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Preface

At the 10th International Symposium on Earth Tides in Madrid, September 1985, the new working group was formed with the name

"Working Group on High Precision Tidal Data Processing"

The tasks of this working group were described by resolution no. 8: The group should examine the introduction of new advances in computing technology and instrumentation into tidal data processing and report back to the next meeting of the Permanent Commission on Earth Tides.

Therefore, it was decided to have a meeting to discuss these topics and to prepare a report to the IUGG General Assembly in Vancouver, August 1987. This meeting took place at the "Institut für Theoretische Geodäsie", University of Bonn, Oct. 8-10, 1986, and Prof M. Bonatz was our host. The members of the working group and other interested collegues took part, and more than 25 scientists from 11 countries were present.

The content of this volume covers the topics of our meeting. The onclusions drawn are printed in first place, and they allow an overview over the following papers.

Here I should like to thank all participants for their contributions, and Prof. Bonatz for his hospitality. We all acknowledge the support of the "Deutsche Forschungsgemeinschaft". I thank Prof. Melchior for publishing all the material in the Bulletin of the International Center of Earth Tides.

Gerhard Jentzsch

Conclusions

made at the meeting of the working group on

HIGH PRECISION TIDAL DATA PROCESSING

Bonn, October 8-10, 1986

On the basis of the conclusions of the previous working group on "Acquisition, Preprocessing and Analysis of Earth Tidal Data", published in BIM 94, 1985, this working group now suggests the following conclusions:

1. Instrumentation and computing technology

The working group realizes the progress made with the Super Conducting Gravimeter. We recommend to improve calibration methods (in situ), esp. by comparison with absolute instruments.

We are aware of the possibility of the additional Yukawa - term in the evaluation of G. This possible effect should be taken into account in connection with heavy mass calibration. Recognizing the problem of calibration of gravimeters we refer to the resolution no. 3, passed during the 10th International Symposium on Earth Tides in Madrid, 1985.

Regarding the measurement of gravity, tilt and strain we encourage the construction of new sensors.

The working group realizes the progress made in computer-controlled data acquisition systems. This technology provides the application of high sampling rates (down to 1 sec) and extensive use of numerical filters instead of analog filters. Due to oversampling a high resolution of more than 16 bits is achieved, which covers all long period geophysical signals, e.g. surface waves, free oscillations, tides, etc.

2. Tidal potential

The working group realizes that new developments of the tidal potential are available. We especially acknowledge the fact that two different methods are applied: The analytical development by Xi (Beijing), and the spectral development by Büllesfeld (Bonn) and Tamura (Mizusawa).

We recommend that these three authors or representatives of these institutes should form a subgroup to compare their developments under the condition that identical astronomical constants and ephemeris are applied. A report should be prepared for the next meeting.

Although developments of a higher accuracy are now available the applied development should be consistent with the resolution of the measurements. The updated Cartwright-Tayler-Edden development (505 terms) remains a standard.

We encourage work for a further improvement of these methods and applications.

4. Tidal residuals

The accuracy of loading corrections based on the maps of Schwiderski is generally not better than $\pm$ 0.2 μgal for M2 and $\pm$ 0.1 μgal for O1. For stations adjacent to the sea this may be increased up to $\pm$ 0.5 μgal.

More local maps of the shelf areas should be provided in order to refine the available global models.

5. Standard earth tide model

This group recognizes the contribution made by Mrs. Dehant to reconcile the difference in frames of reference of the gravity tidal observations and the earth tidal model.

The inertial correction should not be applied to the observations if they are compared to this model.

6. Next meeting

The members of the working group recommend another meeting in autumn 1988 (preferably in Bonn) to continue the work and to prepare a report to the 11th International Symposium on Earth Tides in Helsinki, 1989.

During this meeting the relations between satellite geodesy and tides should be investigated.

Multichannel Analysis and
Instrumental Drift of Spring Gravimeters
by Manfred Bonatz

The potential performance of geodynamical instruments can frequently not be completely utilized due to essential insufficiencies in the data evaluation tools: in general the observed signal is more or less a composition of different individual signals of different origin such as that modelling on the basis of one single process only must lead to limited results depending on the characteristics of the additionally observed processes. This situation has in the recent past been thought to be easily overcome by develloping appropriate multichannel evaluation techniques.

Unfortunately the former optimism has not been confirmed in the meantime. This is mainly due to the fact that most of the methods are based on linear regression modells which lead only in favorable cases to a sufficiently precise description of an individual physical process. But it is obvious that the problem becomes the easier the smaller the "perturbing" effect is.

The complex signal observed by any sophisticated geophysical sensor can be separated into two groups: the direct response to variations of the investigated physical quantity and the instrumental reaction to changes of evironmental parameters. The measurement of the first is by definition the goal of experimental research and is at a fixed observation point out of taking influence; the latter however, which is for instruments of tidal resolution in most cases a major part and as a matter of fact a real perturbation effect, can within limits be influenced by appropriate instrumental improvements and by screening of relevant quantities as well. Thus, taking into account the present difficulties of multichannel data evaluation, the effort must be (in terms of measuring data) to minimize the perturbation effects rather than to correct the data later for these effects by an a-priori unknown regression function. These instrumental perturbation

2/-

effects which only pretend a variation of the investigated physical quantity will in the following be designated as instrumental drift.

The main source of instrumental drift (for instruments under discussion) is the response of the sensor to variations of temperature. It should be reminded that the termal expansion of matter is of the order of 10^{-5}/°C (with one magnitude scattering), whereas the temperature coefficients of the moduli of elasticity are about 10^{-4}/°C (except some alloys for which by special thermal treatments values down to 10^{-6}/°C can be reached - but for narrow temperature ranges only). Thus, in the case of spring gravimeters it is obvious that the major problem is how to handle the thermoelastic spring effects or how to keep them sufficiently small. If in unfavorable cases a spring simultaneously defines an axis of rotation, as in torque gravimeters of Askania type, by changes of the elastic equilibrium this axis changes its position as well producing an additional torque variation due to corresponding changes of the length of the lever arm; the latter effect seems to be the main reason for the relatively high temperature sensitivity of such instruments.

The temperature induced drift behavior of Askania gravimeters demonstrates especially clearly the problem of multichannel analysis: the response of the sensor to periodical variations of the room temperature (up to daily periods) contains a linear and a nonlinear part as well. The latter represents mainly an irreversible thermoelastic effect which can be recognized by a step pattern of the instrumental drift for a corresponding sinoidal temperature variation. It is obvious that any linear regression arrangement will never be able to model such an effect.

If nonlinear responses of the sensor can not be prevented by instrumental improvements or if a too large rest remains, respectively, it is necessary to keep the environmental conditions of the sensor sufficiently constant; but in the case of reducing temperature effects the problem becomes the more complicated the larger the volume is to be stabilized. Therefore the problem has to be solved by two measures: minimizing room

temperature variations and (as for reasonable efforts the degree of temperature "constancy" is limited to about one tenth of a degree) stabilizing the temperature of the sensor meaning mainly the gas volume in the close vicinity of the sensor. It is partly a very time consuming procedure to find empirically that particular position of the temperature detector where it is most efficient to controll "constant" (better than $\pm 10^{-3}$/°C) temperature; recent experiments have shown that by appropriate positioning the temperature effect of Askania gravimeters can be reduced by a factor of ten to hundred. Nevertheless a certain rest of outside temperature variations will get through. Therefore a further reduction of the temperature effects will be achieved when placing gravimeters in boreholes, as according to our experiments already in a depth of 0.5 m diurnal (meteorological) temperature variations do not exceed 10^{-3}/°C; following that idea a borehole gravimeter is under construction.

Compared with the temperature problem minimizing of other perturbation effects (e.g. by air pressure, magnetic and electric field) seem to be less difficult except perhaps the effect of microseismically induced short period differential movements of "static" sensors.

The I.O.S. Bidston high precision tidal gravity programme: progress since 1985

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Summary

Since the Madrid Symposium in 1985 progress has continued with the completion of a six month duration experiment with La Coste and Romberg ET13 at Zurich Switzerland and the completion of a six month duration experiment with La Coste and Romberg ET10 at Edinburgh Scotland. The first provisional results from Zurich indicate that, within the uncertainties of calibration error (≏0.2%) and the uncertainties in the body tide model and ocean tide loading models the theory and observations agree well. Results from the Edinburgh experiment have yet to be analysed. Plans are well advanced for further installations during 1987 in Chur, Switzerland and Wuhan, China in order further to help constrain the present body tide and ocean tide loading models.

A new, and potentially exciting, use for well calibrated tidal gravimeters has come about with the renewed interest in geophysical measurement of the Newtonian gravity constant G. Some results from deep mines have suggested that 'G' may depend on distance and that to explain the results an additional "Yukawa" potential must be added to the currently accepted Newtonian potential. Various experiments and observations suggest the range of the extra force is likely to be of the range ~100 metres with a possible strength of 1% of the Newtonian potential. If such a variation exists the consequences for fundamental physics are enormous. I.O.S. Bidston is presently (Oct 1986) investigating the possibilities of installing La Coste and Romberg ET10 at the pumped water storage Electricity Generating Station at Dinorwic, N. Wales. At this site it is possible to install a gravimeter within 100m of the edge of a reservoir which can experience a change in mass of water of 6.10^6 tonnes (volume 30mx400mx500m) in about 5 hours on a daily basis. By measuring a time series of gravimeter data at this and other similar sites, and with careful theoretical modelling it should be possible to determine G to the required accuracy.

Parallelregistration with two Superconducting Gravimeters

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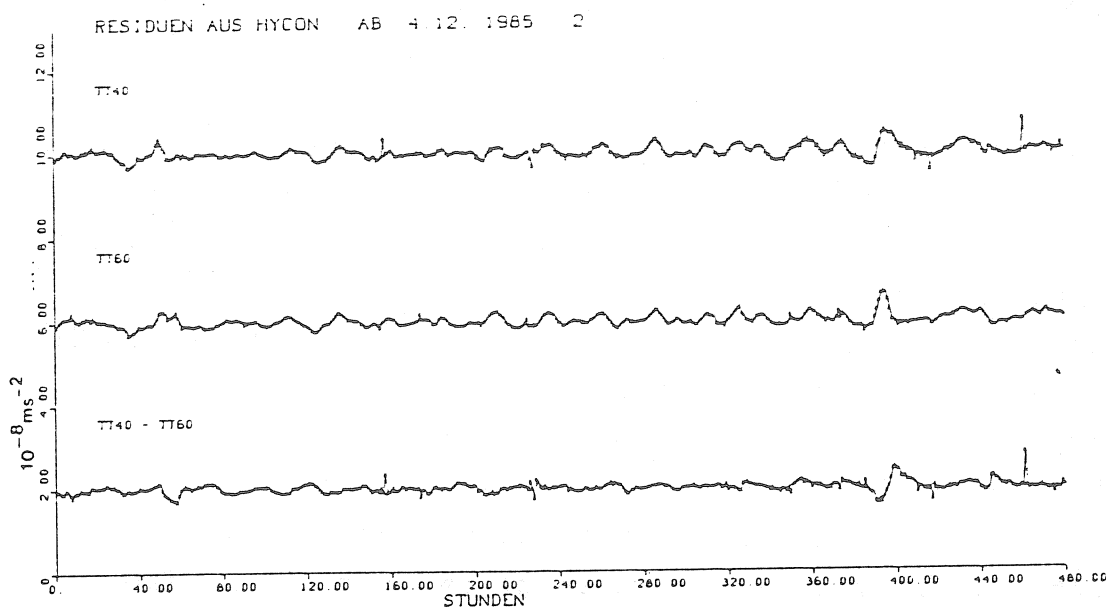
Abstract

Since June 1985 two Superconducting Gravimeters are running side by side at the earthtidal observation station Bad Homburg.

The analysis of a nine month registration show no significant difference in the tidal parameters, except for S1. The calibration factor of the second instrument is adjusted to the first older one. The residuals of the two analysis are highly correlated (80%). This leads to the assumption that the resolution of the instruments is better than $1 \cdot 10^{-10}$ ms^{-2} (the standard error of the analysis) and that the used model does not describe perfectly the registered data.

Welle	TT40		TT60		TT40		TT60	
	δ	σ	δ	σ	Phase [°]	σ [°]	Phase [°]	σ [°]
σ_1	1.1497	0.0067	1.1505	0.0054	-1.29	0.34	-1.42	0.27
Q_1	1.1408	0.0014	1.1408	0.0011	-0.36	0.07	-0.45	0.05
O_1	1.1449	0.0003	1.1449	0.0002	-0.03	0.01	-0.04	0.01
M_1	1.1430	0.0056	1.1451	0.0043	0.49	0.14	0.43	0.11
P_1	1.1473	0.0012	1.1461	0.0007	0.12	0.06	0.00	0.03
S_1	1.4423	0.2051	1.2303	0.0487	-5.25	4.10	3.93	2.27
K_1	1.1335	0.0004	1.1333	0.0002	0.06	0.02	0.07	0.01
ψ_1	1.1741	0.0212	1.1720	0.0311	-2.26	1.03	-0.32	0.77
J_1	1.1553	0.0037	1.1516	0.0028	0.09	0.18	0.23	0.14
OO_1	1.1541	0.0043	1.1539	0.0032	-0.08	0.21	0.05	0.16
V_1	1.1271	0.0223	1.1482	0.0171	0.05	1.14	0.20	0.85
ϵ_2	1.0774	0.0290	1.0912	0.0264	0.74	1.54	0.51	1.38
$_2N_2$	1.1359	0.0060	1.1412	0.0055	3.29	0.30	3.09	0.28
N_2	1.1678	0.0013	1.1670	0.0011	2.65	0.06	2.55	0.05
M_2	1.1835	0.0002	1.1835	0.0002	1.66	0.01	1.65	0.01
L_2	1.1722	0.0052	1.1732	0.0043	0.69	0.25	0.48	0.21
S_2	1.1848	0.0005	1.1855	0.0004	0.25	0.02	0.22	0.02
K_2	1.1842	0.0014	1.1860	0.0012	0.45	0.07	0.46	0.06
η_2	1.2062	0.0234	1.2004	0.0203	1.56	1.11	0.72	0.97
M_3	1.0570	0.0081	1.0606	0.0059	-0.23	0.44	-0.13	0.32

The results of the analysis of a nine-month registration with two Superconducting Gravimeters.



A section of 480 hours of the residuals of the above analysis and the difference between the records.

Some new investigations for the development of the calibration accuracy of recording gravimeters

Peter VARGA

During the last years the internal accuracy of gravity earth tide observations has been significantly improved. Recently for the amplitude ratios of the biggest waves /O_1,K_1 and M_2/ the tipical value is /0.1-0.2/%. The plot of the recordlength dependence of m.s.e. values completed on the basis of observations carried aout in Europe and collected by the I.C.E.T. /Ducarme, 1983/ shows that these error data - if the recordlength is adequate />1 year/ - are practically no time dependent. /Fig.1./ As far as the internal accuracy is concerned the most acurately determined wave is M_2, while the noise level of O_1 wave is definitely higher.

This relatively low m.s.e. level in principle allows the study of the areal distribution of the gravity earth tide parameters and the use of them for the investigation of the lateral inhomogenities of the Earth, while the theoretically expected anomalies of this origin are able to produce variations in amplitude ratio of the order of 1% /Molodensky, Kramer, 1980/.

At the same time the results of instrumental intercalibrations show, that in many cases the external accuracy of the recording instruments is much worse as the internal one /Table 1/. This result is probably connected with the fact, that the problem of the reliable in situ calibration of the instruments - based on an external, independent system - is not solved at present with needed accuracy.

For that reason we theoretically studied the possibility of gravimeter calibration by means of the gravity field of a hanged homogeneous circular ring. The principal advantages of this method are as follows

/Barta, Hajósy, Varga, 1986/:

- if we move the suspended ring along the vertical geometrical axis of a gravimeter installed on a high column we can produce a doubled gravity effect;
- uncertainties caused by the geometrical arrangement are smaller then in case of other bodies, due to the characteristics of the gravity field of the ring and they can be excluded owing to the symmetry of the artifically produced field;
- the source body does not exert a loading effect.

A serious problem of calibrations carried out in this way can be connected with the fact, that we don't know exactly in case of mechanical gravimeters which point of the instrumental system is attacked by the gravity field of the circular ring. It is obvious therefore that in this case we need a gravity field which is at his extremums as homogeneous as possible. To illustrate this the gravity field of a ring has been investigated /density=10 g/cm^3; radius of the medium circle=10 cm, radius of the small circle=6 cm/. For this body the value of the maximum is 16.549 microgal. A neighbourhood of the maximum having the dimension of 6x1 cm^2 is shown on Fig.2. One can see that the error of the distance determination in direction perpendicular to the axis of the ring is of the order of 0.1% if the uncertainly of the distance between the ring and the sensor of the instrument is the half of the radius of the medium circle. In reality this uncertainly is much smaller.

Error due to the distance determination in direction along the axis is somewhat bigger /0.3% if the uncertainly is 0.5 cm/ but it can be excluded using the symmetry of the extremums obtained if the ring is above and under the sensor of the gravimeter.

An another important problem of principle present

themselves in connection with the instrument internal reference system used for the absolute calibration. For this purpose we couldn't use the scale of the instrument. We studied for example for this purpose the reading accuracy of an Askania gravimeter between scale divisions 40 and 65 /Fig.3/. On the basis of this study it can be concluded, that the mean reading accuracy is 0.3% and the error never exceeds 0.7%. This means that for the calibration of needed 0.1% accuracy we have to found a more perfed frame of reference as the scale of the gravimeter.

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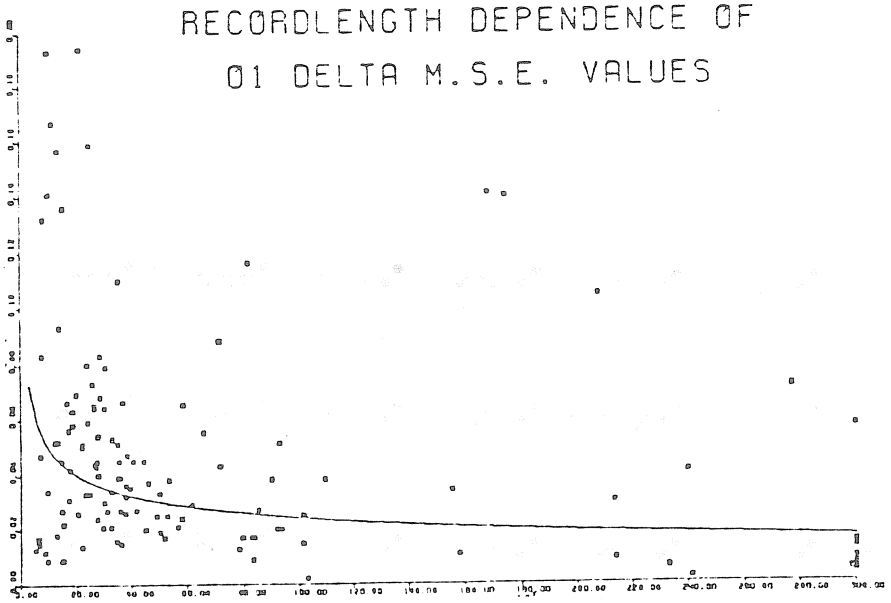
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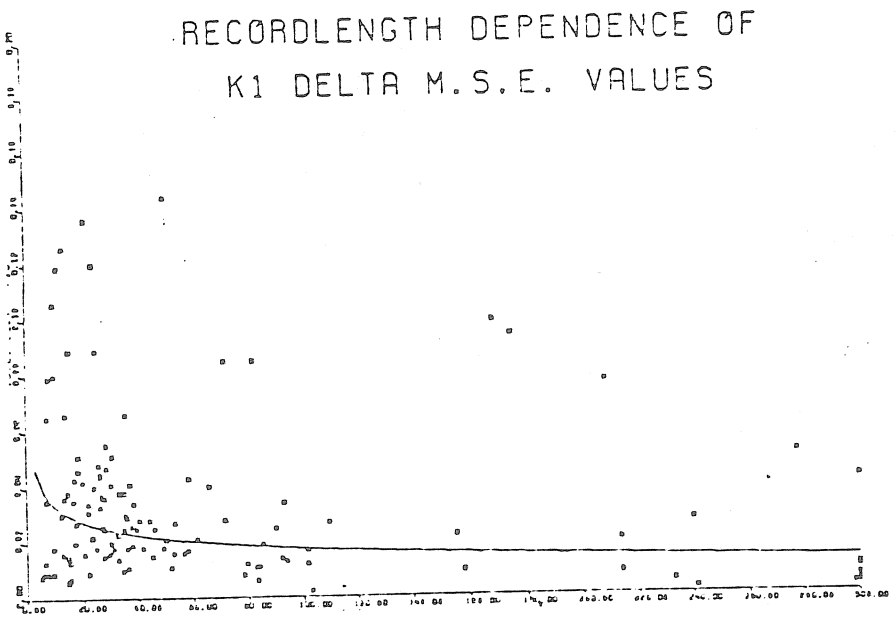
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Table 1. Results of instrument intercalibrations

Station	Used instruments	Duration of the observations in hours	Deviations between amplitude ratios /in % obtained by different instruments			Ref.
			O_1	K_1	M_2	
Bidston	L,G	5124	0.60%	1.10%	0.20%	Baker, Lennon, 1976.
Sofia	ASK	~8000	0.07	0.10	0.04	Dittfeld et al.,1981.
Mizusawa 1.	L	864	0.60	0.40	0.80	Nakagawa, 1977.
Mizusawa 2.	L	888	1.00	0.60	0.80	Nakagawa, 1977.
Hannover	ASK, ET	~4800	0.20	0.20	0.10	Torge,Wenzel,1977.
Potsdam	ASK, BN	7930	0.60	0.10	0.20	Dittfeld,Varga,1983.
Tihany	ET, BN	~5000	0.04	0.50	0.30	Varga et al.,1983.

