	-1.22±1.42	-0.65±0.08	0.14±1.79

Time delay : 1 min
Visual Recording
Time : Quartz clock
Calibration : 4 digits

Table 6

Tidal gravimetric factors with GS-15, LaCoste and CG-2 gravimeters at Kunming Station

Instrument	Epoch	δ(O1)	δ(K1)	δ(O1)-δ(K1)	δ(M2)	α(O1)	α(K1)	α(M2)
GS-15 N°211	1980.7-1981.5	1.164	1.140	0.024	1.166	-0.6°	-0.4°	-0.4°
GS-15 N°231	1980.1-1980.12	1.167	1.133	0.034	1.167	-0.8°	-0.3°	-0.8°
CG-2 N°317	1977.8-1977.10	1.185	1.152	0.033	1.182	-1.6°	-2.6°	-0.4°
LaCoste N°402	1980-1980.5	1.190	1.158	0.032	1.177	-1.5°	-1.1°	-0.7°
(*)	revised ICET 1993	1.1867	1.1571	0.030	1.1738	-1.35°	-1.13°	-0.67°

Main factors defining tidal strain sensitivity of system aquifer-observation wells in the Kopetdagh seismoactive region

G.A. Ishankuliev, V.M. Belikov
Institute of Seismology, TAS
Komsomolskaya 20a, 744000, Ashgabat, Turkmenistan

I.G. Kissin
Institute of Physics of the Earth
B. Gruzinskaya 10, 123810 Moscow D-242, Russia

Many factors, such as peculiarities of well construction, elastic and reservoir characteristics of rocks opened by wells, water bearing layers orientation, availability and orientation in space of tectonic faults and cracks, etc. may influence the peculiarities of holes behaviour in response to earth tidal deformations [1, 2]. So, tidal strain sensitivity of observation holes has been defined by combinations of natural and technical factors. Several of them have been analyzed in this study.

Earth tidal variations of ground water level have been studied in ten piezometric boreholes, located at the Front Kopetdagh fault zone (fig. 1). Geologic - hydrogeologic characteristics of the observation holes are given in table 1. Observation holes are characterized by a great range of filter length variations and open part of the well variations from 18 to 1153 m (table 1). The depth of the open part of the well depends on the wide spread of Upper Jurassic and Lower Cretaceous dense, fractured limestone. Measurements have been made with float-type level indicators. Table 1 illustrates the maximal double amplitude of water level tidal variations, defined as mean value for syzygy periods.

The analysis of ground water level tidal variations have been made on initial data time series of atmospheric pressure P(t) and borehole water level H(t) with a digitization interval of one hour. Graph fragments of level variations and atmospheric pressure are given on fig. 2.

As a result of computer processing (IBM PC/AT) theoretical and observed amplitudes and phases of seven main tidal waves have been evaluated with methods presented in this work [3]. To study the system reaction adequacy "borehole-aquifer systems" to the earth tidal deformations, theoretical evaluations of the deformations in the region of observation boreholes have been compared with measured amplitudes of main tidal variations of ground water level (fig. 3). Evidently, the dependence at the borehole Manush, 13r is linear (fig. 3a) while at the borehole Yanbash, 12m it is non-linear (fig. 3b).

Influence of the tectonic faults on the tidal variations.

The analysis of the observations has been made to establish the influence of the fault tectonic system disturbances on the medium deformations and its representation in tidal hydrogeologic effects. Tidal amplitude variation values have been studied depending on the location of the boreholes relative to the fault (fig. 1, table 1) [4, 5].

Peak to peak amplitudes of the tidal variations greatly differ according to two groups of boreholes. The first group consisting of the boreholes 13r, 13a, 21, 6b opens the terrigenic Quaternary or Neogenic deposits with mainly porous type of collector. These amplitudes reach 17-30 mm. For this group there is no dependence of the amplitude in function of the distance to the fault. For other boreholes where tidal variations have been observed with peak amplitudes 22-125 mm, the dependence is rather clear (fig. 4a). All these boreholes open fractured, mainly carbonate deposits of the Lower Cretaceous and Upper Jurassic.

Variations of the ground water tides are important through the first 100m from the fault, decrease and disappear when moving away from the fault to 2 km. Changes at great distances do not confirm by enough factual material. They are supposed to be of less importance. This conclusion is confirmed by the mathematical modelling of pressure distribution, deformations and movements at the rock massive, where zone of tectonic fault crushing is approximated as a cylindric discontinuity [6].

Hydrogeodynamic effects are determined by the influence of two factors-medium deformation and strain sensitivity of the system "borehole-aquifer systems (or borehole-fractured zone)". These factors have a definite influence on the near fault structures: deformation values and strain sensitivity may be sufficiently greater there than inside the unit.

It is known that tidal deformations and slopes have abnormal high values in a fault zone. So, tidal deformations at the Surkhob zone are 2,9 times larger for the waves M_2 and 3,6 times for O_1 than normal values [7, 8]. These fault features are conditioned by their elastic characteristics, mainly defined by a fracture system development. Fracture density increases when approaching the tectonic fault and zones of the fault influence have a width from 50 to 1700 m and become the more larger the more larger the fault is [9].

The zone of influence of the Front Kopetdagh fault with great extent and deep contour interval is revealed by the hydrogeodynamic effects (as has been mentioned above) at a distance of at least 2 km. High deformation level in the strip of the Front Kopetdagh fault makes it possible to consider this fault to be a structure separating large free blocks of the lithosphere [10].

The strain sensitivity index of the hydrodynamic system is defined as the ratio of the corresponding indicator change (ground water level) to the volume deformation. The lack of deformation measurements at points where hydrogeodynamic observations have been made do not allow to calculate this index.

Thus, in order to define the role of the Front Kopetdagh fault in tidal variations of the ground water level, we may consider that the amplitudes of the tidal variations greatly reduce when moving away from the fault. The influence of the fault is clearly revealed in the neighbouring zone (the first hundreds metres) and is weakened at the distance of 2 km. Other analogous structures seem to have the same fault influence. It depends on medium deformation decrease and fluid system strain sensitivity decrease on tidal deformations when moving away from the fault.

Influence of the depths of open parts of the wells on tidal variation amplitudes of the ground water level.

The problem of the influence of the observation boreholes construction characteristics on the study of the hydrogeologic and geodeformational processes is not sufficiently investigated [11]. Thus, in discussing and processing hydrogeologic observations the question of defining a more optional borehole construction demands a solution. It this connection the question of the influence of depth of open part of the well on the tidal variation amplitudes of the ground water level is discussed here.

Those circumstances, that depth of open part of the well has big separation make it possible to investigate the influence of the observation hole depth of open part of the well on its strain sensitivity to the earth tidal deformations. This is a very important question of method for the optimization of the observations. Figure 4b illustrates the dependence of the tidal variation amplitudes of the ground water level on the water permeable parts of the observation boreholes. Stable tendency of increasing above mentioned anomalous characteristics with increasing the depth of the open part of the observation borehole may be observed. So the borehole Lower Phiruza, 2g is characterized by the maximal value indicators. It should be mentioned, that the studied relation is multifactor and characteristic properties of the rock massives, opened boreholes and the level of elastic compressibility of the massives may influence it in each separate section. The rock massive permeability in the tectonic fault zones is defined mainly by steeply deeping fractures, being ten kilometres apart. Evidently, in given conditions the reaction of the borehole on the deformation effects will depend on whether the borehole has crossed large fractures or not. Probably, if the borehole crosses the fractured zone, it would respond to comparatively short period deformation disturbances, and the borehole passed in the massive blocks would slightly react on these disturbances. The effects in excellent geologic-tectonic conditions will differ in amplitude. Under the existing conditions the extent of the depth of open part of the borehole will be of great importance for the increase of hydrodynamic observation informativity, as it is difficult to cross steeply deeping main fractures with limited opening if the depth of open part of the well has insignificant extent. In multibedded water bearing systems the influence of the deformation processes will be developed more clearly than in the borehole opening on water bearing horizon of insignificant power. So, the tendency of the dependence of the earth tidal variation amplitudes of the ground water level on the extent of depth of open part of the borehole (fig. 4b) has been shown to have similar morphology with the dependence of the amplitude of the short period hydrodynamic effects on the depth of open part of the well.

Strain sensitivity of the system "borehole-aquifer systems" depends on the extent of the massive opened by the borehole (i.g. depth of open part of the well), in which beds or fractures heterogeneous in its fluid characteristics may be present. As far as jointing of the massive (as has been mentioned above) is increasing in proximity to the fault, strain sensitivity of the system should be increased in the same direction. The large extent of the depth of open part of the well promotes to reveal the high tidal strain sensitivity. It is necessary to note that the dependence of the earth tidal variation amplitudes of the ground water level on the borehole depth is not observed.

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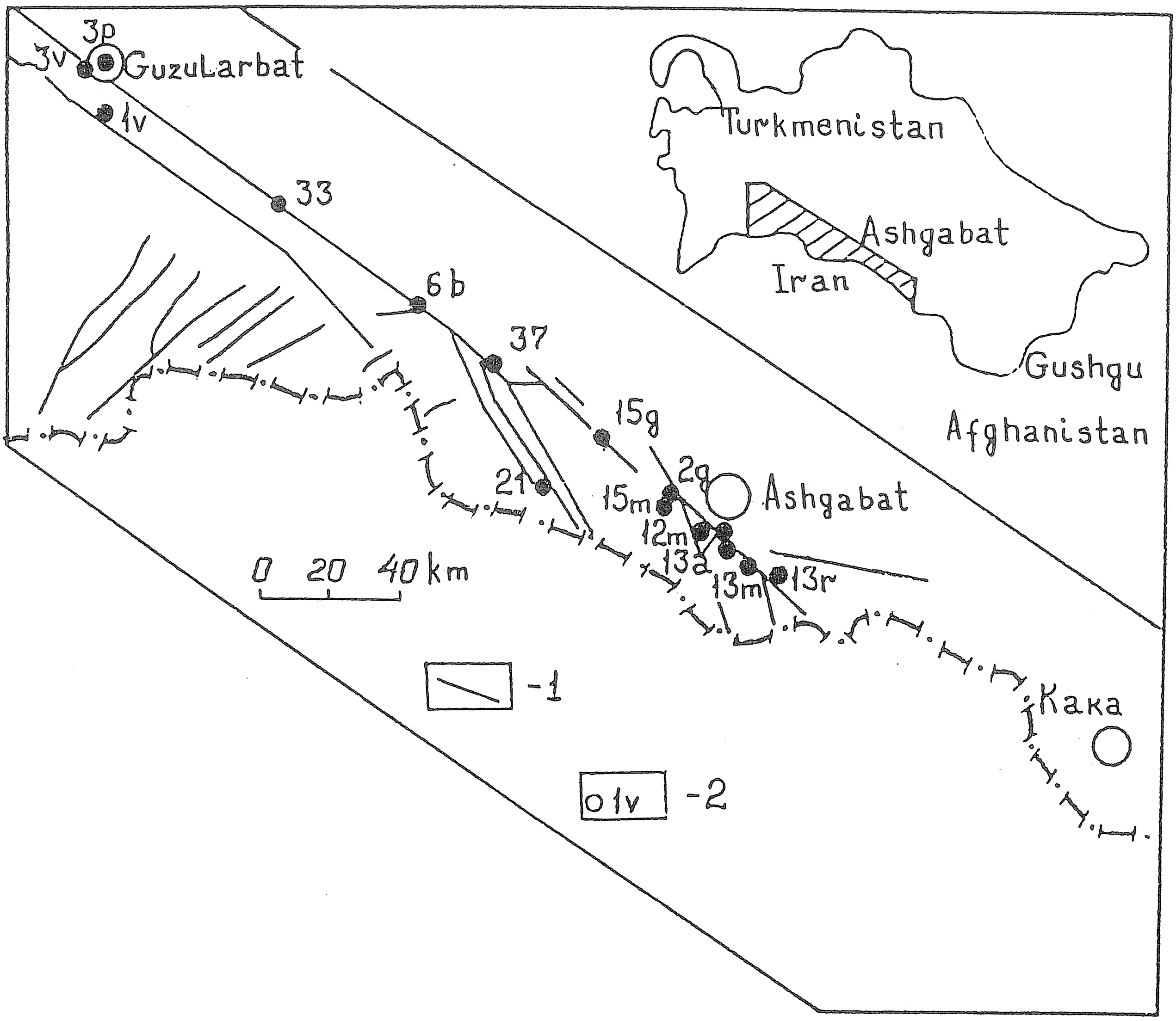

Figure 1. Geographical distribution of observation wells with respect to the tectonic fault of Kopetdagh seismoactive region: 1 - tectonic fault (by data of V.N. Crimus and other, 1989); 2 - observation wells and their numbers.

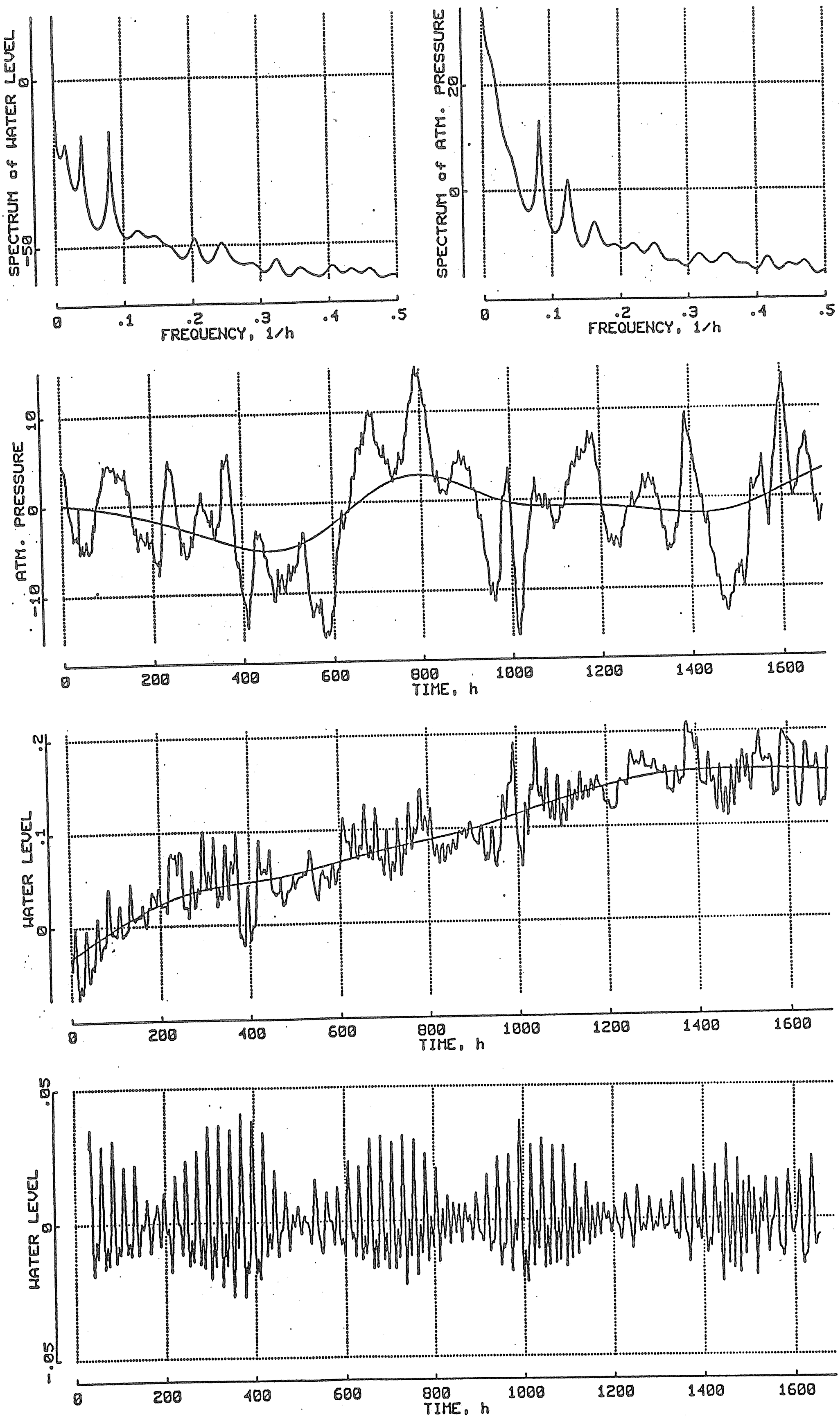

Figure 2. Example of computer processing of ground water level time sequences and atmospheric pressure.

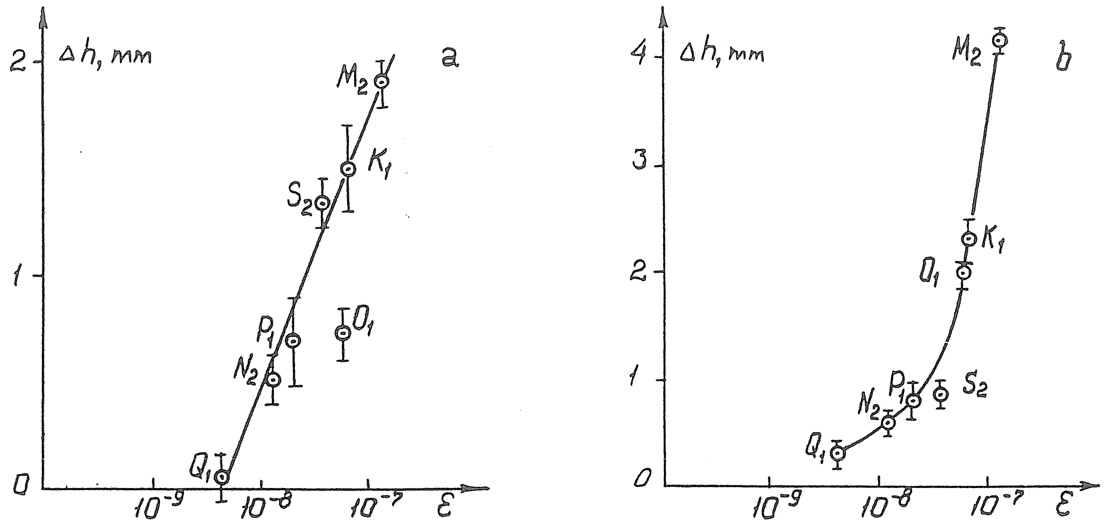

Figure 3. The dependence of amplitudes of the main earth tidal fluctuation of the level of underground waters from earth tidal deformation with include Love numbers; a) well of Yanbash, 12 m; b) well of Manush, 13r.

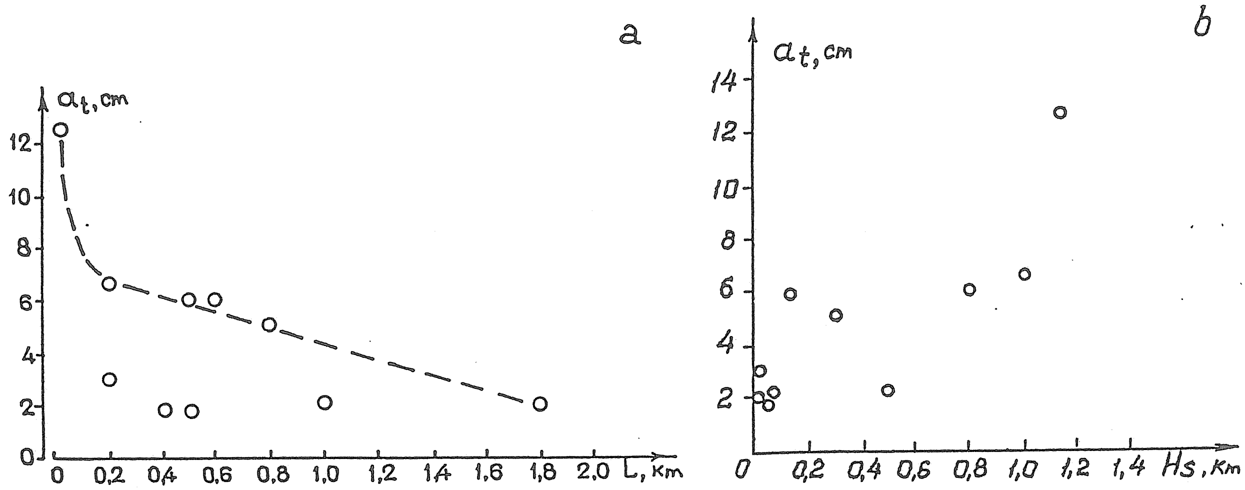

Figure 4. The influence of middle maximum amplitudes earth tidal fluctuation of the level of underground waters: a) distance to tectonic of fault L; b) depths of open part of the well Hs.

TABLE 1

Main Characteristics of observation wells

N°	Area, well	Depth of open part of the well	Waters-bearing rock and their age	Period of analysis of observations (month, year)	Distance to nearest tectonic fault, km	Maximum amplitude of tidal fluctuations of the level, cm
1	Manush, 13r	171-179	Sandstone, aleurolite Neogene	9.87-06.92	0,2	3,0
2	Berzengi, 13a	249-299,5	Gravel-Pebbly deposits Quaternary age	7.83-06.92	0,4	1,7
3	Yanbash, 12m	500-625	Jointing limestone Lower Cretaceous	2.85-06.92	0,5	6,0
4	Nijnaya Phiruza, 2g	57-1210	Limestones, dolomites Lower Cretaceous and Upper Jurassic	6.78-06.92	0	12,5
5	Nijnaya Phiruza, 15m	1140-1950	Limestones, dolomites Upper Jurassic	1.79-06.92	0,6	6,0
6	Gokdepe, 15g	1500-2002	Dolomites, limestones anhydrites, Upper Jurassic	2.81-06.92	1,8	2,2
7	Germab, 21	15-33	Boulder-pebbly deposits Quaternary age	2.81-06.92	0,5	1,8
8	Archman, 6b	200-250	Terrigenous deposits Neogene	9.83-06.92	0	2,0
9	Purnuar, iv	646-1670	Limestone, sandstone, aleurolites, Lower Cretaceous and Upper Jurassic	2.80-06.92	0,2	6,6
10	Djanahir, 3v	1300-1600	Limestone, sandstone, aleurolites, Lower Cretaceous and Upper Jurassic	5.88-06.92	0,8	5,0

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OBSERVATION OF TIDAL GRAVITY CHANGES BY MEANS OF AN ABSOLUTE GRAVIMETER AND AN ASKANIA GRAVIMETER AT NOVOSIBIRSK STATIONS.

Timofeev V.Y. *, Arnautov G.P. **, Saricheva Y.K. *,
Kalish E.N. **, Stus Y.F. **, Tarassyuk V.G. **,
Smirnov M.G. **, Khommutov S.Y. *.

* Institute of Geophysics UIGGM SB RAS, Novosibirsk, Russia.
** Institute of Automation and Electrometry SB RAS, Novosibirsk.

1. Introduction

An Askania gravimeter is being used at the tidal station Novosibirsk-Kluchi since 1966. Long records were analyzed and results were presented in the paper [1]. These results are in good agreement with Wahr-Dehant tidal model [2, 3, 4, 5, 6].

The first models of an absolute laser ballistic gravimeter (GABL) were developed by Dr Arnautov's team about twenty years ago. Presently the precision of this absolute gravimeter is sufficient to observe tidal gravity changes [7, 8, 9, 10]. However it is generally not possible to obtain records long enough to perform conventional tidal analyses. It is however possible to obtain records every hour along a one day period or at every extrema points (minimum and maximum) along a month period.
The results allow:

- to check the calibration of the Askania gravimeter records by the absolute gravimeter and traditionnal scaling means.

- to confirm the validity of the Wahr-Dehant model at Novosibirsk station.

2. GABL type gravimeter observations.

The GABL gravimeter is a free fall gravimeter developed in the Institute of Automation and Electrometry SB RAS (Novosibirsk), which can be operated automatically following a proposed scheme. The scattering of the individual measurements is high, ranging from 100 nm/s^2 to 500 nm/s^2 according to the site quality (vibration noise). It is the reason why a personal computer (PC-AT type) gives mean values for data sets of 54 drops at ten-minute series of measurements. Additional parameters (pressure, temperature, residual vacuum, level of ground water) are measured at the same time.

We present here results observed at three Novosibirsk stations. The Novosibirsk-Kluchi station is a tidal gravity station and it is a fundamental station of the russian seismic network. The Novosibirsk-IAE station is situated in the basement of the Institute of Automation and Electrometry building. The noise level is very high there and 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. The Novosibirsk-Ob station is close to the Novosibirsk hydro-electric power station's reservoir, at 15 kilometres from Novosibirsk-Kluchi.

3. Tidal observations with the Askania n° 186 gravimeter.

The base earth-tide station operates in Novosibirsk-Kluchi since 1966 in the mode of repeated cycles of continuous measurements with intermediate observations carried out at temporary stations (Irkutsk, Talgar). Three series of observations have been obtained in 24 years [1]. As the observation accuracy directly depends on the error of calibration, we consider this problem in more detail. Until 1983 we used the method of coupled shifts, whose precision is no more than a few per cent. Since 1983 the calibration procedure has involved no micrometer. The new procedure is based on the inclination technique. The gravimeter is fixed on a base plate of 1200 mm with a 0.5 mm level screw pitch, as at Novosibirsk-Kluchi station. Under the given width of records, the plate inclination varies within the limits determined by the fixed screw positions n0 (horizon), n0+ (0.5-1.0) and n0+ (1.5-3.0) turns. Gravity changes for calibration can be written under the form

$$g = g_0 \, (a1 - a2)^2 / 2$$

g_0: absolute gravity at the observing point
a1 = (a1+ + a1-) /2, a big tilt of a plate (+ up), (- down)
a2 = (a2+ + a2-) /2, a small tilt of a plate.

The calibration factor can be written under the form $K = \Delta g/\Delta s$, Δs being the recorded displacement. The calibration record is illustrated by figures 1, 2. The estimations show that the calibration by this method lies within a precision of (1-2) 10^{-3} [1].

Simultaneous record of GABL and Askania at Novosibirsk-Kluchi is illustrated by figures 3, 4 and table 1. Unfortunately, simultaneous records were measured during a weak tidal and earthquake period. It was possible to obtain GABL records at every extrema tidal points in june-july 1991, table 2. For that period we obtained a scale value $K = 2.704 \pm 0.001$ microgal/mm by the inclination technique while using GABL records at extrema points we obtain $K = 2.705 \pm 0.005$ microgal/mm. There results are in good agreement. Tidal analysis results of many years with the Askania gravimeter GS 12 n° 186 were presented in the paper [1]. These results are in good agreement with the Wahr-Dehant earth tide model.