ET - LaCoste-Romberg earth tide type gravimeter
L - LaCoste-Romberg gravimeter
ASK - Askania gravimeter
BN - Askania, reconstructed by M.Bonatz
G - Geodynamics gravimeter





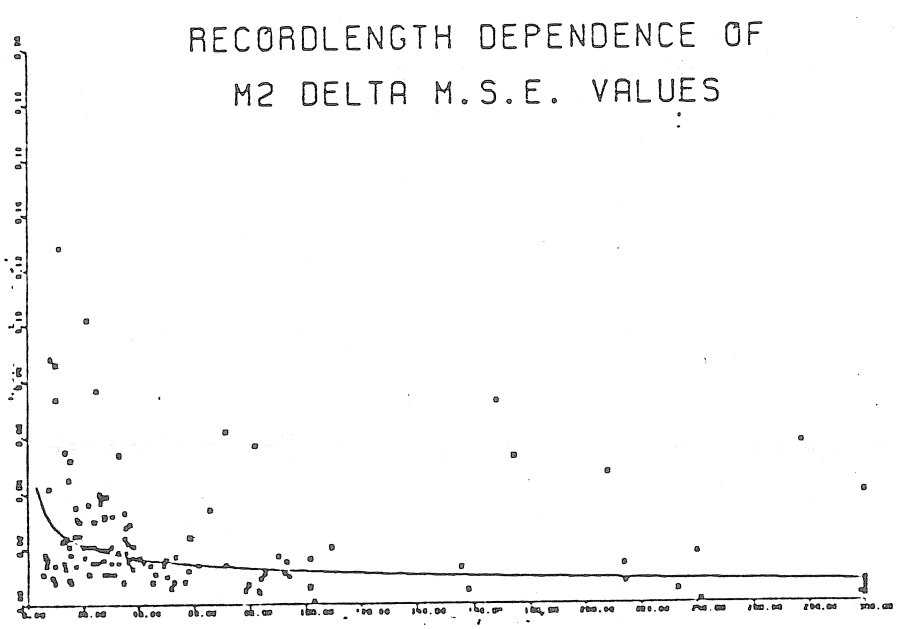


Fig.1. Recordlength dependence of m.s.e. values of O_1, K_1 and M_2 amplitude ratios

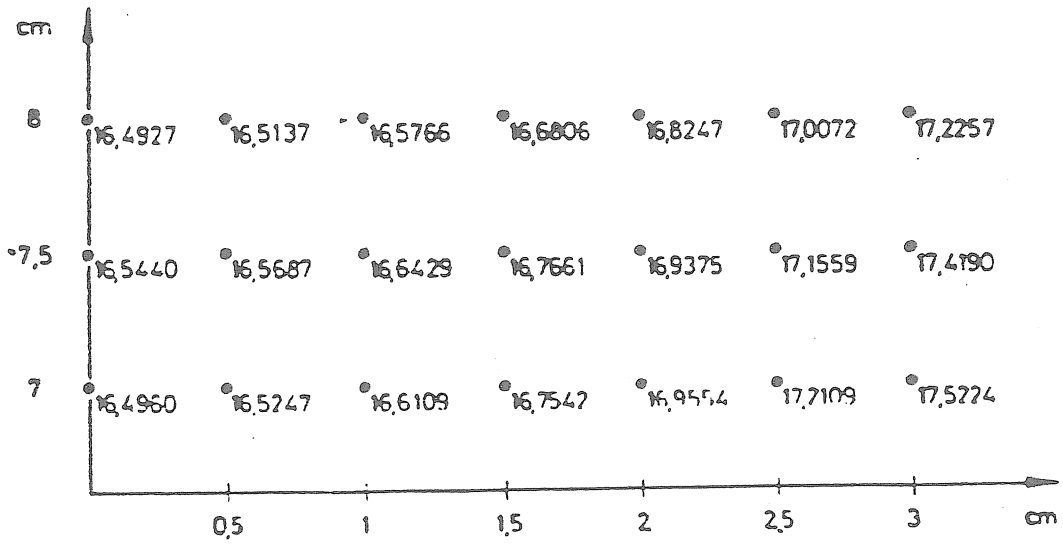


Fig.2. Part of the gravity field generated by a circular ring. Vertical axis is perpendicular to the plane of the ring values of the gravity field are in microgals.

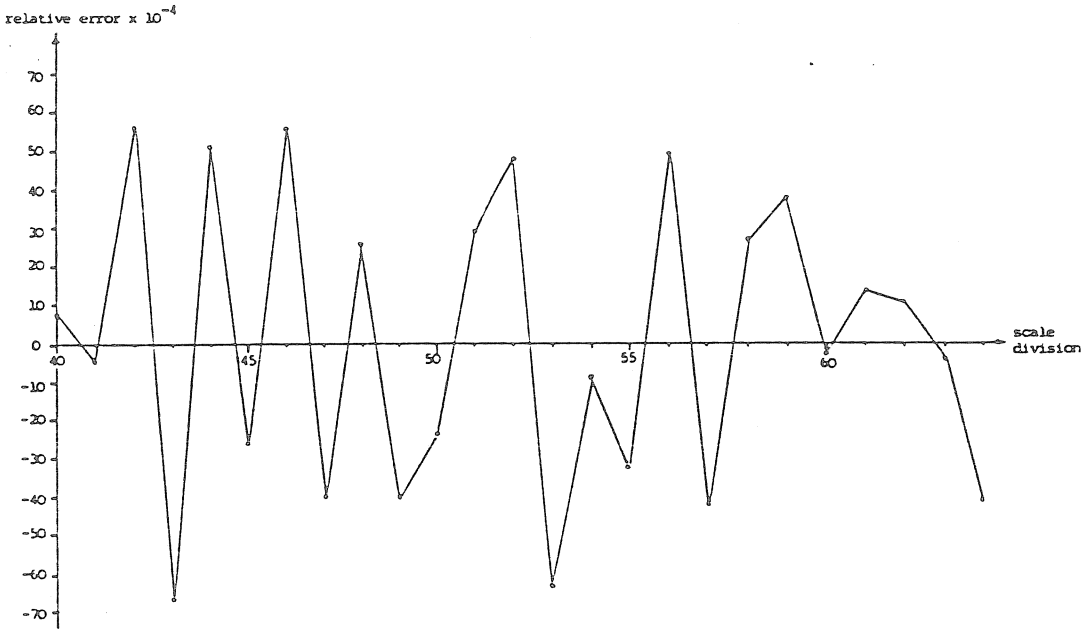


Fig.3. Reading errors of an Askania type gravimeter

The newest results on the N-S tilt in Lohja, Finland

by
Jussi Kääriäinen
Finnish Geodetic Institute

1. Introduction

Since 1977 The Finnish Geodetic Institute has carried out tilt recordings in a deep underground limestone mine in Lohja, about 50 km west of Helsinki. Recordings have been made with Verbaandert-Melchior pendula and long water tube tiltmeters as reported by Kääriäinen (1979) and Kääriäinen, Välimäki (1981) (1982).

There are two water-tube instruments in the underground laboratory at the depth of 166 m. The older, 177m long lies in the direction East-West while the shorter, 62 m long instrument is installed in the North-South direction. The recordings using this instrument began at the end of 1982 and the preliminary results of 56 days' recording were given in the meeting of The Permanent Commission for Earth Tides at the 18th General Assembly of IUGG in Hamburg 1983.

The present paper gives the results which are obtained using the same instrument but the tidal parameters are evaluated from somewhat longer time series.

2. Instrumentation

The construction of the N-S instrument is equal to that of the E-W tiltmeter. The diameter of the tube is 53 mm and it is half-filled with water. The recording method is the interferometric one with Na-light (λ = 0.58938 µm) as a source of illumination and the interference pattern is photographed on the continuously moving 35-mm film.

The reading accuracy of the interference rings on the film is 1/12 of the ring interval which means

$$\pm \frac{1}{12} \cdot \frac{1}{2} \cdot \frac{\lambda}{n} = \pm 0.02 \text{ µm}$$

where n is the refractive index of water. The figure above corresponds the tilt of around ±0.1 mseca in this 61.67 m long tube.

The azimuth of the instrument is $-0^{o}.21$ from the north, this value is determined using the gyrotheodolite Wild GAK-1. The accuracy of this azimuth determination is better than 0.5.

3. The records

The results given in this paper are evaluated from the records, performed during April 1983 - April 1985. As usually there are gaps in recording, some of them caused by technical defects. The amount of analysed days, however is 280, totally.
The data is treated using the Venedikov method with a programme, written in ICET by Ducarme (1975).

4. Results and discussion

The tidal parameters obtained from the analysis for the main tidal constituents are presented in Table 1.
According to earlier experiences with E-W instrument the obtained tidal parameters for the main waves do not alter significantly after 200 days' recording. The accuracy of the amplitude factor and the phase will not be improved, neither and thus the parameters in the Table 1 remain to be interpretated even after still longer records.
Comparing the γ-values with those obtained from E-W instrument a significantly great difference in the results can be found.
In diurnal band the differences $\gamma(EW) - \gamma(NS)$ are -0.051, -0.067 and -0.073 for the O_1, P_1 and S_1K_1 while those differences in semidiurnal band are +0.123, +0.084 and +0.118 for M_2, S_2 and N_2, respectively.
These figures are without any geophysical corrections. It seems, however, that when the observed tilt is corrected for the ocean load, the mentioned differences will decrease.
All the observed phases for the main waves are slightly negative except the phase of S_2 and K_2. The difference $\alpha(S_2) - \alpha(M_2)$ is $+6^{o}.3$ which is similar to many other European stations (Melchior 1978).

GEODEETTINEN LAITOS J KAARIAINEN

LONG WATER TUBE
STATION LOHJA, FINLAND NS HORIZONTAL COMPONENT
METHODE DES MOINDRES CARRES / FILTRES VENEDIKOV / LECTURES HORAIRES
POTENTIEL CARTWRIGHT TAYLER EDDEN / DEVELOPPEMENT COMPLET

AZIMUT -0.21N-E

WT	83	4	28	83	5	24	83	5	27	83	6	18	83	6	23	83	7	7
WT	84	1	19	84	2	4	84	2	13	84	2	27	84	3	3	84	3	25
WT	84	3	28	84	6	28	85	2	20	85	3	2	85	3	5	85	3	29
WT	85	4	10	85	4	30												

NOMBRE TOTAL DE JOURS 280 6720 LECTURES

GROUPE	SYMBOLE	AMPLITUDE	PHASE EPOQUE CENTRALE	FACT.AMPL.	EQM	DEPHASAGE	EQM	AMPLITUDE MOYENNE
1- 62	Q1	0.4081	306.83	0.7033	0.0433	3.80	3.53	0.4928
63- 88	O1	2.7314	138.60	0.7657	0.0085	-1.10	0.63	2.7256
89-110	M1	0.2925	129.38	0.7873	0.0840	-1.87	6.11	0.2684
111-120	P1	1.1661	66.12	0.7832	0.0201	-8.13	1.47	1.1815
121-143	S1K1	3.8817	319.56	0.7967	0.0062	-4.64	0.45	3.8780
144-165	J1	0.1800	129.45	0.6635	0.1038	-23.52	8.97	0.1891
166-197	OO1	0.1299	294.79	0.6775	0.1431	-17.70	12.09	0.1387

ERREUR Q.M. D 1.548884

GROUPE	SYMBOLE	AMPLITUDE	PHASE EPOQUE CENTRALE	FACT.AMPL.	EQM	DEPHASAGE	EQM	AMPLITUDE MOYENNE
198-236	2N2	0.1180	90.64	0.6511	0.0375	-13.00	3.31	0.1662
237-260	N2	0.7377	256.64	0.5779	0.0076	-6.07	0.76	0.7821
261-286	M2	3.8614	99.33	0.5748	0.0015	-0.46	0.15	3.8614
287-300	L2	0.0822	82.85	0.6283	0.0637	-5.75	5.79	0.0953
301-309	S2	1.9265	51.21	0.6217	0.0032	5.87	0.30	1.9450
310-347	K2	0.5710	105.72	0.6229	0.0107	2.35	0.99	0.5905

ERREUR Q.M. SD 0.521670

O1/K1 0.9611 1-O1/1-K1 1.1523 M2/O1 0.7507
EPOQUE DE REFERENCE TJJ= 45819.0

Table 1.

The γ-values and phases in N-S direction as measured with the water-tube tiltmeter.

The water tube instrument, used in FGI has some clear advantages. It is basically very simple, the scale comes from Nature herself and calibration is continuous and direct.
Further, just to record in the N-S direction, the azimuth is fixed and can easily be determined with sufficient accuracy.

Bearing these fundamental features in mind, no essential modifications of the instrument are to be expected in the nearest future.
The most severe disadvantage in the recording, however, is the rather tedious and time consuming reading of the films. To help this, the image of the interference pattern is discussed to be enlarged in the microfilm reading device.
The integer number and the fractions of the interference rings are already read directly to the discets of the computer.

4. Acknowledgements

The author is deeply grateful to the firm Lohjan Kalkkitehdas OY for having the tidal station in the mine and for the kind cooperation.

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Some initial experiences with the intelligent tidal data acquisition system

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Introduction

In order to enable an elimination of the disturbances (eigenoscillation, steps, spikes etc.) from tidal signals without distorting the useful information, tidal signals should be sampled at least at a rate of one sample in a minute (Jentzsch, 1981). Even uptodate mass data storing units can hardly store such quantities of data in the rather adverse conditions of the tidal observatories (low temperature, high humidity). This led in our Institute to the development of an intelligent digital data acquisition system which enables a preprocessing of the densely sampled (1-100 s) tidal records. In consequence only filtered data corresponding to the hourly time marks should be stored which can be already stored in the internal high reliability semiconductor memory of the data acquisition system.

Construction of the intelligent data acquisition system

The data acquisition system is microprocessor

controlled, its construction can be seen on Fig. 1 (Mentes, 1986). The real time clock interrupts the system in each second. In that moment the processor chooses the channel to be sampled. The signal from this channel is digitized by the 12 bit A/D converter and the processor carries out the prefiltering of the channel according to the programme. The filtered values are stored in the internal semi-conductor memory of the data acquisition system, for each channel in a given area of the memory. The data from these areas should be sent in every 15 days to a cassette tape recorder. This process does not disturb the process of filtering. The data are stored BCD-coded in the semi-conductor, while on the tape in ASCII code.

The data acquisition system should be programmed with the help of the keyboard and of the display. The followings are to be given for each channel:

- whether the channel should be sampled or not,
- the sampling rate in s,
- prefilter programme to be used.

During operation, the display shows continuously the time. The signals of the channels can be controlled independently of sampling and prefiltering by automatic or manual channel selection on the display.

There are two kinds of prefiltering programmes in the system. The first one is a simple averaging filter

which computes from the densely sampled signal an average around the hourly time mark (Fig. 2).

The second filtering procedure is a predictive filter which is described in details by Mentes (1986). The principle of this filtering is illustrated on Fig. 3. In this filtering method, the microprocessor identifies the peaks a_i of the oscillations superimposed on the tidal record. From these values, the mean values of the swings y_i are determined using Schuler averaging. From this mean value the next mean value is predicted using linear prediction. If the mean differs by more than a prescribed quantity from the predicted value, then the mean value is substituted by the predicted one.

The values obtained from this process are again filtered mathematically by the processor. The filtering is carried out continuously according to the given sampling rate and around each hourly time mark, the filtered data are stored.

First results

The described data acquisition system collected data from the analogue output signal of the horizontal pendulum with capacitive transducer constructed in our Institute over 4 months. Simultaneously, an analogue recording has also been carried out, and the deviations

of the pendulum arm have been recorded photographically immediately with the help of the mirror on the pendulum arm.

Figure 4 shows a 9-days portion of the records obtained using the three recording methods.

The digital recording has been made by bringing the analogue output signal of the capacitive pendulum on the two input channels of the system, with the simple averaging filter on the first input, and with the predictive filter on the second. The sampling rate has been chosen based on preliminary mathematical modelling (Mentes, 1986) in 20 s; the filtering was carried out on the first channel from 7 data, on the second from 6 data. There were no steps and spikes in the tidal record during the given interval. In cases when spikes occur, they are eliminated by the predictive filter, while they cause significant errors with the averaging filter.

The four months long, several times interrupted tidal record available presently is not accurate enough to enable an opinion on the efficiency of the present recording system. Therefore the curves obtained by the different methods have been compared so that the photographical and analogue electrical records have been fitted to the digital data. The average fitting error of the photorecord is 4.2 percent, that of the electrical

analogue record 2.5 percent. The difference between the values may be mostly due to a higher reading accuracy of the analogue record, as amplitudes are greater on this type than on the photorecord.

As the accuracy of the analogue records is much less than that of the digital records, nothing can be said from these values about the expected error of the digital series; they show, however, that digital recording and preprocessing do not cause a significant loss of information. A proof for the correctness of the digital record is the fact that the values from the two kinds of filtering coincide.

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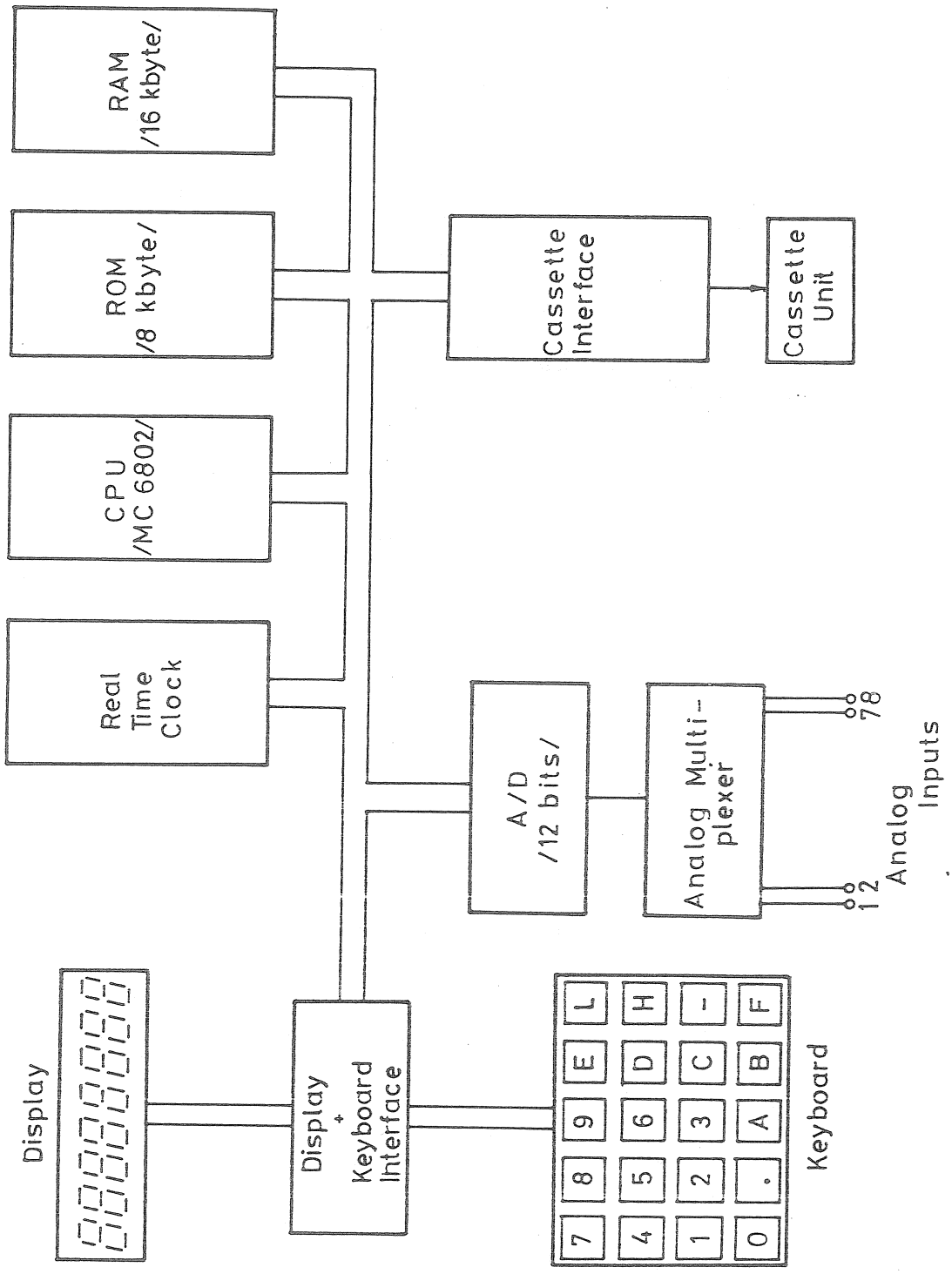

RAM
/16 kbyte/
ROM
/8 kbyte/
CPU
/MC 6802/
Real
Time
Clock
Cassette
Interface
Cassette
Unit
A/D
/12 bits/
Analog Multi-
plexer
12
78
Analog
Inputs
Display
Display
+
Keyboard
Interface
Keyboard
7 8 9 E L
4 5 6 D H
1 2 3 C -
0 . A B F

Fig. 1

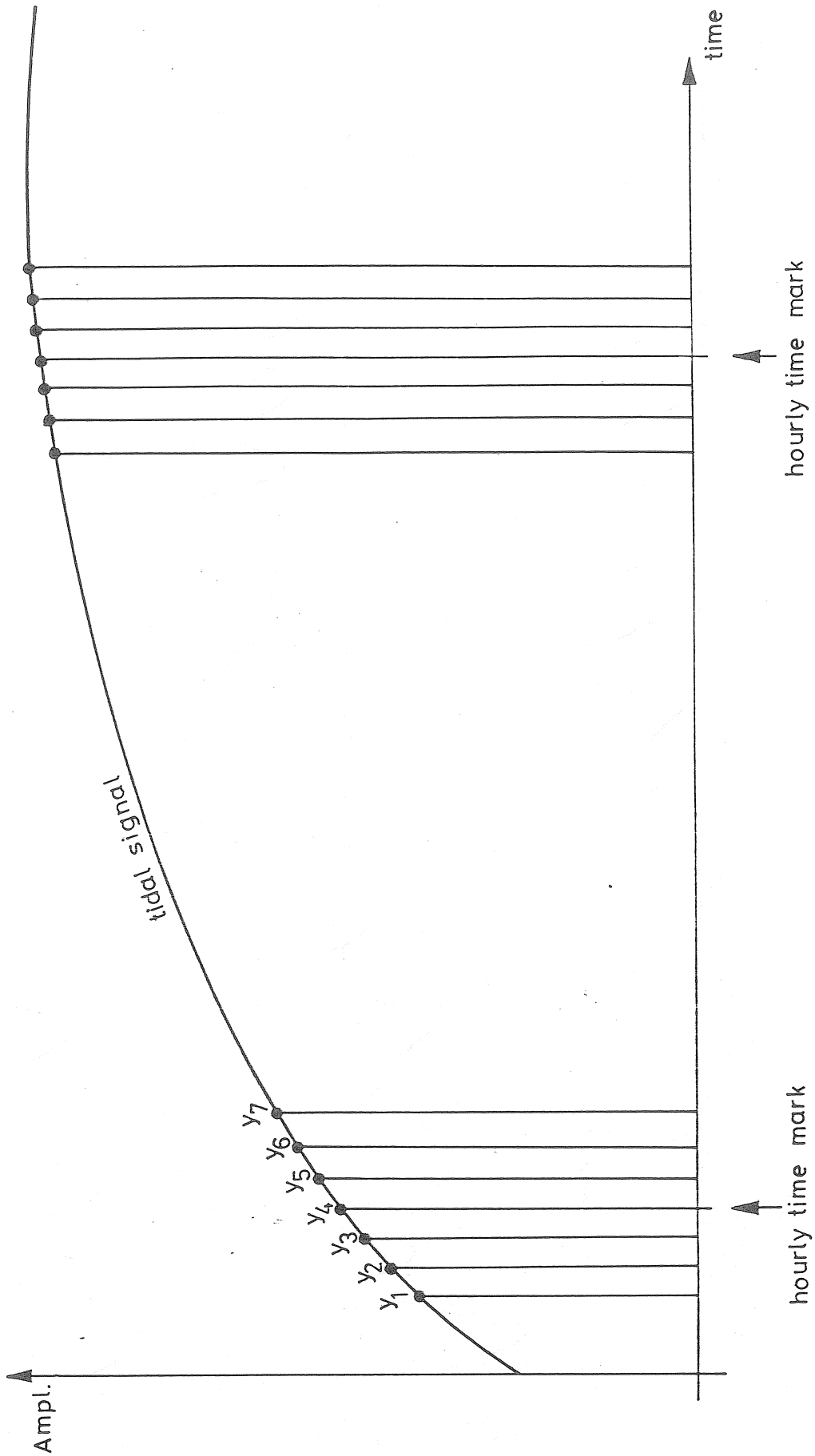

time
hourly time mark
hourly time mark
tidal signal
Ampl.
y_1
y_2
y_3
y_4
y_5
y_6
y_7

Fig. 2

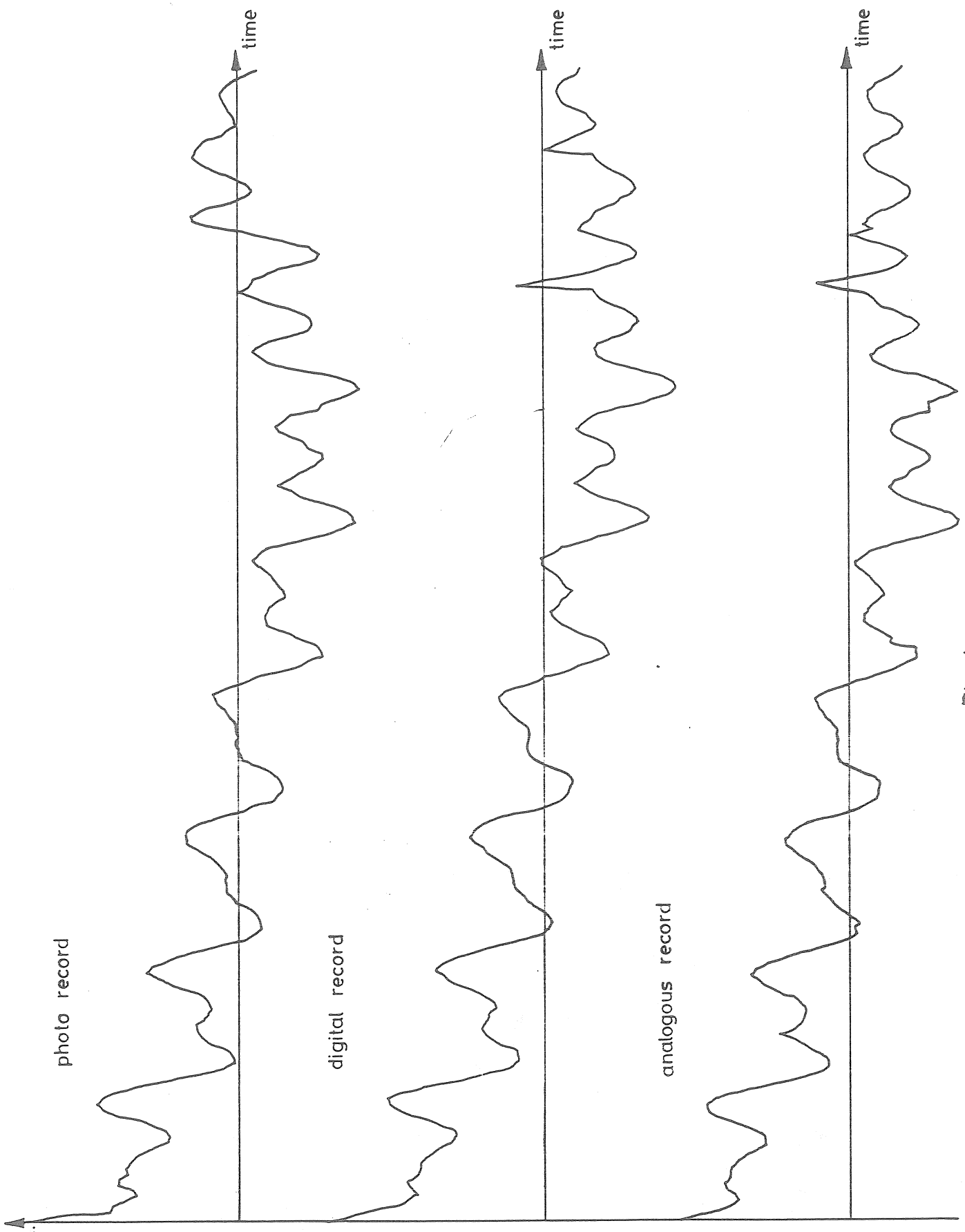

Ampl.
photo record
time
digital record
time
analogous record
time

Fig. 4

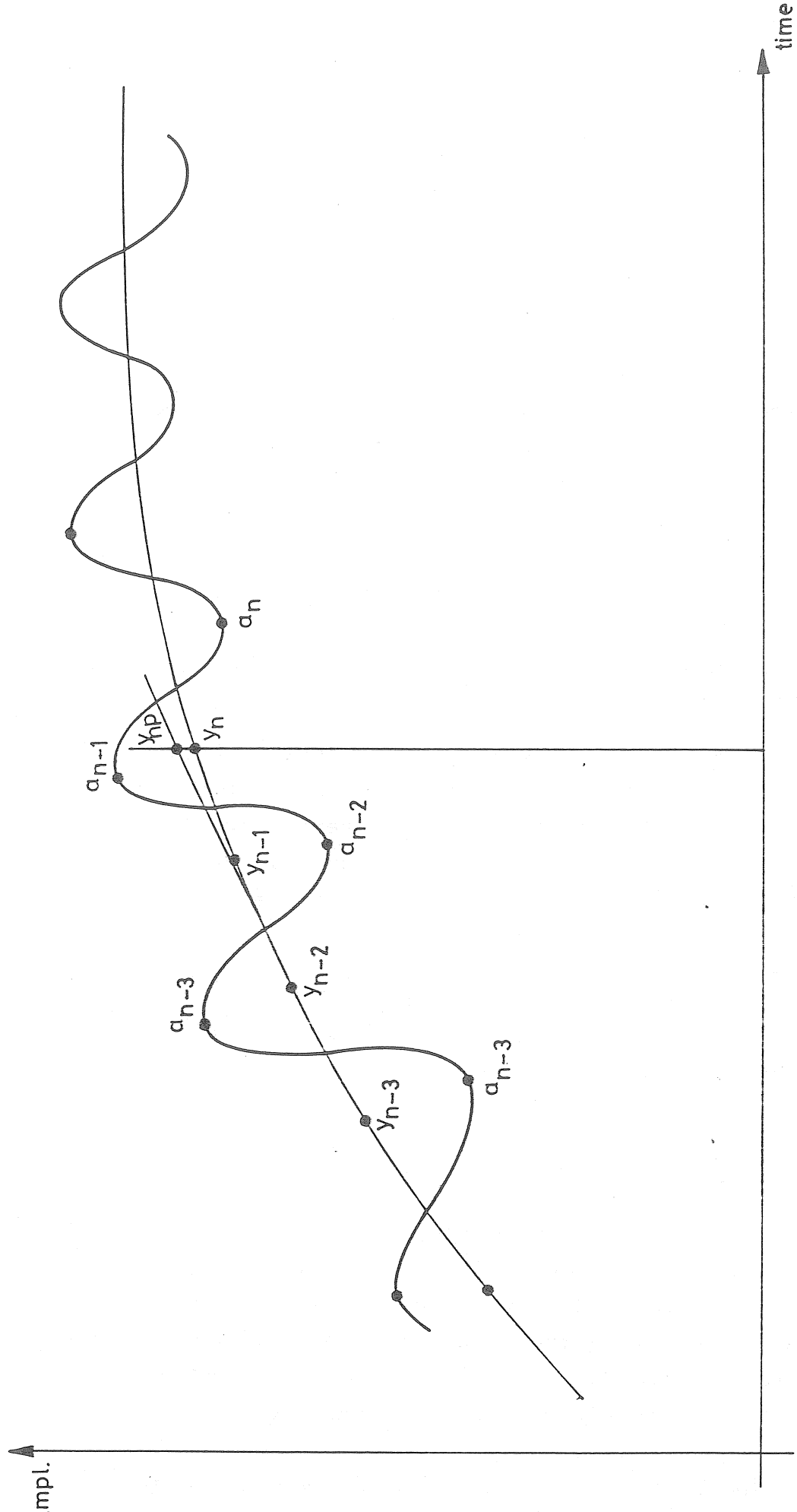


Fig. 3

High Sampling of Tidal Data

by

G. Asch and G. Jentzsch *

1. Introduction

Based upon the experiences gained with automatic data acquisition systems of a resolution of 12 bit or 14 bit, resp., and recording on magnetic tape cassettes, we tried to achieve a solution serving the following requirements:

- sufficient number of data channels for various inputs;
- high storage capicity;
- as flexible as possible regarding sampling rates, numerical filtering, instrumental control, etc.

These requirements are met applying a microprocessor controlled system. The system developed by us is already in operation in connection with three ASKANIA borehole tiltmeters recording in Norway (2) and Finland. A forth, modified unit is attached to the LaCOSTE - ROMBERG gravimeter ET - 18, which is also recording in Finland forming a three component station together with the borehole tiltmeter (Asch & Jentzsch, 1986).

In the following the hard- and software are described and first experiences are discussed.

2. Hardware and general design

The basic concept of the data acquisition system is to provide a resolution good enough to record the whole signal spectrum (surface waves, free oscillations, tides, meteorology, ...) without analog band pass filtering and different preamplifications. This is only achieved by a proper design of hardware and software applying the advantage of oversampling, e.g. high

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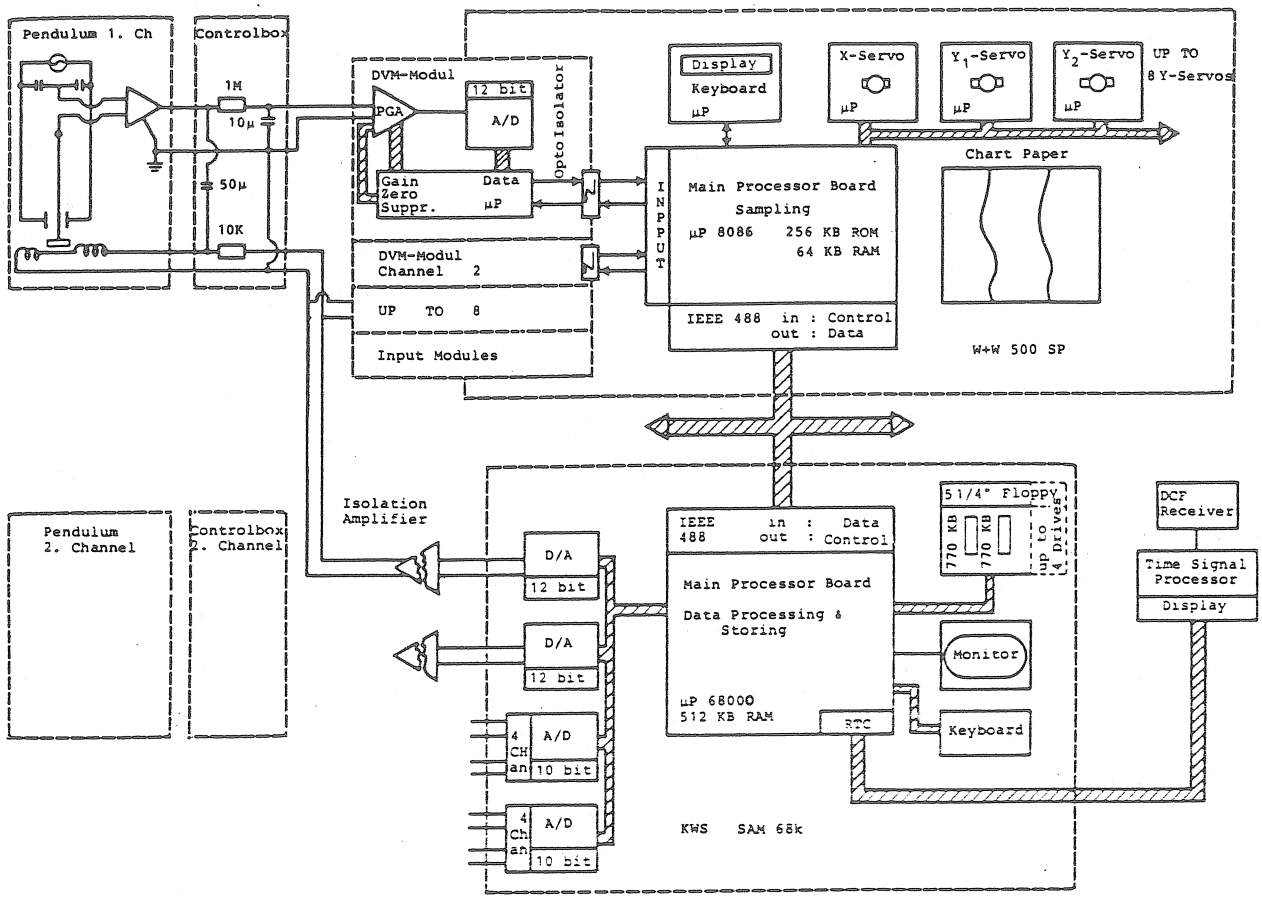


Figure 1. Block diagram of the digital data acquisition system (see text).

sampling and numerical filtering. According to fig. 1 the data acquisition system consists of three different components:

(1) Control box of the pendulum:

This contains devices for adjustment of the pendulum and calibration. Analog prefiltering is applied to the output signal. The damping of the movement of the pendulum is provided, as well as an offset compensation using the coils at the lower end of the pendulum, if necessary.

(2) A/D-conversion:

The programmable digital writer Kontron W+W 500 is used for A/D-conversion and analog output. Both channels are sampled every 10 ms and numerically filtered to 5 s cut off period, and 2 to 3 values are transferred per second. The dynamic range of one page is 12 bit, and one tidal amplitude covers about three pages.

This results in a resolution of the tidal amplitudes of about 14 bit, equivalent to about 84 dB.

(3) Digital recording system:

A microcomputer system is applied for data treatment and storage on 5 1/4" diskettes. It consists of the 32-bit microprocessor 68000 with a 16 bit data bus. First the data (2 to 3 per second) is transferred to 1 s samples. Then numerical filtering is carried out applying a FIR-operator of 358 s length and 40 s cut off. Thus 20 s samples are stored. Due to oversampling the resolution is better than 20 bit (120 dB).

The time base of the system is provided by a radio clock receiver (DCF) and a time signal processor. The whole system is controlled by the microcomputer, esp. the shifting of the window of the A/D-conversion and the offset compensation of the pendulum, if the end of the range of the A/D-converter is reached. All actions of the system are recorded, too.

More data channels are provided for the meteorological data. The whole system is battery buffered to overcome noisy mains and power fail of up to five hours.

3. Software

The concept of 'oversampling' includes recording with a very high sampling rate, low pass filtering and data reduction. According to Henkel (1986) we can calculate the improvement I in resolution in bit by the formula (1)

$$(1) \qquad I = \log_2 \sqrt{\frac{S(out)}{S(in)}}$$

where S(in) denotes the original sample interval (high sampling rate) and S(out) the sample interval of the reduced data. Applying the already mentioned values of 10 ms for S(in) and 20 s for S(out) the improvement in resolution results in 5.5 bit. But this improvement is only true if the numerical pro-

cesses applied are of low noise. In detail, the following steps are carried out:

(1) analog prefiltering:

The analog data is damped applying a filter with a corner period of about 50 s (passive RC, one stage). This is necessary to avoid effects of high noise peaks.

(2) A/D-conversion:

Due to the sampling rate one 14 bit data word per 10 ms is produced. These samples are numerically filtered with a cut off of 5 s. Then 2 to 3 samples per second are transferred to the recording system, and by a suitable interpolation one second samples are calculated. These samples are synchronized to Universal Time. This step results in an improvement of resolution of about 3.3 bit.

(3) data reduction to 20 s samples:

The numerical filter used has a cut off period of 40 s and a very steep slope. The filter was designed applying a special algorithm by (Heute, 1979). The result of the design process is a filter of 359 coefficients with a word length of 30 bit. The numerical noise is smaller than 120 dB (comp. fig. 2). The improvement in resolution of this step is about 2.2 bit.

Finally the data are stored blockwise every 20 minutes on flexible disks (5 1/4", 770 kB). Applying a binary representation with 24 bit mantissa this results in a storage capacity of almost five weeks data per disketta and channel.

4. Advantages and first experiences

The hardware and software components developed provide a digital recording system that meets the above mentioned requirements. Worth mentioning are esp. the flexibility of the system and the high resolution achieved: In the case of the pendulums two data

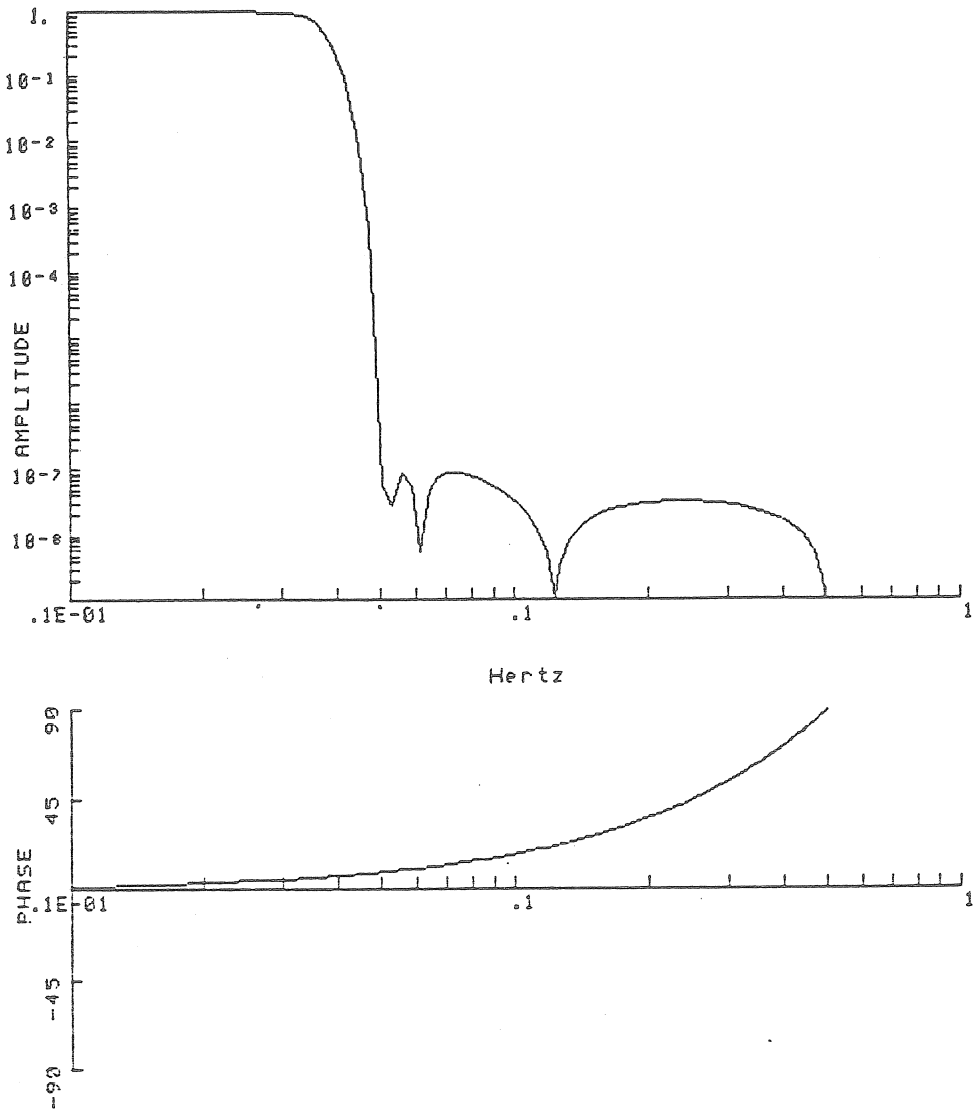


Figure 2. Gain of the numerical FIR filter; linear phase means no phase shift to center of filter intervall; input 1 s samples, data reduction to 20 s samples.

channels are provided as well as inputs from a water level sensor and a meteorological station (air pressure, several temperatures, precipitation, humidity). All the data is stored on one diskette covering a period of 14 days.

The high resolution of the data and the wide dynamic range cover all signal amplitudes of interest. No complex alias filtering is necessary, and for further processing, e.g. band pass filtering, numerical procedures can be applied.

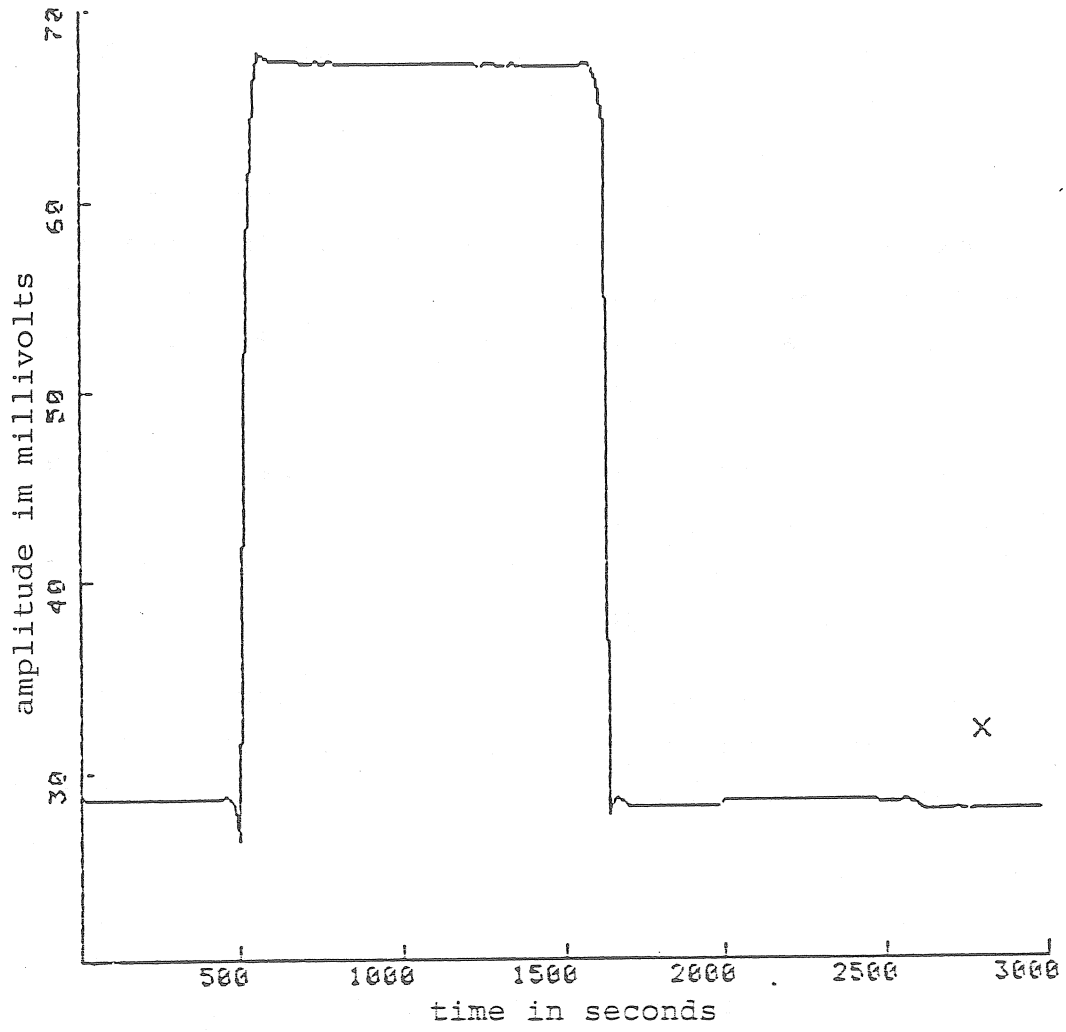


Figure 3. Calibration pulse of pendulum 1, channel X, recorded at the Norwegian station Mosvatnet; date: July 2, 1986, 14:42h.