4. GABL observation results and discussion.

Each observation of GABL gravimeter, which is the mean of 54 drops, can be written under the form:

$$G_i = g_0 + T_i + B_i\, C + 0.306\, (P_i - 994) + D_i \quad \text{for } 1 < i < n \qquad (1)$$

n : number of data,
G_i: observed values of g,
g_0: constant term,
T_i: tides,
B_i: residual vacuum (resistance of air),
C : coefficient,
P_i: observed value of the atmospheric pressure,
D_i: residuals.

The figures and tables present each observation in the form:

$$G_{i1} = g_1 + T_i + D_i \quad (2)$$

g_1: constant term.

For comparison with GABL data, we are synthesizing tidal gravity data using the tidal potential development of Cartwright-Tayler-Edden together with tidal factors. We controlled values of tidal gravity factor from 1.12 to 1.17 and by minimization of residuals we stopped at the Wahr-Dehant model corrected for oceanic tidal effect computed from the Schwiderski cotidal maps [11] (table 3) as it has been already shown that such a modelisation fits the observations in Novosibirsk (figure 4). We have also to take into account the fact that in the equation (2) a linear factor was introduced. It can be written under the form:

$$G_{i1} = g_2 + T_i + F\ t_i + D_{i1} \quad (3)$$

g_2 : constant term,
F : coefficient,
t_i : time,
D_{i1}: residuals.

The value of F was close to 0.1 microgal/day. The linear factor reflected the fact that the water level at Novosibirsk-Ob station close to Novosibirsk-hydro-electric power station's reservoir was not constant in time. For example, during june-october 1991 the (Novosibirsk-Ob Station) level changes by 0.7 metres, a reason for gravity changes of 11 microgal (± 1 microgal). It was difficult to correct the gravity value, because of a phase with respect to the ground water level. At the same time, at Novosibirsk-IAE station the gravity value remained constant in time (± 1 microgal).

In conclusion, the authors note that confirming the calibration of gravimeter GS 12 n° 186 by GABL measurements results in tidal analyses in good agreement with Wahr-Dehant model, with loading computation based on the Schwiderski maps.

5. Acknowledgements.

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Table 1. Observed GABL data at Novosibirsk-Kluchi

May 1992

N°	U.T.	Observed value microgal	R.M.S. error on mean values	Correction for res.vacuum pressure		Tidal change
25.05.92						
1.	12-30/12-40	509	1.5	+11	-1	519
2.	13-30/13-40	512	1.2	+10	-1	521
3.	14.30/14-40	522	1.5	+10	-1	531
4.	15-30/15-40	538	1.3	+9	-1	549
5.	16-30/16-40	554	1.6	+9	-1	562
6.	17-30/17-40	561	6.6	+9	-1	569
7.	18-30/18-40	561	6.1	+9	-1	569
8.	19-30/19-40	576	1.6	+9	-1	584
9.	20-30/20-40	572	1.1	+8	-1	574
10.	21-30/21-40	557	1.3	+8	-1	564
11.	22-30/22-40	545	1.4	+8	-1	552
12.	23-30/23-40	528	1.6	+8	-1	535
26.05.92						
13.	0-30/ 0-40	511	1.7	+7	-1	517
14.	1-30/ 1-40	504	1.5	+7	-1	510

1 microgals = 10 nms-2

Table 2. Tidal data of GABL at Novosibirsk-Ob

June-July 1991

N° U.T.	Observed data tidal changes in microgal	R.M.S error on mean values in microgal
24.06.91		
1. 20-15	389	0.5
25.06.91		
2. 5-30	209	2.0
3. 14-35	385	0.7
4. 17-50	377	2.1
5. 20-55	383	1.0
26.06.91		
6. 6-05	208	2.0
7. 15-00	387	1.1
8. 18-20	376	0.7
9. 21-40	385	0.8
27.06.91		
10. 6-35	208	0.6
11. 15-25	381	1.4
12. 18-55	372	0.8
13. 22-20	380	1.1
28.06.94		
14. 7-05	208	1.2
15. 15-45	384	1.1
16. 19-25	377	1.6
17. 23-00	385	3.2
29.06.91		
18. 7-35	220	2.6
19. 16-05	386	1.3
20. 20-10	369	0.2
21. 23-40	378	0.8
30.06.91		
22. 8-00	237	2.4
23. 16-05	385	2.1
24. 21-08	362	0.3
1.07.91		
25. 0-35	373	6.9
26. 8-30	256	5.2
27. 16-30	381	0.2
28. 22-15	347	1.4
2.07.91		
29. 1-25	355	3.5
30. 8-55	280	3.8
31. 16-40	385	1.5
32. 23-20	337	0.9
3.07.91		
33. 2-45	347	0.7
34. 9-15	296	0.5
35. 16-55	391	0.1
4.07.91		
36. 0-25	321	0.6
37. 5.20	337	0.8
38. 9-20	328	0.4
39. 17-05	393	1.0
5.07.91		
40. 1-25	294	2.0
41. 17-25	397	1.2
6.07.91		
42. 2-15	269	1.8
43. 17-35	396	1.9
7.07.91		
44. 3-05	236	0.4
45. 12-30	388	0.3
46. 18-10	401	0.4
8.07.91		
47. 3-50	213	1.0
48. 13-50	402	2.8
49. 15-50	402	0.6
50. 18-55	409	0.7
9.07.91		
51. 4-40	198	1.2
52. 14-00	408	1.6
53. 20-05	417	0.4
10.07.91		
54. 5-25	185	1.9
55. 14.25	414	1.7

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N°	U.T.	Observed data tidal changes in microgal	R.M.S error on mean values in microgal
56.	17-55	400	0.3
57.	21-15	409	2.0
11.07.91			
58.	6.10	181	1.6
59.	14-50	416	0.2
60.	18-40	397	1.0
61.	22.25	415	1.0
12.07.91			
62.	6-55	196	2.3
63.	15-15	414	2.6
64.	23-30	406	1.7
13.07.91			
65.	7.35	214	6.5
66.	15.30	412	0.1
67.	20-20	368	1.0
14.07.91			
68.	0-30	402	1.9
69.	5-05	309	7.0
70.	8-10	253	1.4
71.	11-10	311	2.4
72.	15-45	408	1.3
73.	21-15	352	0.5
15.07.91			
74.	1-55	381	1.8
75.	6-20	310	2.2
76.	10-50	312	4.0
77.	15-55	411	2.3
78.	22-15	334	1.1
16.07.91			
79.	3-00	362	1.1
80.	9-00	311	1.0
81.	16-05	400	1.4
17.07.91			
82.	0-20	317	1.2
83.	4-45	345	1.7
84.	9-00	330	1.5
85.	16-15	402	1.7
86.	22-30	306	2.2

N°	U.T.	Observed data tidal changes in microgal	R.M.S error on mean values in microgal
18.07.91			
87.	0-30	295	1.4
88.	3-00	313	1.1
89.	19-25	392	2.1
19.07.91			
90.	1-35	275	1.2
91.	16-35	389	1.8
20.07.91			
92.	2-40	260	3.4
93.	16-50	388	0.4
21.07.91			
94.	3-25	245	3.6
95.	17-30	385	1.5
22.07.91			
96.	4-10	233	0.6
97.	14-00	387	0.3
98.	17-00	385	0.4
99.	18-40	384	0.2
23.07.91			
100.	4-45	225	0.3
101.	14-00	388	1.6
102.	17-20	383	2.9
103.	20-05	385	1.2
24.07.91			
104.	5-20	220	1.4

1 microgal = 10 nms-2

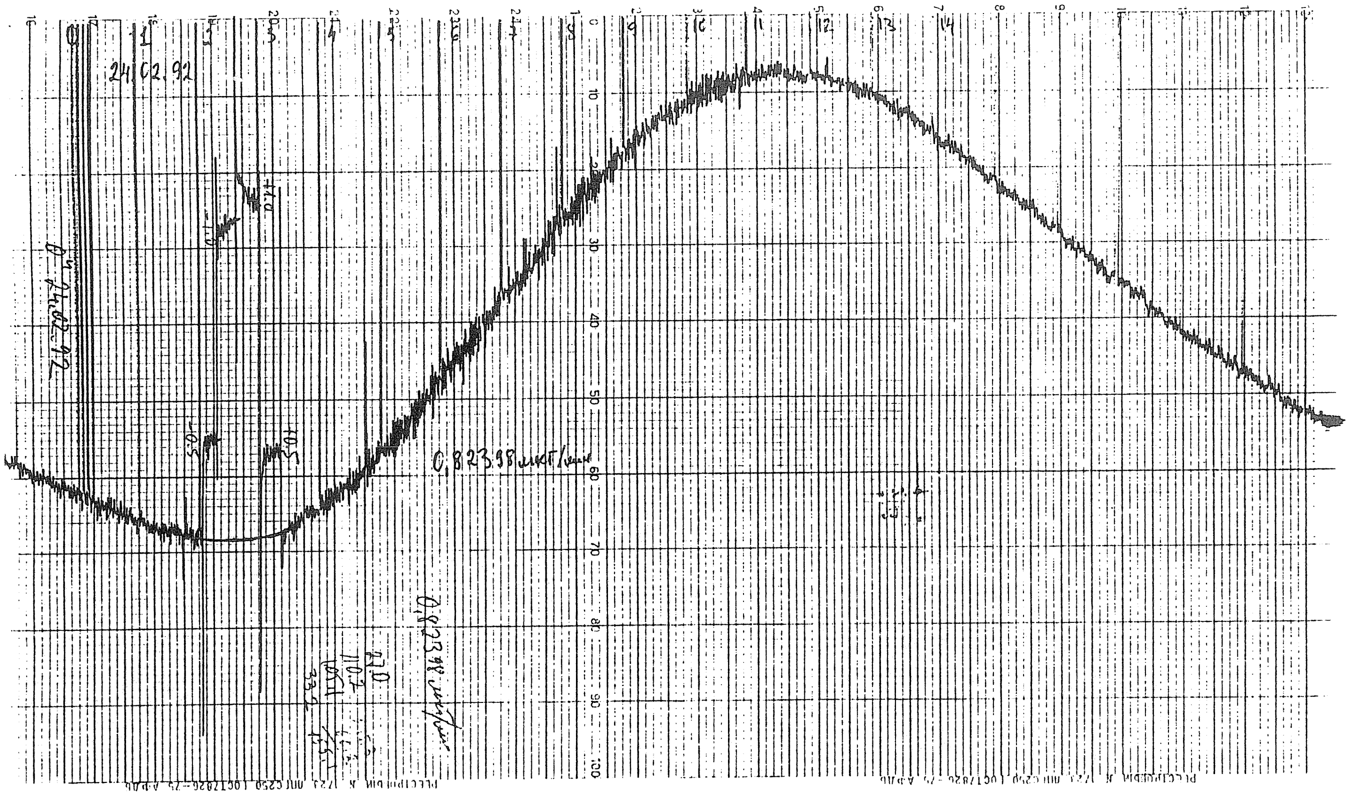


Figure 1 - Calibration of GS12 - N° 186

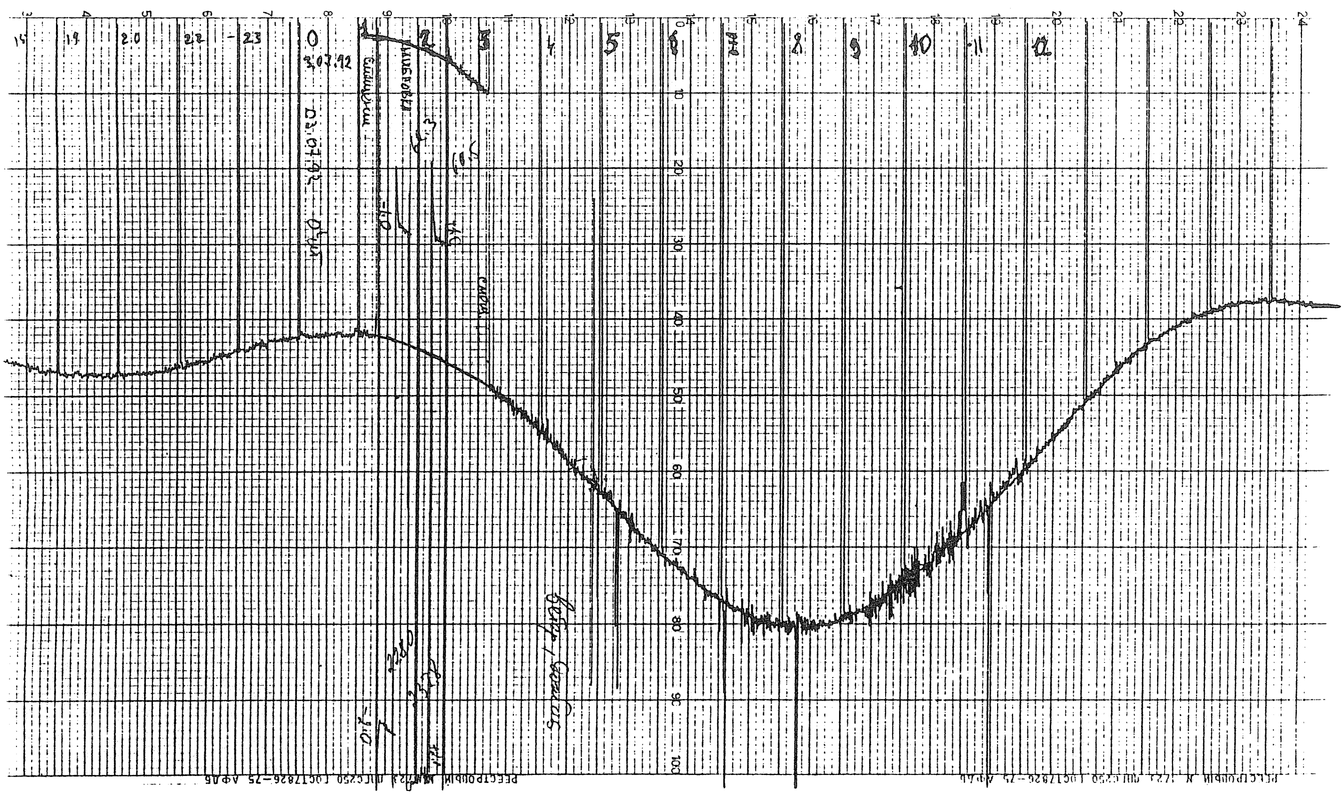


Figure 2 - Calibration of GS12 - N° 186

Table 3. Tidal gravity factors for the Wahr-Dehant model and Schwiderski cotidal maps at Novosibirsk.

Onde	Delta modelises	Alfa SCW80	Onde	Delta modelises	Alfa SCW80
MM	1.1632	0.0	2N2	1.1590	-0.42
MF	1.1632	0.0	N2	1.1590	-0.42
MS	1.1632	0.0	M2	1.1541	-0.32
Q1	1.1598	0.35	L2	1.1530	0.0
O1	1.1604	0.28	S2	1.1527	0.02
M1	1.1600	0.20	K2	1.1522	0.08
P1	1.1536	0.21	M3	1.0680	0.0
K1	1.1375	0.22	XOH	1.1600	0.0
J1	1.1600	0.20			
OO1	1.1600	0.20			

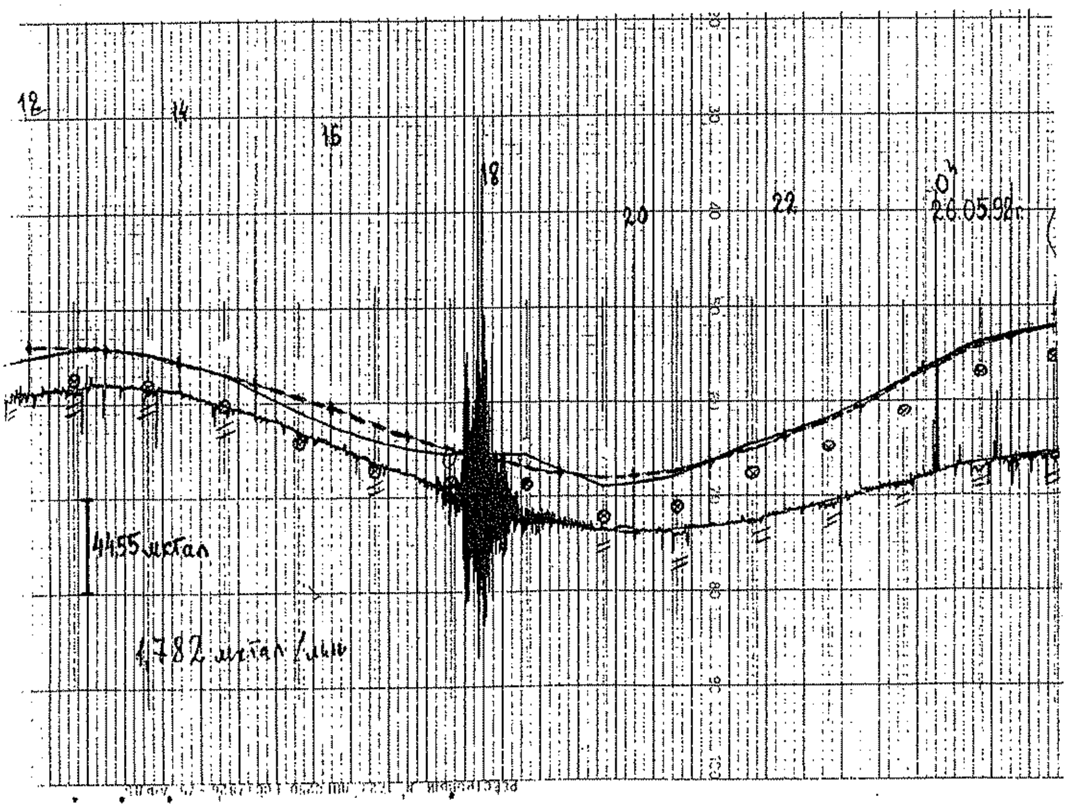
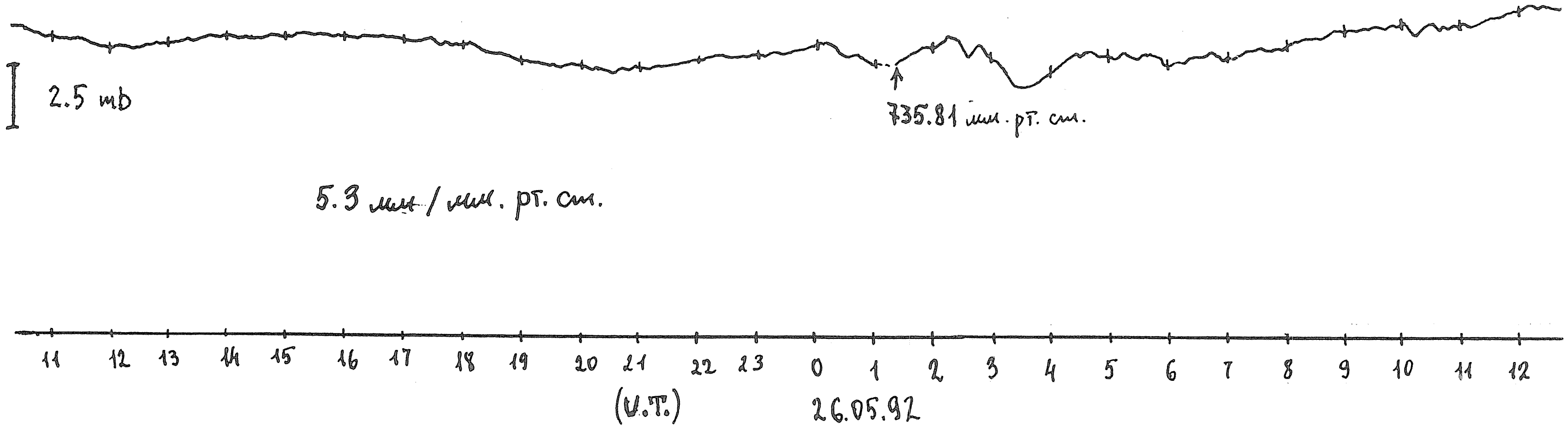


Figure 3 - Theoretical tide by table 3 (- - - -) and observed GABL and Askania GS-12 N° 186 data. There are vibration effect (T = 11 s) on GS data.

Figure 4. Observed record of air pressure



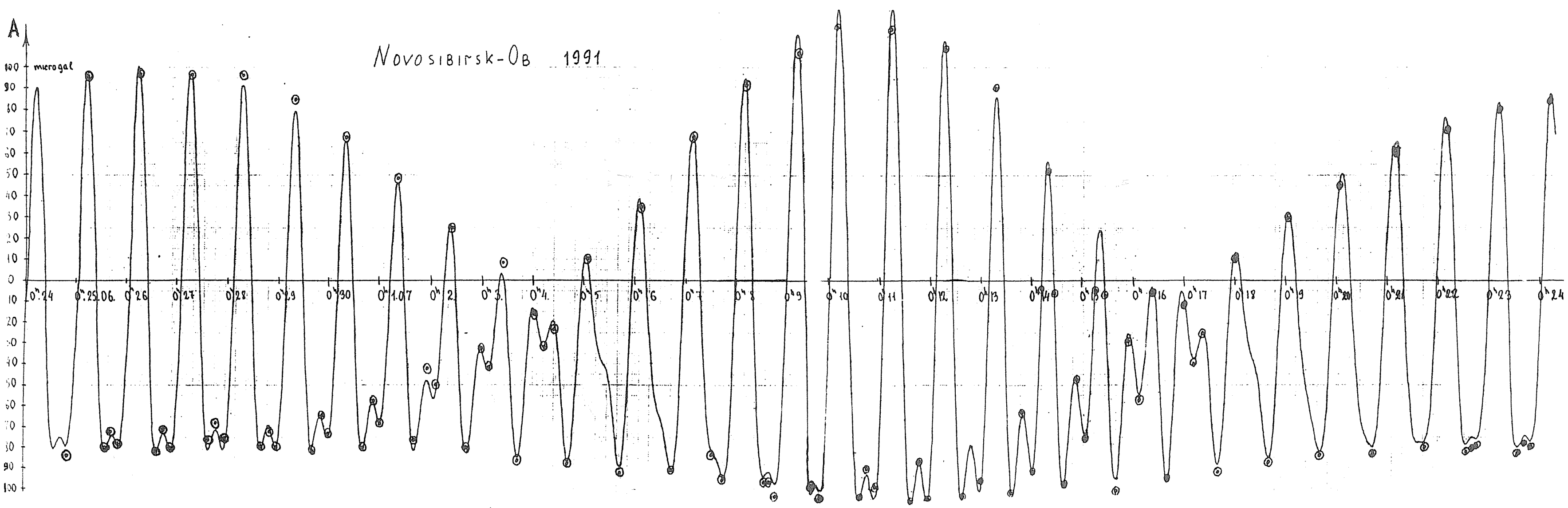


Figure 5. Theoretical tide according to Table 3 and observed GABL data

Traduction

PARAMETRES DES MAREES TERRESTRES D'APRES LES RESULTATS DES OBSERVATIONS DE MAREES (Station Klioutchi, Novosibirsk)

You K. Saritcheva, V. You Timofeiev

Méthode et Résultats de l'Etude des variations spatio-temporelles des Champs Géophysiques.

Section Sibérienne de l'Académie des Sciences de Russie. Novosibirsk 1992, page 129-147.

Abrégé (Les auteurs décrivent d'abord les conditions de mesure des marées gravimétriques).

Jusqu'en 1985 nous utilisions pour déterminer l'échelle d'enregistrement le procédé des déplacements pairs: le levier du gravimètre étant successivement haussé et baissé à l'aide de la vis micrométrique.
On peut faire l'étalonnage sur des polygones gravimétriques de haute précision ou à l'aide d'un équipement construit dans le gravimètre. Mais dans les deux cas, à cause de l'imprécision des échelles du micromètre l'erreur de détermination atteignait 1,6%. Seuls les divers moyens et les calibrations fréquentes ont permis d'obtenir des valeurs acceptables dans les longues séries de mesures. Lorsqu'on s'est posé le problème de déceler des variations temporelles des paramètres de marées avec une limite inférieure de ± 1%, les exigences de précision de la calibration se sont accrues.

Depuis 1986 on applique une autre méthode éliminant le micromètre, à savoir le procédé par inclinaisons.

On a construit une dalle en forme de triangle rectangle avec une base de 1200 mm, le pas de la vis de réglage étant de 0,5 mm. Avec la connaissance précise des paramètres de la dalle la variation d'inclinaison se traduit par une variation de la pesanteur. La comparaison avec le déplacement enregistré donne la valeur de l'échelle sans utiliser le micromètre et sans l'étalonnage du gravimètre. L'appareil reste en permanence sur la dalle et constamment en régime nonobstant l'étalonnage hebdomadaire. La dalle permet également de régler avec une grande précision le minimum de sensibilité à l'inclinaison. Les déterminations de l'échelle ont été faites d'après le schéma:
$+ n_1$, $- n_1$, $- n_2$, $+ n_2$ où n_1 et n_2 sont les tours de la vis de calage de la dalle. Pour éliminer le calcul dans la position de départ correspondant au minimum de sensibilité à l'inclinaison on a utilisé les différences Δg par inclinaison de n_1 à n_2. Pour cette dalle la variation de la pesanteur correspondant à une variation de l'inclinaison de ± 1 à ± 3 tours de la vis atteint 686,6 μgal ce qui dépasse de presque 3 fois la variation de marée maximale. La méthode permet d'obtenir cette relation sans connaître la base de la dalle et du pas de la vis. On a utilisé le système de vérification proposé par A.V. Ladinin de l'appareil de mesure des gravimètres (   ) et du gravimètre de campagne   . Le   a une vis micrométrique d'inclinaison et une installation optique pour la mesure de l'angle d'inclinaison. Le gravimètre de campagne installé à l'intérieur du   ne s'utilise dans notre cas que

comme indicateur de la position initiale de УЭГП

Le gravimètre de marée a été déplacé de sa position habituelle près du côté court de la dalle près des vis et, après nivellement de la dalle, on a déduit le minimum de sensibilité à l'inclinaison. Ensuite on a installé sur la dalle, en série avec le gravimètre, un système de contrôle. Après un certain temps au cours duquel s'est produite la relaxation des tensions dans la dalle provoquées par une charge supplémentaire, on a reprécisé la position du minimum de la sensibilité à l'inclinaison pour le gravimètre de marée. Lors de l'installation aussi bien du gravimètre que du УЭГП il faut maintenir le parallélisme des axes de la dalle, de l'émetteur du gravimètre et des limbes de УЭГП . Ensuite le gravimètre de campagne installé dans УЭГП a été nivelé grâce à ses niveaux et a été amené à une sensibilité plus grande. Ensuite on a déterminé la gamme des tours de la vis de serrage de la dalle dans les limites de laquelle on peut procéder à des inclinaisons de la dalle, sans craindre la sortie des limites de l'enregistreur. Dans notre cas c'était de -3 à +3 tours de vis. Dans la position où le gravimètre indicateur montrait 0, on a fixé le comptage d'après les limites de l'УЭГП. Ensuite la dalle a été inclinée suivant le schéma -3, -1, +1, +3 tours. Après chaque inclinaison de la dalle l'indicateur du gravimètre de campagne retournait dans la position de départ par une inclinaison de compensation de l'УЭГП et le calcul s'effectuait d'après les limbes. Les limites permettent de mesurer l'angle avec une précision allant jusqu'à 0,1 s. d'arc. Pour éviter une diminution de la précision lors du fonctionnement près du minimum de sensibilité à l'inclinaison on a utilisé dans les calculs les différences moyennes des angles pour des inclinaisons de -1 à -3 et de +1 à +3 tours. Ces différences α_1 - α_2 ont été transformées ultérieurement en variations de la pesanteur:

$$\Delta g = \frac{1}{2} g (\sin^2 \alpha_1 - \sin^2 \alpha_2)$$

La précision réelle de l'accroissement mesuré de la pesanteur est ainsi de 0,1 μgal et elle peut être encore un peu augmentée par de nombreux moyens de l'inclinaison et du calcul de la dérive de l'appareil. Après la mesure des déplacements y_1 et y_2 correspondant aux inclinaisons α_1 et α_2, l'échelle de l'enregistrement s'obtient ainsi

$$K = \frac{\Delta g}{y_1 - y_2} \quad \mu gal/mm$$

Nous donnons le graphique des valeurs de l'échelle (fig. 1, courbe "a") obtenues de juin 1987 à août 1989. Dans cet intervalle la valeur moyenne de l'échelle et l'écart quadratique moyen de celle-ci sont 5,940 ± 0,013 μgal/mm donc une précision de ± 0,2% ce qui est d'un ordre plus élevé que la précision de la méthode des déplacements pairs.