Regarding the calibration of the tiltmeters (ball calibration) the advantages are obvious (comp. fig 3.): Previous authors could only use the analog data, were the calibration pulse could hardly be evaluated to better than 1 %. Later, the numerical treatment in connection with a suitable analog prefiltering provided an improvement of the accuracy of down to 0.2 %. Now, compared to the physical resolution of the calibration the process of recording is of neglegible influence to the result: Only the physics of the instruments and the properties of the ground signals constrain the evaluation of the calibration. During suitable periods error bars of less than 0.1 % should be considered as normal (comp. Flach et al., 1971 ; Große-Brauckmann, 1976).

5. Acknowledgements

The construction and design of the first unit of this data acquisition system was supported by the Free University of Berlin under the special study program "Long Period Crustal dynamics in Scandinavia" (Forschungsprojektschwerpunkt "Langperiodische Erdkrustendynamik in Skandinavien"). The measurements in Fennoscandia, esp. the equipments of the field stations were supported by the German Research Soc. (Deutsche Forschungsgemeinschaft) under the research grants Je 107/9-1, 9-2, 12-1, 12-2.

All three tiltmeters were modernized with the help of the Institute of Geophysics, University of Kiel. G. Lohr did much of the work himself and helped us to get started with these instruments; this is greatfully acknowledged!

The design of the data acquisiton systems and most of the considerations regarding the recording program have been carried out by the co-author G. Asch as part of his doctoral thesis.

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A NEW COMPLETE DEVELOPMENT OF THE TIDE-GENERATING POTENTIAL FOR THE EPOCH J2000.0

XI QINWEN

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At the last meeting held in Madraid I presented a paper on the development of the tide-genarating potential. That development basiclly is an algebraic deduction for the formulars of the tidal-generating potential by Doodson's original method with the computer. The original tables ($\theta-s$, λ, $\frac{c}{R}$) used in Doodson's paper were not changed except the table of the longitude of the moon, in which one numerical coefficient was corrected as a biger error. The coefficient 0.46040 for the sun was replaced by 0.459227. For this reason that development still belongs to the system J1900. The origin of time is the epoch J1900.0. At the end of the paper mentioned above we declared that the new complete development for the tide-generating potential will be obtain in the nearest future. Now I will report the new results.

As we know, according to the resolution of IUGG,the following system of astronomical and geophysical constants was taken for the 1984 edition of the Astronomical Almanac.

Equatorial radius for the earth	6378140 m
Flatting factor for the earth	1/298.257
Geocentric gravitational constant	GE=3.986005x10 cm/s
Sine paralleax of the moon	$\sin\pi=\frac{a}{c}$=0.01659251 (3422".451)
Ratio of mass of the moon to that of the earth	M/E=0.01230002
Solar parallax	8".794148
Ratio of mass of the sun to that of the earth	S/E=332946.0

The original data used by Doodson as he worked out the development were taken form Brown and Newcomb; the value of the obliquity of the ecliptic is the velue on January 1. 1900. i.e. ε=23°27'08".26. At present, Brown's coefficients have already been recalculated, the obliquity of the ecliptic have relative changes of 5×10^{-4} per century and 25×10^{-4} per century in the eccentricity of the earth orbit. The secular trends due to those are discenible in the tidal amplitudes. This is called the time dependency of tidal amplitudes. In order to solve the problem, we have rededuced a new

complete development belonged to the system of the epoch J2000.0.

In the process , the table of Eckert, Jones and Clark (referend to as EJC) and the sine parallax of the moon mentioned above have been used for the position of the moon; For the sun, the ecliptical longitude λ_S and $(\frac{C}{R})_S$ are expended as follows

$$\lambda_S=h+(2e-\frac{1}{4}e^3)\sin(h-p_s)+\frac{5}{4}e^2\sin2(h-p_s)+\frac{13}{12}e^3\sin3(h-p_s)+\cdots\cdots$$
$$(\frac{C}{R})_S=1+(e-\frac{1}{8}e^3)\cos(h-p_s)+e^2\cos2(h-p_s)+\frac{9}{8}e^3\cos3(h-p_s)+\cdots\cdots \quad (1)$$

where h is mean ecliptical longitude of the moon; p is that of the solar perigee. The value of the eccentricity of the earth orbit e used in (1) is the value corresponding to the epoch J2000.0, i.e. 0.016709113. If we take it into (1), then we have

$$\lambda_S=h+0.033417\sin(h-p_s)+0.000349\sin2(h-p_s)+0.000005\sin3(h-p_s)+\cdots\cdots$$
$$(\frac{C}{R})_S=1+0.016709\cos(h-p_s)+0.000279\cos2(h-p_s)+0.000005\cos3(h-p_s)+\cdots\cdots \quad (2)$$

The new complete development consists of 1178 hamornic terms (the original,1142 terms). We have calculated Legender polynomial of degree 4. So except the low frequency tides, diurnal tides, semi-diurnal tides and ter-diurnal tides, there are 7 terms of the quadri-diurnal tides. The new complete development have been copied into a floating diskette and available for anyone.

The table 1. is for comparing the new complete development with others. We can see the differences and the order of the time dependence for the pricnipal tidal amplitudes.

Table 1. Comparison between the different tidal developments

Wave / Epoch	Doodson 1900	CET 1900	CTE 1960	XI 1900	XI 2000	Argument
$M_o S_o$	73869	73806	73819	73803	73832	055.555
18 year	6552	6556	6555	6553	6553	055.565
Ssa	7299	7281	7275	7281	7273	057.555
Mm	8254	8254	8256	8254	8258	065.455
Mf	15642	15647	15637	15649	15642	075.555
Mtm	2995	2996	2995	2996	2994	085.455
Q1	7216	7217	7214	7218	7217	135.655
O1	37689	37694	37683	37698	37690	145.555

P1	17584	17543	17537	17539	17531	163.555
K1	53050	53011	52998	53015	53002	165.555
J1	2964	2964	2963	2965	2965	175.455
001	1623	1624	1623	1624	1623	185.555
N2	17387	17386	17388	17386	17389	245.655
M2	90812	90809	90814	90808	90823	255.555
L2	2567	2567	2567	2568	2567	265.455
S2	42358	42248	42251	42249	42254	273.555
K2	11506	11498	11491	11499	11491	275.555
M3	1188	1188	1187	1188	1187	355.555
M4					16	455.555

I wish the new complete development is convenient for research of the time dependence and tidal data processing.

Finally, I would like to put some words to touch on the problem of the system J2000.0. As a match for the new complete development, I suggest it should be considered to adopt the tidal constands corresponding to the new astronomical and geophysical constands. In this connection we got

$$G=G(\rho)=\frac{3}{4}fE\frac{M}{E}\left(\frac{a}{c}\right)^3\frac{1}{Q}\left(\frac{\rho}{a}\right)^3=G(a)\left(\frac{\rho}{a}\right)^2=D\left(\frac{\rho}{a}\right)^2 \tag{3}$$

where

$$D=G(a)=\frac{3}{4}fE\frac{M}{E}\left(\frac{a}{c}\right)^3\frac{1}{Q}=26335.938\,cm^2/s^2 \tag{4}$$

and

$$G_S(\rho)=\frac{3}{4}fS\frac{\rho^2}{c_s^3}=\left(\frac{c}{c_s}\right)^3\frac{S}{M}G(\rho)=\frac{\left(\frac{a}{c_s}\right)^3\frac{S}{E}}{\left(\frac{a}{c}\right)^3\frac{M}{E}}G(\rho)=0.45923780G(\rho) \tag{5}$$

The 5 astronomical arguments are

$$\begin{aligned}
s&=281^\circ.31643+481267^\circ.88128T-0^\circ.00161T^2+0^\circ.000005T^3\\
h&=280^\circ.46607+36000^\circ.76980T+0^\circ.00030T^2\\
p&=83^\circ.35345+4069^\circ.01388T-0^\circ.01031T^2-0^\circ.00001T^3\\
N&=125^\circ.04452-1934^\circ.13626T+0^\circ.00207T^2+0^\circ.000002T^3\\
p&=282^\circ.93835+1^\circ.71946T+0^\circ.00046T^2+0^\circ.000003T^3
\end{aligned} \tag{6}$$

and the obliquity of the ecliptic

$$\varepsilon=23^\circ.43929-0^\circ.01300T-0^\circ.00000016T^2+0^\circ.0000005T^3 \tag{7}$$

Of corse the epoch of this T is J2000.0 (i.e. Jan. 0.5. 2000, JD=2452545.0 TDB)

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THE TABLE OF THE DEVELOPMENT OF THE TIDE-GENERATING POTENTIAL J 2000.0

XI QINWEN

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BEIJING

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3-3 0 3 0 0	325.855	0	41.84303224				1	2	-8
3-3 2 1 0 0	327.655	0	41.91588589			1	2	3	-16
3-3 4-1 0 0	329.455	0	41.98873955					4	-3
3-2 0 1 0 0	335.655	-1	42.38276513					5	3
3-2 0 2-1 0	335.745	0	42.38520054					6	3
3-2 0 2 0 0	335.755	0	42.38740695			2	3	7	-57
3-2 2 0-1 0	337.545	0	42.45805419					8	3
3-2 2 0 0 0	337.555	0	42.46026060			3	4	9	-57
3-2 3 0 0-1	338.554	0	42.50132728					10	-3
3-2 4-2 0 0	339.355	0	42.53311425					11	-1
3-1-2 3 0 0	343.855	0	42.85892800					12	2
3-1-1 1 0 1	344.656	0	42.89071498					13	3
3-1 0 0-1 0	345.545	-1	42.92493343					14	1
3-1 0 0 0 0	345.555	-1	42.92713984				5	15	9
3-1 0 1-1 0	345.645	0	42.92957525			4	6	16	18
3-1 0 1 0 0	345.655	0	42.93178165		1	5	7	17	-326
3-1 1 0 0 0	346.555	0	42.96820848					18	2
3-1 1 1 0-1	346.654	0	42.97284833					19	-4
3-1 2-1-1 0	347.445	0	43.00242890					20	4
3-1 2-1 0 0	347.455	0	43.00463531			6	8	21	-61
3-1 2 1 0 0	347.655	0	43.01391893					22	-1
3-1 3-1 0-1	348.454	0	43.04570199					23	-3
3 0-2 2 0 0	353.755	0	43.40330271				9	24	7
3 0-1 0 0 1	354.556	0	43.43508968				10	25	6
3 0 0-1 0 0	355.455	-1	43.47151455					26	-1
3 0 0 0-2 0	355.535	0	43.47174355					27	-2
3 0 0 0-1 0	355.545	0	43.47394995			7	11	28	66
3 0 0 0 0 0	355.555	0	43.47615636		2	8	12	29	-1187
3 0 0 1 0 0	355.655	-1	43.48079817					30	-1
3 0 0 2 0 0	355.755	0	43.48543999					31	-3
3 0 0 2 1 0	355.765	0	43.48764639					32	-1
3 0 1 0 0-1	356.554	0	43.51722304				13	33	-6
3 0 2-2 0 0	357.355	0	43.54901001					34	3
3 0 2 0 0 0	357.555	0	43.55829364					35	-3
3 1-3 1 0 1	362.656	0	43.90661074					36	1
3 1-2 1-1 0	363.645	0	43.94547101					37	-1
3 1-2 1 0 0	363.655	0	43.94767741			9	14	38	16
3 1 0-1-1 0	365.445	0	44.01832466					39	-4
3 1 0-1 0 0	365.455	0	44.02053107			10	15	40	67
3 1 0 0 0 0	365.555	-1	44.02517288				16	41	-8
3 1 0 0 1 0	365.565	-1	44.02737929					42	-1
3 1 0 1-1 0	365.645	0	44.02760829					43	1
3 1 0 1 0 0	365.655	0	44.02981469			11	17	44	-25
3 1 0 1 1 0	365.665	0	44.03202110			12	18	45	-11
3 1 0 1 2 0	365.675	0	44.03422751					46	-2
3 1 2-3 0 0	367.255	0	44.09338472					47	1
3 1 2-1 0 0	367.455	0	44.10266835				19	48	-5
3 1 2-1 1 0	367.465	0	44.10487475					49	-3
3 2-4 2 0 0	371.755	0	44.41919847					50	1
3 2-2 0-1 0	373.545	0	44.48984571					51	-2
3 2-2 0 0 0	373.555	0	44.49205212					52	1
3 2 0-2-1 0	375.345	0	44.56269937					53	-1
3 2 0-1 0 0	375.455	-1	44.56954759					54	-1
3 2 0 0-1 0	375.545	0	44.57198299				20	55	6
3 2 0 0 0 0	375.555	0	44.57418940		3	13	21	56	-155
3 2 0 0 1 0	375.565	0	44.57639581			14	22	57	-68
3 2 0 0 2 0	375.575	0	44.57860221				23	58	-7
3 3-2 1 0 0	383.655	0	45.04571045					59	-1
3 3-2 1 1 0	383.665	0	45.04791686					60	-1

3 3 0-1-1 0	385.445	0	45.11635770			61		1
3 3 0-1 0 0	385.455	0	45.11856411		24	62		-8
3 3 0-1 1 0	385.465	0	45.12077051			63		-4
3 3 0-1 2 0	385.475	0	45.12297692			64		-1
3 3 0 0 0 0	385.555	-1	45.12320592			65		-1
3 3 0 1 0 0	385.655	0	45.12784773			66		-1
3 3 0 1 1 0	385.665	0	45.13005414			67		-1
3 4-2 0 0 0	393.555	0	45.59008516			68		-3
3 4-2 0 1 0	393.565	0	45.59229157			69		-1
3 4 0-2 0 0	395.355	0	45.66293881			70		-1
3 4 0-2 1 0	395.365	0	45.66514522			71		-1
3 4 0 0 0 0	395.555	0	45.67222244		25	72		-7
3 4 0 0 1 0	395.565	0	45.67442885		26	73		-6
3 4 0 0 2 0	395.575	0	45.67663525			74		-2
3 5-2-1 0 0	3A3.455	0	46.13445987			75		-1
3 5 0-1 0 0	3A5.455	0	46.21659715			76		-1
3 5 0-1 1 0	3A5.465	0	46.21880355			77		-1

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4-1 0 1 0 0	445.655	0	57.42383377			1	1	6
4 0 0 0-1 0	455.545	0	57.96600207				2	-1
4 0 0 0 0 0	455.555	0	57.96820848		1	2	3	16
4 1 0-1 0 0	465.455	0	58.51258319				4	-1
4 2 0-2 0 0	475.355	0	59.05695789				5	-1
4 2 0 0 0 0	475.555	0	59.06624152				6	3
4 2 0 0 1 0	475.565	0	59.06844793				7	1

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A Harmonic Development of the Tide-Generating Potential

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Abstract

Harmonic development of the tide-generating potential is numerically made with the MERIT standards and the JPL ephemerides. The expansion is made up to the 4th order potential for Moon and the 3rd one for Sun, and the secular variation of harmonic amplitude is also taken into account for the period between 1950 and 2030. All tidal constituents, whose amplitudes (in Doodson's scale) are larger than 10×10^{-6} for the 2nd order potential, 7×10^{-6} for the 3rd one and 5×10^{-6} for the 4th one, are picked up. These amplitude thresholds are correspond to 1n*Gal* for each constituent.

1. Introduction

Recent earth tide observations, such as gravity tide ones with superconductivity gravity meter or null method LaCoste G meter, have high precision and stability. These observations give us precious informations of earth's interior. In order to obtain much more knowledge of the earth, not only precise and intense observations but precise analysis methods are required.

It is needless to say that the precise theoretical tide calculation is needed in tidal analysis and prediction. Several authors (Doodson, 1921, 1954), (Cartwright and Tayler, 1971), (Cartwright and Edden, 1973), (Tsukamoto, 1980a, 1980b), (Xi, 1985), (Büllesfeld, 1985) have developed the tide-generating potential till now for these purposes. The calculation of the theoretical tide directly from the positions of Moon and Sun requires less cost compared with the synthesis of harmonic constituents to obtain same accuracy (Tamura, 1982). But in tidal analysis, the determination of the amplitude factor and phase delay of each component is rather difficult if one uses the direct calculation method except response method.

The purpose of tidal analysis is to extract useful informations from observation data. If the theoretical tide computations in analysis have some errors, the output informations should be distorted. To avoid such situation, the theoretical values must keep much higher precision than that of recent earth tide observations.

The tidal constituents tables developed by Cartwright and Tayler (1971) and Cartwright and Edden (1973) are used as a standard now, but their developments are not so perfect and harmonic coefficients are given only five digits validity. More over, after their publication of tables, astronomical constants are revised. The author developed new harmonic tables of the tide-generating potential numerically using the MERIT (A programme of international collaboration to Monitor Earth

Rotation and Intercompare the Techniques of observation and analysis) standards (1983) and the JPL (Jet Propulsion Laboratory) ephemerides (Standish and Williams, 1981). These improved tables contain up to the fourth order potential which are derived from Moon, and also contain up to the third one from Sun. The amplitude coefficients in the tables are given in six figures under decimal point. In present development, all constituets, whose amplitudes are larger than 10×10^{-6} for the second order potential, 7×10^{-6} for the third one and 5×10^{-6} for the fourth one, are picked up. These amplitude thresholds are equivalent to 0.8n*Gal* for each order.

2. Arguments

Doodson and other authors who developed tidal potential used below six arguments to express phase and angular velocitiy for each constituent.

1 τ : time angle in lunar days

2 s : Moon's mean longitude

3 h : Sun's mean longitude

4 p : longitude of Moon's mean perigee

5 N' : negative longitude of Moon's mean node

6 p_1 : longitude of Sun's mean perigee

In above arguments, τ can be expressed with s and h ignoring the aberration and the difference between the dynamical time (TD) and the univarsal time (UT) as

$$\tau = 15^\circ\times t + h - s + \lambda \qquad (1)$$

where t is the univasal time in hour, and λ is the east longitude of a site. Those variables are related to the fundamental arguments of nutation series used in the MERIT standards by

$$\left.\begin{aligned} s &= F + \Omega, \\ h &= F + \Omega - D, \\ p &= F + \Omega - l, \\ N' &= -\Omega, \\ p_1 &= F + \Omega - D - l' \end{aligned}\right\} \quad (2)$$

where

F : Moon's mean elongation from node,

D : Moon's mean elongation from Sun,

Ω : longitude of Moon's perigee,

l : Moon's mean anomaly,

l' : Sun's mean anomaly.

In order to develope the tidal potential up to 10×10^{-6} amplitude constituents for the second order, following eight arguments are necessary. They are defined by the author as

$$\left.\begin{aligned} f_1 &= 15^\circ\times t + \alpha_m - s + \lambda, \\ f_2 &= s + \Delta s, \\ f_3 &= h + \Delta h, \\ f_4 &= p, \\ f_5 &= N', \\ f_6 &= p_1, \\ f_7 &: \text{ period of Jupiter's opposition.} \end{aligned}\right\} \quad (3)$$

f_8 : period of Venus's conjunction

where α_m is the right ascention of a *supposed* object to define the univasal time. Δs and Δh denote the long period perturbations in the longitude of Moon and Sun, respectively. These corrections of Δs and Δh are added to reduce the phase shift for the principal constituents such as O_1, K_1, M_2, S_2 and K_2. The existance of the arguments f_7 and f_8 does not mean the direct tidal effect by Jupiter and Venus, but the indirect effect of Sun generating potential by peturbing the earth's orbit.

Concerning the argument f_1, one should use α_m instead of h. There are differences between α_m and h in two points. For the first one, the time argument for α_m is UT, but h is TD. For the second one, there is a permanent difference of the aberration (about 20.″5) between their constant terms. If one uses h in place of α_m like Doodson's definition, tidal potential becomes to be calculated based on "apparent" places of Moon and Sun. On the other hand, if one uses α_m, tidal potential is calculated based on "true" places. In other words, when one compute the angle hour of an object whose right ascension is α, he calculates $h-\alpha$ in former case, and $\alpha_m-\alpha$ in later case. Though this difference between apparent and true places is only 20.″5, this gives systematic phase shift for all constituents. For example, all components of semidiurnal species are caused 0.°01 phase shift by this difference.

Since the gravitation operates as an "action at a distance"

(note gravity field is not energy propagation nor particle movement!), true place should be used in dynamics computations. (In addition, the aberration is a phenomenon propotinal to v/c, where v is the velocity of the earth's revolution, and c is the light velocity. Some forces propotinal to $(v/c)^2$ exist in theory of relativity.)

The eight arguments in equations (3) are concretely denoted as follows (Aoki *et al.*, 1982), (Kubo, 1980), (Bretagnon, 1982) (Chapront, 1982).

$$\left.\begin{aligned}
a_m &= 280.^\circ4606184 + 36000.^\circ7700536t_u + 0.^\circ00038793t_u^2 \\
&\qquad - 0.^\circ0000000258t_u^3, \\
s &= 218.^\circ316656 + 481267.^\circ881342t_d - 0.^\circ001330t_d^2, \\
h &= 280.^\circ466449 + 36000.^\circ769822t_d + 0.^\circ0003036t_d^2, \\
\Delta s &= 0.^\circ0040\cdot\cos(\ 29^\circ + 133^\circ t_d\ ), \\
\Delta h &= 0.^\circ0018\cdot\cos(\ 159^\circ + 19^\circ t_d\ ), \\
f_4 &= 83.^\circ353243 + 4069.^\circ013711t_d - 0.^\circ010324t_d^2, \\
f_5 &= 234.^\circ955444 + 1934.^\circ136185t_d - 0.^\circ002076t_d^2, \\
f_6 &= 282.^\circ937348 + 1.^\circ719533t_d + 0.^\circ0004597t_d^2, \\
f_7 &= 248.^\circ1 + 32964.^\circ47t_d, \\
f_8 &= 81.^\circ5 + 22518.^\circ44t_d
\end{aligned}\right\} \quad (4)$$

where t_u is the universal time measured from 2000 Jan. 1 12^h UT1 (JD 2451545.0) in 36525 days unit, and t_d is the dynamical time measured from 2000 Jan. 1 12^h TD in 36525 days unit. The arguments s, h, p, N' and p_1 are slightly differ from the MERIT standards. But those differences are small enough to calculate the tidal potential.