Résultats des observations à Novosibirsk

La station de Novosibirsk fonctionne depuis 1966. En 24 ans on a obtenu trois séries d'observations (2, 7, 9 à 16, 15).

Dans la première période de 1966 à 1970 l'enregistrement a été fait avec un seul gravimètre dans le but des mesures d'obtenir les paramètres de marées.

L'enregistrement a été fait à l'aide de l'enregistreur Bruno Lange.
On a étalonné le gravimètre sur le polygone gravimétrique de Novosibirsk et avec les billes. L'analyse harmonique des observations de 1966 à 1967 a été faite par la méthode de Lecolazet, ensuite par la méthode de Venedikov. Les résultats sont donnés dans la table 1. Plus tard, en 1974-1975, lors de la comparaison de l'appareil n° 186 avec un autre gravimètre similaire (3) on a découvert une diminution systématique de l'amplitude de la marée liée à une erreur de l'équipement de 1,2%. A l'inverse des publications précédentes (7, 9) pour la comparaison avec les résultats de 1976 à 1989 dans la table 1 cette diminution a été prise en compte en introduisant une correction correspondante.

En appliquant des poids proportionnels aux amplitudes des composantes M_2, S_2, O_1 et K_1 (23, 11, 27, 39 respectivement) les valeurs moyennes du facteur gravimétrique étaient égales à 1,157 ± 0,013 pour 1966-1967 et 1,154 ± 0,002 pour 1967 à 1970.

La seconde série d'observations (de 1977 à 1979) a été réalisée à Novosibirsk par quatre appareils, mais pour l'homogénéité des résultats représentés on n'a utilisé que les données du gravimètre n° 186. Les déterminations de l'échelle d'enregistrement à cette époque ont été faites par le procédé des déplacements pairs en utilisant le micromètre. Les résultats de cette série d'observations sont donnés dans la table 2.

En 1986, à la fin des observations à la station temporaire d'Irkoutsk, les mesures ont été reprises à Novosibirsk et se poursuivent jusqu'à présent. Leur raison principale est de mettre en évidence et d'évaluer les limites des variations temporelles des paramètres des marées et par là même de déterminer les limites de la variation des propriétés élastiques de la Terre. Les valeurs des paramètres de marées à Novosibirsk ont été déduites d'après les observations jusqu'en 1990. Les résultats pour 1986 à 1989 et le résumé des résultats pour toutes les observations sont donnés dans la table 2.

Variation dans le temps du facteur d'amplitude

Avec l'augmentation de la précision de détermination de l'échelle d'enregistrement il est devenu possible d'étudier de façon plus détaillée les variations dans le temps du facteur d'amplitude de marée. Ainsi, de juin 1987 à juin 1989 on a réalisé l'analyse harmonique de séries mensuelles ne se recouvrant pas dont le résultat se reflète par la courbe "6" (voir fig. 1) représentant la variation du paramètre δ_{M2}. On note ici des variations de période quasi annuelle. Les maxima se produisent en juillet-août 1987 et août-septembre 1988, les minima en février 1988 et, en jugeant d'après la tendance de la courbe, en février-mars 1989. Une variation de période analogue s'est rencontrée lors de la réduction des observations d'Irkoutsk (2). Alors, ne possédant pas une série suffisamment longue d'observations nous avions interprété le minimum net comme anormal (fig. 2.a).

A présent, en s'appuyant sur les résultats des observations de Novosibirsk on déterminera cette "anomalie" plus sûrement comme conséquence de la périodicité quasi annuelle du facteur d'amplitude (comme à Novosibirsk). La cause de ces variations peuvent être trouvée en particulier dans les processus hydrométéorologiques: les variations saisonnières de la température, de la pression atmosphérique, du niveau des eaux souterraines, de la déformation des socles impliquant des roches lors de leur congélation ou du dégel.

C'est pourquoi on peut en admettre la régularité, même dans un degré différent, dans diverses stations. On n'a pas exclu que l'augmentation de la marée introduit son apport dans le processus de l'activité séismique de la région. Il doit y avoir un lien inverse: le processus de la dilatance, stade de l'activité séismique de la région, peut provoquer des variations des paramètres des marées particulièrement dans les observations clinométriques. C'est pourquoi il est aussi important d'avoir un réseau permanant de stations de marées gravimétriques, clinométriques et déformographiques se faisant de façon synchrone, ce qui permet, bien que partiellement, de séparer les effets d'origines tectonique et météorologique. Il est important également de tenir compte des variations de la pression atmosphérique influençant directement l'amplitude de la marée. Ainsi, l'évaluation de l'apport direct de la pression atmosphérique dans δ d'après les données des observations barométriques à Talaïa (Sud du Baïkal) a montré que pour les ondes O_1 et K_1 cet apport ne dépasse pas 0,5% mais que pour l'onde S_2 il atteint 1% (ce qui dépasse de deux fois l'erreur de détermination de δ).

Les mesures continues et l'analyse harmonique glissante permettent de vérifier expérimentalement l'effet dynamique du noyau liquide de la Terre. Comme l'a montré M.S. Molodenski (5, 6), à cause de la résonance du mouvement de nutation du noyau liquide de la Terre et de la marée diurne (voir fig. 2) il apparaît une différence systématique entre les paramètres de marées δ aux fréquences des deux ondes diurnes O_1 et K_1, égale à 0,0220. Cette valeur théorique de $\Delta\delta$ a été admise comme constante et a été utilisée comme correction dans δ_{K1} lors de la déduction des nombres de Love. Cependant les observations à Irkoutsk en 1980-1981 ont montré que dans l'intervalle donné, le paramètre $\Delta\delta$ a changé avec une périodicité distincte de l'ordre de 290 jours par rapport à la valeur moyenne 0,0100 dans les limites de - 0,040 à + 0,060 (voir fig. 2.b). La variation de $\Delta\delta$ avec une période d'environ un an pourrait être la conséquence de la présence en δ_{K1} (t) de l'onde météorologique de période quasi diurne mais avec une amplitude variant au cours de l'année. Alors comme nous l'avons observé dans deux stations à Irkoutsk et à Novosibirsk, la période de variation de $\Delta\delta$ est plus petite qu'un an. La cause la plus probable de la variation du paramètre $\Delta\delta$ peut être la non-concordance des valeurs de la fréquence de résonance établie pour celle utilisée dans les calculs du modèle de la Terre et également l'irrégularité de la dynamique de son noyau liquide à cause de l'effet réciproque électromagnétique du noyau et du manteau (4). A Novosibirsk, d'après les données des observations de 1987 à 1989 on a noté également des variations du paramètre $\Delta\delta = (\delta_{O1} - \delta_{K1})$: de mai 1988 la période des variations était proche de 280 jours et ensuite les variations deviennent de plus en plus fréquentes en atteignant deux mois à la fin de 1988 (voir fig. 1.c). La présence des variations de $\Delta\delta$ témoigne en faveur de l'hypothèse de la nature physique des variations temporelles observées du facteur δ. Il paraît probable qu'elle est apparentée à la nature de la variation de la période de Chandler. Les données de Dittfeld (19) obtenues sur la base d'une série de 8 ans des observations de marées parallèles à Potsdam (Allemagne) et Pecny (Tchécoslovaquie) témoignent en faveur de l'hypothèse sur les causes du caractère global déterminant les variations des paramètres de marées (et comme conséquence - des paramètres élastiques de la Terre). Cet auteur a obtenu des anomalies synchrones du facteur δ en corrélation avec la variation de la vitesse de rotation de la Terre mais le pas trop grand de l'analyse glissante (3,5 mois) pris par Dittfeld rend difficile la comparaison des résultats avec nos données d'Irkoutsk sur les parties se recouvrant dans le temps.

Les nombres de Love

Si on utilise les données de marées pour la détermination des nombres de Love ou pour les constructions régionales, il faut introduire dans les paramètres de marée δ (ω), où ω est la fréquence de l'onde, une série de corrections tenant compte des effets qui apparaissent à différents degrés en différents sites d'observation. Ces corrections tiennent compte de:

1. Les forces d'inertie résultant des variations de marées de la surface de la Terre (8).

2. La résonance de la marée diurne et de la nutation diurne résultant de la rotation du noyau liquide de la Terre (5).

3. La non concordance de la normale au géoïde avec la direction du rayon vecteur depuis le centre de la Terre au point d'observation et respectivement des observations des composantes mesurées et calculée de la force de pesanteur (correction de Wenzel, 2). Pour les ondes diurnes cette correction est égale à $+ \delta \operatorname{tg} \psi \sin (\phi - \psi)$, ϕ et ψ sont respectivement les latitudes géographique et géocentrique du lieu d'observation.

4. L'inégalité du retard de phase X du bourrelet de marée d'une Terre élastique visqueuse et du retard de phase de l'onde, obtenue par analyse harmonique (correction de Slichter/ 2),

$$\Delta\delta = \frac{1}{\cos \chi} (\delta_{obs} \cos \Delta\phi - 1) + 1 - \delta_{obs}$$

où δ_{obs} - δ avec corrections 1, 2, 3, mais

$$\chi = \operatorname{arctg} \frac{\delta_{obs} \sin \Delta\phi}{\delta_{obs} \cos \Delta\phi - 1}$$

5. L'attraction des masses océaniques (les corrections que nous avons utilisées sont calculées par B.P. Pertsev et M.V. Ivanova sur la base des cartes cotidales).

Dans la table 3 on a tenu compte des erreurs énumérées et on a calculé la valeur moyenne de δ en tenant compte de l'apport de l'onde dans la marée totale. Pour Novosibirsk on a obtenu $\delta = 1,1527 \pm 0,0039$. Sous la condition que les nombres de Love k et h sont liés par le rapport k = 0,495h [5, 20] et également par le rapport $\delta = 1 + h - 3/2\ k = 1 + 0,258\ h$ nous avons pour Novosibirsk

$$k = 0,293, \ h = 0,592$$

D'après nos observations les valeurs globales des nombres de Love et du facteur d'amplitude δ à Novosibirsk sont un peu plus basses que celles d'Irkoutsk. Elles correspondent à la répartition des paramètres élastiques dans le modèle Gutenberg-Bullen (avec noyau interne solide/17) indiqué dans la table 4.

Après introduction de toutes les corrections, excepté les corrections de l'influence du noyau liquide, ces paramètres δ et $\Delta\delta$ étaient différents à Novosibirsk et à Irkoutsk (table 5).

Ainsi, d'après les données des observations à Novosibirsk l'effet dynamique du noyau liquide est nettement plus près de la valeur calculée que d'après les observations à Irkoutsk. Les paramètres de la marée gravimétrique reflètant les particularités de la structure du manteau supérieur (jusqu'aux profondeurs de 300 km) il est naturel de supposer que le modèle MII sur la base duquel M.S. Molodenski (5) a déterminé $\Delta\delta = 0,0220$ est plus correct pour les régions de plate-formes que pour les zones de rift tectoniquement actives.

En ne nous arrêtant pas en détail sur les problèmes des différences régionales dans les paramètres de marées, ce qui a déjà été examiné dans l'article (2) nous noterons seulement que les valeurs moyennes des paramètres de marées à Novosibirsk et à Irkoutsk pour les fréquences des ondes de marées principales après avoir tenu compte de toutes les corrections sont voisines (table 6). La différence consiste dans le caractère et l'amplitude des variations des paramètres de marées dans le temps: à Irkoutsk les limites de la variation de δ étaient deux fois plus grandes.

Table 1 - Paramètres de marée à Novosibirsk d'après les observations de 1966-1970.

Intervalles années	Facteur d'amplitude δ				Retard de phase (degrés)			
	M2	S2	O1	K1	M2	S2	O1	K1
1967 - 1970	1,157 (0,002)	1,169 (0,013)	1,160 (0,006)	1,116 (0,003)	-1,52 (0,17)	-0,35 (0,20)	-0,50 (0,30)	-0,09 (0,20)
1967 - 1970 I 187 jours	1,148 (0,004)	1,142 (0,019)	1,140 (0,009)	1,103 (0,008)	-1,14 (0,36)	-0,55 (0,37)	-0,14 (0,59)	+0,57 (0,58)
II 304 jours	1,166 (0,012)	1,149 (0,018)	1,134 (0,012)	1,127 (0,012)	-1,12 (0,48)	+0,74 (0,74)	-0,94 (0,50)	+0,53 (0,73)
III 203 jours	1,149 (0,009)	1,153 (0,017)	1,137 (0,012)	1,120 (0,008)	-0,77 (0,61)	-2,35 (0,84)	-2,04 (0,82)	-0,63 (0,87)
IV 295 jours	1,156, (0,012)	1,154 (0,022)	1,156 (0,017)	1,144 (0,008)	-1,40 (0,52)	-2,49 (0,89)	-0,72 (0,88)	-0,44 (0,87)
Moyenne I-IV poids proportionnel à la longueur de la série	1,156 ±0,004	1,150 0,002	1,143 (0,005)	1,126 (0,008)	-1,14 (0,13)	-1,09 (0,80)	-0,93 (0,36)	+0,02 (0,31)

Les nombres entre parenthèses sont les erreurs (±).

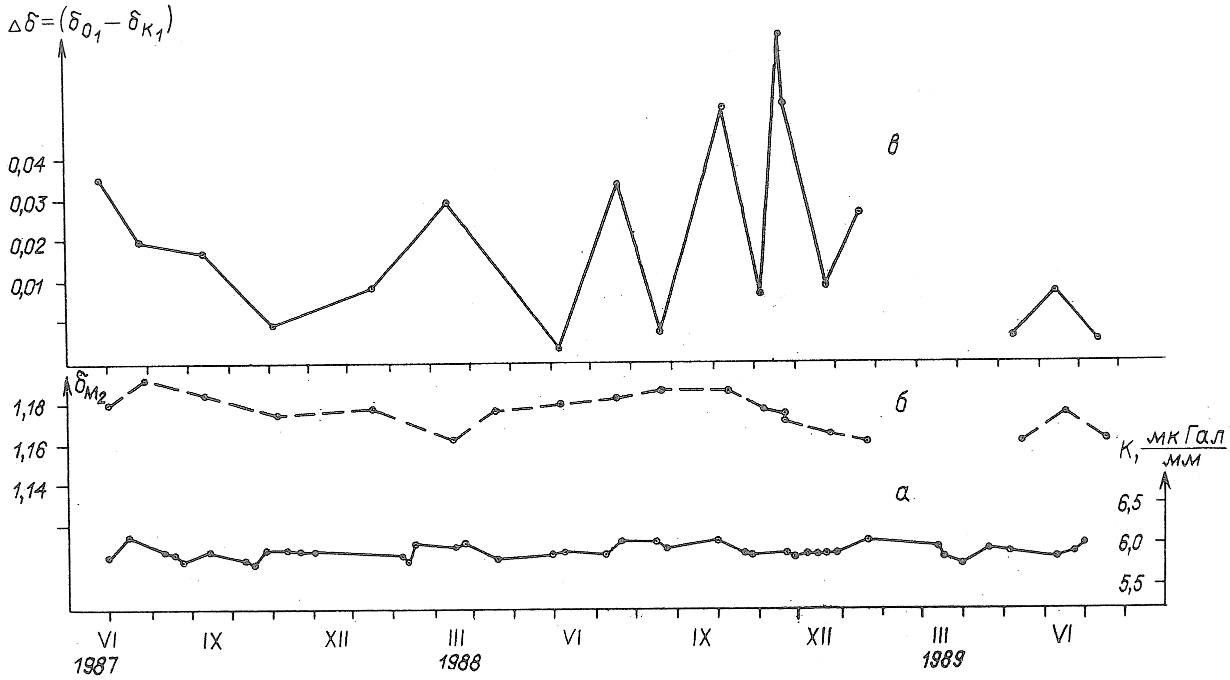


Figure I Résultats des observations de la marée gravimétrique à Novosibirsk: a - échelle d'enregistrement K du gravimètre n° 186; b - variation temporelle du facteur d'amplitude δ de l'onde M_2; c'est la variation temporelle du paramètre $\Delta\delta_{O1}$ - δ_{K1} contenant l'effet du noyau liquide de la Terre.

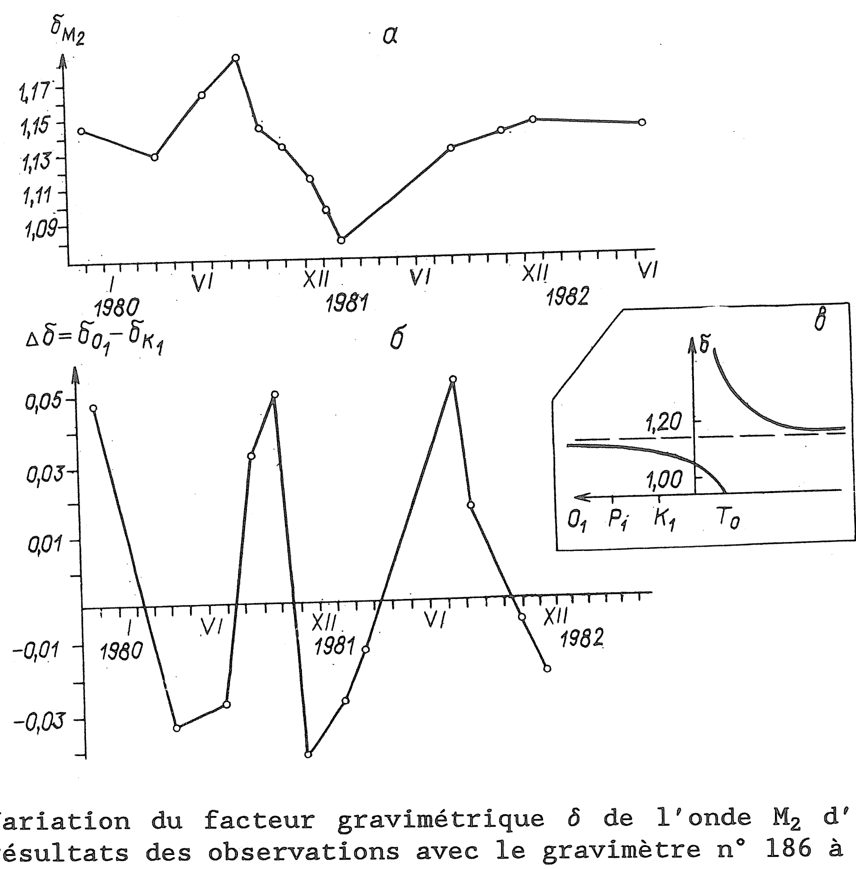


Figure II Variation du facteur gravimétrique δ de l'onde M_2 d'après les résultats des observations avec le gravimètre n° 186 à Irkoutsk: a - graphique δ de l'onde M_2; b - variations du paramètre $\Delta\delta = \delta_{O1} - \delta_{K1}$ dans la même période; c - résonance de la marée diurne et de la nutation (selon /5/): T_0 - période correspondant à la fréquence de résonance.

Table 2 - Résultats de l'analyse harmonique des variations de marée à la station de Novosibirsk d'après l'ensemble des observations.

Intervalles années	Nombre de jours	Facteur gravimétrique δ				Méthode d' Analyse	Retard de phase			
	D	M2	S2	O1	K1		M2	S2	O1	K1
1966 - 1967	80	1,157	1,169	1,160	1,116	L	-1,52	-0,35	-0,50	-0,09
		± 0,002	0,013	0,006	0,003)		± 0,17	0,20	0,30	0,20
1967 - 1970	989	1,156	1,150	1,143	1,126	V65	-1,14	-1,09	-0,93	+0,02
		± 0,004	0,002	0,005	0,008		± 0,13	0,80	0,36	0,31
1977 - 1979	552	1,1513	1,1382	1,1594	1,1325	V74	-1,29	+1,32	-0,13	+0,66
		± 0,0018	0,0002	0,0034	0,0041		± 0,33	0,72	0,72	0,48
1986 - 1988	572	1,1590	1,1541	1,1441	1,1291	V74	-0,06	+0,97	+0,76	+0,32
		± 0,0025	0,0067	0,0043	0,0057		± 0,16	0,27	0,17	0,16
1989	232	1,1374	1,1768	1,1364	1,1148	V74	+0,48	+1,00	+0,26	+0,70
		± 0,0055	0,0111	0,0074	0,0055		± 0,28	0,57	0,38	0,30
Moyenne pondérée		1,1539	1,1515	1,1469	1,1268		-0,78	+0,18	-0,22	+0,30
Poids (P D)		± 0,0030	0,0053	0,0039	0,0026		± 0,32	0,54	0,34	0,14

L méthode Lecolazet
V méthode Venedikov

Table 3 - Calcul des corrections au facteur gravimétrique δ

Onde	M2	S2	O1	K1
δ sans correction Erreur quadratique moyenne de ϵ	1,1539 ±0,0030	1,1515 0,0053	1,1469 0,0039	1,1268 0,0026
1. Influence des forces d'inertie	-0,0033	-0,0036	-0,0012	-0,0010
2. Influence du noyau liquide de la Terre	-	-	-	+0,0220
3. Correction de Wenzel	+0,0052	+0,0052	+0,0013	+0,0012
δ avec corrections 1-3 ϵ	1,1558 +0,0030	1,1531 0,0053	1,1470 0,0039	1,1490 0,0026
Retard de phase de Δδ en degrés	-0,78	+0,18	-0,22	+0,30
χ, en degrés	5,76	1,35	1,71	2,00
4. Correction de Slichter	+0,0007	0,0000	+0,0001	+0,0001
5. Influence des océans Δδ	+0,0060	+0,0074	-0,0010	+0,0002
δ corrigé	1,1625	1,1605	1,1461	1,1493
ϵ *1	±0,0036	0,0058	0,0039	0,0026
Poids proportionnel à l'amplitude de l'onde	23	11	27	39
δ moyennes d'ondes	1,1527 ± 0,0039			

* L'erreur ϵ_1 se calcule par $\sqrt{\ \epsilon^2 + \epsilon^2}$ où l'erreur de la correction de l'influence des océans (ϵ_{ok}) est égale ≈ 1/3 $\Delta\delta_{ok}$

Table 4 - Valeurs des paramètres élastiques d'après les données théoriques et celles des observations à Novosibirsk et Irkoutsk et (selon /17))

Résultats	δ moyenne d'onde	h	k
Modèle de Gutenberg-Bullen	1,153 1,158	0,585 0,605	0,288 0,298
Expérimentaux Observations à Novosibirsk 1966 à 1989	1,1527	0,592	0,293
Observations à Irkoutsk 1979 à 1983	1,1589	0,615	0,304

Table 5 - Paramètres d'amplitude des ondes diurnes et de leur différence

Station	δo1	δk1	Δδ=δo1-δk1	Δδ Theor.	Caractérist. tectonique
Novosibirsk	1,1461	1,1273	0,0188	0,0220	plate-forme
Irkoutsk	1,1486	1,1392	0,0094	0,0220	rift

Table 6 - Valeurs moyennes du facteur d'amplitude après le calcul de toutes les corrections.

Station	δ moyenne	δ M2	δ 01	δ K1
Novosibirsk	1,1527 ± 0,0039	1,1625 0,0036	1,1461 0,0039	1,1493 0,0026
Irkoutsk	1,1589 ± 0,0032	1,1641 0,0049	1,1497 0,0098	1,1618 0,0064

Traduction

INCLINAISONS ANORMALES DE LA SURFACE DE LA TERRE A GARM ET AU BAIKAL AVANT LES TREMBLEMENTS DE TERRE PROCHES.

D.G. Gridniev, Y.Y. Naoumenko-Bondarenko
V.Y. Timofeiev, A.Y. Sidorin,
L.V. Anissimova, S.F. Panin.

Méthode et résultats de l'étude des variations spatio-temporelles des champs géophysiques. Rosskiiskaia Akad. Nauk, Sibirskoe Otdelennie Novosibirsk 1992, pp. 195-201.

L'enregistrement des inclinaisons de la surface de la Terre dans le but d'étudier la structure interne et de rechercher des signes précurseurs des tremblements de terre par les clinomètres en quartz HK [2] dans le polygone géophysique de Garm de l'Institut de Physique terrestre de l'Académie des Sciences d'URSS est poursuivie depuis 1986 à la station séismique de Talaya (Baïkal) [4].

L'utilisation des clinomètres en quartz dans ces buts est déterminée par une série de préférences de leurs systèmes sensibles en comparaison avec les systèmes métalliques.

Le système sensible du clinomètre en quartz et son cadre de montage sont faits en quartz fondu. Les fils de suspension du pendule de type Zollner sont soudés au levier et au cadre de montage. Ce montage élimine la possibilité de déformations élastiques et de tensions aux points d'attache des fils de suspension c'est pourquoi le système sensible en quartz ne peut avoir de dérive propre. La variation de la période des oscillations propres du pendule dans de larges limites ne provoque pas de variation de la valeur de la dérive des clinomètres. Le coefficient de température de dilatation linéaire du quartz est pour le moins d'un ordre plus petit que pour le métal. La masse du système sensible de quartz est une dizaine de fois plus petite que la masse du système des clinomètres métalliques. De plus pour la fabrication des clinomètres en quartz il ne faut pas d'équipement complexe coûteux, leurs montage et réparation peuvent être organisés dans des conditions de campagne.

Le problème le plus difficile lors de la fabrication des systèmes sensibles métalliques des clinomètres est l'attache des fils de suspension du pendule. Le montage des fils amène à des déformations élastiques inévitables et à des tensions aux points d'attache ce qui amène à l'apparition de la dérive propre du système. La période de relaxation de ces déformations et des tensions peut durer de façon imprévisible longtemps. L'augmentation de la période des oscillations propres du pendule des systèmes métalliques jusqu'à 8 à 10 amène à une augmentation importante de la dérive du clinomètre (clinomètre d'Ostrovskii).

Dans la galerie de la station séismique de Garm les clinomètres en quartz ont été installés dans les azimuts NS et EW. L'enregistrement des clinomètres se faisait dans une des salles d'enregistrement de la station séismologique, l'échelle de l'enregistrement était de l'ordre de 0.001 sec. d'arc/mm.

Les recherches préliminaires de ces clinomètres à Obninsk ont montré que la dérive ne dépasse pas 0,2 s. d'arc par an. On a établi qu'elle est liée aux effets de température et de pression sur le milieu environnant [3].

Les données d'observations dans la galerie témoignent d'inclinaisons périodiques importantes jusqu'à 0,1 à 0,2 s. d'arc par jour du socle sur lequel ont été placés les clinomètres. Ainsi on a observé dans les courbes des inclinaisons à maintes reprises des "sauts" d'une amplitude de 0,01 à 0,009 s. d'arc.

Pour juger plus objectivement la nature des déclinaisons assez importantes et des "sauts" sur un même socle on a installé un second complexe de clinomètres en quartz dans les mêmes azimuts qui a commencé à enregistrer des phénomènes analogues.

Parmi tous les cas d'anomalies des inclinaisons nous avons attribué notre attention à sa rareté d'inclinaison dans les périodes précédant les tremblements de terre proches du 12 novembre 1987 (T = 09h 35min, classe K = 11.3, profondeur H = 5,6 km, distance jusqu'à l'épicentre R = 80 km, azimut de l'épicentre A = 323.0°) et le 11 avril 1988 (T = 10h 36min, K = 9.2, H = 2,7 km, R = 20,1 km, A = 18.9°). Depuis le 9 novembre 1987 on commence d'après les deux composantes dans la courbe de l'allure des inclinaisons à suivre nettement les inclinaisons avec des périodes de quelques minutes à une heure et des amplitudes de 0.001 à 0.015 s. d'arc. Les inclinaisons anormales de périodes plus longues manquaient pratiquement. Pour 4,5 h jusqu'au tremblement de terre les inclinaisons à courtes périodes d'interruption simultanément pour les deux composantes, on ne les observe pas non plus après le tremblement de terre (fig. 1, 2).

Comme on le constate sur la figure 2b, l'allure vectorielle de l'inclinaison est douce puisqu'ainsi on observe une certaine anomalie de l'allure déterminée par une inclinaison à longue période de la surface de la Terre. Au même moment le 12 novembre 1987 l'allure vectorielle de l'inclinaison est brusquement anormale.

L'allure des inclinaisons pour les composantes NS et EW; mais également les indications du séismographe à torsion KC [1] sont données sur la figure 3. Sur l'allure anormale des inclinaisons pour les deux composantes de 14h 30min le 9 avril 1988 on suit les inclinaisons avec une période de 7 min et une amplitude de 0.002 s. d'arc. Le séismographe à torsion commence à ce moment à enregistrer les oscillations torsionnelles de la surface de la Terre qui, comme les inclinaisons, s'observent jusqu'à 2 h le 10 avril.

La station séismique Garm 3 est située sur l'aile nord de la fracture tectonique et de l'épicentre des tremblements de terre par rapport à la station de Garm 3 différent de 56° et la distance entre leurs épicentres est de 17 km. C'est pourquoi il est tout à fait probable que le mécanisme de l'apparition de la préparation de ces tremblements de terre peut être le même. Il convient de noter que les inclinaisons de ce caractère ne sont pas observées avant les tremblements de terre dont les épicentres sont situés sur la partie sud de la fracture mais sont éloignées de 40 km et plus de Garm. On n'observe pas d'inclinaisons tellement caractéristiques avant les tremblements de terre dont les épicentres sont situés sur la partie nord de la fracture. C'est pourquoi on peut supposer que ces inclinaisons sont inhérentes uniquement aux tremblements de terre proches (R = 10 à 25 km) entre les foyers de celles-ci et la station des observations se situe la fracture tectonique.

Dans la galerie de la station séismique de Talaya (à quelques kilomètres au sud de la fracture principale de Saïansk et à 6 km à l'ouest du lac Baïkal) les clinomètres en quartz ont été installés dans les azimuts NS et EW. Les mesures des inclinaisons se font à un régime continu depuis 1985. L'échelle de l'enregistrement est de 500 mm/s. d'arc à 2000mm/s. d'arc. Les clinomètres sont du même type que les appareils installés dans la station séismique de

Garm 3. A la station de Talaya on a obtenu de bons et nets enregistrements des inclinaisons de marées. Comme on l'a montré dans le travail [4] l'analyse de marée donne les valeurs du facteur de marée, voisines de la normale avec une erreur de 0 + 3% sur une série d'un mois. Le niveau des bruits augmente de façon plus importante pendant les mois d'été.

Exception rare il y a une anomalie dans les inclinaisons enregistrée le 6-7 avril 1987 (fig. 4) dans la période précédant un tremblement de terre proche (T = 22h 47min 47.70 en 1987; K = 103, R = 7 km A = 31°). Depuis 17h le 6 avril 1987 sont apparues en composante EW des inclinaisons d'amplitude de 0.017 s. d'arc avec une période d'environ 1.5h et une amplitude d'environ 0.001 s. d'arc. On a noté un accroissement des amplitudes de 0,7 10^{-3} s. d'arc à 1,6.10^{-3} s. d'arc et on a observé ensuite une anomalie en forme de raie des inclinaisons pour les deux composantes, les anomalies cessent à 18h avant le tremblement de terre. De 1985 à 1990 c'était le tremblement de terre le plus proche du site de mesure. La station séismique de Talaya est située sur le bord sud de la fracture de Saïansk Principal et l'épicentre du tremblement de terre se trouvait dans la région de la fracture. On a observé les mêmes anomalies pour les tremblements de terre plus éloignés dans la zone de la fracture. Pour le tremblement de terre du 7 avril de 1987 (le mécanisme du foyer d'après les données séismologiques est la faille et la surface du mouvement se trouve dans l'azimut de la fracture) il faut également noter une variation de l'allure de plusieurs mois d'inclinaison pour deux mois jusqu'au tremblement de terre et ensuite l'allure de l'inclinaison est à peu près dans l'azimut de fracture.

En conclusion il convient de noter que dans les régions séismiquement actives il se prépare simultanément beaucoup de tremblements de terre. Les processus de déformations pendant cette période en se superposant l'une sur l'autre créent dans chaque station prise séparément d'observation une image complexe des mouvements tectoniques. C'est pourquoi le calcul de préparation de chaque tremblement de terre est un problème extrêmement difficile. Pour la solution réelle des problèmes de prévision des tremblements de terre il faut une répartition des stations d'observations en surface.

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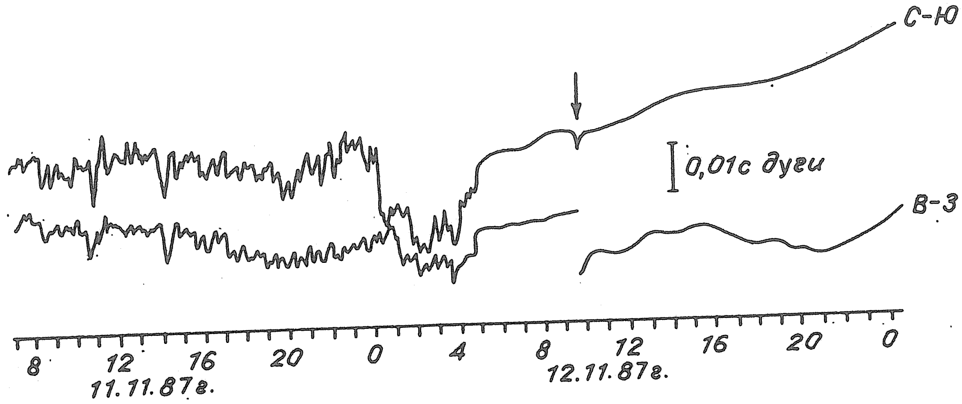

FIGURE 1

Fin des enregistrements en 1987 à GARM, montrant l'allure des inclinaisons dans les azimuts NS et EW du 11 novembre à 7h au 13 novembre à 0h. L'instant du tremblement de terre est marqué par une flèche.

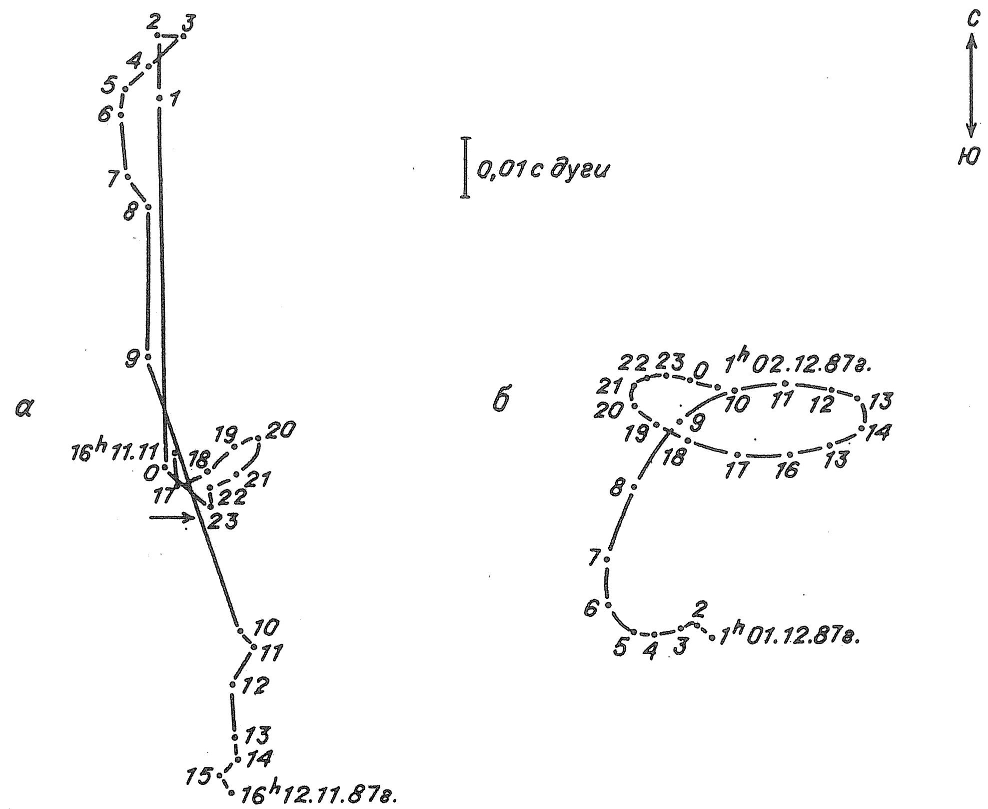

FIGURE 2

Diagrammes vectoriels des inclinaisons du socle à GARM en 1987 pour les époques (a) du 11 novembre à 16h au 12 novembre à 16h; (b) du 1 décembre à 0h au 2 décembre à 0h (les chiffres indiquent les heures).

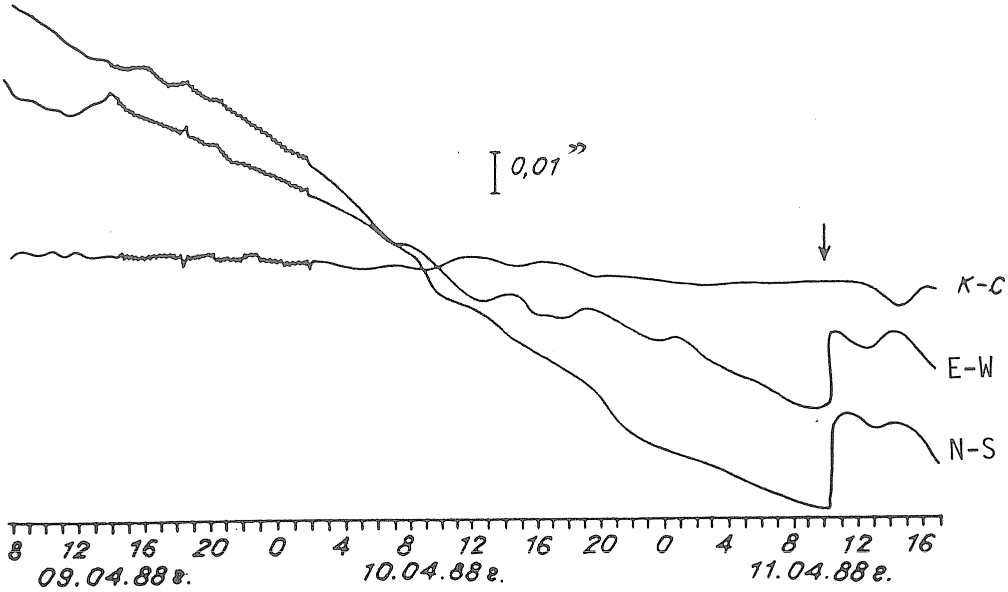

FIGURE 3

Copie de l'enregistrement (Garm) avec les courbes de l'allure des inclinaisons dans les azimuts NS, EW depuis 08h le 9 avril à 17h le 11 avril 1988. KC est le séismographe à torsion.

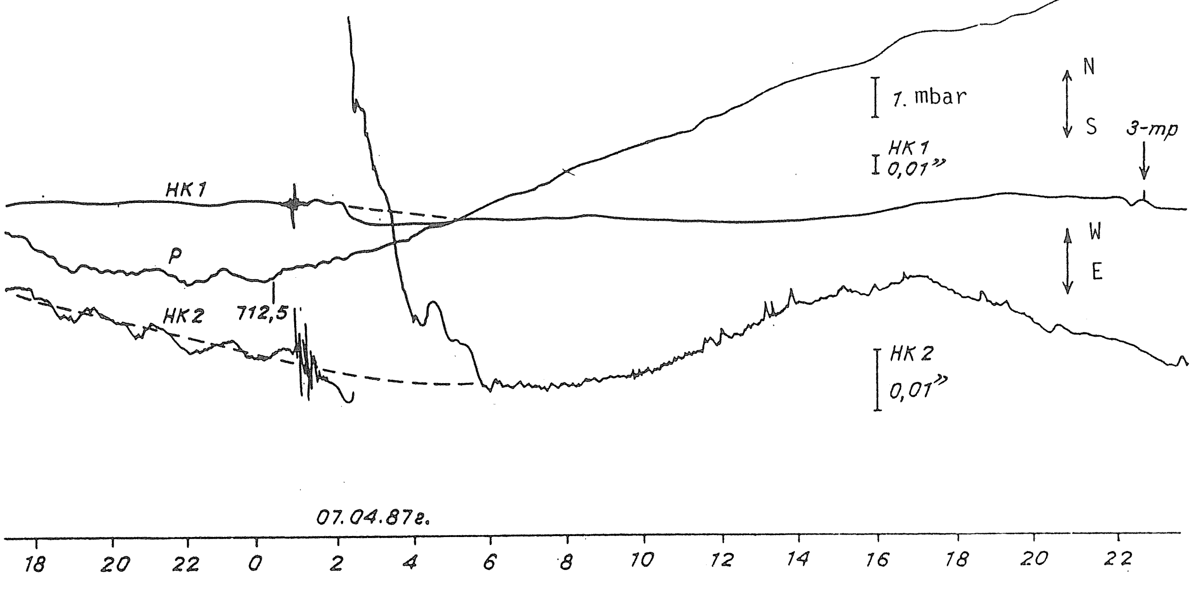

FIGURE 4

Copie de l'enregistrement à la station de Talaya: allure des inclinaisons dans les azimuts NS et EW depuis le 6 avril à 17h jusqu'au 7 avril à 24h, 1987. On a noté par une flèche (3-TP) le tremblement de terre du 7 avril 1987 à 22h 47min 47,7 sec; L = 5 km, K = 10, 3, les coordonnées de 51.74° et 103.71°E (coordonnées de la station: 51.68°N, 103.65°E). On a noté les ondes de surface du tremblement de terre sur la rive Est de l'île Honshu (Japon) le 7 avril 1987 à 00h 40min 47,31 de coordonnées de 37.83°N, 141.57°E, H = 42 km, M = 6,7. P est la variation de la pression atmosphérique (la valeur de la pression a été notée par une flèche).

Traduction
(abrégé)

Paramètres de marées d'après les résultats des observations déformographiques dans la zone de rift du Baïkal.

V. You Timofeev, You K. Saritcheva, S.F. Panin, L.V. Anissimova.

Méthode et résultats de l'étude des variations spatio-temporelles des champs géophysiques. Rosskiiskaia Akad. Nauk, Sibirskoe Otdellenie Novosibirsk 1992, page 202-207.

En 1989, des mesures continues des déformations ont commencé dans la galerie de la station séismique de Talaïa, dans la région du rift du Baïkal. Ces mesures qui se font à l'aide de déformographes à tiges (2) avec une haute précision (10^{-9} - 10^{-10}) ont pour but l'étude des variations de la déformation dans le temps importante pour la recherche des mouvements actuels et également la détection d'anomalies précédant les tremblements de terre. L'étude des déformations de marée en est une partie importante qui permet de déterminer la répartition régionale des paramètres de marées et également de déceler leurs variations temporelles.

La théorie des marées a été développée pour une Terre sphérique homogène [1]. Les déplacements sont exprimés par des perturbations du potentiel de marée W_2 en coordonnées polaires sous la forme suivante:

$$S_r = \frac{h}{g} W_2 \quad , \qquad S_\theta = \frac{1}{g}\frac{\partial W_2}{\partial \theta} \quad , \qquad S_\lambda = \frac{1}{g \sin\theta}\frac{\partial W_2}{\partial \lambda}$$

Les six composantes du tenseur des déformations sont:

$$\varepsilon_1 = e_{rr} = \frac{\partial S_r}{\partial r} = \frac{1}{ag}\left(a\frac{dH(a)}{dr} + 2h\right)W_2 ,$$

$$\varepsilon_2 = e_{\theta\theta} = \frac{1}{r}\frac{\partial S_\theta}{\partial \theta} + \frac{S_r}{r} = \frac{\ell}{gr}\frac{\partial^2 W_2}{\partial \theta^2} + \frac{h}{gr}W_2 ,$$

$$\varepsilon_3 = e_{\lambda\lambda} = \frac{1}{r\sin\theta}\frac{\partial S_\lambda}{\partial \lambda} + \frac{S_\theta}{r}ctg\theta + \frac{S_r}{r} =$$

$$= \frac{\ell}{gr\sin^2\theta}\frac{\partial^2 W_2}{\partial \lambda^2} + \frac{\ell}{gr}\frac{1}{\sin\theta}\cos\theta\frac{\partial W_2}{\partial \theta} + \frac{h}{gr}W_2 ,$$

$$\gamma_1 = e_{\theta\lambda} = \frac{1}{r}\left(\frac{\partial S_\lambda}{\partial \theta} - S_\lambda ctg\theta\right) + \frac{1}{r\sin\theta}\frac{\partial S_\theta}{\partial \lambda} =$$

$$= \frac{2\ell}{gr\sin\theta}\frac{\partial^2 W_2}{\partial \theta \partial \lambda} - \frac{2\ell}{gr\sin\theta}ctg\theta\frac{\partial W_2}{\partial \lambda} ,$$

$$\gamma_2 = e_{\lambda r} = \frac{1}{r\sin\theta}\frac{\partial S_r}{\partial \lambda} + \frac{\partial S_\lambda}{\partial r} - \frac{S_\lambda}{r} =$$

$$= \frac{h}{gr\sin\theta}\frac{\partial W_2}{\partial \lambda} + \frac{\ell}{gr\sin\theta}\frac{\partial W_2}{\partial \lambda} + \frac{\ell'}{g\sin\theta}\frac{\partial W_2}{\partial \lambda} ,$$

$$\gamma_3 = e_{r\theta} = \frac{\partial S_\theta}{\partial r} - \frac{S_\theta}{r} + \frac{1}{r}\frac{\partial S_r}{\partial \theta} =$$

$$= \frac{\ell}{gr}\frac{\partial W_2}{\partial \theta} + \frac{h}{gr}\frac{\partial W_2}{\partial \theta} + \frac{\ell'}{g}\frac{\partial W_2}{\partial \theta}$$

Pour les ondes semi-diurnes et diurnes, les déformations tangentielles dans les directions principales (méridien et premier vertical), ont pour coefficients:

Ondes	Composante NS	Composante EW
diurnes	$h - 4l$	$h - 2l$
semi-diurnes	$\frac{h \sin^2\theta + 2l(1-2\sin^2\theta)}{\sin^2\theta}$	$\frac{h \sin^2\theta - 2l(1+\sin^2\theta)}{\sin^2\theta}$

Les nombres de Love et Shida sont liés à la répartition de la densité et du module de rigidité dans la Terre par des équations différentielles. Conformément aux dernières représentations de modèles, ces nombres sont [1]:

Modèle de	h	ℓ
Gutenberg	0.6055	0.0829
Gutenberg-Dziewonski	0.6130	0.0853

Des valeurs globales de ces nombres sont obtenues aussi bien par moyennisation des données du réseau mondial que par l'observation laser des satellites artificiels. Pour le réseau mondial, à partir des différentes mesures (gravimétriques, clinométriques, astronomiques, déformographiques), une des solutions avait été obtenue en 1968 par P. Melchior [1]: $k_2 = 0.290$, $h_2 = 0.584$, $\ell_2 = 0.045$. Selon les mesures de satellites Lageos de septembre 1983 à mai 1985: $h_2 = 0.605 \pm 0.004$ et $\ell_2 = 0.087 \pm 0.002$; dans le système Standard MERIT (1983): $h_2 = 0.609$ et $\ell_2 = 0.0852$; d'après d'autres observations (1985) Lageos 1: $h_2 = 0.606 \pm 0.009$ et $\ell_2 = 0.088 \pm 0.006$ et également (1985) Lageos 2: $h_2 = 0.58 \pm 0.02$ [3].

Il existe beaucoup de constructions de déformographes à tige [1]. Nous avons utilisé une tige en quartz fondu d'une longueur d'environ 1,5m et un capteur d'induction des déplacements [1, 3]. Quelques mois avant le début des mesures (automne 1988) une extrémité de la tige était logée dans un petit socle de béton sur la roche, la seconde extrémité étant placée sur le capteur de déplacements. La sensibilité de celui-ci a été déterminée depuis le début des mesures (fig. 1) qui ont été faites dans une galerie de 90 mètres percée horizontalement dans la zone la plus éloignée de l'entrée à gauche de la galerie, à 20m de l'axe de la galerie principale (azimut d'environ 330°). La tige a été placée dans l'azimut nord, en travers de la galerie. Dans la galerie éloignée, le long de l'axe, on observe une zone de crevassements, bien que la galerie soit creusée en entier dans une roche d'âge archéen. L'enregistrement a commencé en février 1989 avec un enregistreur du type H 399, placé dans le bâtiment de la station séismique à 200m de l'entrée dans la galerie. Pendant cette période l'échelle d'enregistrement était $1{,}7.10^{-9}$/mm, la vitesse étant de 20mm/heure avec marque horaire automatique. L'allure de la déformation pendant les premiers mois de mesures est donnée sur la figure 2.

Les résultats des mesures sont soumis à l'analyse de marée à l'aide du programme standard de Venedikov.

Pour les coordonnées de la station $\phi = 51.68°$, $\lambda = 103.65°$, en composante NS, le facteur d'amplitude pour les ondes semi-diurnes M_2 et S_2 est égal à (h + 1.20) et pour les ondes diurnes O_1 et K_1 à $(h - 4\ell)$. Les résultats pour les quatre ondes de marée les plus importantes sont données dans la table.

La détermination la meilleure du facteur d'amplitude pour la période de mars-avril-mai 1989 a été obtenue pour l'onde M_2 - 0,6515 ± 0,0043 (± 0,66%)- car cette onde est moins soumise à l'influence météorologique. La détermination la meilleure pour cette période pour les ondes diurnes a été obtenue pour l'onde O_1 - 0,3076 ± 0,0168 (± 5,4%). En utilisant les rapports 0.652 = h + 1.20 et 0.308 = h - 4 , nous obtenons les valeurs des nombres de Love et Shida = 0.066 ± 0.003 et h = 0.573 ± 0.028.

La table permet de déterminer la valeur moyenne du facteur de marée pour trois périodes d'observations: d'après les ondes semi-diurnes M_2 et S_2 = 0.665, d'après les ondes diurnes: 0.248. Cela permet de déterminer la valeur des nombres de Love et Shida: = 0.080 ± 0.008 et h = 0.569 ± 0.062.

Enfin par les résultats de l'analyse pour la période 1 - 26.05.89 où les valeurs pour les ondes diurnes sont les plus proches, nous obtenons: pour les ondes semi-diurnes 0.7025 et pour les ondes diurnes - 0.2465. D'après ces valeurs les nombres de Love et Shida sont:

$$\ell = 0.088 \pm 0.009, \quad h = 0.597 \pm 0.065.$$

Ces estimations sont voisines des valeurs des modèles et des valeurs obtenues d'après les résultats de la poursuite laser sur satellites [3].

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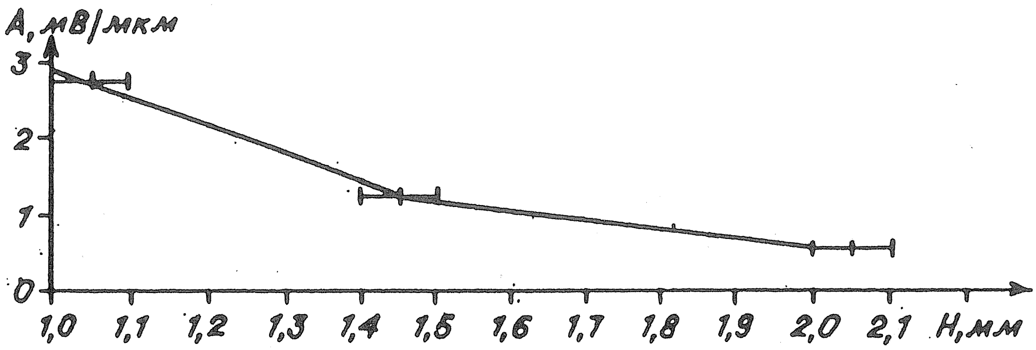

FIGURE 1 Dépendance de la sensibilité (A) du capteur inductif de déplacements du déformographe depuis la largeur de la fente (H) entre les bobines de l'émetteur. Les déterminations ont été faites à l'aide du micromètre et du micro amperemètre H399 à la station de marée "Klioutchi" (Novosibirsk).