3. Method of Development

Since the author developed the tide-generating potential numerically, his method is essentially the same as the way by Cartwright and Tayler (1971). The expansion process is simply explained as follows. At first, the tide-generating potential is calculated directly from the positions of Moon and Sun. Next, suitable sets of tidal constituents and their arguments are assumed. Lastly, the amplitude coefficients are determined by least square method, and the phases are checked whether the assumption of arguments is right or not.

In the development, there are some distinctive features compared with their expansion method. (1) Eight fundamental arguments are defined as mentioned in the previous section. (2) The filters, that Cartwright and Tayler designed to resolve the tidal constituents in the same species into subgroups defined by the argument f_2, are not used. Therefore, all amplitude coefficients of constituents in the same order and same species are determined in batch processing. The improvement of computer ability makes such a simple method possible. (3) Sampling

intervals for calculation of the tidal potential by direct method are 24, 6, 4, 3 and 2 hours for the long period, diurnal, semidiurnal, terdiurnal and 1/4 diurnal species, respectively. (4) In order to obtain the secular trends of the amplitudes of large constituents, four sets of coefficients are determined varying central epoch of 1960, 1980, 2000 and 2020 with 18.6 year data length. Using the preliminary determination of the secular trends of M_0S_0, K_1, O_1, M_2 and S_2, the variations of those principal terms are more precisely determined in the main computation. (5) Adopted ephemerides by JPL are given as numerical tables.

Figure 1 shows the flow of development process. The tables developed by Cartwright, Tayler and Edden are used as an initial set of the tidal constituents in this process.

As to paired constituents, whose frequencies differ only by $2f_6$, Xi's development is also initially used. For example, φ_1 constituent is formed with two terms of $f_1+f_2+2f_3-2f_6$ and $f_1+f_2+2f_3$. Numerical development can determine the amplitudes of such paired terms if the angular velocities are known, but it cannot determine what the coefficients of f_6 are. If the one of a pair's amplitude is smaller than 12×10^{-6}, those terms are represented by one term, whose angular velocity is the same as that of the bigger one, and whose amplitude is signified by "bigger one minus smaller one". This simplification is possible because the phase difference of $2f_6$ is $205^\circ \approx 180^\circ$ (see fig. 2).

The tidal potential P_{30} (third order long period tide) is

developed up to the 4×10^{-6} amplitude terms in present development, though the expansion threshold of the third order is adopted to 7×10^{-6}. Because Doodson mistaked its nomalization factor 2 for $2/\sqrt{5}$, that scale is also used in this time.

The constants used in present development are listed in table 1. The sine parallax of Moon is not included in the standards, but it is used conveniently. There is no trouble with the precision in the theoretical tide calclulations, if one uses the same value of Moon's sine parallax used in present development.

4. Results

The results of the harmonic development are shown in tables 2-20 to 2-44. The Moon origin constituents and Sun origin ones, which have the same frequencies, are combined in one term in the tables.

Noman but for Büllesfeld has developed the fourth order potential till now, because they are small and most cases negligible. But some constituents have the same frequencies of the second order terms, and have relative amplitudes of 10^{-3}. So the tidal factors of some second order potential may suffer modulation if one does not take the fourth order one into consideration in tidal analysis.

Several constituents are detected in present development, which are not listed in Xi's(1985) tables, though his threshold is 10×10^{-6} as same as mine. In opposition, several terms listed

in his tables have less than 5×10^{-6} amplitude or do not appear, and some small terms have opposite signs (table 3). This discrepancy may be caused by his treatment of five digits operations or the difference of nutation calculation.

The internal error of the amplitude coefficient, which is estimated from the deviation of amplitudes in four epochs, is $\pm1\times10^{-6}$ in present development. But some constituents (about 2% terms) have rather large deviations. Such large deviations may be caused by the small amplitude side bands.

In the second order potential, there are a few terms whose amplitudes are slightly larger than the threshold level of 10×10^{-6}, and whose frequencies and phases cannot be denoted by the combination of the eight arguments. They have angular velocities of about 0.4671 °/*h*, 12.8499 °/*h* and 13.3918 °/*h*, and have amplitudes of about 12×10^{-6}. This result shows that more precise harmonic development is difficult if one uses only traditional arguments which are defined by Doodson or the author.

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Table 1. Constants used in present development.

Geocentric Constant of Gravitation	$GE = 3.98600448\times10^{14}\mathrm{m^3s^{-2}}$
Heliocentric Constant of Gravitation	$GS = 1.3271244\times10^{20}\mathrm{m^3s^{-2}}$
Earth-Moon Mass Ratio	$\mu = 0.012300034$
Equatorial Radius of the Earth	$Re = 6378137\mathrm{m}$
Astronomical Unit	$au = 1.4959787066\times10^{11}\mathrm{m}$
Moon's Sine Parallax	$\sin \Pi = 3422.''448$

Table 2-20. Tidal harmonics derived from the potential P20. The amplitudes are normalized in Doodson's scale. The valiable T is the time measured from J2000.0 in 36525 days unit.

No.	Arguments Tau	S	H	P	N'	P	J	V	Angular V. deg./hour	Amplitude (-0.5 =< T =< 0.3) A	+ B * T
1	0	0	0	0	0	0			0.00000000	0.738300	0.000241
2	0	0	0	0	1	0			0.00220641	-0.065547	0.000027
3	0	0	0	0	2	0			0.00441281	0.000642	-0.000001
4	0	0	0	2	1	0			0.01149003	-0.000089	
5	0	0	0	2	2	0			0.01369644	-0.000034	
6	0	0	1	-1	0	0			0.03642683	-0.000020	
7	0	0	0	0	0	0	1	0	0.03760492	0.000011	
8	0	0	1	0	-1	-1			0.03886027	0.000098	
9	0	0	1	0	0	-1			0.04106668	0.011549	-0.000024
10	0	0	1	0	0	1			0.04107060	-0.000609	
11	0	0	1	0	1	-1			0.04327309	-0.000073	
12	0	0	1	0	1	1			0.04327701	0.000036	
13	0	0	0	0	0	0	0	2	0.05137677	-0.000011	
14	0	0	2	-2	-1	0			0.07064725	-0.000048	
15	0	0	2	-2	0	0			0.07285365	0.000732	0.000001
16	0	0	2	-2	1	0			0.07506006	-0.000073	
17	0	0	2	0	0	-2			0.08213336	0.000288	
18	0	0	2	0	0	0			0.08213728	0.072732	-0.000081
19	0	0	2	0	1	0			0.08434369	-0.001799	-0.000003
20	0	0	2	0	2	0			0.08655009	-0.000400	
21	0	0	2	0	3	0			0.08875650	0.000012	
22	0	0	3	-2	0	-1			0.11392033	0.000025	
23	0	0	3	0	0	-1			0.12320396	0.004246	-0.000014
24	0	0	3	0	1	-1			0.12541037	-0.000074	
25	0	0	3	0	2	-1			0.12761677	-0.000018	
26	0	0	4	0	0	-2			0.16427064	0.000173	
27	0	1	-4	1	-1	0			0.38717737	-0.000028	
28	0	1	-4	1	0	2			0.38938770	0.000021	
29	0	1	-4	3	0	0			0.39866740	0.000014	
30	0	1	-3	1	-1	1			0.42824797	-0.000051	
31	0	1	-3	1	0	1			0.43045438	0.000675	-0.000001
32	0	1	-3	1	1	1			0.43266078	-0.000042	
33	0	1	-2	-1	-2	0			0.45782461	-0.000056	
34	0	1	-2	-1	-1	0			0.46003102	-0.000153	
35	0	1	-2	1	-1	0			0.46931465	-0.001133	0.000001
36	0	1	-2	1	0	0			0.47152105	0.015791	0.000005
37	0	1	-2	1	1	0			0.47372746	-0.001025	0.000001
38	0	1	-2	1	2	0			0.47593387	0.000010	
39	0	1	-1	-1	-1	1			0.50110162	-0.000046	
40	0	1	-1	-1	0	1			0.50330803	0.000507	
41	0	1	-1	-1	1	1			0.50551443	-0.000027	
42	0	1	-1	0	-1	0			0.50574147	0.000033	
43	0	1	-1	0	0	0			0.50794788	-0.000458	-0.000001
44	0	1	-1	0	1	0			0.51015429	0.000032	
45	0	1	-1	1	0	-1			0.51258773	-0.000109	
46	0	1	0	-1	-2	0			0.53996189	0.000068	
47	0	1	0	-1	-1	0			0.54216830	-0.005419	0.000003
48	0	1	0	-1	0	0			0.54437471	0.082569	0.000027
49	0	1	0	-1	1	0			0.54658111	-0.005358	0.000007
50	0	1	0	-1	2	0			0.54878752	0.000052	

51	0 1 0 0 0-1	0.54901456	0.000068	
52	0 1 0 1 0 0	0.55365833	-0.004410	0.000004
53	0 1 0 1 1 0	0.55586474	-0.001798	0.000001
54	0 1 0 1 2 0	0.55807115	-0.000483	
55	0 1 0 1 3 0	0.56027755	0.000024	
56	0 1 1-1-1-1	0.58323498	0.000033	
57	0 1 1-1 0-1	0.58544138	-0.000426	
58	0 1 1-1 1-1	0.58764779	0.000017	
59	0 1 1 0 0 0	0.59008516	0.000027	
60	0 1 1 0 1 0	0.59229157	0.000011	
61	0 1 1 1 0-1	0.59472501	-0.000015	
62	0 1 1 1 1-1	0.59693142	-0.000009	
63	0 1 2-1 0 0	0.62651199	-0.001148	0.000001
64	0 1 2-1 1 0	0.62871839	-0.000574	
65	0 1 2-1 2 0	0.63092480	-0.000103	
66	0 1 3-1 0-1	0.66757866	-0.000055	
67	0 1 3-1 1-1	0.66978507	-0.000026	
68	0 2-5 2 0 1	0.90197543	0.000022	
69	0 2-4 0-1 0	0.93155207	-0.000025	
70	0 2-4 0 0 2	0.93376240	0.000041	
71	0 2-4 2-1 0	0.94083570	-0.000018	
72	0 2-4 2 0 0	0.94304211	0.000257	
73	0 2-4 2 1 0	0.94524851	-0.000017	
74	0 2-3 0-1 1	0.97262267	0.000023	
75	0 2-3 0 0 1	0.97482908	0.000902	-0.000001
76	0 2-3 0 1 1	0.97703549	-0.000057	
77	0 2-3 1 0 0	0.97946893	-0.000022	
78	0 2-2-2-1 0	1.00440573	-0.000013	
79	0 2-2 0-2 0	1.01148295	0.000029	
80	0 2-2 0-1 0	1.01368935	0.000977	
81	0 2-2 0 0 0	1.01589576	0.013695	0.000004
82	0 2-2 0 1 0	1.01810217	-0.000879	
83	0 2-2 0 2 0	1.02030857	0.000010	
84	0 2-2 2 0 0	1.02517939	-0.000089	
85	0 2-2 2 1 0	1.02738579	-0.000036	
86	0 2-2 2 2 0	1.02959220	-0.000013	
87	0 2-1-2 0 1	1.04768273	0.000083	
88	0 2-1-1 0 0	1.05232259	-0.000074	
89	0 2-1 0-1-1	1.05475603	-0.000029	
90	0 2-1 0 0-1	1.05696244	-0.000151	
91	0 2-1 0 0 1	1.05696636	0.000474	
92	0 2-1 0 1 1	1.05917277	0.000100	
93	0 2 0-2-1 0	1.08654301	-0.000360	
94	0 2 0-2 0 0	1.08874941	0.006767	0.000003
95	0 2 0-2 1 0	1.09095582	-0.000439	
96	0 2 0-1 0-1	1.09338926	0.000015	
97	0 2 0 0 0 0	1.09803304	0.156303	-0.000165
98	0 2 0 0 1 0	1.10023945	0.064805	-0.000035
99	0 2 0 0 2 0	1.10244585	0.006060	0.000001
100	0 2 0 0 3 0	1.10465226	-0.000130	
101	0 2 1-2 0-1	1.12981609	-0.000066	
102	0 2 1-1 0 0	1.13445987	0.000024	
103	0 2 1 0 0-1	1.13909972	-0.000537	
104	0 2 1 0 1-1	1.14130612	-0.000141	
105	0 2 2-2 0 0	1.17088669	-0.000469	
106	0 2 2-2 1 0	1.17309310	-0.000181	
107	0 2 2-2 2 0	1.17529951	-0.000022	
108	0 2 2 0 2 0	1.18458313	-0.000068	
109	0 2 2 0 3 0	1.18678954	-0.000025	

110	0 2 3-2 0-1	1.21195337	-0.000019	
111	0 3-5 1 0 1	1.44635013	0.000046	
112	0 3-4 1-1 0	1.48521041	0.000041	
113	0 3-4 1 0 0	1.48741681	0.000413	
114	0 3-4 1 1 0	1.48962322	-0.000030	
115	0 3-3-1 0 1	1.51920379	0.000158	
116	0 3-3-1 1 1	1.52141019	-0.000012	
117	0 3-3 1 0 1	1.52848741	0.000269	
118	0 3-3 1 1 1	1.53069382	0.000105	
119	0 3-2-1-1 0	1.55806406	0.000222	
120	0 3-2-1 0 0	1.56027047	0.002167	
121	0 3-2-1 1 0	1.56247687	-0.000140	
122	0 3-2 1 0 0	1.56955409	0.005684	-0.000006
123	0 3-2 1 1 0	1.57176050	0.002356	-0.000001
124	0 3-2 1 2 0	1.57396691	0.000213	
125	0 3-1-3 0 1	1.59205744	0.000010	
126	0 3-1-2 0 0	1.59669729	-0.000008	
127	0 3-1-1 0-1	1.60133714	-0.000035	
128	0 3-1-1 0 1	1.60134107	0.000279	
129	0 3-1-1 1 1	1.60354747	0.000097	
130	0 3-1 0 0 0	1.60598092	-0.000157	
131	0 3-1 0 1 0	1.60818733	-0.000066	
132	0 3-1 1 0-1	1.61062077	-0.000059	
133	0 3-1 1 1-1	1.61282718	-0.000020	
134	0 3 0-3-1 0	1.63091771	-0.000020	
135	0 3 0-3 0 0	1.63312412	0.000543	
136	0 3 0-3 1 0	1.63533053	-0.000035	
137	0 3 0-1 0 0	1.64240775	0.029926	-0.000033
138	0 3 0-1 1 0	1.64461415	0.012405	-0.000010
139	0 3 0-1 2 0	1.64682056	0.001161	-0.000001
140	0 3 0-1 3 0	1.64902697	-0.000019	
141	0 3 0 0 0-1	1.64704760	0.000026	
142	0 3 0 1 2 0	1.65610419	-0.000114	
143	0 3 0 1 3 0	1.65831059	-0.000047	
144	0 3 1-1 0-1	1.68347442	-0.000252	
145	0 3 1-1 1-1	1.68568083	-0.000088	
146	0 3 2-3 0 0	1.71526140	-0.000096	
147	0 3 2-3 1 0	1.71746781	-0.000037	
148	0 3 2-1 2 0	1.72895784	-0.000025	
149	0 3 2-1 3 0	1.73116425	-0.000010	
150	0 4-6 2 0 0	1.95893787	0.000009	
151	0 4-5 0 0 1	1.99072484	0.000027	
152	0 4-5 2 0 1	2.00000847	0.000013	
153	0 4-4 0-1 0	2.02958511	0.000044	
154	0 4-4 0 0 0	2.03179152	0.000211	
155	0 4-4 0 0 2	2.03179544	0.000016	
156	0 4-4 0 1 0	2.03399793	-0.000019	
157	0 4-4 2 0 0	2.04107515	0.000146	
158	0 4-4 2 1 0	2.04328155	0.000060	
159	0 4-3-2 0 1	2.06357849	0.000020	
160	0 4-3 0 0 1	2.07286212	0.000327	
161	0 4-3 0 1 1	2.07506853	0.000131	
162	0 4-2-2-1 0	2.10243877	0.000033	
163	0 4-2-2 0 0	2.10464517	0.000258	
164	0 4-2-2 1 0	2.10685158	-0.000017	
165	0 4-2 0 0 0	2.11392880	0.004779	-0.000005
166	0 4-2 0 1 0	2.11613521	0.001981	-0.000001
167	0 4-2 0 2 0	2.11834161	0.000185	

168	0 4-1-2 0 1	2.14571577	0.000066	
169	0 4-1-2 1 1	2.14792218	0.000023	
170	0 4-1-1 0 0	2.15035563	-0.000041	
171	0 4-1-1 1 0	2.15256203	-0.000018	
172	0 4-1 0 0-1	2.15499548	-0.000068	
173	0 4-1 0 1-1	2.15720188	-0.000025	
174	0 4 0-4 0 0	2.17749882	0.000043	
175	0 4 0-2 0 0	2.18678245	0.003960	-0.000005
176	0 4 0-2 1 0	2.18898886	0.001642	-0.000002
177	0 4 0-2 2 0	2.19119527	0.000158	
178	0 4 0 0 2 0	2.20047889	-0.000024	
179	0 4 0 0 3 0	2.20268530	-0.000010	
180	0 4 1-2 0-1	2.22784913	-0.000053	
181	0 4 1-2 1-1	2.23005554	-0.000020	
182	0 4 2-4 0 0	2.25963610	-0.000015	
183	0 5-5 1 0 1	2.54438317	0.000026	
184	0 5-5 1 1 1	2.54658958	0.000010	
185	0 5-4-1-1 0	2.57395982	0.000011	
186	0 5-4-1 0 0	2.57616623	0.000040	
187	0 5-4 1 0 0	2.58544985	0.000223	
188	0 5-4 1 1 0	2.58765626	0.000092	
189	0 5-3-1 0 1	2.61723683	0.000089	
190	0 5-3-1 1 1	2.61944323	0.000036	
191	0 5-2-3 0 0	2.64901988	0.000027	
192	0 5-2-1 0 0	2.65830351	0.001155	
193	0 5-2-1 1 0	2.66050991	0.000478	
194	0 5-2-1 2 0	2.66271632	0.000045	
195	0 5-1-3 0 1	2.69009048	0.000010	
196	0 5-1-1 0-1	2.69937018	-0.000022	
197	0 5 0-3 0 0	2.73115716	0.000446	
198	0 5 0-3 1 0	2.73336356	0.000185	
199	0 5 0-3 2 0	2.73556997	0.000018	
200	0 6-5 0 0 1	3.08875788	0.000016	
201	0 6-4 0 0 0	3.12982456	0.000119	
202	0 6-4 0 1 0	3.13203097	0.000049	
203	0 6-3-2 0 1	3.16161153	0.000016	
204	0 6-2-2 0 0	3.20267821	0.000191	
205	0 6-2-2 1 0	3.20488462	0.000079	
206	0 6 0-4 1 0	3.27773827	0.000019	
207	0 6 0-4 0 0	3.27553186	0.000046	
208	0 7-4-1 0 0	3.67419927	0.000032	
209	0 7-4-1 1 0	3.67640567	0.000013	
210	0 7-2-3 0 0	3.74705292	0.000026	
211	0 7-2-3 1 0	3.74925932	0.000011	

Table 2-21. Tidal harmonics derived from the potential P21.