TABLE

Résultats des mesures déformographiques (NS) à la station de Talaïa d'après diverses séries (1989).

Onde	Période 04 - 29.03	30.03 - 30.04	01 - 26.05
M2	0,653 ± 0,032	0,643 ± 0,016	0,657 ± 0,023
	13,8 ± 2,7	10,0 ± 1,4	6,0 ± 1,9
S2	0,640 ± 0,044	0,648 ± 0,027	0,748 ± 0,056
	14,3 ± 4,2	10,5 ± 2,5	10,3 ± 4,4
O1	0,333 ± 0,044	0,313 ± 0,036	0,276 ± 0,034
	4,6 ± 7,7	3,0 ± 6,4	10,6 ± 7,1
K1	0,157 ± 0,042	0,193 ± 0,030	0,217 ± 0,024
	47,4 ± 15,2	21,1 ± 8,9	27,6 ± 5,7

Remarque: le facteur d'amplitude (A) est au-dessus de la ligne - la phase ($\Delta\phi$), en degrés, est sous la ligne

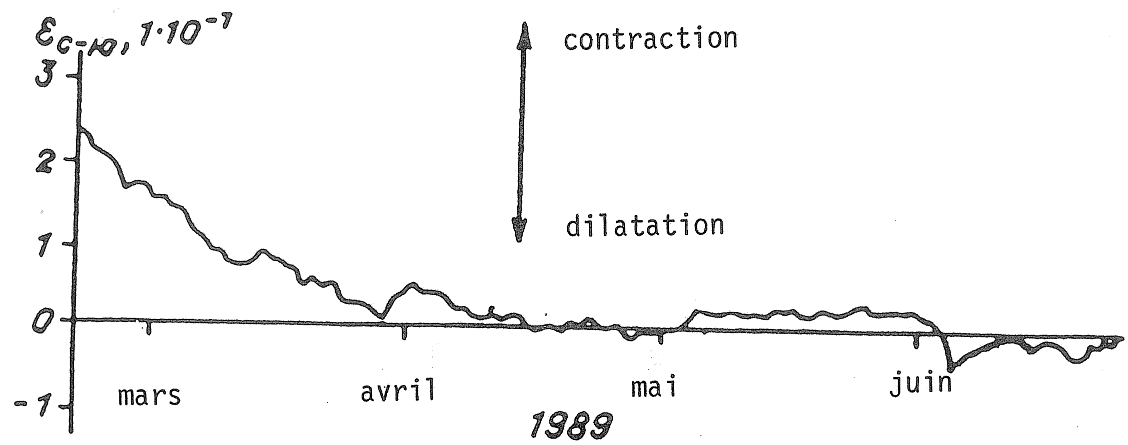

FIGURE 2 Variation dans le temps de la déformation ϵ enregistrée dans l'azimut Nord-Sud dans la galerie de Talaïa de février à juin 1989, d'après les calculs journaliers à 00h de chaque jour.

Traduction

INCLINAISONS DE MAREES A TALAIA
(zone de rift du Baïkal)

You K. Saritcheva, V. You Timofeiev

Méthode et Résultats de l'Etude des variations spatio-temporelles des Champs Géophysiques

Section Sibérienne de l'Académie des Sciences de Russie.
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Abrégé

Conformément à la théorie l'amplitude des inclinaisons de marées reflète les hétérogénéités de l'écorce terrestre et sa constitution élastique [8]. Les observations dont la précision doit garantir 0.0010 à 0.0001 s. d'arc, se font en régime continu et par série (un à deux mois).
Des recherches [6] témoignent de ce que celles qui sont effectuées dans une zone séismo-active peuvent contenir des signes reflétant le processus d'activité séismique de la région: temps "d'accalmie" sur le diagramme vectoriel, "inversion" de l'allure de l'inclinaison, faible gradient et autres. Les données sur l'allure de la variation temporelle des propriétés élastiques présentent également un grand intérêt.

Nos observations ont été réalisées dans la zone du rift Baïkal - la zone la plus hautement séismique sur le territoire de la Sibérie, où il se produit jusqu'à 3.000 faibles tremblements de terre par an tandis que l'intensité des forts séismes peut atteindre 10 degrés. La région de la station séismique de Talaïa se trouve dans les limites Baïkal - Toumkins à l'articulation de quatre fractures profondes importantes - Tcherskov, Toumkimskii, Saïanskii principal et Primorskii (fig. I).

La station d'observations clinométriques azimutales est située dans les limites de la zone de rift du Baïkal et près de l'importante fracture Saïamskii principal, afin de déterminer les valeurs moyennes des paramètres élastiques et les caractéristiques de leurs variations temporelles dans la région d'anisotropie probable du milieu [5]. Parallèlement à l'obtention des paramètres de marées, la station clinométrique fonctionnant en régime continu donne une information sur les inclinaisons anormales accompagnant l'activité séismique de la région et également sur les inclinaisons systématiques dans les deux azimuts ce qui, dans les conditions de la zone de fracture, permet d'enregistrer "les oscillations" du bloc (sur lequel est placée la station) ou les inclinaisons systématiques dans les limites de la zone en entier.

A Talaïa, les clinomètres ont été placés dans une galerie orientée NW-SE traversant horizontalement le massif de granit gneiss à la profondeur d'environ 90m avec des voies latérales d'une longueur atteignant 20 à 25m. D'après les données géologiques le massif n'est pas perturbé par des fractures.

Les clinomètres (construction de D.G. Gridniev) ont une sensibilité d'environ 600 mm/s d'arc pour HK1 et 1800 mm/s d'arc pour HK2. Cela a permis de déterminer l'amplitude de la marée avec une erreur de l'ordre de 2% et la phase avec une erreur d'environ 7% pour l'onde principale M_2. Les orientations NS et EW ont été déterminées à l'aide d'une référence et d'une boussole dont la précision atteignait ± 1°. La déclinaison magnétique n'a pas été prise en considération car elle entre dans le retard de phase mesurée comme une constante et nous étudions la variation du retard dans le temps. Pour cette même raison on n'a pas déterminé le retard constant de l'appareil. On sait cependant que pour ce système qui a été utilisé précédemment à Irkoutsk le retard ne dépasse pas 1°.

On a soumis à l'analyse harmonique (méthode Venedikov) les séries d'observations d'avril 1985 à juillet 1990 [2]. Les tables 1 et 2 donnent, pour les composantes NS et EW, les valeurs du facteur d'amplitude et du déphasage (où intervient la petite valeur constante correspondant à l'azimut de l'appareil) pour les ondes principales: O_1, K_1, M_2 et S_2. Elles sont représentées graphiquement (fig. 2) où on a comparé l'allure temporelle du facteur γ de l'onde M_2 en composante NS et EW. Chaque point est le résultat de l'analyse harmonique d'une série de 1 à 2 mois. La figure 2 montre que les limites de variation du facteur d'amplitude pour les deux composantes azimutales sont différentes: en NS de 0,6 à 1,0, en EW de 0,6 à 0,8 (à l'exclusion du début de 1990).

Théoriquement γ_{NS} et γ_{EW} doivent être égaux en milieu isotrope. Dans nos conditions où la station est située dans une zone de fracture on peut s'attendre à une augmentation de l'amplitude près des fractures et à une inégalité des amplitudes pour les différents azimuts. Lors de l'étude de l'allure systématique de l'inclinaison dans la région des observations on a découvert en effet des "balancements" du bloc sur lequel est située la station, orientés dans la période de 1986 à 1989 du SW au NE et en 1990 du N-NW au S-SE. L'analyse permet de conclure que les valeurs de γ moyennées pour toute la période des observations, et d'après toutes les ondes, sont plus petites en composante EW qu'en composante NS (tables 3, 4) ce qui témoigne de l'anisotropie du milieu dans la région des observations.

Il faut noter qu'à cause de la dépendance théorique en fonction de la latitude [3], les amplitudes de l'inclinaison dans la direction NS sont faibles pour les ondes diurnes et nulles à la latitude 45°. C'est pourquoi γ_{O1} et γ_{K1} pour NS sont moins sûrs par rapport à EW (dans nos latitudes) ce qui se reflète aussi sur la valeur de l'erreur quadratique moyenne (voir table 4). D'autre part, les amplitudes des ondes diurnes des composantes NS ont un grand intérêt pour préciser le modèle de la structure interne de la Terre par l'application au modèle de la théorie de la nutation.

Lors de la rotation diurne de la Terre l'effet des forces de marées appliquées au bourrelet équatorial donne le moment total des différentes composantes de la force de marée. Ainsi il n'y a que les moments découlant des termes diurnes tesseraux par la composante méridienne de force de marée qui ne soient pas égaux à zéro. A cause de l'aplatissement de la Terre ce moment tend à déplacer le plan équatorial dans la direction de l'écliptique en provoquant un mouvement de précession-nutation de l'axe de figure de la Terre. Ce moment agit aussi sur le noyau liquide de la Terre en provoquant son déplacement par rapport au manteau. La théorie montre que lors de la rotation diurne de la Terre il apparaît une résonance de la composante diurne de la marée avec la nutation diurne, provoquée par la dynamique du noyau liquide de la Terre. L'effet du noyau liquide de la Terre se fait sentir sur les amplitudes des marées terrestres diurnes.

Le calcul théorique de la différence $\Delta\gamma$ des paramètres des ondes K_1 et O_1 ($\Delta\delta$ dans le cas des observations de marées gravimétriques) donne $\Delta\gamma = \gamma_{O1} - \gamma_{K1} = - 0{,}041$ pour le modèle de la Terre avec noyau liquide élaboré par M.S. Molodenski [3]. La détermination expérimentale de ce paramètre est favorisée par le fait que les ondes O_1 et K_1 sont peu perturbées par l'effet indirect (marées océaniques) d'autant plus si le point (comme dans notre cas) est très éloigné des océans. En outre, la moyennisation des résultats sur de grands intervalles d'observations facilite un peu le problème de l'obtention de données expérimentales sûres. Dans notre cas une série de six ans d'observations concorde assez bien avec la théorie (table 5). Ainsi à Talaïa on a obtenu pour la composante EW $\Delta\gamma = - 0{,}05$ ce qui est une assez bonne approximation de la théorie, pour la composante NS $\Delta\gamma = 0{,}07$. Quant à ce paramètre obtenu d'après les données de neuf stations européennes [4] (en soit plus de 14.000 jours d'observations) sa valeur est - 0,06.

Pour expliquer le caractère des variations temporelles des paramètres de marées on a utilisé les données de séries de 1 à 2 mois successifs sans recouvrement (tables 1, 2). Sur le graphique γ_{M2} (NS) on note deux minima (fig. 2) ce qui permet de supposer l'existence de variations d'une période de l'ordre de deux ans. Pour la composante EW on ne note pas de variations nettes. Comme dans le cas de l'onde M_2, les limites des variations γ pour les ondes O_1 et S_2 sont plus grandes en composante NS qu'en EW. En moyenne pour toute la période des observations on a obtenu $\gamma(M_2) = 0{,}777$ (NS) et $\gamma(M_2) = 0{,}702$ (EW) (table 5).

Pour la représentation des variations du facteur γ on propose la forme de M. Kharnicha [9] - construction graphique utilisant les données pour γ, le retard de phase $\Delta\phi°$ et le temps (fig. 3). Les diagrammes présentent les champs de points des coordonnées γ et $\Delta\phi°$, reportées et reliées conformément à leur succession temporelle. D'après la méthode de M. Kharnicha avec une série de plusieurs années d'observations (comme pour T. Chojnicki [9]) chaque paire de points γ - $\Delta\phi$ peut être le résultat de la moyenne des données sur les intervalles de calendriers ordinaires: moyenne pour tous les janviers, pour tous les févriers, etc ...

Dans notre cas, on a reporté les résultats de l'analyse harmonique des séries dans l'ordre chronologique mais sur un intervalle ne dépassant pas un an. Ainsi, pour chaque intervalle annuel on a établi un plan séparé, ce qui permet de contrôler la carte des variations de manière dynamique. Comme pour T. Chojnicki [9] les diagrammes montrent en moyenne la cyclicité annuelle de la variation de la relation entre γ et $\Delta\phi$ (fig. 3). L'amplitude des variations ou plus précisément "le degré de compacité" du diagramme est plus grande pour la composante NS que pour l'EW. Le cycle annuel correspond à notre avis en ce qu'au cours d'un an, pour un site donné d'observation, l'orientation réciproque du Soleil et de la Lune varie sur la sphère céleste. Par conséquent la relation entre les composantes solaire et lunaire de la marée varie et ainsi la hauteur et l'orientation du bourrelet de marée (son maximum) par rapport au site d'observation. Par conséquent le retard de phase observé par rapport à la phase de la force génératrice est lié à l'apparition de la crête de marée. La période annuelle de rotation de la Terre autour du Soleil a dû ainsi provoquer une période analogue de la variation de γ et $\Delta\phi$. La forme anormale du diagramme dans notre présentation doit refléter le degré d'hétérogénéité des régions sur lesquelles se projete la crête de marée.

Pour comparer les données obtenues à Talaïa avec les modèles et avec les observations dans les autres stations on a reproduit la table 6 empruntée chez P. Melchior et complétée par nous.
Nous noterons seulement que nous n'avons pas de données pour le Baïkal outre des mesures lointaines dans des îles. Ainsi, les données de Talaïa représentées dans cet article ne concordent pas mal avec les résultats obtenus dans les autres stations nationales.

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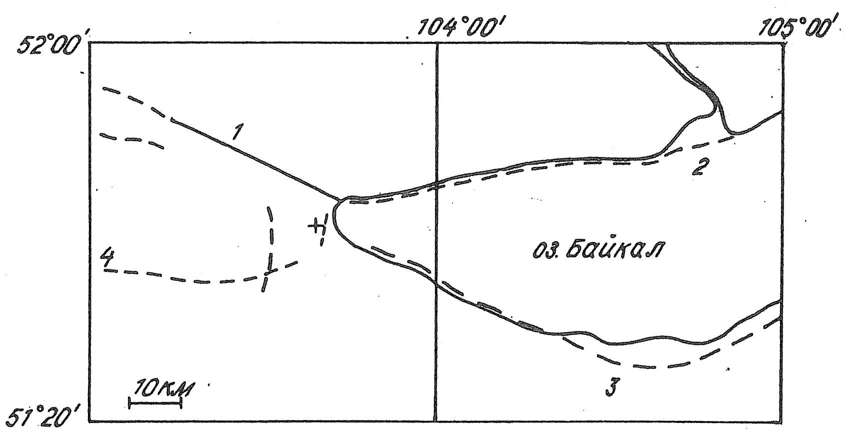

Figure I Schéma des fractures dans la région de Talaïa (la position de la station est notée par une petite croix):
1 - Saïanskii principal; 2 - Littoral; 3 - Tchorskii;
4 - Tounkinskii.
Ligne continue : fractures certaines - traits interrompus: fractures présumées.

Table 1 - Résultats de l'analyse harmonique des inclinaisons à Talaïa latitude 51°68', longitude 103°65', clinomètre HK-I N-S.

Intervalles d'observations	Facteur d'amplitude γ et retard de phase Δφ°				Echelle d'enregistrement ms/mm	
	M_2	S_2	O_I	K_I		
I	2	3	4	5	6	
2.04.-I.05.85	0,847±0,030	0,887±0,046	0,966±0,33I	3,326±0,258		I,7450-2,I600
	I4,49 ±2,0I	I,28 ±2,0I	8,33 ±I9,7I	-6,I0 ±4,58		
2.05-3I.05.85	0,888±0,05I	0,960±0,I00	0,869±0,688	3,573±0,427		2,I790-2,8650
	I5,70 ±3,28	-8,72 ±6,36	8,5I ±44,73	-27,I9 ±5,96		
I-27.06.85	0,725±0,072	0,792±0,2I0	0,575±0,805	I,279±0,489		2,8555-3,9447
	I7,87 ±5,95	-24,99 ±I5,7I	-58,70 ±80,90	-22,60 ±I8,30		
I.06.-I0.07.85	0,74I±0,066	0,772±0,I69	0,44I±0,728	I,454±0,477	I-27.06	2,8555-3,9447
	I3,24 ±5,43	0,49 ±I3,25	55,72 ±95,74	-II,45 ±I4,77	29.06-4.07	4,3725
					5-I0.07	I,7295
I-30.I0.85	0,657±0,046	0,898±0,066	I,425±0,398	I,088±0,384		4,7I7-6,0976
	I6,23 ±4,02	-I3,23 ±4,39	-I4,05 ±I5,80	67,72 ±I9,5I		
3I.I0-23.II.85	0,68I±0,069	0,642±0,II6	I,5I0±0,574	0,420±0,383	3I.I0-5.II	6,0976-6,329I
	26,02 ±5,55	7,I5 ±I0,60	35,42 ±2I,59	84,68 ±60,05	6-23.II	2,3669-2,4I54
25.II-3I.I2.85	0,632±0,025	0,493±0,062	0,843±0,330	0,64I±0,I94	25-30.II	2,42I3-2,4360
	I5,34 ±2,30	0,II ±7,7I	4,I5 ±2I,74	I7,80 ±I4,I0	3-3I.I2	2,45I0-2,63I6
I-30.0I.86	0,686±0,029	0,706±0,064	I,346±0,362	0,877±0,2II		2,63I6-3,I066
	I0,43 ±2,44	8,83 ±5,78	2I,52 ±I5,38	27,78 ±II,93		
3I.0I-86-I.03.86	0,776±0,037	0,968±0,058	0,650±0,380	I,I44±0,232		3,I250-3,7879
	I2,23 ±2,79	I,04 ±3,77	55,30 ±33,47	47,08 ±II,70		
3.03-I.04.86	0,794±0,040	I,I89±0,056	0,546±0,342	3,67I±0,335		3,8760-4,5249
	I5,89 ±2,85	-2,38 ±3,00	-4,97 ±36,65	62,04 ±4,56		
3-29.04.86	0,846±0,054	I,26I±0,087	I,579±0,553	2,300±0,506		4,5662-5,I8I3
	I5,95 ±3,49	20,44 ±4,II	-I,42 ±20,47	46,59 ±I2,55		
2-30.05.86	0,902±0,04I	I,I2I±0,085	I,094±0,338	2,I34±0,243	2-I9.05	5,4644-5,6905
	II,0I ±2,68	24,36 ±4,44	0,0I ±I8,I2	I2,66 ±5,50	22-30.05	2,8900-2,94I2
I-30.06.86	0,847±0,024	0,9I8±0,076	I,590±0,273	I,59I±0,I68		2,94I2-2,9940
	I3,49 ±I,65	22,43 ±5,0I	I,87 ±9,78	7,38 ±4,8I		
2-3I.07.86	0,892±0,026	0,948±0,065	I,458±0,I56	I,244±0,I00		2,9940-3,0864
	I3,I7 ±I,65	29,67 ±4,I4	-4,49 ±5,90	-II,36 ±3,86		
I-30.08.86	0,924±0,038	0,99I±0,067	I,077±0,298	I,550±0,236	I-30.08	3,I250
	I5,29 ±2,28	I7,66 ±4,24	3I,3I ±I6,03	-I7,44 ±8,42		
I-30.09.86	0,886±0,029	0,936±0,046	I,9I5±0,274	0,7I0±0,223		3,I750
	I7,35 ±I,94	I8,95 ±3,0I	I2,I4 ±7,78	-6,49 ±22,42		
I-30.I0.86	0,674±0,048	0,764±0,078	I,458±0,2I8	0,764±0,I9I		3,2260
	I6,34 ±4,I6	23,5I ±6,07	43,05 ±8,59	6,86 ±I4,76		
3I.I0-I.I2.86	0,955±0,044	I,008±0,086	0,984±0,473	0,434±0,297	3I.I0-I7.II	3,2770
	I5,75 ±2,59	I2,I4 ±5,02	57,87 ±27,62	-25,86 ±34,I0	20.II-I.I2	3,2787
2-3I.I2.86	0,669±0,027	0,522±0,077	I,03I±0,256	0,970±0,I5I		I,0958
	I2,95 ±2,33	48,76 ±8,35	-0,29 ±I4,39	I6,56 ±7,30		
8.0I-5.02.87	0,956±0,2I0	0,574±0,I70	I,834±I,852	0,536±I,I26	8-I8.0I	I,0958
	26,30 ±I3,39	-37,06 ±I7,40	I2,I8 ±49,92	-49,29 ±I20,88	29.0I-I.02	I,0958
					I-5.02	I,0958
5-27.02.87	0,9I2±0,038	0,782±0,054	I,I24±0,438	I,787±0,377		2,232I
	I6,I7 ±2,44	I7,98 ±3,89	-42,35 ±22,33	24,98 ±I2,03		
I-30.03.87	0,8I3±0,0I8	0,829±0,026	I,0I0±0,207	I,272±0,I70		2,232I
	I5,89 ±I,29	I9,67 ±I,9I	2,7I ±II,68	4,8I ±9,59		
I-24.04.87	0,842±0,033	0,838±0,052	I,362±0,I99	0,927±0,I58		2.232I
	I5,68 ±2,22	I9,73 ±3,60	I0,24 ±8,43	4,79 ±9,92		
29.04-3I.05.87	0,834±0,023	0,939±0,046	0,782±0,I89	0,680±0,I3I		2,232I
	II,34 ±I,60	23,54 ±2,94	2,I9 ±I3,55	20,34 ±9,66		

Table 1 - Suite

I	2	3	4	5		6
I-27.06.87	0,860±0,030	0,938±0,093	I,752±0,479	I,I96±0,275	I-I5.06	2,232I
	I6,69 ±I,92	34,24 ±5,77	I9,92 ±I6,07	I3,07 ±I3,I2	22-27.06	2,232I
I.06-9.08.87	0,774±0,05I	0,620±0,I2I	I,328±0,468	I,050±0,29I	I-I5.06	2,232I
	I5,88 ±3,89	25,26 ±II,60	8,44 ±I8,45	II,II ±I3,43	22-27.06	2,232I
					2-6.07	2,232I
					8-I9.07	I,7724
					I-9.08	I,7724
2.07-9.08.87	0,630±0,237	0,432±0,27I	3,I75±2,08I	I,9I6±I,657	2-6.07	2,232I
	24,37 ±23,59	35,I8 ±36,8I	-58,50 ±37,02	8I,74 ±45,27	8-I9.07	I,7724
					I-9.08	I,7724
I6.I0-30.II.87	0,687±0,0I2	0,675±0,023	0,930±0,I28	I,054±0,092	I6-30.I0	I,7724
	I5,25 ±I,00	23,57 ±I,98	I2,86 ±7,63	9,39 ±4,I6	I-30.II	I,7724
2-30.I2.87	0,730±0,0I6	0,773±0,04I	I,I76±0,267	0,987±0,I53	2-I6.I2	I,7724
	I5,I3 ±I,26	30,40 ±3,08	I5,63 ±I4,03	I4,33 ±8,27	22-30.I2	I,7724
I-30.0I.88	0,595±0,022	0,7I7±0,045	I,2I2±0,I54	0,88I±0,092		I,7724
	I2,72 ±2,06	26,I4 ±3,83	II,07 ±6,96	6,7I ±4,88		
I.02-I0.03.88	0,586±0,028	0,576±0,043	0,974±0,I25	0,872±0,09I		3,2596
	I6,96 ±3,69	22,64 ±6,20	I7,56 ±9,89	5,05 ±8,34		
I8.03-30.04.88	0,593±0,072	0,535±0,I0I	0,847±0,284	0,6I8±0,249		I,7895
	II,79 ±6,98	45,0I ±I0,79	30,24 ±I9,I6	-6,64 ±23,2I		
I.05-28.06.88	0,67I±0,025	0,709±0,060	I,326±0,205	I,020±0,I34		I,7895
	I7,05 ±2,09	I5,63 ±4,I9	II,33 ±8,84	I0,56 ±7,23		
4.07-28.09.88	0,828±0,I49	0,370±0,I5I	I,077±0,487	I,I2I±0,40I	4-9.07	I,2297
	9,8I ±6,96	-2,80 ±I6,23	I8,29 ±I8,57	7,80 ±I8,57	23.07-3.08	-"-
					30.08-I3.09	-"-
					20.09-28.09	-"-
23.I0.88-I.02.89	0,9I3±0,I03	0,905±0,I53	I,I43±0,546	I,I83±0,400	23-28.I0.88	0,5869
	I6,23 ±3,27	I8,55 ±4,86	5,45 ±II,79	2,87 ±8,55	8-25.II.	-"-
					I-I5.0I.89	-"-
					27.0I-I.02	-"-
2.02-27.03.89	0,838±0,0I9	0,848±0,028	I,307±0,II3	I,I62±0,086		0,74I4
	I4,63 ±I,65	I6,54 ±2,63	I3,57 ±6,38	9,2I ±5,86		
8.04-5.08.89	0,78I±0,0I4	0,775±0,030	I,264±0,I02	0,994±0,069	8-30.04	0,7323
	I4,98 ±I,02	I8,2I ±2,35	I9,36 ±4,6I	I3,84 ±3,39	I-I8.05	-"-
					27.05-4.07	-"-
					I0.07-5.08	-"-
I0-27.08.89	0,872±0,04I	0,927±0,047	0,927±0,344	I,477±0,3II		0,74I4
	22,4I ±2,82	2I,47 ±2,98	I,I3 ±I7,94	I2,89 ±I2,39		
I.II-22.I2.89	0,795±0,0I2	0,854±0,026	I,366±0,II2	0,928±0,075	I-29.II	I,4623
	I8,43 ±0,84	II,84 ±I,84	II,59 ±4,79	2I,69 ±3,76	2-22.I2	I,0034
8.I0.89-30.0I.90	0,783±0,022	0,905±0,042	I,I46±0,I4I	0,938±0,093	8-3I.I0.89	I,4623
	I9,22 ±I,66	I4,24 ±2,88	2,9I ±6,78	I0,89 ±4,92	I-30.0I.90	I,0034
I-27.02.90	0,728±0,034	0,828±0,044	0,666±0,3I3	0,628±0,I95		I,0034
	I6,85 ±2,58	I0,97 ±3,24	26,77 ±25,27	34,74 ±I7,76		
I7.04-30.05.90	0,622±0,027	0,660±0,059	0,898±0,I85	0,95I±0,I32	I7-30.04	0,6697
	20,0I ±2,55	-I,70 ±5,48	I7,3I ±I2,I8	I3,86 ±6,67		
I.06-28.08.90	0,755±0,0I7	0,89I±0,040	I,I62±0,I36	I,043±0,085	I-29.06	0,6697
	I6,25 ±I,30	I0,93 ±2,8I	I4,70 ±6,67	7,67 ±3,74	2-I6.08	-"-
					20-28.08	-"-
Moyenne γ	0,777±0,0I6	0,806±0,029	I,I89±0,070	I,265±0,II5		
$\Delta\varphi°$	+I6,02 ±0,56	+I4,I3 ±2,53	+I0,I4 ±3,63	+I2,9I ±4,I2		

Table 2 - Résultats de l'analyse harmonique des inclinaisons à Talaïa, latitude 51°6833, longitude 103°65', clinomètre HK-2 E-W.