No.	Arguments Tau S H P N'P J V	Angular V. deg./hour	Amplitude (-0.5 =< T =< 0.3) A	+ B * T
1	1-7 4 2 0 0	10.82249467	0.000015	
2	1-6 0 5 0 0	11.22116207	0.000011	
3	1-6 2 3-1 0	11.29180932	0.000012	
4	1-6 2 3 0 0	11.29401572	0.000063	
5	1-6 4 1-1 0	11.36466297	0.000014	
6	1-6 4 1 0 0	11.36686937	0.000076	
7	1-6 5 1 0-1	11.40793605	0.000011	
8	1-6 6-1 0 0	11.43972303	0.000015	
9	1-5 0 4-1 0	11.76333037	0.000021	
10	1-5 0 4 0 0	11.76553678	0.000110	
11	1-5 1 2 0 1	11.79732375	-0.000011	
12	1-5 2 2-1 0	11.83618402	0.000087	
13	1-5 2 2 0 0	11.83839043	0.000461	
14	1-5 3 2 0-1	11.87945711	0.000038	
15	1-5 4 0-1 0	11.90903767	0.000054	
16	1-5 4 0 0 0	11.91124408	0.000286	
17	1-5 5 0 0-1	11.95231076	0.000037	
18	1-5 6-2 0 0	11.98409773	0.000017	
19	1-4-1 3 0 1	12.26884480	-0.000020	
20	1-4 0 1-2 0	12.29621504	-0.000009	
21	1-4 0 3-1 0	12.30770508	0.000203	
22	1-4 0 3 0 0	12.30991148	0.001074	
23	1-4 1 1-1 1	12.33949205	-0.000009	
24	1-4 1 1 0 1	12.34169846	-0.000053	
25	1-4 1 2 0 0	12.34633831	-0.000017	
26	1-4 1 3 0-1	12.35097816	0.000023	
27	1-4 2-1-2 0	12.36906869	-0.000012	
28	1-4 2 1-2 0	12.37835232	-0.000014	
29	1-4 2 1-1 0	12.38055873	0.000525	
30	1-4 2 1 0 0	12.38276513	0.002783	-0.000002
31	1-4 2 3 0 0	12.39204876	-0.000010	
32	1-4 3-1 0 1	12.41455211	-0.000011	
33	1-4 3 0 0 0	12.41919196	-0.000014	
34	1-4 3 1-1-1	12.42162541	0.000039	
35	1-4 3 1 0-1	12.42383181	0.000210	
36	1-4 4-1-1 0	12.45341238	0.000101	
37	1-4 4-1 0 0	12.45561879	0.000538	
38	1-4 4 1 0 0	12.46490241	-0.000026	
39	1-4 4 1 1 0	12.46710882	0.000012	
40	1-4 5-1-1-1	12.49447906	0.000011	
41	1-4 5-1 0-1	12.49668547	0.000061	
42	1-3-2 4 0 0	12.78143254	-0.000036	
43	1-3-2 2-2 0	12.76773609	-0.000012	
44	1-3-1 2-1 1	12.81101310	-0.000022	
45	1-3-1 2 0 1	12.81321951	-0.000129	
46	1-3 0 0-3 0	12.83838334	-0.000011	
47	1-3 0 0-2 0	12.84058975	-0.000057	
48	1-3 0 2-2 0	12.84987337	-0.000045	
49	1-3 0 2-1 0	12.85207978	0.001801	-0.000005

50	1-3 0 2 0 0	12.85428619	0.009545	-0.000007
51	1-3 0 4 0 0	12.86356982	-0.000015	
52	1-3 1 0-1 1	12.88386676	-0.000028	
53	1-3 1 0 0 1	12.88607316	-0.000162	
54	1-3 1 1-1 0	12.88850661	-0.000019	
55	1-3 1 1 0 0	12.89071301	-0.000102	
56	1-3 1 2-1-1	12.89314646	0.000025	
57	1-3 1 2 0-1	12.89535287	0.000146	
58	1-3 2-2-2 0	12.91344340	-0.000013	
59	1-3 2 0-2 0	12.92272703	-0.000065	
60	1-3 2 0-1 0	12.92493343	0.002173	
61	1-3 2 0 0 0	12.92713984	0.011520	-0.000005
62	1-3 2 2 0 0	12.93642347	-0.000096	
63	1-3 2 2 1 0	12.93862987	0.000037	
64	1-3 3-1 0 0	12.96356667	-0.000029	
65	1-3 3 0-1-1	12.96600011	0.000144	
66	1-3 3 0 0-1	12.96820652	0.000776	-0.000001
67	1-3 4-2-1 0	12.99778709	0.000066	
68	1-3 4-2 0 0	12.99999349	0.000352	
69	1-3 4 0 0-2	13.00927320	0.000037	
70	1-3 4 0 0 0	13.00927712	-0.000075	
71	1-3 4 0 1 0	13.01148353	0.000049	
72	1-3 5-2 0-1	13.04106017	0.000032	
73	1-3 5 0 0-1	13.05034380	-0.000011	
74	1-2-2 1-3 0	13.30990439	-0.000011	
75	1-2-2 1-2 0	13.31211080	-0.000061	
76	1-2-2 3-1 0	13.32360083	-0.000040	
77	1-2-2 3 0 0	13.32580724	-0.000232	
78	1-2-1 1-1 1	13.35538781	-0.000097	
79	1-2-1 1 0 1	13.35759422	-0.000607	0.000001
80	1-2-1 2 0 0	13.36223407	0.000017	
81	1-2 0-1-3 0	13.38275805	-0.000052	
82	1-2 0-1-2 0	13.38496445	-0.000276	
83	1-2 0 0 0 1	13.39402104	0.000052	
84	1-2 0 1-2 0	13.39424808	-0.000411	-0.000003
85	1-2 0 1-1 0	13.39645449	0.013607	-0.000003
86	1-2 0 1 0 0	13.39866089	0.072136	-0.000035
87	1-2 0 3 0 0	13.40794452	-0.000195	
88	1-2 0 3 1 0	13.41015093	-0.000022	
89	1-2 1-1-1 1	13.42824146	-0.000022	
90	1-2 1-1 0 1	13.43044787	-0.000133	
91	1-2 1 0-1 0	13.43288131	-0.000072	
92	1-2 1 0 0 0	13.43508772	-0.000390	0.000001
93	1-2 1 1-1-1	13.43752117	0.000109	
94	1-2 1 1 0-1	13.43972757	0.000673	-0.000001
95	1-2 1 1 0 1	13.43973150	0.000013	
96	1-2 1 1 1 1	13.44193790	-0.000009	
97	1-2 2-1-2 0	13.46710173	-0.000077	
98	1-2 2-1-1 0	13.46930814	0.002584	
99	1-2 2-1 0 0	13.47151455	0.013702	-0.000006
100	1-2 2 1-1 0	13.47859177	0.000021	
101	1-2 2 1 0 0	13.48079817	-0.000789	
102	1-2 2 1 1 0	13.48300458	0.000244	
103	1-2 3-1-1-1	13.51037482	0.000116	
104	1-2 3-1 0-1	13.51258123	0.000630	
105	1-2 3 1 0-1	13.52186485	-0.000057	
106	1-2 3 1 1-1	13.52407126	0.000009	
107	1-2 4-1 0-2	13.55364790	0.000023	
108	1-2 4-1 0 0	13.55365183	-0.000151	

109	1-2 4-1 1 0	13.55585823	0.000045	
110	1-2 5-1 0-1	13.59471851	-0.000017	
111	1-1-3 2 0 1	13.82911527	-0.000046	
112	1-1-2 0-3 0	13.85427910	-0.000028	
113	1-1-2 0-2 0	13.85648551	-0.000163	
114	1-1-2 0 0 2	13.86090224	-0.000013	
115	1-1-2 2-1 0	13.86797554	-0.000198	
116	1-1-2 2 0 0	13.87018195	-0.001132	
117	1-1-1 0-1 1	13.89976251	-0.000154	
118	1-1-1 0 0 1	13.90196892	-0.001296	0.000002
119	1-1-1 1 0 0	13.90660877	0.000057	
120	1-1-1 2 0 1	13.91125255	0.000033	
121	1-1 0-2-2 0	13.92933916	0.000014	
122	1-1 0 0-3 0	13.93641638	0.000021	
123	1-1 0 0-2 0	13.93862279	-0.002178	0.000003
124	1-1 0 0-1 0	13.94082919	0.071081	0.000020
125	1-1 0 0 0 0	13.94303560	0.376763	-0.000178
126	1-1 0 0 1 0	13.94524201	0.000015	
127	1-1 0 2-1 0	13.95011282	0.000070	
128	1-1 0 2 0 0	13.95231923	-0.002429	0.000002
129	1-1 0 2 1 0	13.95452563	-0.000396	
130	1-1 0 2 2 0	13.95673204	0.000015	
131	1-1 1-1 0 0	13.97946243	-0.000014	
132	1-1 1 0-1-1	13.98189587	0.000119	
133	1-1 1 0 0-1	13.98410228	0.001141	-0.000002
134	1-1 1 0 0 1	13.98410620	0.000055	
135	1-1 1 0 1 1	13.98631261	-0.000035	
136	1-1 1 1 0 0	13.98874605	0.000025	
137	1-1 1 2 0-1	13.99338591	-0.000030	
138	1-1 2-2-1 0	14.01368285	-0.000040	
139	1-1 2-2 0 0	14.01588925	-0.000215	
140	1-1 2 0-1 0	14.02296647	0.000140	
141	1-1 2 0 0-2	14.02516896	0.000014	
142	1-1 2 0 0 0	14.02517288	-0.004914	0.000002
143	1-1 2 0 1 0	14.02737929	0.001071	
144	1-1 2 0 2 0	14.02958569	0.000072	
145	1-1 3-2 0-1	14.05695593	-0.000010	
146	1-1 3 0-1-1	14.06403315	0.000010	
147	1-1 3 0 0-1	14.06623956	-0.000324	
148	1-1 3 0 1-1	14.06844597	0.000025	
149	1-1 4-2 0 0	14.09802653	-0.000092	
150	1-1 4-2 1 0	14.10023294	-0.000019	
151	1-1 4 0 0-2	14.10730624	-0.000015	
152	1 0-3 1-1 1	14.37128357	-0.000028	
153	1 0-3 1 0 1	14.37348998	-0.000133	
154	1 0-2-1-2 0	14.40086021	0.000009	
155	1 0-2 1-2 0	14.41014384	0.000037	
156	1 0-2 1-1 0	14.41235025	-0.000629	
157	1 0-2 1 0 0	14.41455665	-0.002780	
158	1 0-1-1-1 1	14.44413722	-0.000010	
159	1 0-1-1 0 1	14.44634363	-0.000044	
160	1 0-1 0-1 0	14.44877707	0.000012	
161	1 0-1 0 0 0	14.45098348	0.000064	
162	1 0-1 1 0 1	14.45562726	0.000146	
163	1 0-1 1 1 1	14.45783366	0.000036	
164	1 0 0-1-2 0	14.48299749	0.000173	
165	1 0 0-1-1 0	14.48520390	-0.001972	-0.000001
166	1 0 0-1 0 0	14.48741031	-0.010653	0.000005

167	1 0 0 0 0-1	14.49205016	-0.000014	
168	1 0 0 0 0 1	14.49205408	-0.000037	
169	1 0 0 1-1 0	14.49448753	0.000856	0.000002
170	1 0 0 1 0 0	14.49669393	-0.029631	0.000013
171	1 0 0 1 1 0	14.49890034	-0.005946	-0.000001
172	1 0 0 1 2 0	14.50110675	0.000167	
173	1 0 1-1 0-1	14.52847698	0.000012	
174	1 0 1-1 0 1	14.52848091	0.000037	
175	1 0 1 0 0 0	14.53312076	0.000164	
176	1 0 1 0 1 0	14.53532717	0.000036	
177	1 0 1 1 0-1	14.53776061	-0.000183	
178	1 0 1 1 1-1	14.53996702	-0.000046	
179	1 0 2-1-1 0	14.56734118	0.000164	
180	1 0 2-1 0 0	14.56954759	-0.005667	0.000003
181	1 0 2-1 1 0	14.57175399	-0.001244	
182	1 0 2-1 2 0	14.57396040	0.000029	
183	1 0 2 1 1 0	14.58103762	0.000025	
184	1 0 2 1 2 0	14.58324403	0.000020	
185	1 0 3-1 0-1	14.61061426	-0.000242	
186	1 0 3-1 1-1	14.61282067	-0.000056	
187	1 1-5 0 0 3	14.83573132	0.000014	
188	1 1-4 0 0 2	14.87679800	0.000416	
189	1 1-2 0 0 0 0-2	14.90755459	-0.000008	
190	1 1-3 0-1 1	14.91565827	-0.000081	
191	1 1-3 0 0 1	14.91786468	0.010251	-0.000030
192	1 1-2 0 0 0-1 0	14.92132644	0.000011	
193	1 1-3 2 0 1	14.92714831	-0.000009	
194	1 1-2 0-2 0	14.95451855	0.000143	
195	1 1-2 0-1 0	14.95672495	-0.001973	-0.000006
196	1 1-2 0 0 0	14.95893136	0.175307	-0.000083
197	1 1-2 0 0 2	14.95893528	-0.000112	
198	1 1-2 2-1 0	14.96600858	0.000013	
199	1 1-2 2 0 0	14.96821499	-0.000263	
200	1 1-2 2 1 0	14.97042139	-0.000053	
201	1 1-1 0-1-1	14.99779163	0.000029	
202	1 1-1 0 0-1	14.99999804	-0.001467	0.000005
203	1 1-1 0 0 1	15.00000196	-0.004145	0.000015
204	1 1-1 0 1 1	15.00220837	0.000108	
205	1 1 0-2-2 0	15.02737220	0.000012	
206	1 1 0-2-1 0	15.02957861	-0.000097	
207	1 1 0 0-2 0	15.03665583	-0.000067	
208	1 1 0 0-1 0	15.03886223	0.010492	-0.000008
209	1 1 0 0 0 0	15.04106864	-0.529876	0.000224
210	1 1 0 0 0 2	15.04107256	0.000019	
211	1 1 0 0 1 0	15.04327505	-0.071886	-0.000019
212	1 1 0 0 2 0	15.04548145	0.001543	
213	1 1 0 2 1 0	15.05255867	0.000014	
214	1 1 0 2 2 0	15.05476508	0.000012	
215	1 1 1 0-1-1	15.07992891	-0.000013	
216	1 1 1 0 0-1	15.08213532	-0.004145	0.000013
217	1 1 1 0 0 1	15.08213924	0.000063	
218	1 1 1 0 1-1	15.08434173	-0.000075	
219	1 1 2-2 0 0	15.11392229	-0.000263	
220	1 1 2-2 1 0	15.11612870	-0.000073	
221	1 1 2 0 0-2	15.12320200	-0.000104	
222	1 1 2 0 0 0	15.12320592	-0.007545	0.000011
223	1 1 2 0 1 0	15.12541233	0.000289	
224	1 1 2 0 2 0	15.12761873	0.000143	
225	1 1 2 0 3 0	15.12982514	0.000013	

226	1 1 3-2 0-1	15.15498897	-0.000009	
227	1 1 3 0 0-1	15.16427260	-0.000439	
228	1 1 3 0 1-1	15.16647901	0.000012	
229	1 1 4 0 0-2	15.20533928	-0.000018	
230	1 2-4 1-1 0	15.42824601	-0.000032	
231	1 2-4 1 0 2	15.43045634	-0.000012	
232	1 2-3 0 0 0	15.46687924	-0.000013	
233	1 2-3 1 0 1	15.47152302	-0.000242	
234	1 2-3 1 1 1	15.47372942	-0.000047	
235	1 2-2-1-2 0	15.49889325	0.000020	
236	1 2-2-1-1 0	15.50109966	-0.000168	
237	1 2-2-1 0 0	15.50330607	0.000029	
238	1 2-2 1-1 0	15.51038329	0.000181	
239	1 2-2 1 0 0	15.51258969	-0.005666	0.000002
240	1 2-2 1 1 0	15.51479610	-0.001124	
241	1 2-2 1 2 0	15.51700251	0.000024	
242	1 2-1-1 0 1	15.54437667	-0.000182	
243	1 2-1-1 1 1	15.54658307	-0.000031	
244	1 2-1 0 0 0	15.54901652	0.000164	
245	1 2-1 0 1 0	15.55122293	0.000028	
246	1 2-1 1 0-1	15.55365637	0.000038	
247	1 2 0-1-1 0	15.58323694	0.000868	
248	1 2 0-1 0 0	15.58544335	-0.029630	0.000012
249	1 2 0-1 1 0	15.58764975	-0.005875	
250	1 2 0-1 2 0	15.58985616	0.000124	
251	1 2 0 0 0-1	15.59008320	-0.000022	
252	1 2 0 1 0 0	15.59472697	0.000455	
253	1 2 0 1 1 0	15.59693338	0.000287	
254	1 2 0 1 2 0	15.59913979	0.000173	
255	1 2 0 1 3 0	15.60134619	0.000026	
256	1 2 1-1 0-1	15.62651002	0.000152	
257	1 2 1-1 1-1	15.62871643	0.000023	
258	1 2 2-1 0 0	15.66758063	0.000118	
259	1 2 2-1 1 0	15.66978703	0.000092	
260	1 2 2-1 2 0	15.67199344	0.000037	
261	1 3-4 0-1 0	15.97262071	-0.000027	
262	1 3-4 0 0 2	15.97483104	-0.000019	
263	1 3-4 2 0 0	15.98411075	-0.000092	
264	1 3-4 2 1 0	15.98631715	-0.000018	
265	1 3-3 0 0 1	16.01589772	-0.000324	
266	1 3-3 0 1 1	16.01810413	-0.000062	
267	1 3-2-2-1 0	16.04547437	-0.000015	
268	1 3-2 0-1 0	16.05475799	-0.000157	
269	1 3-2 0 0 0	16.05696440	-0.004915	0.000003
270	1 3-2 0 1 0	16.05917081	-0.000962	
271	1 3-2 0 2 0	16.06137721	0.000020	
272	1 3-2 2 0 0	16.06624803	0.000009	
273	1 3-1-2 0 1	16.08875137	-0.000030	
274	1 3-1-1 0 0	16.09339123	0.000026	
275	1 3-1 0 0-1	16.09803108	0.000053	
276	1 3-1 0 0 1	16.09803500	-0.000049	
277	1 3-1 0 1 1	16.10024141	-0.000026	
278	1 3 0-2-1 0	16.12761165	0.000058	
279	1 3 0-2 0 0	16.12981805	-0.002428	0.000002
280	1 3 0-2 1 0	16.13202446	-0.000481	
281	1 3 0 0 0 0	16.13910168	-0.016212	0.000026
282	1 3 0 0 1 0	16.14130809	-0.010385	0.000012
283	1 3 0 0 2 0	16.14351449	-0.002175	0.000001

284	1 3 0 0 3 0	16.14572090	-0.000142	
285	1 3 1-2 0-1	16.17088473	0.000024	
286	1 3 1 0 0-1	16.18016836	0.000056	
287	1 3 1 0 1-1	16.18237476	0.000023	
288	1 3 2-2 0 0	16.21195533	0.000048	
289	1 3 2-2 1 0	16.21416174	0.000029	
290	1 4-5 1 0 1	16.48741877	-0.000017	
291	1 4-4 1 0 0	16.52848545	-0.000150	
292	1 4-4 1 1 0	16.53069186	-0.000029	
293	1 4-3-1 0 1	16.56027243	-0.000057	
294	1 4-3-1 1 1	16.56247883	-0.000011	
295	1 4-3 1 0 1	16.56955605	-0.000030	
296	1 4-3 1 1 1	16.57176246	-0.000017	
297	1 4-2-1-1 0	16.59913270	-0.000036	
298	1 4-2-1 0 0	16.60133911	-0.000779	
299	1 4-2-1 1 0	16.60354551	-0.000152	
300	1 4-2 1 0 0	16.61062273	-0.000590	
301	1 4-2 1 1 0	16.61282914	-0.000377	
302	1 4-2 1 2 0	16.61503555	-0.000076	
303	1 4-1-1 0-1	16.64240578	0.000012	
304	1 4-1-1 0 1	16.64240971	-0.000029	
305	1 4-1-1 1 1	16.64461611	-0.000018	
306	1 4-1 0 0 0	16.64704956	0.000015	
307	1 4-1 0 1 0	16.64925597	0.000010	
308	1 4 0-3 0 0	16.67419276	-0.000195	
309	1 4 0-3 1 0	16.67639917	-0.000039	
310	1 4 0-1 0 0	16.68347639	-0.003104	0.000005
311	1 4 0-1 1 0	16.68568279	-0.001988	0.000002
312	1 4 0-1 2 0	16.68788920	-0.000419	0.000001
313	1 4 0-1 3 0	16.69009561	-0.000028	
314	1 4 0 1 2 0	16.69717283	0.000012	
315	1 4 1-1 0-1	16.72454306	0.000026	
316	1 4 1-1 1-1	16.72674947	0.000014	
317	1 4 2-3 0 0	16.75633004	0.000010	
318	1 5-5 0 0 1	17.03179348	-0.000010	
319	1 5-4 0 0 0	17.07286016	-0.000074	
320	1 5-4 0 1 0	17.07506657	-0.000014	
321	1 5-4 2 0 0	17.08214379	-0.000015	
322	1 5-3 0 0 1	17.11393076	-0.000035	
323	1 5-3 0 1 1	17.11613717	-0.000021	
324	1 5-2-2 0 0	17.14571381	-0.000093	
325	1 5-2-2 1 0	17.14792022	-0.000018	
326	1 5-2 0 0 0	17.15499744	-0.000496	
327	1 5-2 0 1 0	17.15720385	-0.000317	
328	1 5-2 0 2 0	17.15941025	-0.000066	
329	1 5 0-4 0 0	17.21856746	-0.000016	
330	1 5 0-2 0 0	17.22785109	-0.000411	
331	1 5 0-2 1 0	17.23005750	-0.000263	
332	1 5 0-2 2 0	17.23226391	-0.000056	
333	1 6-4-1 0 0	17.61723487	-0.000015	
334	1 6-4 1 0 0	17.62651849	-0.000023	
335	1 6-4 1 1 0	17.62872490	-0.000015	
336	1 6-3-1 0 1	17.65830547	-0.000009	
337	1 6-2-3 0 0	17.69008852	-0.000010	
338	1 6-2-1 0 0	17.69937215	-0.000120	
339	1 6-2-1 1 0	17.70157855	-0.000077	
340	1 6-2-1 2 0	17.70378496	-0.000016	

341	1 6 0-3 0 0	17.77222580	-0.000046
342	1 6 0-3 1 0	17.77443220	-0.000030
343	1 7-4 0 0 0	18.17089320	-0.000012
344	1 7-2-2 0 0	18.24374685	-0.000020
345	1 7-2-2 1 0	18.24595326	-0.000013

Table 2-22. Tidal harmonics derived from the potential P22.