Intervalles d'observations	Facteur d'amplitude γ et retard de phase $\Delta\phi°, \varphi°$				Echelle d'enregistrement ms/mm	
	M_2	S_2	O_I	K_I		
I	2	3	4	5	6	
7.04-I.05.85	0,809±0,0I3	0,75I±0,020	0,732±0,068	0,937±0,06I		0,9370-I,II00
	4,76 ±0,9I	II,38 ±I,48	-4,73 ±5,76	I5,85 ±3,50		
2-3I.05.85	0,757±0,02I	0,525±0,04I	0,773±0,070	0,656±0,040		I,II70-I,3450
	4,08 ±I,58	I7,85 ±4,28	-I,93 ±5,27	-I,35 ±4,30		
I-27.06.85	0,608±0,032	0,36I±0,093	0,535±0,059	0,575±0,028		I,3550-I,6784
	5,75 ±2,84	43,70 ±I4,72	I,98 ±6,32	5,38 ±3,63		
I.06-I0.07.85	0,598±0,029	0,40I+0,084	0,465+0,073	0,578+0,035	I-27.06	I,3550-I,6784
	7,I6 ±2,67	26,59 ±II,40	I,60 ±8,95	7,34 ±4,49	29.06-4.07	I,7725
					5-I0.07	0,7840
7-30.I0.85	0,692+0,020	0,650+0,029	0,544+0,063	0,7II+0,054		I,I428-I,I9I0
	0,I8 ±I,59	2,06 ±2,59	-4,3I ±6,29	2,49 ±4,40		
I0.I0-I.II.85	0,747±0,0I3	0,695±0,02I	0,652±0,054	0,689±0,042		I,I530-I,2025
	0,90 ±I,05	-3,68 ±I,73	-6,35 ±4,85	I,98 ±3,50		
3I.I0-23.II.85	0,724±0,052	0,582±0,097	0,385±0,2I9	0,735±0,I32		I,I929-I,234I
	5,80 ±3,96	9,45 ±9,77	I7,I7 ±32,00	-9,63 ±II,82		
25.II-3I.I2.85	0,7I6±0,040	0,676±0,087	0,679±0,II6	0,667±0,056	25-30.II	I,2378-I,2472
	5,83 ±3,I9	-4,25 ±7,I2	-I5,5I ±I0,05	I3,24 ±6,00	3-3I.I2	I,2563-I,35I4
I-30.0I.86	0,752±0,024	0,652±0,06I	0,476±0,092	0,65I±0,046		I,35I3-I,5699
	3,66 ±I,7I	-I,20 ±4,88	-3,50 ±II,I2	4,I8 ±5,00		
3I.0I-I.03.86	0,638±0,048	0,7I6±0,087	I,009±0,I65	0,593±0,I24		I,5699-I,8248
	3,89 ±4,26	-I6,60 ±6,42	-8,46 ±9,50	7,98 ±I2,58		
3.03-I.04.86	0,766±0,024	0,705±0,038	0,632±0,I04	0,666±0,I09		I,8282-I,8975
	2,59 ±I,8I	-I,24 ±2,83	I,89 ±9,I4	2,77 ±7,50		
3-29.04.86	0,677±0,038	0,720±0,064	0,472±0,060	0,839±0,05I		I,90II-I,9802
	7,88 ±3,34	-2,I9 ±4,72	I0,65 ±7,24	-4,I4 ±3,32		
2-30.05.86	0,722±0,024	0,546±0,052	0,7I7±0,082	0,699±0,040	2-I9.05	I,9800-2,0300
	2,48 ±I,82	-2,62 ±5,20	5,I8 ±6,24	I,94 ±3,95	22-30.05	I,6I00
I-30.06.86	0,670±0,030	0,6I6±0,080	0,472±0,069	0,643±0,037	I-I2.06	I,6I8I-I,6260
	-0,34 ±2,53	3,99 ±7,05	-2,47 ±8,25	0,04 ±4,II	I4-I9.06	I,6260-I,63I3
2-3I.07.86	0,700±0,0I6	0,734±0,048	0,752±0,059	0,738±0,032		I,6367-I,6556
	3,8I ±I,35	3,05 ±3,34	I4,27 ±4,48	I,77 ±3,02		
I-30.08.86	0,657±0,034	0,6I0±0,064	0,740±0,I07	0,679±0,077		I,6556-I,6779
	I,34 ±2,9I	II,75 ±5,4I	4,87 ±8,32	I,34 ±6,84		
I-29.09.86	0,664±0,030	0,678±0,044	0,7I2±0,II7	0,532±0,I25	I-I2.09	I,6807-I,6949
	3,30 ±2,60	5,43 ±3,43	5,I8 ±9,60	3,38 ±I0,8I	I5-29.09	I,6878-I,6949
I-30.I0.86	0,702±0,029	0,68I±0,046	0,774±0,099	0,640±0,085		I,6949-I,7065
	3,82 ±2,39	-0,3I ±3,64	-I2,I0 ±7,4I	0,II ±7,43		
3I.I0-I.I2.86	0,727±0,0I8	0,642±0,034	0,528+0,075	0,704±0,043	3I.I0-I7.II	I,7065-I,7I23
	5,56 ±I,49	-0,68 ±2,95	-2,82 ±8,3I	3,33 ±4,38	20.II-I.I2	I,7I36-I,7I69
2-3I.I2.86	0,586±0,032	0,527±0,083	0,455±0,097	0,58I±0,045		0,5850
	5,66 ±3,I3	25,75 ±8,57	-8,20 ±I2,I8	2,7I ±5,77		
8-27.02.87	0,646±0,028	0,663±0,034	0,637±0,I57	0,757±0,I27		0,6354
	8,I2 ±2,76	I,5I ±2,84	-I3,09 ±I2,27	8,96 ±9,78		
I-30.03.87	0,708±0,0I6	0,696±0,023	0,592±0,060	0,7I2±0,063		0,6354
	5,I0 ±I,23	5,93 ±I,78	4,56 ±5,95	0,I2 ±4,I4		
I-24.04.87	0,745±0,0I8	0,609±0,030	0,68I±0,I22	0,68I±0,I05		0,6354
	4,I0 ±I,44	6,80 ±2,72	9,53 ±I0,52	-I,67 ±8,52		

Table 2 - Suite

I	2	3	4	5		6
29.04-3I.05.87	0,709±0,020	0,6I3±0,042	0,682±0,045	0,769±0,026		0,6354
	3,55 ±I,66	2,75 ±3,69	4,79 ±3,86	0,28 ±2,39		
I.06-I8.07.87	0,698±0,022	0,665±0,079	0,576±0,069	0,565±0,036		0,6354
	3,I4 ±I,79	-I4,65 ±6,70	2,I0 ±6,7I	-I,64 ±4,32		
7.08-23.09.87	0,534±0,034	0,47I±0,060	0,377±0,055	0,528±0,044		0,5262
	5,57 ±3,02	-4,05 ±5,5I	-4,56 ±6,74	6,56 ±3,76		
I6.I0-30.II.87	0,636±0,009	0,59I±0,0I6	0,534±0,037	0,63I±0,022		0,5262
	5,62 ±0,76	6,54 ±I,50	2,89 ±4,I3	5,85 ±2,40		
I-30.I2.87	0,640±0,0I0	0,556±0,029	0,543±0,037	0,6I2±0,0I8		0,5262
	3,I6 ±0,92	6,96 ±2,75	6,30 ±3,93	2,66 ±2,20		
I-30.0I.88	0,649±0,006	0,635±0,0I6	0,550±0,025	0,632±0,0I3		0,5262
	3,60 ±0,59	-I,42 ±I,32	2,I9 ±2,53	6,I9 ±I,38		
I.02-I0.03.88	0,643±0,0I7	0,562±0,028	0,528±0,052	0,663±0,04I		0,6202
	4,52 ±I,55	I,95 ±2,6I	6,93 ±5,47	-0,9I ±3,37		
I8.03-30.04.88	0,686±0,0I8	0,599±0,025	0,552±0,058	0,635±0,05I		0,5836
	4,63 ±I,45	4,95 ±2,85	I7,9I ±6,08	8,06 ±4,6I		
I.05-28.06.88	0,700±0,0I0	0,654±0,023	0,634±0,05I	0,678±0,033		0,5836
	4,I8 ±0,8I	5,49 ±2,29	4,88 ±4,63	I,39 ±2,86		
3.I0-I2.I2.88	0,804±0,0I4	0,783±0,03I	0,654±0,034	0,737±0,0I9		0,6826
	2,34 ±0,95	6,60 ±2,I7	2,40 ±3,22	5,72 ±I,88		
I6.I2.88-3I.0I.89	0,767±0,028	0,769±0,065	0,822±0,045	0,773±0,023		0,6826
	0,66 ±2,02	0,II ±4,42	I,27 ±3,II	3,I2 ±2,07		
6.02-27.03.89	0,730±0,020	0,707±0,032	0,702±0,036	0,789±0,032		0,6826
	3,4I ±I,60	I,66 ±2,37	5,39 ±2,94	4,II ±2,07		
8.04-8.08.89	0,69I±0,0II	0,633±0,024	0,586±0,039	0,607±0,024		0,660I
	3,03 ±0,9I	0,80 ±2,03	I,44 ±4,04	3,98 ±2,63		
I0.08-30.08.89	0,763±0,024	0,784±0,035	0,640±0,093	0,706±0,085		0,6826
	6,55 ±I,89	2,9I ±2,57	5,64 ±8,48	7,I2 ±6,87		
I.II-I0.I2.89	0,9I3±0,030	0,83I±0,063	0,922±0,I34	0,796±0,067	I-29.II	0,6598
	5,55 ±I,84	I,32 ±4,22	-I,60 ±7,96	4,83 ±6,I3	2-I0.I2	0,8007
9.09-3I.I0.89	0,74I±0,0I6	0,729±0,025	0,704±0,054	0,776±0,046		0,6598
	4,57 ±I,22	4,44 ±I,96	I3,99 ±4,65	6,94 ±3,42		
I.0I.90-I5.02.90	0,645±0,0I9	0,652±0,037	0,49I±0,054	0,622±0,03I		0,8007
	5,60 ±I,69	0,44 ±2,97	7,89 ±6,38	I,34 ±3,22		
6.03-30.04.90	0,664±0,0I9	0,688±0,033	0,6I0±0,063	0,720±0,054		0,5848
	5,29 ±I,35	-3,90 ±2,06	-0,75 ±4,7I	-2,36 ±3,32		
I-30.05.90	0,76I±0,0I8	0,67I±0,040	0,658±0,042	0,734±0,023		0,5848
	5,07 ±I,05	0,54 ±2,58	6,64 ±2,98	0,85 ±I,8I		
I-30.06.90	0,745±0,0I6	0,669±0,05I	0,694±0,060	0,670±0,029		0,5848
	3,70 ±0,98	-4,22 ±3,I9	I,58 ±3,97	0,52 ±2,59		
I-30.07.90	0,740±0,022	0,69I±0,054	0,666±0,087	0,643±0,048		0,5848
	5,I9 ±I,34	-I,72 ±3,24	3,94 ±5,94	-0,I4 ±4,06		
3I.07-3I.08.90	0,7I8±0,027	0,694±0,046	0,658±0,095	0,655±0,077		0,5848
	6,25 ±I,68	0,24 ±2,82	+I0,57 ±6,79	2,67 ±5,29		
Moyenne γ	0,702±0,0I4	0,647±0,0I7	0,627±0,02I	0,680±0,0I5		
$\Delta\varphi$	+4,24 ±0,28	+3,56 ±I,48	+2,I2 ±I,I0	+3,0I ±0,65		

Table 3 - Résultats de l'analyse harmonique des inclinaisons à Talaïa clinomètre HK-I.

Intervalles d'observations	Facteur d'amplitude γ et retard de phase $\Delta\phi°$					Nombre d'ordonnées
	M_2	S_2	O_I	K_I	P_I	
2.04-I0.07.85	0,8I3±0,02I	0,852±0,036	0,707±0,288	2,II6±0,202		3384
	I5,85 ±I,48	-3,04 ±2,65	-I,88 ±23,I2	-II,9I ±4,76		
25.II.85-I.03.86	0,668±0,0I7	0,7I4±0,039	0,974±0,I69	0,867±0,I02		2268
	I2,48 ±I,48	4,98 ±3,4I	3,0I ±9,64	2I,75 ±5,69		
2.05-I7.II.86	0,852±0,0I8	0,897±0,036	I,308±0,III	I,I27±0,082	I,874±0,28I	4680
	I4,75 ±I,I8	20,50 ±2,45	II,98 ±4,93	-3,75 ±4,I6	I0,5I ±8,76	
2.I2.86-3I.05.87	0,74I±0,0I6	0,78I±0,030	I,004±0,I07	0,930±0,076		2808
	I3,89 ±I,26	24,54 ±2,38	4,I2 ±6,07	I6,45 ±4,07		
I.06-30.I2.87	0,7I3±0,0I4	0,664±0,032	I,033±0,I22	0,998±0,082		2772
	I5,62 ±I,I7	25,9I ±2,85	I0,54 ±6,47	II,93 ±3,90		
2.05.86-3I.0I.87	0,685±0,027	0,789±0,058	I,057±0,I06	0,95I±0,080	I,232±0,272	5544
	I4,45 ±2,29	22,79 ±4,48	I5,27 ±5,82	2,62 ±4,99	-II,32 ±I3,43	
8.04-5.08.89	0,78I±0,0I4	0,775±0,030	I,264±0,I02	0,994±0,069		2568
	I4,98 ±I,02	I8,2I ±2,35	I9,36 ±4,6I	I3,84 ±3,39		
8.I0.89-27.02.90	0,68I±0,0I8	0,7I3±0,03I	0,920±0,I03	0,8I6±0,068		3432
	20,42 ±I,56	II,I2 ±2,7I	5,49 ±6,04	I7,67 ±4,34		
Среднее γ	0,742±0,024	0,773±0,027	I,033±0,067	I,I00±0,I49		
$\Delta\varphi°$	I5,30 ±0,82	I6,25 ±3,23	8,48 ±2,49	8,32 ±4,I5		

Table 4 - Résultats de l'analyse harmonique des inclinaisons à Talaïa clinomètre HK-2.

Intervalles d'observations	Facteur d'amplitude γ et retard de phase $\Delta\phi°$					Nombre d'ordonnées
	M_2	S_2	O_I	K_I	P_I	
7.04.85÷I.03.86	0,728±0,008	0,620±0,020	0,630±0,026	0,683±0,02I	0,535±0,068	6I20
	2,47 ±0,65	-I,I7 ±I,68	-0,48 ±2,38	8,35 ±I,76	-5,7I ±7,55	
3.03.86-3I.0I.87 *	0,666±0,0I2	0,624±0,025	0,584±0,030	0,665±0,024	0,6I0±0,078	7524
	3,72 ±I,0I	5,00 ±2,I2	-0,35 ±2,94	I,0I ±I,88	6,95 ±6,92	
То же самое без 2-3I.I2.86 и 8-3I.0I.87	0,703±0,008	0,669±0,0I8	0,662±0,026	0,689±0,0I9	0,747±0,065	6228
	3,I3 ±0,67	I,5I ±I,37	3,89 ±2,22	0,87 ±I,57	-5,58 +5,05	
8.02.87-3I.05.87	0,694±0,008	0,628±0,0I5	0,620±0,032	0,7I2±0,023		2556
	3,70 ±0,69	3,46 ±I,22	2,37 ±2,89	I,94 ±I,96		
I.06.87-30.I2.87	0,6I6±0,0I0	0,544±0,020	0,508±0,02I	0,600±0,0I2		3528
	4,7I ±0,9I	2,25 ±2,00	4,48 ±2,42	4,52 ±I,43		
I6.I0.87-30.0I.88	0,640±0,005	0,598±0,0II	0,534±0,0I9	0,6I6±0,0I0		2520
	4,29 ±0,45	3,69 ±I,0I	5,I8 ±2,05	4,54 ±I,20		
I8.03.88-28.06.88	0,692±0,0II	0,606±0,0I9	0,55I±0,028	0,652±0,022		I980
	5,72 ±0,96	5,34 ±I,64	9,89 ±2,85	7,66 ±I,99		
8.04.89-8.08.89	0,69I±0,0II	0,633±0,024	0,586±0,039	0,607±0,024		2808
	3,03 ±0,9I	0,80 ±2,03	I,44 ±4,04	3,98 ±2,63		
9.09.89-I5.02.90	0,7I6±0,020	0,740±0,036	0,589±0,048	0,690±0,030		2064
	5,04 ±I,58	3,83 ±2,5I	I2,35 ±4,72	2,46 ±2,74		
I.06.90-3I.08.90	0,73I±0,0I2	0,694±0,030	0,672±0,044	0,659±0,024		2040
	4,6I ±0,76	-I,5I ±I,77	2,88 ±2,9I	-0,I0 ±2,00		
Среднее γ	0,688±0,0II	0,636±0,0I7	0,594±0,0I7	0,657±0,0I2		
$\Delta\varphi°$	+4,04 ±0,32	2,32 ±0,76	4,I6 ±I,3I	3,52 ±0,90		

Table 5 - Amplitude de l'inclinaison à la latitude de Talaïa et facteur γ

Onde	H théor. sec. d'arc		Facteur γ		Effet du noyau liquide $\Delta\gamma = \gamma O1 - \gamma K1$	
	NS	EW	NS	EW	NS	EW
O_1	0,99	3,01	1,189 ± 0,070	0,627 ± 0,021	-0,07	-0,05
K_1	1,32	4,96	1,265 ± 0,115	0,680 ± 0,015		
M_2	5,59	7,02	0,777 ± 0,016	0,702 ± 0,014		
S_2	2,96	3,37	0,806 ± 0,029	0,647 ± 0,017		

Table 6 - Facteur d'amplitude et retard de phase d'après les observations clinométriques

Modèles et sites d'observation	γ(M2) généralisé	γ(M2) NS	$\Delta\phi$(M2) NS	γ(M2) EW	$\Delta\phi$(M2) EW
Modèles M.S. Molodenski [3]	0,686				
Modèle Gilbert Dziewonski n° 508 [3]	0,691				
Poltava		0,661	-4,50	0,659	+0,93
Kasan		0,76	+7,6	0,66	+4,0
Schmakovo		0,588	-7,53	0,717	+2,12
Achkhabad		0,574	-5,95	0,735	-7,52
Kondara III		0,777	-4,91	0,603	-4,67
Alma Ata		0,671	-9,47	0,712	+6,34
Petchainaia (Baïkal) nivellement	0,72				
Tankhoï (Baïkal) nivellement	0,55				
Saïano Schouchenskaïa [7]		0,686	-8,7	0,661	+8,1
Talaïa		0,777	+16,2	0,702	+4,2

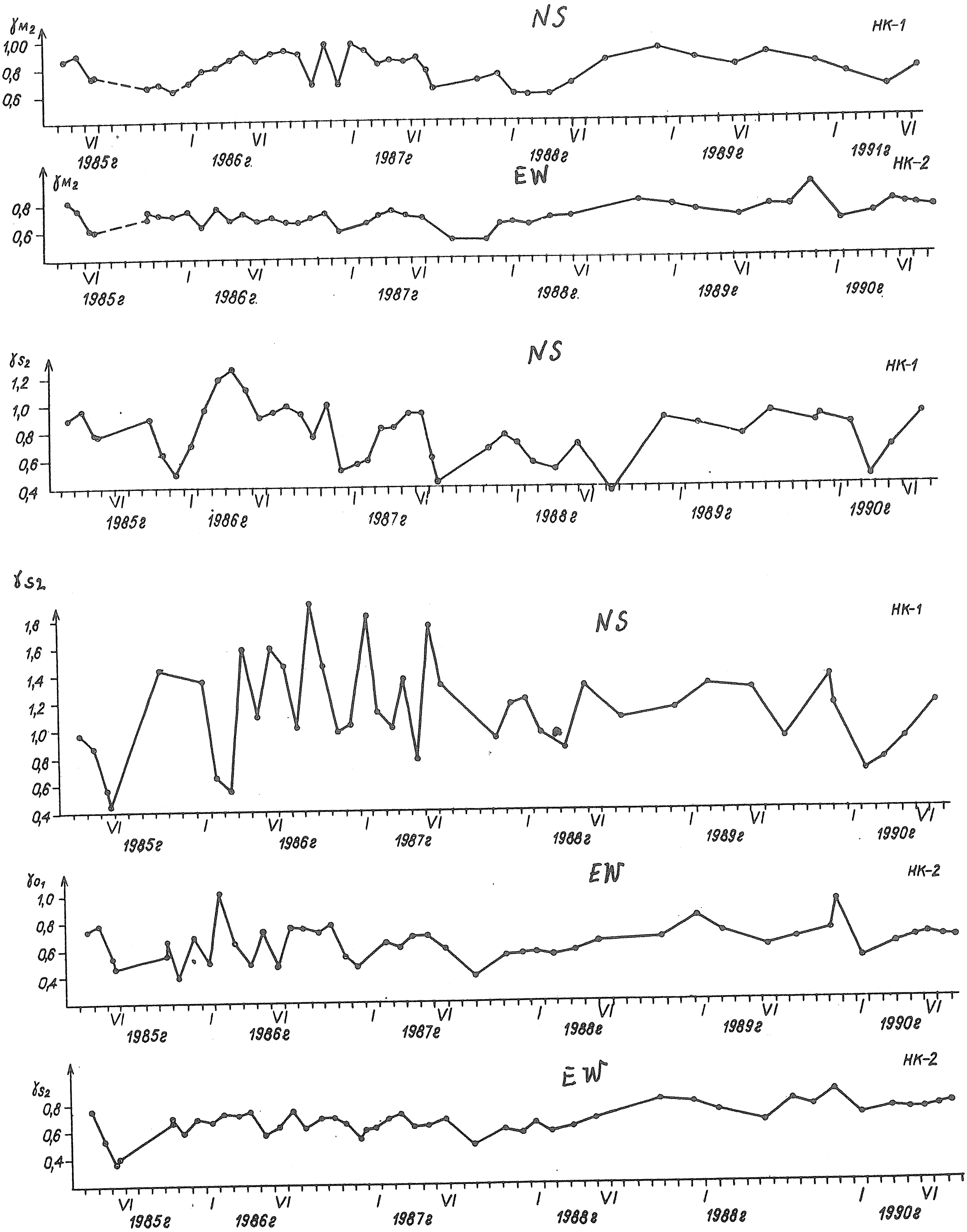

Figure 2 Variations temporelles du facteur d'amplitude γ

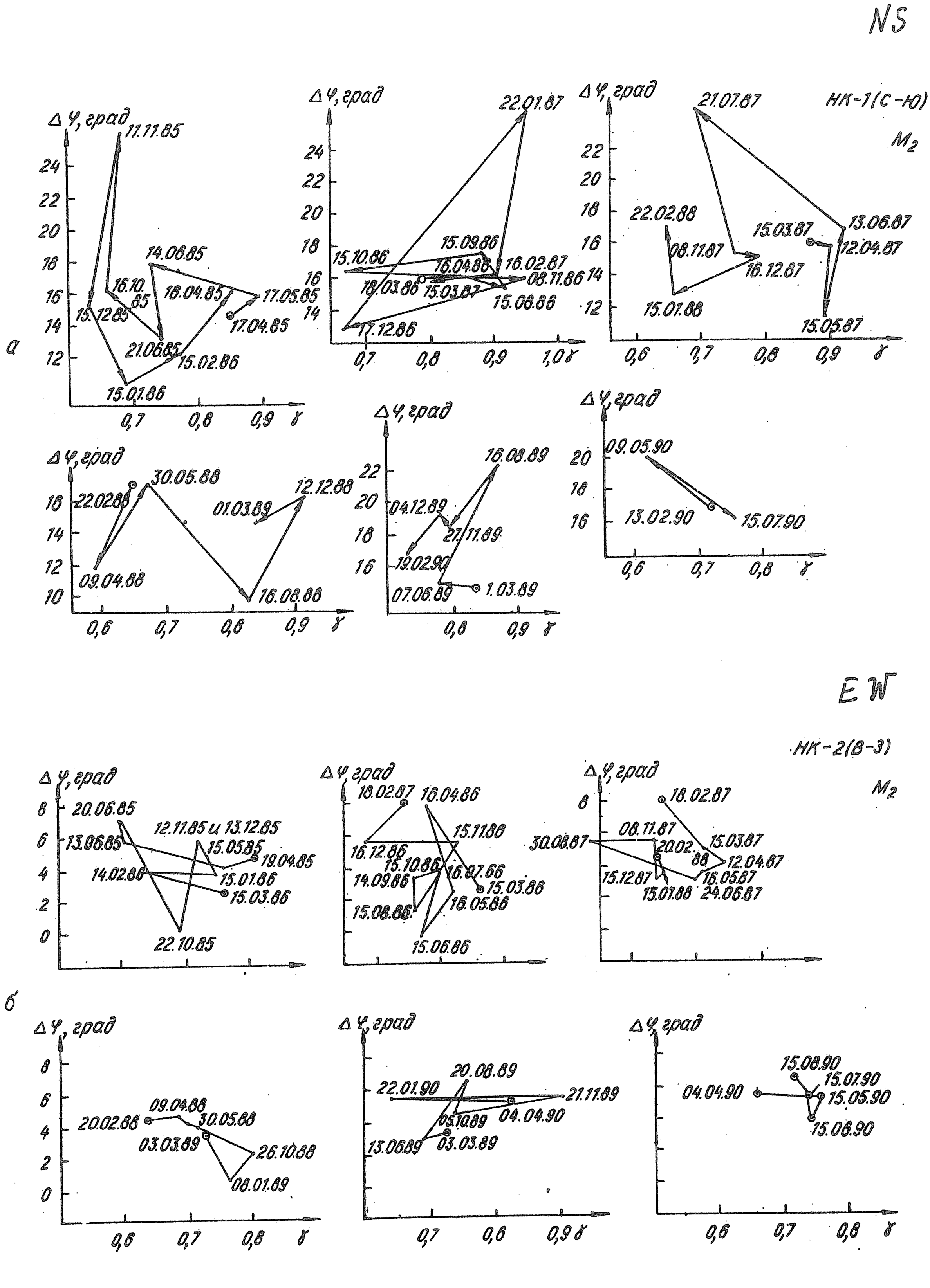

Figure 3 Variations temporelles du rapport entre le facteur d'amplitude γ et le déphasage $\Delta\phi$ de l'onde M_2.