No.	Arguments Tau S H P N'P J V	Angular V. deg./hour	Amplitude (-0.5 =< T =< 0.3) A	+ B * T
1	2-6 2 4 0 0	25.79070966	0.000018	
2	2-6 4 2 0 0	25.86356331	0.000035	
3	2-6 6 0 0 0	25.93641696	0.000016	
4	2-5 0 5 0 0	26.26223071	0.000026	
5	2-5 2 3 0 0	26.33508436	0.000151	
6	2-5 3 3 0-1	26.37615104	0.000014	
7	2-5 4 1 0 0	26.40793801	0.000183	
8	2-5 5 1 0-1	26.44900469	0.000026	
9	2-5 6-1 0 0	26.48079167	0.000036	
10	2-4 0 4-1 0	26.80439901	-0.000010	
11	2-4 0 4 0 0	26.80660542	0.000265	
12	2-4 1 2 0 1	26.83839239	-0.000027	
13	2-4 2 2-1 0	26.87725266	-0.000042	
14	2-4 2 2 0 0	26.87945907	0.001111	
15	2-4 3 0 0 1	26.91124604	-0.000017	
16	2-4 3 1 0 0	26.91588589	-0.000009	
17	2-4 3 2 0-1	26.92052575	0.000092	
18	2-4 4 0-1 0	26.95010631	-0.000026	
19	2-4 4 0 0 0	26.95231272	0.000689	
20	2-4 5 0 0-1	26.99337940	0.000090	
21	2-4 6-2 0 0	27.02516637	0.000042	
22	2-3-2 5 0 0	27.27812647	-0.000011	
23	2-3-1 3 0 1	27.30991344	-0.000049	
24	2-3 0 1-2 0	27.33728368	-0.000022	
25	2-3 0 3-1 0	27.34877372	-0.000097	
26	2-3 0 3 0 0	27.35098012	0.002589	
27	2-3 1 1 0 1	27.38276710	-0.000128	
28	2-3 1 2 0 0	27.38740695	-0.000041	
29	2-3 1 3 0-1	27.39204680	0.000055	
30	2-3 2-1-2 0	27.41013733	-0.000028	
31	2-3 2 1-1 0	27.42162737	-0.000250	
32	2-3 2 1 0 0	27.42383377	0.006709	
33	2-3 3-1 0 1	27.45562075	-0.000026	
34	2-3 3 0 0 0	27.46026060	-0.000032	
35	2-3 3 1-1-1	27.46269405	-0.000019	
36	2-3 3 1 0-1	27.46490045	0.000508	
37	2-3 4-1-1 0	27.49448102	-0.000048	
38	2-3 4-1 0 0	27.49668743	0.001296	
39	2-3 4 1 0-2	27.50596713	0.000023	
40	2-3 5-1 0-1	27.53775411	0.000147	
41	2-3 6-3 0 0	27.56954108	0.000019	
42	2-2-2 2-2 0	27.80880473	-0.000029	
43	2-2-2 4 0 0	27.82250118	-0.000086	
44	2-2-1 2-1 1	27.85208174	0.000010	
45	2-2-1 2 0 1	27.85428815	-0.000311	
46	2-2 0 0-2 0	27.88165839	-0.000138	
47	2-2 0 1 0 1	27.89071498	0.000046	
48	2-2 0 2-1 0	27.89314842	-0.000859	
49	2-2 0 2 0 0	27.89535483	0.023009	0.000003
50	2-2 1 0-1 1	27.92493540	0.000013	

51	2-2 1 0 0 1	27.92714180	-0.000392	
52	2-2 1 1 0 0	27.93178165	-0.000246	
53	2-2 1 2-1-1	27.93421510	-0.000012	
54	2-2 1 2 0-1	27.93642151	0.000356	
55	2-2 2-2-2 0	27.95451204	-0.000033	
56	2-2 2 0-2 0	27.96379567	0.000019	
57	2-2 2 0-1 0	27.96600207	-0.001037	-0.000001
58	2-2 2 0 0 0	27.96820848	0.027768	0.000002
59	2-2 2 2 0 0	27.97749211	0.000013	
60	2-2 2 2 1 0	27.97969851	-0.000017	
61	2-2 3-2 0 1	27.99999545	-0.000013	
62	2-2 3-1 0 0	28.00463531	-0.000064	
63	2-2 3 0-1-1	28.00706875	-0.000069	
64	2-2 3 0 0-1	28.00927516	0.001874	-0.000003
65	2-2 4-2-1 0	28.03885573	-0.000031	
66	2-2 4-2 0 0	28.04106213	0.000848	
67	2-2 4 0 0-2	28.05034184	0.000090	
68	2-2 4 0 0 0	28.05034576	0.000016	
69	2-2 4 0 1 0	28.05255217	-0.000023	
70	2-2 5-2 0-1	28.08212881	0.000076	
71	2-1-3 3 0 1	28.32580920	-0.000019	
72	2-1-2 1-2 0	28.35317944	-0.000147	
73	2-1-2 1 0 2	28.35759618	-0.000012	
74	2-1-2 3-1 0	28.36466947	0.000019	
75	2-1-2 3 0 0	28.36687588	-0.000560	
76	2-1-1 1-1 1	28.39645645	0.000047	
77	2-1-1 1 0 1	28.39866286	-0.001463	0.000003
78	2-1-1 2 0 0	28.40330271	0.000040	
79	2-1 0-1-3 0	28.42382669	0.000025	
80	2-1 0-1-2 0	28.42603309	-0.000666	
81	2-1 0-1 0 2	28.43044983	-0.000020	
82	2-1 0 0 0 1	28.43508968	0.000140	
83	2-1 0 1-2 0	28.43531672	0.000092	
84	2-1 0 1-1 0	28.43752313	-0.006484	-0.000002
85	2-1 0 1 0 0	28.43972953	0.173881	0.000015
86	2-1 0 3 0 0	28.44901316	0.000042	
87	2-1 0 3 1 0	28.45121957	0.000011	
88	2-1 1-1-1 1	28.46931010	0.000011	
89	2-1 1-1 0 1	28.47151651	-0.000323	
90	2-1 1 0-1 0	28.47394995	0.000034	
91	2-1 1 0 0 0	28.47615636	-0.000937	
92	2-1 1 1-1-1	28.47858981	-0.000052	
93	2-1 1 1 0-1	28.48079621	0.001625	-0.000002
94	2-1 2-1-2 0	28.50817037	0.000016	
95	2-1 2-1-1 0	28.51037678	-0.001232	0.000001
96	2-1 2-1 0 0	28.51258319	0.033027	0.000002
97	2-1 2 1 0-2	28.52186289	0.000028	
98	2-1 2 1 0 0	28.52186681	0.000169	
99	2-1 2 1 1 0	28.52407322	-0.000116	
100	2-1 2 1 2 0	28.52627963	-0.000013	
101	2-1 3-2 0 0	28.54901001	-0.000009	
102	2-1 3-1-1-1	28.55144346	-0.000056	
103	2-1 3-1 0-1	28.55364987	0.001525	-0.000002
104	2-1 3 1 0-1	28.56293349	0.000011	
105	2-1 4-1 0-2	28.59471654	0.000055	
106	2-1 4-1 0 0	28.59472047	0.000033	
107	2-1 4-1 1 0	28.59692687	-0.000021	
108	2 0-3 0-2 1	28.85648747	-0.000016	

109	2 0-3 2 0 1	28.87018391	-0.000110	
110	2 0-2 0-3 0	28.89534774	0.000013	
111	2 0-2 0-2 0	28.89755415	-0.000394	
112	2 0-2 0 0 2	28.90197088	-0.000030	
113	2 0-2 2-1 0	28.90904418	0.000095	
114	2 0-2 2 0 0	28.91125059	-0.002728	-0.000001
115	2 0-1 0-1 1	28.94083115	0.000074	
116	2 0-1 0 0 1	28.94303756	-0.003123	0.000008
117	2 0-1 1 0 0	28.94767741	0.000137	
118	2 0-1 2 0-1	28.95231727	-0.000016	
119	2 0 0-2-2 0	28.97040780	0.000032	
120	2 0 0 0-2 0	28.97969143	0.000472	
121	2 0 0 0-1 0	28.98189783	-0.033885	0.000020
122	2 0 0 0 0 0	28.98410424	0.908184	0.000086
123	2 0 0 0 1 0	28.98631065	0.000019	
124	2 0 0 1 0-1	28.98874409	-0.000010	
125	2 0 0 2-1 0	28.99118146	-0.000010	
126	2 0 0 2 0 0	28.99338787	0.000525	-0.000001
127	2 0 0 2 1 0	28.99559427	0.000189	
128	2 0 0 2 2 0	28.99780068	0.000036	
129	2 0 1-2 0 1	29.01589121	0.000011	
130	2 0 1-1 0 0	29.02053107	-0.000032	
131	2 0 1 0-1-1	29.02296451	-0.000057	
132	2 0 1 0 0-1	29.02517092	0.002749	-0.000007
133	2 0 1 0 0 1	29.02517484	-0.000012	
134	2 0 1 0 1 1	29.02738125	0.000017	
135	2 0 1 1 0 0	29.02981469	-0.000009	
136	2 0 2-2-1 0	29.05475149	0.000019	
137	2 0 2-2 0 0	29.05695789	-0.000518	
138	2 0 2 0-1 0	29.06403511	-0.000019	
139	2 0 2 0 0-2	29.06623760	0.000033	
140	2 0 2 0 0 0	29.06624152	0.001066	
141	2 0 2 0 1 0	29.06844793	-0.000510	
142	2 0 2 0 2 0	29.07065433	0.000173	
143	2 0 3-2 0-1	29.09802457	-0.000023	
144	2 0 3 0 0-1	29.10730820	0.000070	
145	2 0 3 0 1-1	29.10951461	-0.000012	
146	2 0 4-2 0 0	29.13909517	0.000021	
147	2 0 4-2 1 0	29.14130158	0.000009	
148	2 1-4 1 0 2	29.37349194	-0.000013	
149	2 1-3 1-1 1	29.41235221	0.000013	
150	2 1-3 1 0 1	29.41455862	-0.000321	
151	2 1-2-1-2 0	29.44192885	0.000022	
152	2 1-2 1-1 0	29.45341889	0.000300	
153	2 1-2 1 0 0	29.45562529	-0.006697	
154	2 1-1-1 0 1	29.48741227	-0.000103	
155	2 1-1 0 0 0	29.49205212	0.000156	
156	2 1-1 1 0-1	29.49669197	0.000016	
157	2 1-1 1 0 1	29.49669590	-0.000033	
158	2 1-1 1 1 1	29.49890230	-0.000017	
159	2 1 0-1-2 0	29.52406613	-0.000038	
160	2 1 0-1-1 0	29.52627254	0.000939	-0.000001
161	2 1 0-1 0 0	29.52847895	-0.025670	-0.000002
162	2 1 0 0 0-1	29.53311880	-0.000024	
163	2 1 0 1-1 0	29.53555617	-0.000119	
164	2 1 0 1 0 0	29.53776257	0.006420	-0.000008
165	2 1 0 1 1 0	29.53996898	0.002832	-0.000002
166	2 1 0 1 2 0	29.54217539	0.000400	
167	2 1 1-1 0-1	29.56954562	0.000038	

168	2 1 1 0 0 0	29.57418940	-0.000036	
169	2 1 1 0 1 0	29.57639581	-0.000016	
170	2 1 1 1 0-1	29.57882925	0.000038	
171	2 1 1 1 1-1	29.58103566	0.000022	
172	2 1 2-1-1 0	29.60840982	-0.000023	
173	2 1 2-1 0 0	29.61061623	0.001228	-0.000001
174	2 1 2-1 1 0	29.61282263	0.000592	
175	2 1 2-1 2 0	29.61502904	0.000069	
176	2 1 3-1 0-1	29.65168290	0.000052	
177	2 1 3-1 1-1	29.65388931	0.000026	
178	2 2-5 0 0 3	29.87679996	0.000035	
179	2 2-4 0 0 2	29.91786664	0.001002	-0.000002
180	2 2-2 0 0 0-2 0	29.92479017	0.000011	
181	2 2-2 0 0 0 0-2	29.94862323	-0.000021	
182	2 2-3 0-1 1	29.95672691	0.000038	
183	2 2-3 0 0 1	29.95893332	0.024701	-0.000059
184	2 2-2 0 0 0-1 0	29.96239508	0.000025	
185	2 2-2 0 0 0 0-1	29.97431161	0.000013	
186	2 2-2 0-2 0	29.99558719	-0.000030	
187	2 2-2 0-1 0	29.99779359	0.000946	-0.000004
188	2 2-2 0 0 0	30.00000000	0.422535	0.000040
189	2 2-2 2 0 0	30.00928363	0.000057	
190	2 2-2 2 1 0	30.01149003	0.000025	
191	2 2-1 0-1-1	30.03886027	-0.000017	
192	2 2-1 0 0-1	30.04106668	-0.003536	0.000010
193	2 2-1 0 0 1	30.04107060	0.000899	
194	2 2-1 0 1 1	30.04327701	-0.000052	
195	2 2-1 0 2 1	30.04548342	-0.000012	
196	2 2 0-2-1 0	30.07064725	0.000046	
197	2 2 0-2 0 0	30.07285365	0.000011	
198	2 2 0 0-1 0	30.07993087	-0.001472	-0.000002
199	2 2 0 0 0 0	30.08213728	0.114860	-0.000121
200	2 2 0 0 1 0	30.08434369	0.034240	-0.000021
201	2 2 0 0 2 0	30.08655009	0.003718	-0.000002
202	2 2 1 0 0-1	30.12320396	0.000904	-0.000001
203	2 2 1 0 1-1	30.12541037	0.000038	
204	2 2 1 0 2-1	30.12761677	0.000008	
205	2 2 2-2 0 0	30.15499093	0.000057	
206	2 2 2-2 1 0	30.15719734	0.000035	
207	2 2 2 0 0-2	30.16427064	0.000022	
208	2 2 2 0 0 0	30.16427456	0.000782	
209	2 2 2 0 1 0	30.16648097	-0.000041	
210	2 2 2 0 2 0	30.16868737	-0.000031	
211	2 2 3 0 0-1	30.20534124	0.000045	
212	2 3-4 1-1 0	30.46931465	0.000015	
213	2 3-4 1 0 0	30.47152105	0.000009	
214	2 3-3 0 0 0	30.50794788	-0.000032	
215	2 3-3 1 0 1	30.51259166	0.000053	
216	2 3-3 1 1 1	30.51479806	0.000022	
217	2 3-2-1-1 0	30.54216830	0.000080	
218	2 3-2-1 0 0	30.54437471	0.000065	
219	2 3-2 1-1 0	30.55145193	-0.000025	
220	2 3-2 1 0 0	30.55365833	0.001228	-0.000001
221	2 3-2 1 1 0	30.55586474	0.000535	
222	2 3-2 1 2 0	30.55807115	0.000058	
223	2 3-1-1 0 1	30.58544531	0.000040	
224	2 3-1-1 1 1	30.58765171	0.000014	
225	2 3-1 0 0 0	30.59008516	-0.000035	

226	2 3-1 0 1 0	30.59229157	-0.000014	
227	2 3-1 1 0-1	30.59472501	-0.000009	
228	2 3 0-1-1 0	30.62430558	-0.000121	
229	2 3 0-1 0 0	30.62651199	0.006422	-0.000007
230	2 3 0-1 1 0	30.62871839	0.002799	-0.000003
231	2 3 0-1 2 0	30.63092480	0.000307	-0.000001
232	2 3 0 1 0 0	30.63579561	-0.000047	
233	2 3 0 1 1 0	30.63800202	-0.000040	
234	2 3 0 1 2 0	30.64020843	-0.000037	
235	2 3 0 1 3 0	30.64241483	-0.000012	
236	2 3 1-1 0-1	30.66757866	-0.000033	
237	2 3 1-1 1-1	30.66978507	-0.000011	
238	2 3 2-1 0 0	30.70864927	-0.000012	
239	2 3 2-1 1 0	30.71085567	-0.000013	
240	2 4-4 0-1 0	31.01368935	0.000013	
241	2 4-4 2 0 0	31.02517939	0.000020	
242	2 4-4 2 1 0	31.02738579	0.000009	
243	2 4-3 0 0 1	31.05696636	0.000070	
244	2 4-3 0 1 1	31.05917277	0.000030	
245	2 4-2 0-1 0	31.09582663	0.000022	
246	2 4-2 0 0 0	31.09803304	0.001066	
247	2 4-2 0 1 0	31.10023945	0.000458	
248	2 4-2 0 2 0	31.10244585	0.000049	
249	2 4-1 0 0-1	31.13909972	-0.000016	
250	2 4 0-2 0 0	31.17088669	0.000527	
251	2 4 0-2 1 0	31.17309310	0.000229	
252	2 4 0-2 2 0	31.17529951	0.000025	
253	2 4 0 0 0 0	31.18017032	0.001682	-0.000002
254	2 4 0 0 1 0	31.18237673	0.001457	-0.000002
255	2 4 0 0 2 0	31.18458313	0.000472	
256	2 4 0 0 3 0	31.18678954	0.000068	
257	2 5-4 1 0 0	31.56955409	0.000033	
258	2 5-4 1 1 0	31.57176050	0.000014	
259	2 5-3-1 0 1	31.60134107	0.000013	
260	2 5-2-1 0 0	31.64240775	0.000169	
261	2 5-2-1 1 0	31.64461415	0.000072	
262	2 5-2 1 0 0	31.65169137	0.000061	
263	2 5-2 1 1 0	31.65389778	0.000053	
264	2 5-2 1 2 0	31.65610419	0.000017	
265	2 5 0-3 0 0	31.71526140	0.000042	
266	2 5 0-3 1 0	31.71746781	0.000018	
267	2 5 0-1 0 0	31.72454503	0.000322	
268	2 5 0-1 1 0	31.72675143	0.000279	
269	2 5 0-1 2 0	31.72895784	0.000091	
270	2 5 0-1 3 0	31.73116425	0.000013	
271	2 6-4 0 0 0	32.11392880	0.000016	
272	2 6-2-2 0 0	32.18678245	0.000020	
273	2 6-2-2 1 0	32.18898886	0.000009	
274	2 6-2 0 0 0	32.19606608	0.000052	
275	2 6-2 0 1 0	32.19827249	0.000045	
276	2 6-2 0 2 0	32.20047889	0.000014	
277	2 6 0-2 0 0	32.26891973	0.000043	
278	2 6 0-2 1 0	32.27112614	0.000037	
279	2 6 0-2 2 0	32.27333255	0.000012	
280	2 7-2-1 0 0	32.74044079	0.000013	
281	2 7-2-1 1 0	32.74264719	0.000011	

Table 2-30. Tidal harmonics derived from the potential P30.

No.	Arguments Tau S H P N'P	Angular V. deg./hour	Amplitude (-0.5 =< T =< 0.3) A	+ B * T
1	0 0 0 1-1 0	0.00243541	-0.000013	
2	0 0 0 1 0 0	0.00464181	0.000254	
3	0 0 0 1 1 0	0.00684822	0.000041	
4	0 0 1 0 0 0	0.04106864	0.000004	
5	0 0 2-1 0 0	0.07749547	0.000047	
6	0 0 2-1 1 0	0.07970187	0.000007	
7	0 1-2 0-1 0	0.46467283	0.000013	
8	0 1-2 0 0 0	0.46687924	-0.000053	
9	0 1-2 2 0 0	0.47616287	0.000007	
10	0 1-1 0 0 1	0.50794984	0.000006	
11	0 1 0-2 0 0	0.53973289	-0.000019	
12	0 1 0 0-1 0	0.54681011	-0.000241	
13	0 1 0 0 0 0	0.54901652	0.004660	-0.000001
14	0 1 0 0 1 0	0.55122293	0.000735	
15	0 1 0 0 2 0	0.55342933	-0.000057	
16	0 1 1 0 0-1	0.59008320	-0.000009	
17	0 1 2 0 1 0	0.63336021	-0.000007	
18	0 1 2 0 2 0	0.63356661	-0.000004	
19	0 2-3 1 0 1	0.97947089	0.000007	
20	0 2-2-1 0 0	1.01125395	-0.000007	
21	0 2-2 1-1 0	1.01833117	-0.000008	
22	0 2-2 1 0 0	1.02053757	0.000148	
23	0 2-2 1 1 0	1.02274398	0.000023	
24	0 2-1-1 0 1	1.05232455	0.000006	
25	0 2-1 0 0 0	1.05696440	-0.000004	
26	0 2 0-1-1 0	1.09118482	-0.000040	
27	0 2 0-1 0 0	1.09339123	0.000762	
28	0 2 0-1 1 0	1.09559763	0.000120	
29	0 2 0-1 2 0	1.09780404	-0.000009	
30	0 2 0 1 0 0	1.10267485	-0.000021	
31	0 2 0 1 1 0	1.10488126	-0.000013	
32	0 2 0 1 2 0	1.10708767	-0.000006	
33	0 2 1-1 0-1	1.13445790	-0.000005	
34	0 2 2-1 0 0	1.17552851	-0.000005	
35	0 2 2-1 1 0	1.17773491	-0.000004	
36	0 3-4 2 0 0	1.49205863	0.000003	
37	0 3-3 0 0 1	1.52384560	0.000008	
38	0 3-2 0 0 0	1.56491228	0.000128	
39	0 3-2 0 1 0	1.56711869	0.000020	
40	0 3 0-2-1 0	1.63555953	-0.000004	
41	0 3 0-2 0 0	1.63776593	0.000092	
42	0 3 0-2 1 0	1.63997234	0.000014	
43	0 3 0 0 0 0	1.64704956	0.000379	
44	0 3 0 0 1 0	1.64925597	0.000236	
45	0 3 0 0 2 0	1.65146237	0.000046	
46	0 4-4 1 0 0	2.03643333	0.000005	
47	0 4-2-1 0 0	2.10928699	0.000028	
48	0 4-2-1 1 0	2.11149339	0.000004	
49	0 4-2 1 0 0	2.11857061	0.000019	

50	0 4-2 1 1 0	2.12077702	0.000012
51	0 4 0-3 0 0	2.18214064	0.000010
52	0 4 0-1 0 0	2.19142427	0.000104
53	0 4 0-1 1 0	2.19363067	0.000065
54	0 4 0-1 2 0	2.19583708	0.000013
55	0 5-2-2 0 0	2.65366169	0.000004
56	0 5-2 0 0 0	2.66294532	0.000018
57	0 5-2 0 1 0	2.66515173	0.000011
58	0 5 0-2 0 0	2.73579897	0.000018
59	0 5 0-2 1 0	2.73800538	0.000011
60	0 6-2-1 0 0	3.20732003	0.000006

Table 2-31. Tidal harmonics derived from the potential P31.

No.	Arguments Tau S H P N'P	Angular V. deg./hour	Amplitude (-0.5 =< T =< 0.3) A	+ B * T
1	1-5 2 1-1 0	11.83154221	-0.000012	
2	1-5 2 1 0 0	11.83374861	-0.000031	
3	1-5 0 3 0 0	11.76089496	-0.000014	
4	1-4 0 2-1 0	12.30306326	-0.000040	
5	1-4 0 2 0 0	12.30526967	-0.000100	
6	1-4 2 0-1 0	12.37591691	-0.000040	
7	1-4 2 0 0 0	12.37812332	-0.000101	
8	1-4 3 0 0-1	12.41919000	-0.000007	
9	1-3 0 1-2 0	12.84523156	-0.000018	
10	1-3 0 1-1 0	12.84743797	-0.000229	
11	1-3 0 1 0 0	12.84964437	-0.000580	
12	1-3 0 3 0 0	12.85892800	-0.000014	
13	1-3 1 1 0-1	12.89071105	-0.000007	
14	1-3 2-1-1 0	12.92029162	-0.000043	
15	1-3 2-1 0 0	12.92249803	-0.000108	
16	1-3 2 1 0 0	12.93178165	-0.000040	
17	1-3 4-1 0 0	13.00463531	-0.000008	
18	1-2-2 2 0 0	13.32116543	0.000013	
19	1-2-1 0 0 1	13.35295240	0.000011	
20	1-2 0 0-2 0	13.38960627	-0.000065	
21	1-2 0 0-1 0	13.39181267	-0.000836	
22	1-2 0 0 0 0	13.39401908	-0.002112	0.000002
23	1-2 0 2-1 0	13.40109630	0.000019	
24	1-2 0 2 0 0	13.40330271	-0.000130	
25	1-2 0 2 1 0	13.40550911	0.000016	
26	1-2 1 0 0-1	13.43508576	-0.000012	
27	1-2 2 0-1 0	13.47394995	0.000027	
28	1-2 2 0 0 0	13.47615636	-0.000181	
29	1-2 3 0 0-1	13.51722304	-0.000012	
30	1-1-2 1-1 0	13.86333373	0.000015	
31	1-1-2 1 0 0	13.86554013	0.000029	
32	1-1-1 1 0 1	13.90661074	0.000007	
33	1-1 0-1-2 0	13.93398097	0.000008	
34	1-1 0-1-1 0	13.93618738	0.000047	
35	1-1 0-1 0 0	13.93839379	0.000119	
36	1-1 0 1-1 0	13.94547101	0.000160	
37	1-1 0 1 0 0	13.94767741	-0.001080	
38	1-1 0 1 1 0	13.94988382	0.000141	
39	1-1 1 1 0-1	13.98874409	-0.000008	
40	1-1 2-1-1 0	14.01832466	0.000031	
41	1-1 2-1 0 0	14.02053107	-0.000210	
42	1-1 2-1 1 0	14.02273747	0.000029	
43	1-1 3-1 0-1	14.06159775	-0.000009	
44	1 0-2 0-1 0	14.40770843	0.000025	
45	1 0-1 0 0 1	14.45098544	0.000012	
46	1 0 0 0-2 0	14.48763931	-0.000030	
47	1 0 0 0-1 0	14.48984571	0.000977	-0.000001
48	1 0 0 0 0 0	14.49205212	-0.006608	-0.000005

49	1 0 0 0 1 0	14.49425853	0.000855	-0.000001
50	1 0 0 0 2 0	14.49646493	-0.000013	
51	1 0 0 2 0 0	14.50133575	-0.000010	
52	1 0 1 0 0-1	14.53311880	-0.000010	
53	1 0 2-2 0 0	14.56490577	-0.000010	
54	1 0 2 0 0 0	14.57418940	-0.000027	
55	1 0 2 0 1 0	14.57639581	0.000017	
56	1 1-2 1-1 0	14.96136677	0.000009	
57	1 1-2 1 0 0	14.96357317	-0.000067	
58	1 1-2 1 1 0	14.96577958	0.000009	
59	1 1 0-1-1 0	15.03422042	0.000054	
60	1 1 0-1 0 0	15.03642683	-0.000360	
61	1 1 0-1 1 0	15.03863323	0.000046	
62	1 1 0 1 0 0	15.04571045	-0.000131	
63	1 1 0 1 1 0	15.04791686	-0.000054	
64	1 1 2-1 0 0	15.11856411	-0.000024	
65	1 1 2-1 1 0	15.12077051	-0.000009	
66	1 2-2 0-1 0	15.50574147	-0.000017	
67	1 2-2 0 0 0	15.50794788	-0.000076	
68	1 2-2 0 1 0	15.51015429	0.000009	
69	1 2 0-2 0 0	15.58080153	-0.000027	
70	1 2 0 0-1 0	15.58787875	0.000078	
71	1 2 0 0 0 0	15.59008516	-0.002412	0.000002
72	1 2 0 0 1 0	15.59229157	-0.000977	
73	1 2 0 0 2 0	15.59449797	-0.000081	
74	1 3-2-1 0 0	16.05232259	-0.000010	
75	1 3-2 1 0 0	16.06160621	-0.000077	
76	1 3-2 1 1 0	16.06381262	-0.000031	
77	1 3 0-1-1 0	16.13225346	0.000013	
78	1 3 0-1 0 0	16.13445987	-0.000394	
79	1 3 0-1 1 0	16.13666627	-0.000159	
80	1 3 0-1 2 0	16.13887268	-0.000013	
81	1 4-2 0 0 0	16.60598092	-0.000066	
82	1 4-2 0 1 0	16.60818733	-0.000027	
83	1 4 0-2 0 0	16.67883457	-0.000048	
84	1 4 0-2 1 0	16.68104098	-0.000019	
85	1 4 0 0 0 0	16.68811820	-0.000091	
86	1 4 0 0 1 0	16.69032461	-0.000077	
87	1 4 0 0 2 0	16.69253101	-0.000024	
88	1 5-2-1 0 0	17.15035563	-0.000015	
89	1 5 0-1 0 0	17.23249291	-0.000025	
90	1 5 0-1 1 0	17.23469931	-0.000021	
91	1 5 0-1 2 0	17.23690572	-0.000006	

Table 2-32. Tidal harmonics derived from the potential P32.