About the pseudo-new periodic waves in the tide generating potential based on an analytical method

F.Roosbeek-V.Dehant
Royal Observatory of Belgium
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Abstract. In calculating a tide generating potential (TGP) with an analytical method, long-period waves are produce in addition to the semi-diurnal waves for a TGP of order two and degree two. In the same way, diurnal waves appear in addition to the ter-diurnal waves for a TGP of order three and degree three and other similar waves appear also for the upper orders. Contrary to what is said in a paper of Xi Qinwen (Xi Q. 1989), these waves come only from truncation errors, they are not real physical waves and they must be filtered out before doing any gravity tide computation.

Key words: tide generating potential (TGP), frequency bands.

Introduction

Computing a tide generating potential (TGP) with a spectral method consists principally in locating, in a given spectrum, a series of waves for which you know a-priori the frequencies. So, of course, when you are trying to find waves in the semi-diurnal band of a TGP of order two for example, you do not look for long-periodic waves.

If you use an analytical method, the way of developing the potential is different. The concept is here to start from given ephemerides and to apply a series of mathematical transformations in order to finally obtain a TGP. This second method produces a strange phenomena in specific bands of the potential: additional waves outside the original frequency band appear. For instance, a lot of long-periodic waves appear in addition to the semi-diurnal waves generated by a TGP of order two and degree two; diurnal waves in addition to the ter-diurnal waves classically generated by a TGP of order three and degree three; and other kinds of special waves may appear for the upper orders. Xi Qinwen was the first to show the existence of this kind of waves in Xi Q. 1989. In this article, he gives a physical interpretation for this phenomena in terms of beats and multiple frequencies in physics. This explanation is not correct as we shall see in what follows.

Explanation of the phenomena

The most evident prove that these additional waves are non-real physical waves is locate in their amplitudes. In fact, in his paper, Xi Qinwen (Xi Q. 1989) mentions that all the amplitudes of these waves are not greater than $6\ 10^{-6}$ radians. In the potential that we have developed recently (Roosbeek 1994a) which has considered all the additional effects at one order of magnitude smaller than in Xi's potential, and which is truncated at one order of magnitude smaller, we find also these additional waves but their amplitudes are not greater than $4\ 10^{-7}$ radians. These amplitudes are exactly at the level of truncation, both in our development and in the Xi's development. So these waves are only noise, and in the following we shall see how they appear in the potential development.

Let see how we can obtain a TGP with an analytical method. The most general form of the tidal potential exerted at a point P on the Earth's surface by the an external body is written as:

$$V_B = \frac{GM_B}{d}\left[\sum_{n=2}^{\infty}\left(\frac{c}{d}\right)^n P_n(\cos\psi)\right] = \sum_{n=2}^{\infty} V_B^n \tag{1}$$

Where P_n is the Legendre polynomial of order n.[1] Note that the sum will begin with $n=1$ if we take into account the Earth flattening effect (see Roosbeek 1994b).

[1] All the notations are explained at the end of this paper.

If we refer to Doodson (Doodson 1954) for example, the different orders of the TGP can be written as:

$$V_B^2 = D_B(r)\left(\frac{c}{d}\right)^3 \left[G_{2,0}H_{2,0} + G_{2,1}H_{2,1} + G_{2,2}H_{2,2}\right]$$
$$V_B^3 = D_B(r)\left(\frac{r}{a}\right)\left(\frac{c}{d}\right)^4 \sin\pi_B \left[\frac{1}{3}\Gamma_{3,0}G_{3,0}H_{3,0} + \frac{1}{2}\Gamma_{3,1}G_{3,1}H_{3,1} + 5\Gamma_{3,2}G_{3,2}H_{3,2} + \frac{5}{6}\Gamma_{3,3}G_{3,3}H_{3,3}\right] \quad (2)$$
$$\ldots$$

The separation in different frequency bands is represented by the $H_{i,j}$ coefficients because each of them include the expressions *cos(j H)* where H represents the hour angle of the perturbing body and is quasi-diurnal in a terrestrial reference frame. For the second order, they are written as:

$$\begin{aligned} H_{2,0} &= \frac{2}{3} - 2\sin^2\delta \\ H_{2,1} &= \sin 2\delta \cos H \\ H_{2,2} &= \cos^2\delta \cos 2H \end{aligned} \quad (3)$$

In a TGP, the variable which represent the temporal variation is not H but τ, the lunar time. So, we need to make the following transformation:

$$\cos H = \cos(\chi - \alpha) = \cos(\tau + s - \pi - \alpha) \quad (4)$$

In order to simplify the next steps of our calculations, let us write more simply:

$$\begin{aligned} \cos H &= \cos(\tau + s - \pi - \alpha) \\ &= \cos(\tau + \upsilon) \\ &= A\cos(\tau) + B\sin(\tau) \end{aligned} \quad (5)$$

The expression depending on H in $H_{2,2}$, can be written:

$$\begin{aligned} \cos 2H &= \cos 2(\tau + s - \pi) \\ &= \cos(2\tau + 2\upsilon) \\ &= A'\cos(2\tau) + B'\sin(2\tau) \end{aligned} \quad (6)$$

Because τ has a diurnal variation with time, $H_{2,2}$ is only semi-diurnal. It is not possible to obtain some long-periodic waves. But that is not exactly what we compute when we develop a TGP because the expression *cos2H* is not directly available. In fact, we know only the expression of *cosH*, but this is sufficient because:

$$\begin{aligned} \cos 2H &= 2\cos^2 H - 1 \\ \cos 3H &= 4\cos^3 H - 3\cos H \\ &\ldots \end{aligned} \quad (7)$$

So, in the development of a TGP with an analytical method, we use the following expression:

$$\begin{aligned} \cos 2H &= 2\cos^2 H - 1 \\ &= 2(A\cos\tau + B\sin\tau)^2 - 1 \\ &= 2A^2\cos^2\tau + 2AB\sin 2\tau + 2B^2\sin^2\tau - 1 \\ &= A^2(\cos 2\tau + 1) + 2AB\sin 2\tau - B^2(\cos 2\tau - 1) - 1 \\ &= (A^2 - B^2)\cos 2\tau + 2AB\sin 2\tau + A^2 + B^2 - 1 \end{aligned} \quad (8)$$

Following (5), we have:

$$\begin{aligned} A &= \cos\upsilon \\ B &= -\sin\upsilon \end{aligned} \quad (9)$$

So,

$$A^2 + B^2 = 1 \quad (10)$$

That is why the long-periodic part in (8) must disappear. The problem is that we do no have a precise expression for A and B, but only a series which is truncated to a specific level. This truncation error is responsible for the fact that the value of A^2+B^2-1 is not exactly zero. That is why we find long-period waves in the semi-diurnal band of TGP of order two. A similar explanation could be given for the diurnal waves in the ter-diurnal band of the TGP of order three and for the other orders.

In conclusion, we have seen that the "new waves" described in the Xi Qinwen's article (Xi Q. 1989) are only due to a truncation error in the mathematical development of the TGP and are not real physical waves. So, these waves must not be considered when computing Earth's tides from a TGP.

Notation

M_B	mass of the perturbing body
G	geocentric gravitational constant
c	mean distance Earth-perturbing body
d	instantaneous distance Earth-perturbing body
a	equatorial radius of the Earth
r	geocentric distance of the observation point (P)
$D_B(r)$	Doodson scale factor for the perturbing body
$\sin\pi_B$	sine of the horizontal parallax of the perturbing body
χ	sidereal time
δ	declination of the perturbing body
H	hour angle of the perturbing body
α	right ascension of the perturbing body
τ	lunar time
s	mean longitude of the Moon
ψ	geocentric zenithal distance of the perturbing body from the station position

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Earth's flattening and nutations in obliquity effects on a tide generating potential

F. Roosbeek
Royal Observatory of Belgium
1994

Abstract. A tide generating potential (TGP) used in the theoretical computations of tides must have a precision level that matches as much as possible the precision of the most accurate tidal observations by superconducting gravimeters, i.e. 1 nanogal. This implies, not only very precise ephemerides, but also the consideration of several perturbing effects. The aim of this work is to give additional terms for a harmonic development of the TGP due to two of these effects: the flattening of the Earth and the nutations in obliquity. These effects may be added to the TGP available at this time without recalculating it completely. The maximal influence of these effects is respectively 5 and 17 nanogals on the tides. Note that these corrections have only sense for a TGP developed with an analytical method (like Xi's development) but not for a TGP developed with a spectral method (like Tamura's development).

Key words: tide generating potential (TGP), ephemerides, nutations, Earth's flattening.

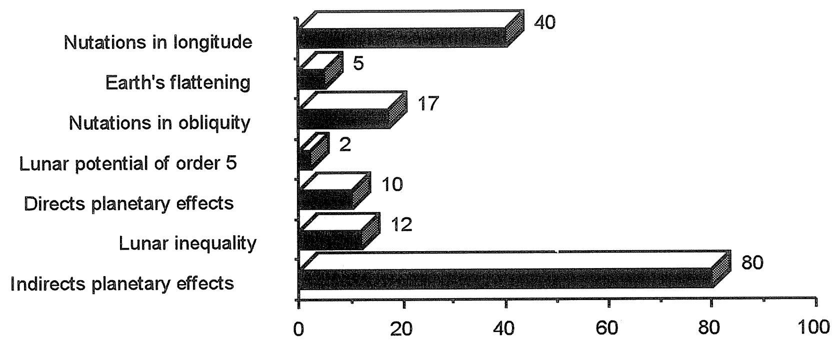
1. Introduction

The perturbing effects at the nanogal level compared to a classical tidal development (i.e. XI2000) may be separated in four categories:

1. Effect that have an influence for an epoch different of J2000.0:
   - time variations of the eccentricity (e) and the obliquity (ε) of the Earth's orbit.
2. Effects that require the recalculation of the TGP:
   - indirect planetary effects;
   - lunar inequality.
3. Effects that can be considered with additional terms:
   - direct planetary effects;
   - degree five of the lunar potential;
   - nutations in obliquity;
   - flattening of the Earth.
4. Effects that have an influence on tides but not on the potential:
   - secular variations of the arguments;
   - nutations in longitude.

We have chosen for this work to develop effects that can be considered by means of additional terms. Indeed, these terms may be added to the recent TGP without recalculating the potential. Among these effects, the direct planetary effects and the degree five of the lunar potential are very easily accounted for by means of additional terms like we have done in a separate paper (Roosbeek 1994). The other terms, the nutations in obliquity and the Earth's flattening effects, are rather complex and in addition, they are not considered in the very recent developments found in the literature. This is the reason why we have chosen to develop into details these computations.

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



2. Ephemerides, constants and physical parameters

For the lunar ephemerides, we have used the ELP2000-85 series from Chapront-Touzé and Chapront (1987). The solution is developed in series for which the arguments are linear combinations of the fundamental arguments of the Moon and of the mean longitudes of the Earth and the planets. More precisely, ELP2000-85 contains as independent variables, the Delaunay's arguments ($D=s-h$, $l'=h-p_s$, $l=s-p$, $F=s-\Omega$), the mean longitude of the Moon from the mean equinox of date (L) and the mean longitudes of the planets (Me, Ve, Te, Ma, Ju, Sa). The ELP2000-85 ephemerides have a precision of about 0.5" on one century before and after the starting time J2000.0 for the longitude and latitude and of 500 meters for the distances.
For the Solar ephemerides, due to the small influence of the perturbing effects, we have used ephemerides calculated manually from the Kepler's equation without considering any planetary perturbations.
The constants used in the computations are presented in table 1. Most of them come from the IERS standards 1989.

Table 1. Constants and physical parameters

Item	Recommended value	Comments
a	6378140 m	equatorial radius of the Earth
J_2	0.001082626	dynamical form factor for Earth
GM_T	3.98600440 10^{14} m^3/s^2	geocentric gravitational constant
$\sin\pi_l$	0.01659251	sine of the horizontal parallax of the Moon
$\sin\pi_s$	4.26345 10^{-5}	sine of the horizontal parallax of the Sun
M_L/M_T	0.012300034	ratio of mass of Moon to that of the Earth
M_S/M_T	332946.045	ratio of mass of Sun to that of the Earth
D_0	2.6276912 m^2/s^2	Doodson constant from Doodson
D_1	2.6335811 m^2/s^2	Doodson constant from Xi
ε	84381".444-46".8 T	obliquity of the Earth's orbit without nutation effects
e	3446".52815-514".71320 T	eccentricity of the Earth's orbit
$\Delta\varepsilon$	-5".7771121	correction for the nutation in obliquity effects
$D_S(r)/D(r)$	0.45923780	ratio of Doodson scale factor of Moon to that of the Sun

3. Earth's flattening effect

Calculation of the additional terms

For the theoretical development of that effect, the reader can for the first step of the computations refer to the article of H. Wilhelm (Wilhelm 1983) entitled "Earth flattening effect on tidal forcing field".
Wahr in his thesis (Wahr 1979) gives the results of the next step by means of additional terms in his general formula of tidal potential. Because our expression does not agree with his expression, we develop in details here the computations.

The complete expression for a tidal potential exerted by an external body that includes the Earth's flattening effect is given by:

$$V_B = \frac{GM_B}{d}\sum_{n=2}^{\infty}\left(\frac{r}{d}\right)^n P_n(\cos\psi) + \frac{GM_B}{d}\frac{r}{d}\sum J_n\left(\frac{a}{d}\right)^n \left(\begin{array}{l} (n+1)P_n(\cos\theta_c)\left[\cos\theta\cos\theta_c + \sin\theta\sin\theta_c\cos(\gamma-\gamma_c)\right] \\ +\left.\dfrac{dP_n}{d\theta}\right|_{\theta=\theta_c}\left[\cos\theta\sin\theta_c - \sin\theta\cos\theta_c\cos(\gamma-\gamma_c)\right] \end{array} \right) \quad (1)$$

Let us substitute $\theta_c = \frac{\pi}{2}-\delta$, $\theta = \frac{\pi}{2}-\varphi$ and $\gamma-\gamma_c = H$ into the previous expression where δ is the declination of the perturbing body, φ, is the geodesic latitude of a point P and H the hour angle of the perturbing body. For the effect of the Earth's flattening on the TGP, only the term corresponding to $n=2$ must be considered because $\frac{J_n}{J_2} \le 10^{-2}$ for $n>2$. Therefore, the second part of (1) may be written for $n=2$:

$$V_B^{EII} = \frac{GM_B}{d}\frac{r}{d}J_2\left(\frac{a}{d}\right)^2 \left(\begin{array}{l} \frac{3}{2}\left(3\cos^2\left(\frac{\pi}{2}-\delta\right)-1\right)\left[\begin{array}{l} \cos\left(\frac{\pi}{2}-\varphi\right)\cos\left(\frac{\pi}{2}-\delta\right) \\ +\sin\left(\frac{\pi}{2}-\varphi\right)\sin\left(\frac{\pi}{2}-\delta\right)\cos H \end{array}\right] \\ -3\cos\left(\frac{\pi}{2}-\delta\right)\sin\left(\frac{\pi}{2}-\delta\right)\left[\begin{array}{l} \cos\left(\frac{\pi}{2}-\varphi\right)\cos\left(\frac{\pi}{2}-\delta\right) \\ -\sin\left(\frac{\pi}{2}-\varphi\right)\sin\left(\frac{\pi}{2}-\delta\right)\cos H \end{array}\right] \end{array} \right)$$

$$= \frac{GM_B}{d}\frac{r}{d}J_2\left(\frac{a}{d}\right)^2 \left(\begin{array}{l} \frac{3}{2}\sin\varphi\left(5\sin^3\delta - 3\sin\delta\right) \\ +\frac{3}{2}\cos\varphi\cos\delta\left(5\sin^2\delta-1\right)\cos H \end{array} \right)$$

$$= D_B(r)\frac{a}{r}\left(\frac{c}{d}\right)^4 J_2\sin\pi_B 2\left(\begin{array}{l} \sin\varphi\left(5\sin^3\delta - 3\sin\delta\right) \\ +\cos\varphi\cos\delta\left(5\sin^2\delta-1\right)\cos H \end{array} \right)$$

$$= D_B(r)\frac{a}{r}\left(\frac{c}{d}\right)^4 J_2\sin\pi_B 2\left(G_0^{EII}H_0^{EII} + G_1^{EII}H_1^{EII}\right) \quad (2)$$

with

$$G_0^{EII} = \sin\varphi \qquad H_0^{EII} = \sin\delta\left(-\frac{4}{3}-\frac{5}{2}H_{2,0}\right)$$
$$G_1^{EII} = \cos\varphi \qquad H_1^{EII} = \cos\xi\left(\frac{2}{3}-\frac{5}{2}H_{2,0}\right) \quad (3)$$

and with

$$H_{2,0} = \frac{2}{3} - 2\sin^2\delta$$
$$\cos\xi = \cos\delta\cos H \quad (4)$$

Presentation of the supplementary terms

At the nanogal level, only the Moon must be taken into account for the Earth's flattening effect. In the table 2 we present a list of waves that we must add to the TGP in order to take into account the Earth's flattening effect with a precision of 10^{-7} radians on each wave. These numerical values are independent of the station position. More precisely:

$$\begin{aligned} V_M^{EM} &= D_M(r)\frac{a}{r}\left(\frac{c}{d}\right)^4 J_2 \sin\pi_M 2\left(G_0^{EM} H_0^{EM} + G_1^{EM} H_1^{EM}\right) \\ &= D_M(r)\frac{a}{r}\left(G_0^{EM} \underbrace{\left(\frac{c}{d}\right)^4 J_2 \sin\pi_M 2H_0^{EM}}_{\text{additional terms (table 2)}} + G_1^{EM} \underbrace{\left(\frac{c}{d}\right)^4 J_2 \sin\pi_M 2H_1^{EM}}_{\text{additional terms (table 2)}} \right) \end{aligned} \tag{5}$$

As we can see, the perturbations act on the long-period and diurnal terms of the TGP.

Table 2. Supplementary terms due to the Earth's flattening effect

Long-period (sin)		diurnal (cos)			
Argument	value (10^{-7})	Argument	value (10^{-7})	Argument	value (10^{-7})
055•555	1	107•655	1	165•665	2
055•655	-18	115•745	1	167•455	1
055•665	-3	115•755	3	167•465	1
057•455	-3	117•545	1	173•555	2
057•465	-1	117•555	3	175•355	1
063•545	-1	123•635	1	175•545	-3
063•555	4	125•645	7	175•555	76
063•755	-1	125•655	18	175•565	31
065•355	2	127•445	1	175•575	3
065•545	18	127•455	3	183•655	2
065•555	-338	127•655	1	183•665	1
065•565	-53	135•535	2	185•455	12
065•575	3	135•545	26	185•465	5
067•355	-1	135•555	66	193•555	2
067•565	1	135•755	4	193•565	1
073•655	-11	137•545	-1	195•355	1
073•665	-1	137•555	6	195•555	3
075•445	3	143•655	-1	195•565	2
075•455	-55	145•445	-2	195•575	1
075•465	-9	145•455	-4	1X5•455	1
075•655	2	145•645	-5		
075•665	1	145•655	34		
083•555	-9	145•665	-4		
083•565	-1	147•445	-1		
085•355	-7	147•455	7		
085•365	-1	153•545	-1		
085•555	-28	155•535	1		
085•565	-17	155•545	-31		
085•575	-3	155•555	208		
093•455	-1	155•565	-27		
093•655	-1	157•555	1		
093•665	-1	163•645	-1		
095•255	-1	163•655	2		
095•455	-8	163•665	-1		
095•465	-5	165•445	-2		
095•475	-1	165•455	11		
0X3•555	-1	165•465	-2		
0X5•355	-1	165•655	4		

Cut-off level of the series

Let us take the radial derivative of the expression (2):

$$\frac{\partial V_M^{Ell}}{\partial r} = \underbrace{D_1 \frac{1}{a}}_{4.13*10^{-7}\, m/s^2} \left(\frac{c}{d}\right)^4 J_2 \sin \pi_M 2\left(G_0^{Ell} H_0^{Ell} + G_1^{Ell} H_1^{Ell}\right) \tag{6}$$

where D_1 is the well known Doodson constant (see table 1).

So, if we want a precision of 1 nanogal on $\frac{\partial V_M^{Ell}}{\partial r}$, the precision on the additional terms must be 2.42 10^{-5} radians. In order to achieved a prescribed precision, all terms larger than about two percent of the prescribed level are include in the summation. So, in order top obtain a precision of 2.42 10^{-5} radians on the additional terms, we must keep all the waves greater than ± 5 10^{-7} radians.

Numerical value of the maximum effect

In order to have an idea of the maximal effect of the Earth flattening on the lunar tides, we have considered all the waves of equation (6) listed in table 2 and added them together:

$$\left(\frac{\partial V_M^{Ell}}{\partial r}\right)_{\max} = 5.21 * 10^{-11}\ m/s^2 = 5.21 \text{ nanogals} \tag{7}$$

Other contributions about the Earth flattening effect

from Wilhelm

Wilhelm gives the equation (1) as the expression for the TGP including the flattening effect (Wilhelm 1983). He gives also an approximation for the magnitude of the $n=2$ part of the additional corresponding force per unit mass:

$$\frac{3}{2}\frac{GM_M}{c^2}\left(\frac{a}{c}\right)^2 J_2 = 1.48 * 10^{-11}\ m/s^2 \cong 1.5 \text{ nanogals} \tag{8}$$

That is about 3% of the magnitude of the vertical force per unit mass for the order four of the potential:

$$4\frac{GM_M}{c^2}\left(\frac{a}{c}\right)^3 = 62.3 \text{ nanogals} \tag{9}$$

from Dahlen

Dahlen has given an expression of the Earth flattening effect on the TGP (Dahlen 1993). In particular, he gives the numerical expression:

$$\frac{V_M^{Ell}}{V_M^2} \cong 3\frac{a}{c} J_2 \cong 5 * 10^{-5} \tag{10}$$

from Wahr

Wahr gives in his thesis, an expression of the TGP that includes the Earth's flattening effect:

$$V_B = -\Re\left[J_2 \frac{r}{a}\sqrt{7}\left(\sqrt{3}C_3^0(t)Y_1^0(\theta,\gamma) + \frac{1}{\sqrt{2}}C_3^1(t)Y_1^1(\theta,\gamma)\right) + \sum_{l=2}^{\infty}\sum_{m=0}^{l}\left(\frac{r}{a}\right)^l C_l^m(t)Y_l^m(\theta,\gamma)\right] \tag{11}$$

with,

$$C_l^m(t) = \begin{cases} -2\dfrac{GM_B}{d}\left(\dfrac{a}{d}\right)^l \dfrac{4\pi}{2l+1} Y_l^{m^*}\left(\tfrac{\pi}{2}-\delta,\alpha\right)\exp\left(im(\Omega t+h)\right) & \text{if } m \neq 0 \\ -\dfrac{GM_B}{d}\left(\dfrac{a}{d}\right)^l \dfrac{4\pi}{2l+1} Y_l^{0^*}\left(\tfrac{\pi}{2}-\delta,\alpha\right) & \text{if } m = 0 \end{cases} \quad (12)$$

$$Y_l^m(\theta,\gamma) = \sqrt{\frac{2l+1}{4\pi}\frac{(l-m)!}{(l+m)!}} P_l^m(\cos\theta)\exp(im\gamma)$$

Let us develop the expression corresponding to the Earth's flattening effect in V in order to compare with (2):

$$V_B^{Ell} = \frac{GM_B}{d} J_2 \left(\frac{a}{d}\right)^3 \frac{4\pi}{7} \frac{r}{a} \sqrt{7} \begin{pmatrix} \sqrt{3}\sqrt{\dfrac{7}{4\pi}} \dfrac{\left(-3\sin\delta + 5\sin^3\delta\right)}{2} \sqrt{\dfrac{3}{4\pi}} \cos\theta \\ +\dfrac{2}{\sqrt{2}}\sqrt{\dfrac{7}{48\pi}} \dfrac{3\left(1-5\sin^2(\delta)\right)\cos\delta}{2} \sqrt{\dfrac{3}{8\pi}} (-\sin\theta)\cos(\Omega t + \gamma + h - \alpha) \end{pmatrix} \quad (13)$$

$$= D_B(r)\frac{a}{r}\left(\frac{c}{d}\right)^4 J_2 \sin\pi_B 2 \begin{pmatrix} \sin\varphi\left(5\sin^3\delta - 3\sin\delta\right) \\ +\dfrac{1}{2}\cos\varphi\cos\delta\left(5\sin^2\delta - 1\right)\cos H \end{pmatrix}$$

Comparing this expression (13) with expression (2), we see that there is a factor of 2 between (13) and (2) in the part that multiplied *cosH*. K.H. Ilk had already mentioned this error in a personal communication to Wahr.

4. Effect of the nutations in obliquity

In order to obtain a development comparable to the one obtained by a spectral method, it is necessary to consider the effect of the nutations because the real Earth orientation and position in space contain the nutations effects. These effects have amplitudes above the nanogal and therefore, for calculation of Earth tides, a correction for nutations in longitude and obliquity must be applied. The nutations in longitude must be considered in all the arguments (s, h, p, Ω, p_s) when one wants to calculate tides for a precise epoch. These nutations have no effect on the coefficients of a TGP. The nutations in obliquity, because they modify the value of the obliquity (ε), affect the coefficients of TGP and must be accounted for with additional terms. These additional terms are presented in table 3.

Table 3. Series of nutation in longitude (Δψ) and obliquity (Δε)

Argument					Longitude		Obliquity	
l	l'	F	D	Ω	A_i	A_i'	B_i	B_i'
0	0	0	0	-1	-17".1996	-0".01742	9".2025	0".00089
0	0	2	-2	-2	-1".3187	-0".00016	0".5736	0".00031
0	0	2	0	-2	-0".2274	-0".00002	0".0977	0".00005
0	0	0	0	-2	0".2062	0".00002	-0".0895	0".00005
0	1	0	0	0	0".1426	-0".00034		
1	0	0	0	0	0".0712	0".00001		
0	1	2	-2	-2	-0".0517	0".00012	0".0224	-0".00006
0	0	2	0	-1	-0".0386	-0".00004	0".0200	
1	0	2	0	-2	-0".0301		0".0129	-0".00001
0	-1	2	-2	-2	0".0217	-0".00005	-0".0095	0".00003
1	0	0	-2	0	-0".0158			
0	0	2	-2	-1	0".0129	0".00001		
-1	0	2	2	-2	0".0123			

$$\Delta\psi = \sum_i \left(A_i + A_i' t\right)\sin(Argument)$$

$$\Delta\varepsilon = \sum_i \left(B_i + B_i' t\right)\cos(Argument)$$

Calculation of the additional terms

In order to compute a TGP, the following expressions must be used:

$$\begin{aligned}\sin\delta &= \sin\varepsilon\cos\beta\sin\lambda+\cos\varepsilon\sin\beta \\ \cos\xi &= \cos\beta\cos\lambda\cos\chi+(\cos\varepsilon\cos\beta\sin\lambda-\sin\varepsilon\sin\beta)\sin\chi\end{aligned} \tag{14}$$

Where λ and β represent respectively the ecliptic longitude and latitude of the perturbing body. χ is the sidereal time. For the epoch J2000.0, we should corrected ε of the nutations. Let us write the corrected value ε_{nut}.
So the correct expressions for $\sin\delta$ and $\cos\xi$ are :

$$\begin{aligned}\sin\delta_{nut} &= \sin\varepsilon_{nut}\cos\beta\sin\lambda+\cos\varepsilon_{nut}\sin\beta \\ \cos\xi_{nut} &= \cos\beta\cos\lambda\cos\chi+(\cos\varepsilon_{nut}\cos\beta\sin\lambda-\sin\varepsilon_{nut}\sin\beta)\sin\chi\end{aligned} \tag{15}$$

The subscript "nut" is for "nutations included". If we write:

$$\begin{aligned}\sin\varepsilon_{nut} &= \sin\varepsilon+\Delta\sin\varepsilon \\ \cos\varepsilon_{nut} &= \cos\varepsilon+\Delta\cos\varepsilon\end{aligned} \tag{16}$$

Then,

$$\begin{aligned}\sin\delta_{nut} &= (\sin\varepsilon+\Delta\sin\varepsilon)\cos\beta\sin\lambda+(\cos\varepsilon+\Delta\cos\varepsilon)\sin\beta \\ \cos\xi_{nut} &= \cos\beta\cos\lambda\cos\chi+((\cos\varepsilon+\Delta\cos\varepsilon)\cos\beta\sin\lambda-(\sin\varepsilon+\Delta\sin\varepsilon)\sin\beta)\sin\chi\end{aligned} \tag{17}$$

therefore,

$$\begin{aligned}\sin\delta_{nut} &= \sin\delta+\underbrace{\Delta\sin\varepsilon\cos\beta\sin\lambda+\Delta\cos\varepsilon\sin\beta}_{\Delta\sin\delta} \\ \cos\xi_{nut} &= \cos\xi+\underbrace{(\Delta\cos\varepsilon\cos\beta\sin\lambda-\Delta\sin\varepsilon\sin\beta)\sin\chi}_{\Delta\cos\xi}\end{aligned} \tag{18}$$

We may now calculated:

$$\begin{aligned}H_{2,0_{nut}} &= \frac{2}{3}-2\sin^2\delta_{nut} \\ &\cong \frac{2}{3}-2(\sin^2\delta+2\sin\delta\Delta\sin\delta) \\ &\cong H_{2,0}-\underbrace{4\sin\delta\Delta\sin\delta}_{\Delta H_{2,0}}\end{aligned} \tag{19a}$$

$$\begin{aligned}H_{2,1_{nut}} &= 2\sin\delta_{nut}\cos\xi_{nut} \\ &= 2(\sin\delta+\Delta\sin\delta)(\cos\xi+\Delta\cos\xi) \\ &\cong H_{2,1}+\underbrace{(2\sin\delta\Delta\cos\xi+2\cos\xi\Delta\sin\delta)}_{\Delta H_{2,1}}\end{aligned} \tag{19b}$$

$$\begin{aligned}H_{2,2_{nut}} &= 2\cos^2\xi_{nut}-\frac{1}{2}H_{2,0_{nut}}-\frac{2}{3} \\ &\cong 2(\cos^2\xi+2\cos\xi\Delta\cos\xi)-\frac{1}{2}(H_{2,0}-4\sin\delta\Delta\sin\delta)-\frac{2}{3} \\ &\cong H_{2,2}+\underbrace{(4\cos\xi\Delta\cos\xi+2\sin\delta\Delta\sin\delta)}_{\Delta H_{2,2}}\end{aligned} \tag{19c}$$

$$
\begin{aligned}
H_{3,0_{nut}} &= \left(\frac{4}{3}+\frac{5}{2}H_{2,0_{nut}}\right)\sin\delta_{nut} \\
&= \left(\frac{4}{3}+\frac{5}{2}\left(H_{2,0}+\Delta H_{2,0}\right)\right)\left(\sin\delta+\Delta\sin\delta\right) \\
&\cong H_{3,0}+\underbrace{\left(\left(\frac{4}{3}+\frac{5}{2}H_{2,0}\right)\Delta\sin\delta+\frac{5}{2}\Delta H_{2,0}\sin\delta\right.}_{\Delta H_{3,0}}
\end{aligned}
\tag{19d}
$$

$$
\begin{aligned}
H_{3,1_{nut}} &= \left(-\frac{2}{3}+\frac{5}{2}H_{2,0_{nut}}\right)\cos\xi_{nut} \\
&= \left(-\frac{2}{3}+\frac{5}{2}\left(H_{2,0}+\Delta H_{2,0}\right)\right)\left(\cos\xi+\Delta\cos\xi\right) \\
&\cong H_{3,1}+\underbrace{\left(\left(-\frac{2}{3}+\frac{5}{2}H_{2,0}\right)\Delta\cos\xi+\frac{5}{2}\Delta H_{2,0}\cos\xi\right)}_{\Delta H_{3,3}}
\end{aligned}
\tag{19e}
$$

$$
\begin{aligned}
H_{3,2_{nut}} &= H_{2,2_{nut}}\sin\delta_{nut} \\
&\cong H_{3,2}+\underbrace{\left(\Delta H_{2,2}\sin\delta+H_{2,2}\Delta\sin\delta\right)}_{\Delta H_{3,2}}
\end{aligned}
\tag{19f}
$$

$$
\begin{aligned}
H_{3,3_{nut}} &= \text{ter-diurnal part of } H_{2,2_{nut}}\cos\xi_{nut} \\
&\cong H_{3,3}+\underbrace{\left(\Delta H_{2,2}\cos\xi+H_{2,2}\Delta\cos\xi\right)}_{\Delta H_{3,3}}
\end{aligned}
\tag{19g}
$$

The fourth order of the potential is too weak to produce additional terms. The calculation of $H_{4,0_{nut}}\ldots H_{4,4_{nut}}$ is therefore useless. The complete expression for a TGP (Roosbeek 1994) is:

$$V=V_2+V_3+V_4+\ldots \tag{20}$$

with

$$
\begin{aligned}
V_2 &= D(r)\left(\frac{c}{d}\right)^3\left[G_{2,0}H_{2,0}+G_{2,1}H_{2,1}+G_{2,2}H_{2,2}\right] \\
V_3 &= D(r)\left(\frac{r}{a}\right)\left(\frac{c}{d}\right)^4\sin\pi\left[\frac{1}{3}\Gamma_{3,0}G_{3,0}H_{3,0}+\frac{1}{2}\Gamma_{3,1}G_{3,1}H_{3,1}+\frac{15}{3}\Gamma_{3,2}G_{3,2}H_{3,2}+\frac{5}{6}\Gamma_{3,3}G_{3,3}H_{3,3}\right] \\
V_4 &= D(r)\left(\frac{r}{a}\right)^2\left(\frac{c}{d}\right)^5\sin^2\pi\left[\begin{array}{l}\frac{1}{48}\Gamma_{4,0}G_{4,0}H_{4,0}+\frac{5}{24}\Gamma_{4,1}G_{4,1}H_{4,1}+\frac{5}{12}\Gamma_{4,2}G_{4,2}H_{4,2} \\ +\frac{35}{6}\Gamma_{4,3}G_{4,3}H_{4,3}+\frac{35}{48}\Gamma_{4,4}G_{4,4}H_{4,4}\end{array}\right] \\
&\ldots
\end{aligned}
\tag{21}
$$

Taking into account the values of $\Delta H_{2,0}\ldots\Delta H_{3,3}$, we can now calculate the additional terms to the TGP of order two and three due to the nutations in obliquity.

Presentation of the supplementary terms

We find at tables 4 and 5 a list of the waves that must be added to a TGP in order to take into account the nutations in obliquity effect with a precision of 10^{-7} radians on each wave. At the nanogal level, both Moon and Sun must be taken into account for the nutations in obliquity effect.

Table 4. Supplementary terms to the TGP of order two due to nutations in obliquity

Long-period (cos)		diurnal (sin)		semi-diurnal (cos)	
Argument	value (10^{-7})	Argument	value (10^{-7})	Argument	value (10^{-7})
055•555	297	117•655	-1	235•755	2
055•565	34	125•755	-6	237•555	3
056•554	5	127•555	-7	245•645	4
056•556	2	135•645	4	245•655	20
057•555	-94	135•655	-42	247•455	4
058•554	-5	137•455	-8	255•545	20
063•655	6	145•535	1	255•555	106
063•665	1	145•545	23	255•755	-1
065•445	3	145•555	-222	257•555	-2
065•455	33	145•755	1	263•655	-1
065•465	3	147•555	2	265•445	-1
065•655	6	153•655	2	265•455	-3
065•665	1	155•445	-1	265•655	-8
067•455	1	155•455	6	265•665	-2
073•555	5	155•645	-1	267•455	-2
075•355	3	155•655	16	272•556	3
075•555	-202	155•665	-2	273•555	50
075•565	-34	157•455	3	274•556	-1
075•575	2	162•556	-6	275•545	3
083•655	-7	163•555	-103	275•555	-148
083•665	-1	164•554	1	275•565	-20
085•455	-39	164•556	2	276•554	-1
085•465	-6	165•545	-13	277•555	-2
093•555	-6	165•555	278	283•655	-2
093•565	-1	165•565	-23	285•455	-8
095•355	-5	166•554	2	285•465	-2
095•365	-1	167•555	15	293•555	-1
0X3•455	-1	168•554	2	295•355	-1
		173•655	3	295•555	-5
		175•445	-1	295•565	-3
		175•455	16	295•575	-1
		175•465	-2		
		175•655	-1		
		183•555	2		
		185•355	1		
		185•555	32		
		185•565	13		
		185•575	1		
		193•655	1		
		195•455	6		
		195•465	3		
		1X3•555	1		
		1X5•355	1		

Table 5. Supplementary terms to the TGP of order three due to nutations in obliquity

long-period (sin)		diurnal (cos)		semi-diurnal (sin)		ter-diurnal (cos)	
Argument	value (10^{-7})	Argument	value (10^{-7})	Argument	value (10^{-7})	Argument	value (10^{-7})
065•555	-2	135•555	3	235•655	1	355•555	1
065•565	1	145•655	-1	245•555	-3	375•555	1
085•555	-1	155•555	-6	265•555	-2		
		175•555	3	285•555	-1		

Cut-off level of the series

Let us calculate the required precision on each additional wave due to the nutations, in order to have a global precision of 1 nanogal:

$$\begin{aligned} V_{2M}^{nut} &= D_M(r)\left(\frac{c}{d}\right)^3\left[G_{2,0}\Delta H_{2,0} + G_{2,1}\Delta H_{2,1} + G_{2,2}\Delta H_{2,2}\right] \\ &= D_1\left(\frac{r}{a}\right)^2\left(\frac{c}{d}\right)^3\left[G_{2,0}\Delta H_{2,0} + G_{2,1}\Delta H_{2,1} + G_{2,2}\Delta H_{2,2}\right] \end{aligned} \tag{22}$$

So,

$$\frac{\partial V_{2M}^{nut}}{\partial r} \cong \underbrace{2D_1\frac{1}{a}}_{0.8*10^{-6}\,m/s^2}\left(\frac{c}{d}\right)^3\left[G_{2,0}\Delta H_{2,0} + G_{2,1}\Delta H_{2,1} + G_{2,2}\Delta H_{2,2}\right] \tag{23}$$

So, if we want a precision of 1 nanogal on $\frac{\partial V_{2M}^{nut}}{\partial r}$, the precision on the additional terms must be 10^{-5} radians. In order to achieved a prescribed precision, all terms larger than about two percent of the prescribed level are included in the summation. So, in order to obtain a precision of 10^{-5} radians on the additional terms, we must keep all the waves of amplitude greater than $\pm\ 2*10^{-7}$ radians.
In the same way,

$$\begin{aligned} V_{3M}^{nut} &= D_M(r)\left(\frac{r}{a}\right)\left(\frac{c}{d}\right)^4 \sin\pi_M\left[\frac{1}{3}\Gamma_{3,0}G_{3,0}\Delta H_{3,0} + \frac{1}{2}\Gamma_{3,1}G_{3,1}\Delta H_{3,1} + \frac{15}{3}\Gamma_{3,2}G_{3,2}\Delta H_{3,2} + \frac{5}{6}\Gamma_{3,3}G_{3,3}\Delta H_{3,3}\right] \\ &= D_1\left(\frac{r}{a}\right)^3\left(\frac{c}{d}\right)^4 \sin\pi_M\left[\frac{1}{3}\Gamma_{3,0}G_{3,0}\Delta H_{3,0} + \frac{1}{2}\Gamma_{3,1}G_{3,1}\Delta H_{3,1} + \frac{15}{3}\Gamma_{3,2}G_{3,2}\Delta H_{3,2} + \frac{5}{6}\Gamma_{3,3}G_{3,3}\Delta H_{3,3}\right] \end{aligned} \tag{24}$$

So,

$$\frac{\partial V_{3M}^{nutl}}{\partial r} \cong \underbrace{3D_1\frac{1}{a}}_{1.23*10^{-6}\,m/s^2}\left(\frac{c}{d}\right)^4 \sin\pi_M\left[\frac{1}{3}\Gamma_{3,0}G_{3,0}\Delta H_{3,0} + \frac{1}{2}\Gamma_{3,1}G_{3,1}\Delta H_{3,1} + \frac{15}{3}\Gamma_{3,2}G_{3,2}\Delta H_{3,2} + \frac{5}{6}\Gamma_{3,3}G_{3,3}\Delta H_{3,3}\right] \tag{25}$$

If we want a precision of 1 nanogal on $\frac{\partial V_{3M}^{nut}}{\partial r}$, the precision on the additional terms must be $7*10^{-6}$ radians, and we must keep all the waves greater than $\pm\ 1.4*10^{-7}$ radians. Because the solar tides are about half the amplitudes of the lunar tides, this cut-off level is certainly sufficient also for the solar potential.

Numerical value of the maximum effect

The maximal effect of the nutations on the tides can be evaluated by using an approximation: like for the Earth's flattening effect, the maximal effect can be obtained by adding all the amplitudes of the waves listed in tables 4 and 5. We obtain therefore for the order two:

$$\begin{aligned} \left(\frac{\partial V_2^{nut}}{\partial r}\right)_{max} &= 16.89*10^{-11}\ m/s^2 \\ &= 16.89 \text{ nanogals} \end{aligned} \tag{26}$$

and for the order three:

$$\begin{aligned} \left(\frac{\partial V_3^{nut}}{\partial r}\right)_{max} &= 0.36*10^{-11}\ m/s^2 \\ &= 0.36 \text{ nanogals} \end{aligned} \tag{27}$$

5. Other effects on tidal potential at the nanogal level

In this last part, other effects having an influence at the nanogal level are considered and for each of them, we show how they can be taken into account and what is the numerical influence on the tides.

Effects that have an influence only for an epoch different of J2000.0

Time variations of e and ε

Up to now, the eccentricity (e) and the obliquity (ε) of the Earth's orbit were taken as constants. Xi Qinwen as suggested (Xi Q. 1985) that, due to the time dependence of e and ε, we should add an argument number for e and ε to Doodson's numbers. Nevertheless, not only the amplitudes but also the frequencies will change. In consequence, we will not be able to compare this new development with the others and we will miss the comparison in frequency with the well known O_1, K_1, ... tidal frequencies.
So, it will be more judicious to consider additional terms that will correct for these variations like we have done in our new potential (Roosbeek 1994). These additional terms will be added when we compute a tide for an epoch different from J2000.0. These additional terms are calculated in a similar way than for the nutations in obliquity effect for example.

Effect that require the recalculation of the TGP

Indirect planetary effects

These perturbations produce differences that can reach ±80 nanogals on the lunar and solar tides (see table 6). Xi's catalogue doesn't contain these perturbations, but Xi suggests that the indirect effect of 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 of the phase of all the partial tides that include the mean longitude of the Sun in their argument. Because any partial tide may have contributions from variations in longitude, latitude and parallax, this scheme is incomplete. By adding planetary perturbations of solar longitude to the argument of any partial tide, its argument is adjusted assuming that the partial tide is entirely due to the variation in solar longitude. Planetary perturbations to latitude and parallax, which have only slightly less consequences than those in longitude, are ignored.

Table 6. the maximum amplitudes of the direct and indirect planetary tides

	Direct (nanogals)	Indirect (nanogals) Sun	Indirect (nanogals) Moon
Mercury	0.36	?	?
Venus	5.9	20	8
Mars	0.1	6	2
Jupiter	0.7	15	30
Saturn	0.02	1	1

Lunar inequality

Most of the terms in the lunar ephemeris are solar perturbations of the Moon's orbit. There is only one lunar perturbation of the Sun's apparent motion orbit and this is due to the influence of the Moon's motion on the Earth's centre of mass. Xi Qinwen (Xi Q. 1989) suggests to include it in a first order approximation by simply adding perturbations to the mean longitude of the Sun argument. But, like previously explained, the lunar inequality in latitude and parallax cannot be corrected in this way. We must add the necessary corrections to the longitude but also latitude and parallax of the Sun before calculating the TGP. Following Merriam, this effect has a contribution in tidal gravity of about 12 nanogals.

Other effects that can be considered with additional terms

Direct planetary effects

Like Moon and Sun, the planets produce tides on the Earth's surface. Only Venus is close and massive enough to the Earth to produce tidal gravity signals larger than one nanogal (see table 6). These perturbations have a maximum effect of about 10 nanogals.

Degree five of the lunar potential

The most recent TGP consider the degree 4 for the Moon and 3 for the Sun. Nevertheless, at the nanogal level, we must include the degree 5 of the lunar potential as we can see from table 7 (see also Wenzel 1992).

Table 7. maximum tidal gravity at the Earth's surface due to the Moon and Sun

Degree	Δg Moon (μgal)	Δg Sun (μgal)
2	1370	534
3	36.8	$3.48\ 10^{-2}$
4	0.877	$2.05\ 10^{-6}$
5	$1.96\ 10^{-3}$	
6	$4.2\ 10^{-4}$	

Effects that have an influence on the tides but not on the potential

Secular variations of the arguments

A TGP is a harmonic development for which the frequencies may be written as a linear combination of the six well known Doodson's variables as well some planetary longitudes. Each of these variables has a polynomial development with respect to T, the dynamical time. These polynomials are generally developed up to T^2 or T^3. The polynomial developments generally used in tidal theory are not very accurate, e.g. the polynomial developments given in Eckert-Jones-Clark (1954). So with these definitions, the fundamental arguments must be corrected by the addition of the so-called "additional" terms, which are long-period influences of the planets. In Xi 1989 one can find a numerical estimation in function of time of the terms to be added when old expressions for the arguments are used. The influence on tidal gravity is about 200 nanogals. But with most recent definitions of the argument developments, e.g. the values given in ELP2000-85 from Chapront-Touzé and Chapront (1987), the polynomial expressions are good at the nanogal level on one century before and after the reference epoch J2000.0 without any correction.

Nutations in longitude

Besides the nutations in obliquity, there are nutations in longitude which produce variations on the Doodson and planetary arguments themselves, so that for computing one particular tide, corrections to the longitudes of the Sun and the Moon, to their perigees, and to the longitude of the lunar node must be considered. Table 3 gives the list of the corresponding perturbations. The effects of the nutations in longitude can reach 40 nanogals in gravity.

6. Conclusion

There are many effects that have an influence at the nanogal level on a TGP. Some of them have an influence only for an epoch different of J2000.0, others require the complete recalculation of the TGP, and others have an influence on tides but not on the potential itself. The Earth flattening and nutations in obliquity effects have the particularity that they can be taken into account by considering additional terms without recalculating completely the TGP. The aim of this work was to show how these effects may be included in a harmonic TGP and to give a list of the additional waves coming from these effects and that can be thus easily included in a new TGP for tide computation for instance. From the numerical values we have obtained, we can conclude that the maximal influence of the Earth flattening effect is of about 5 nanogals and that the maximal influence of the nutations in obliquity is of about 17 nanogals.

Notations

M_B	mass of the perturbing body
G	geocentric gravitational constant
ε	obliquity of the ecliptic
e	eccentricity of Earth's orbit
c	mean distance Earth-Perturbing body
d	instantaneous distance Earth- Perturbing body
a	equatorial radius of the Earth
$(r,,\theta,\gamma)$	spherical coordonates of a mass point of the Earth in a geocentric coordonate system with NS axis
φ	geocentric latitude
$D_B(r)$	Doodson scale factor for the Perturbing body
$\sin\pi_B$	sine of the horizontal parallax of the Perturbing body
χ	sidereal time
δ	declination of the Perturbing body
H	hour angle of the Perturbing body
α	right ascension of the Perturbing body
λ, β	ecliptic longitude and latitude of the Perturbing body
ψ	geocentric zenithal distance of the Perturbing body from the station position

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EARTH TIDE DATA PROCESSING PACKAGE ETERNA 3.20

Hans-Georg Wenzel,
Black Forest Observatory, Universität Karlsruhe, Englerstr. 7, D-76128 KARLSRUHE, Germany.

This is to announce that the new version 3.20 of the earth tide data processing package ETERNA is available after January 1st, 1995. The earth tide data processing package ETERNA version 3.20 allows the recording, preprocessing and analysis of earth tide observations under operation systems MS-DOS or MS-Windows on an IBM-AT compatible personal computer. We have included into the well-known earth tide analysis package ETERNA the data acquisition program RECTID, the step response evaluation program ETSTEP, and the data preprocessing programs PRETERNA and PREGRED. Several parts of the ETERNA earth tide analysis package have been rewritten and several other pieces have been added. In the analysis program ETERNA is e.g. now available the option to correct pole tides using a given transfer function or using adjusted regression parameters, and to correct the gravity variation due to variation of the length of day. All programs have been homogenized, which means that they use the same data formats (e.g. Wenzel 1995) and control parameter files. We believe that a substantial improvement with respect to flexibility and operational comfort has been achieved compared to previous versions of the package. The earth tide data processing package ETERNA version 3.20 consists of the programs

RECTID:	earth tide recording program, in MS-QuickBasic 4.0
ETSTEP:	instr. phase lag determination by step response, in FORTRAN 77
STEPPLOT:	plot of recorded step response, in MS-QuickBasic 4.0
PRETERNA:	earth tide data preprocessing, in FORTRAN 77
PREGRED:	graphical editor for earth tide data preprocessing, in C++
PREPLOT:	plot of recorded earth tide data, in MS-QuickBasic 4.0
ETERNA:	earth tide analysis, in FORTRAN 77
ETGTAB:	prediction of model earth tides, in FORTRAN 77
PLOTDATA:	plot of data and residuals, in MS-FORTRAN 5.0
PLOTHIST:	plot of a histogram of residuals, in MS-FORTRAN 5.0
PLOTSPEC:	plot of a spectrum of residuals, in MS-FORTRAN 5.0
PLOTRESA:	interactive plot of residuals, in MS-QuickBasic 4.0

The program files (source code and executable files), data files and result files are distributed on six 3.5" floppy discs, together with a program manual including listings and plots. All programs may be executed on an IBM-AT compatible personal computer under MS-DOS operating system, and the programs PRETERNA, ETERNA and ETGTAB may also be executed on a work station under UNIX operating system.

The RECTID earth tide data acquisition program allows the sampling of data from different sensors at 1 s or 5 s interval. After subtracting computed model tides from the sampled data, the residuals are displayed on the colour graphic screen of the pc. The sampled data are numerically filtered using a symmetrical FIR lowpass filter with zero phase shift; the filtered data are decimated to 1 min interval and the decimated data are stored on discette and hard disc.

The PRETERNA program (Wenzel 1994c) allows the preprocessing of 1 min earth tide and meteorological data. The data preprocessing is carried out using a remove-restore technique: At first all well-known signals (computed model tides and computed air pressure influence) are removed. The residual signal (the earth tide sensor's drift) is then cleaned (destepped, despiked, and degapped), and the known signals are added back to the cleaned residual signal. The corrected samples at 1 min interval are finally numerically filtered and decimated to 5 min samples and subsequently to hourly samples. The data preprocessing may be carried out in different steps, and may be assisted and checked by the graphical editor PREGRED (Vetter and Wenzel 1995) and the screen plot program PREPLOT. With PRETERNA may be used

- as observations: tidal potential, gravity tides, tilt tides, vertical displacements, horizontal displacements, vertical strain, horizontal strain, areal strain, shear strain, volume strain and ocean tides,
- four different tidal potential developments (Doodson 1921, Cartwright-Tayler-Edden 1973, Büllesfeld 1985 and Tamura 1987),
- up to 85 wavegroups,
- 1 additional meteorological parameter.

The ETERNA earth tide analysis program uses the least squares adjustment procedure with multi channel input to derive tidal parameters and meteorological parameters, and the spectral analysis of the residuals is used to derive standard deviations of the adjusted tidal parameters. The mathematical model of the ETERNA earth tide analysis program has been developed by Chojnicki (1973) and modified and completed by Schüller (1976), (1977a), (1977b), (1978), (1986), and Wenzel (1976a, 1976b, 1977, 1994a, b). With ETERNA version 3.20 may be used

- up to 85 wavegroups,
- up to 175 unknown parameters,
- up to 300 observation blocks,
- unlimited number of observations within each observation block,
- four different tidal potential developments (Doodson 1921, Cartwright-Tayler-Edden 1973, Büllesfeld 1985 and Tamura 1987),
- single- or multi-channel input,
- up to five additional parameters in case of multi-channel input,
- either highpass filtering of the data or drift modelling,
- in case of highpass filtering: 8 symmetric numerical FIR filters of different length and quality are available,
- in case of drift modelling: Tschebyscheff-polynomials of individual degree per observation block may be adjusted,
- unity window or Hann-window may be applied for the weights of the least squares adjustment,
- error estimation by least squares adjustment or by Fourier-spectrum of residuals.

The earth tide data processing package ETERNA 3.20 is available to anybody; the package should however not be copied and given to third parties by any user. In order to cover the expenses for copying and distributing the ETERNA package, a fee of 300 $ US has to be charged to university and research institutes.

Requests for the ETERNA 3.20 package should be submitted to (please use the order form on the last page for your convenience): Prof. Dr.-Ing. H.-G. Wenzel, Black Forest Observatory, Universität Karlsruhe, Englerstr. 7, D-76128 KARLSRUHE, Germany. Tel.: ++49-721-6082307, FAX: ++49-721-694552. e-mail: wenzel@gik.bau-verm.uni-karlsruhe.de

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