No.	Arguments Tau S H P N'P	Angular V. deg./hour	Amplitude (-0.5 =< T =< 0.3) A + B * T
1	2-5 2 2 0 0	26.33044255	-0.000017
2	2-5 4 0 0 0	26.40329620	-0.000009
3	2-4 0 3 0 0	26.80196360	-0.000038
4	2-4 2 1-1 0	26.87261085	-0.000014
5	2-4 2 1 0 0	26.87481725	-0.000082
6	2-4 4-1 0 0	26.94767091	-0.000016
7	2-3 0 2-1 0	27.34413190	-0.000046
8	2-3 0 2 0 0	27.34633831	-0.000270
9	2-3 2 0-1 0	27.41698555	-0.000046
10	2-3 2 0 0 0	27.41919196	-0.000271
11	2-3 3 0 0-1	27.46025864	-0.000018
12	2-3 4-2 0 0	27.49204561	-0.000010
13	2-2-2 3 0 0	27.81785936	0.000008
14	2-2-1 1 0 1	27.84964634	0.000016
15	2-2 0 1-2 0	27.88630020	0.000014
16	2-2 0 1-1 0	27.88850661	-0.000265
17	2-2 0 1 0 0	27.89071301	-0.001562
18	2-2 0 3 0 0	27.89999664	0.000011
19	2-2 1 0 0 0	27.92713984	0.000008
20	2-2 1 1 0-1	27.93177969	-0.000016
21	2-2 2-1-1 0	27.96136026	-0.000050
22	2-2 2-1 0 0	27.96356667	-0.000292
23	2-2 2 1 0 0	27.97285029	0.000032
24	2-2 3-1 0-1	28.00463335	-0.000014
25	2-2 4-1 0 0	28.04570395	0.000007
26	2-1-2 2 0 0	28.36223407	0.000035
27	2-1-1 0 0 1	28.39402104	0.000029
28	2-1 0 0-2 0	28.43067491	0.000052
29	2-1 0 0-1 0	28.43288131	-0.000967
30	2-1 0 0 0 0	28.43508772	-0.005691 0.000002
31	2-1 0 2 0 0	28.44437135	0.000103
32	2-1 0 2 1 0	28.44657775	0.000018
33	2-1 1 0 0-1	28.47615440	-0.000024
34	2-1 2-2 0 0	28.50794137	0.000012
35	2-1 2 0-1 0	28.51501859	-0.000008
36	2-1 2 0 0 0	28.51722500	0.000144
37	2-1 3 0 0-1	28.55829168	0.000010
38	2 0-2 1-1 0	28.90440237	0.000017
39	2 0-2 1 0 0	28.90660877	0.000079
40	2 0 0-1-1 0	28.97725602	0.000055
41	2 0 0-1 0 0	28.97946243	0.000322
42	2 0 0 1-1 0	28.98653965	-0.000051
43	2 0 0 1 0 0	28.98874605	0.000858
44	2 0 0 1 1 0	28.99095246	0.000163
45	2 0 0 1 2 0	28.99315887	-0.000007
46	2 0 1 1 0-1	29.02981273	0.000007
47	2 0 2-1-1 0	29.05939330	-0.000010
48	2 0 2-1 0 0	29.06159971	0.000167

49	2 0 2-1 1 0	29.06380611	0.000034	
50	2 0 3-1 0-1	29.10266639	0.000008	
51	2 1-2 0-1 0	29.44877707	0.000028	
52	2 1-1 0 0 1	29.49205408	-0.000010	
53	2 1 0 0-1 0	29.53091435	-0.000311	
54	2 1 0 0 0 0	29.53312076	0.005250	-0.000001
55	2 1 0 0 1 0	29.53532717	0.000989	
56	2 1 0 0 2 0	29.53753357	-0.000035	
57	2 1 1 0 0-1	29.57418744	0.000007	
58	2 1 2-2 0 0	29.60597441	0.000008	
59	2 2-3 0 0 0	29.95893136	-0.000007	
60	2 2-2 1 0 0	30.00464181	0.000053	
61	2 2-2 1 1 0	30.00684822	0.000010	
62	2 2 0-1-1 0	30.07528906	-0.000017	
63	2 2 0-1 0 0	30.07749547	0.000286	
64	2 2 0-1 1 0	30.07970187	0.000054	
65	2 2 0 1 0 0	30.08677909	0.000026	
66	2 2 0 1 1 0	30.08898550	0.000017	
67	2 3-2 0 0 0	30.54901652	0.000060	
68	2 3-2 0 1 0	30.55122293	0.000011	
69	2 3 0-2 0 0	30.62187017	0.000022	
70	2 3 0 0-1 0	30.62894739	-0.000011	
71	2 3 0 0 0 0	30.63115380	0.000484	
72	2 3 0 0 1 0	30.63336021	0.000311	
73	2 3 0 0 2 0	30.63556661	0.000064	
74	2 4-2-1 0 0	31.09339123	0.000008	
75	2 4-2 1 0 0	31.10267485	0.000015	
76	2 4-2 1 1 0	31.10488126	0.000010	
77	2 4 0-1 0 0	31.17552851	0.000079	
78	2 4 0-1 1 0	31.17773491	0.000051	
79	2 4 0-1 2 0	31.17994132	0.000011	
80	2 5-2 0 0 0	31.64704956	0.000013	
81	2 5-2 0 1 0	31.64925597	0.000008	
82	2 5 0-2 0 0	31.71990321	0.000009	
83	2 5 0 0 0 0	31.72918684	0.000010	
84	2 5 0 0 1 0	31.73139325	0.000011	

Table 2-33. Tidal harmonics derived from the potential P33.

No.	Arguments Tau	S	H	P	N'	P	Angular V. deg./hour	Amplitude (-0.5 =< T =< 0.3) A	+	B * T
1	3	-4	0	4	0	0	41.29865754	-0.000010		
2	3	-4	2	2	0	0	41.37151119	-0.000035		
3	3	-4	4	0	0	0	41.44436484	-0.000019		
4	3	-3	0	3	0	0	41.84303224	-0.000079		
5	3	-3	2	1	-1	0	41.91367949	0.000010		
6	3	-3	2	1	0	0	41.91588589	-0.000171		
7	3	-3	3	1	0	-1	41.95695257	-0.000013		
8	3	-3	4	-1	0	0	41.98873955	-0.000033		
9	3	-2	-1	2	0	1	42.34634027	0.000009		
10	3	-2	0	2	-1	0	42.38520054	0.000032		
11	3	-2	0	2	0	0	42.38740695	-0.000565		
12	3	-2	1	0	0	1	42.41919392	0.000009		
13	3	-2	1	2	0	-1	42.42847363	-0.000010		
14	3	-2	2	0	-1	0	42.45805419	0.000032		
15	3	-2	2	0	0	0	42.46026060	-0.000567		
16	3	-2	3	0	0	-1	42.50132728	-0.000038		
17	3	-2	4	-2	0	0	42.53311425	-0.000020		
18	3	-1	-2	3	0	0	42.85892800	0.000017		
19	3	-1	-1	1	0	1	42.89071498	0.000033		
20	3	-1	0	-1	-2	0	42.91808521	0.000012		
21	3	-1	0	1	-1	0	42.92957525	0.000183		
22	3	-1	0	1	0	0	42.93178165	-0.003260		-0.000001
23	3	-1	1	-1	0	1	42.96356863	0.000007		
24	3	-1	1	0	0	0	42.96820848	0.000017		
25	3	-1	1	1	0	-1	42.97284833	-0.000035		
26	3	-1	2	-1	-1	0	43.00242890	0.000034		
27	3	-1	2	-1	0	0	43.00463531	-0.000609		
28	3	-1	2	1	0	0	43.01391893	-0.000009		
29	3	-1	3	-1	0	-1	43.04570199	-0.000029		
30	3	0	-2	2	0	0	43.40330271	0.000073		
31	3	0	-2	0	-2	0	43.38960627	0.000007		
32	3	0	-1	0	0	1	43.43508968	0.000061		
33	3	0	0	0	-2	0	43.47174355	-0.000015		
34	3	0	0	0	-1	0	43.47394995	0.000665		
35	3	0	0	0	0	0	43.47615636	-0.011881		-0.000002
36	3	0	0	2	0	0	43.48543999	-0.000030		
37	3	0	0	2	1	0	43.48764639	-0.000013		
38	3	0	1	0	0	-1	43.51722304	-0.000055		
39	3	0	2	-2	0	0	43.54901001	0.000026		
40	3	0	2	0	0	0	43.55829364	-0.000042		
41	3	1	-3	1	0	1	43.90661074	0.000008		
42	3	1	-2	1	-1	0	43.94547101	-0.000012		
43	3	1	-2	1	0	0	43.94767741	0.000166		
44	3	1	0	-1	-1	0	44.01832466	-0.000038		
45	3	1	0	-1	0	0	44.02053107	0.000673		
46	3	1	0	1	-1	0	44.02760829	0.000010		
47	3	1	0	1	0	0	44.02981469	-0.000253		
48	3	1	0	1	1	0	44.03202110	-0.000112		

49	3 1 0 1 2 0	44.03422751	-0.000014
50	3 1 2-1 0 0	44.10266835	-0.000049
51	3 1 2-1 1 0	44.10487475	-0.000023
52	3 2-2 0-1 0	44.48984571	-0.000019
53	3 2 0 0-1 0	44.57198299	0.000058
54	3 2 0 0 0 0	44.57418940	-0.001548
55	3 2 0 0 1 0	44.57639581	-0.000679
56	3 2 0 0 2 0	44.57860221	-0.000074
57	3 3-3 0 0 0	45.00000000	-0.000014
58	3 3-2 1 0 0	45.04571045	-0.000016
59	3 3-2 1 1 0	45.04791686	-0.000007
60	3 3 0-1 0 0	45.11856411	-0.000084
61	3 3 0-1 1 0	45.12077051	-0.000037
62	3 4-2 0 0 0	45.59008516	-0.000018
63	3 4-2 0 1 0	45.59229157	-0.000008
64	3 4 0 0 0 0	45.67222244	-0.000067
65	3 4 0 0 1 0	45.67442885	-0.000058
66	3 4 0 0 2 0	45.67663525	-0.000019
67	3 5 0-1 0 0	46.21659715	-0.000011
68	3 5 0-1 1 0	46.21880355	-0.000010

Table 2-40. Tidal harmonics derived from the potential P40.

No.	Arguments Tau S H P N'P	Angular V. deg./hour	Amplitude
1	0 0 0 0 0 0	0.00000000	0.000043
2	0 0 0 0 1 0	0.00220641	-0.000033
3	0 1 0-1-1 0	0.54216830	-0.000004
4	0 1 0-1 0 0	0.54437471	0.000012
5	0 1 0-1 1 0	0.54658111	-0.000004
6	0 2 0 0 0 0	1.09803304	0.000086
7	0 2 0 0 1 0	1.10023945	0.000032
8	0 3 0-1 0 0	1.64240775	0.000021
9	0 3 0-1 1 0	1.64461415	0.000008
10	0 4 0 0 0 0	2.19606608	0.000005

Table 2-41. Tidal harmonics derived from the potential P41.

No.	Arguments Tau	S	H	P	N'P	Angular V. deg./hour	Amplitude
1	1	-3	0	0	-1 0	12.84279615	0.000007
2	1	-3	0	0	0 0	12.84500256	0.000012
3	1	-2	0	1	0 0	13.39866089	0.000024
4	1	-2	2	-1	0 0	13.47151455	0.000005
5	1	-1	0	0	-1 0	13.94082919	0.000011
6	1	-1	0	0	0 0	13.94303560	0.000098
7	1	-1	0	0	1 0	13.94524201	-0.000008
8	1	0	0	1	0 0	14.49669393	-0.000013
9	1	1	0	0	-1 0	15.03886223	0.000010
10	1	1	0	0	0 0	15.04106864	-0.000094
11	1	1	0	0	1 0	15.04327505	-0.000011
12	1	2	0	-1	0 0	15.58544335	-0.000013
13	1	3	0	0	0 0	16.13910168	-0.000017
14	1	3	0	0	1 0	16.14130809	-0.000010

Table 2-42. Tidal harmonics derived from the potential P42.

No.	Arguments Tau	S	H	P	N'P	Angular V. deg./hour	Amplitude
1	2	-3	0	1	-1 0	27.33949009	0.000005
2	2	-3	0	1	0 0	27.34169649	0.000013
3	2	-2	0	0	-1 0	27.88386479	0.000014
4	2	-2	0	0	0 0	27.88607120	0.000036
5	2	-1	0	1	0 0	28.43972953	0.000015
6	2	0	0	0	-1 0	28.98189783	-0.000016
7	2	0	0	0	0 0	28.98410424	0.000062
8	2	0	0	0	1 0	28.98631065	-0.000014
9	2	1	0	1	0 0	29.53776257	0.000006
10	2	2	0	0	0 0	30.08213728	0.000042
11	2	2	0	0	1 0	30.08434369	0.000016
12	2	3	0	-1	0 0	30.62651199	0.000006

Table 2-43. Tidal harmonics derived from the potential P43.

No.	Arguments Tau	S	H	P	N'P	Angular V. deg./hour	Amplitude
1	3	-3	0	2	0	41.83839043	0.000007
2	3	-3	2	0	0	41.91124408	0.000006
3	3	-2	0	1	-1	42.38055873	0.000005
4	3	-2	0	1	0	42.38276513	0.000031
5	3	-2	2	-1	0	42.45561879	0.000006
6	3	-1	0	0	-1	42.92493343	0.000013
7	3	-1	0	0	0	42.92713984	0.000088
8	3	0	0	-1	0	43.47151455	-0.000007
9	3	0	0	1	0	43.48079817	-0.000019
10	3	1	0	0	-1	44.02296647	0.000007
11	3	1	0	0	0	44.02517288	-0.000077
12	3	1	0	0	1	44.02737929	-0.000014
13	3	3	0	0	0	45.12320592	-0.000011
14	3	3	0	0	1	45.12541233	-0.000007

Table 2-44. Tidal harmonics derived from the potential P44.

No.	Arguments Tau	S	H	P	N'P	Angular V. deg./hour	Amplitude
1	4	-2	0	2	0	56.87945907	0.000012
2	4	-2	2	0	0	56.95231272	0.000011
3	4	-1	0	1	0	57.42383377	0.000058
4	4	-1	2	-1	0	57.49668743	0.000011
5	4	0	0	0	-1	57.96600207	-0.000012
6	4	0	0	0	0	57.96820848	0.000162
7	4	1	0	-1	0	58.51258319	-0.000014
8	4	1	0	1	0	58.52186681	0.000007
9	4	2	0	0	0	59.06624152	0.000028
10	4	2	0	0	1	59.06844793	0.000013

Table 3. Comparison of Xi's and Tamura's developments around O_1 constituent. Columns shown with - have smaller amplitudes than Tamura's threshold level.

Argument	Xi 1900 epoch $\times 10^{-5}$	Tamura 1900(extrapolated) $\times 10^{-6}$	
1-1-1 0-1 1	-15	-154	
1-1-1 0 0 1	-130	-1298	
1-1-1 1 0 0	6	57	
1-1-1 2 0-1 *	1	-	(-9)
1-1-1 2 0 1 *	2	33	(24)
1-1 0-2-2 0	1	14	
1-1 0 0-3 0	2	21	
1-1 0 0-2 0	-218	-2181	
1-1 0 0-1 0	7103	71061	
1-1 0 0 0 0	37698	376941	
1-1 0 0 1 0	-	15	
1-1 0 2-1 0	7	70	
1-1 0 2 0 0	-242	-2431	
1-1 0 2 1 0	-40	-396	
1-1 0 2 2 0	1	15	
1-1 1-2 0 1	-1	-	(5)
1-1 1-1 0 0	-1	-14	
1-1 1 0-1-1	13	119	
1-1 1 0 0-1 *	115	1143	
1-1 1 0 0 1 *	5	55	
1-1 1 0 1 1	-4	-35	
1-1 1 1 0 0	3	25	
1-1 1 1 1 0	1	-	(4)
1-1 1 2 0-1	-3	-30	
1-1 1 2 1-1	-1	-	(-6)

* : paired terms

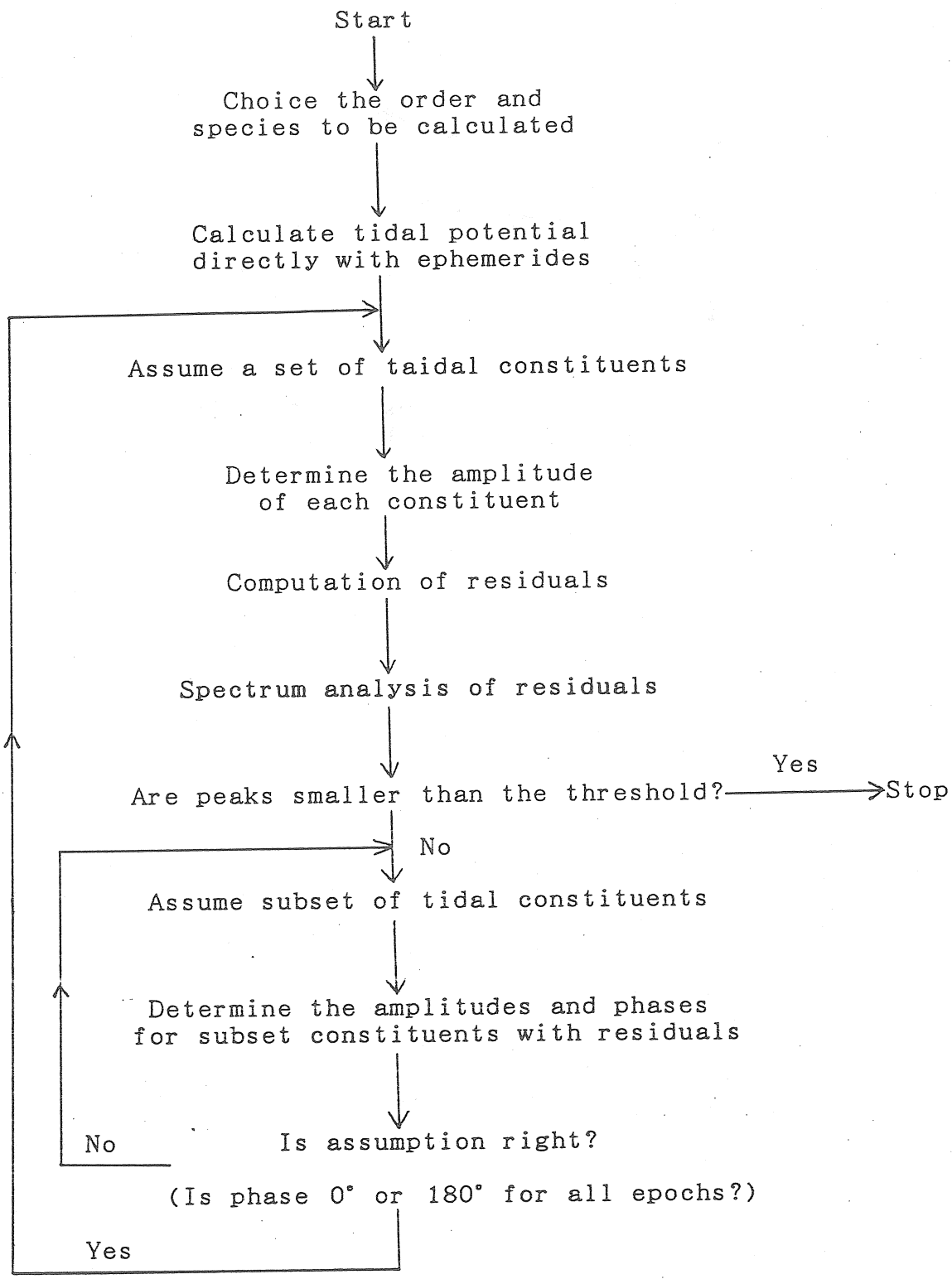


Figure 1. Flow chart of the harmonic development of the tide-generating potential by numerical method.

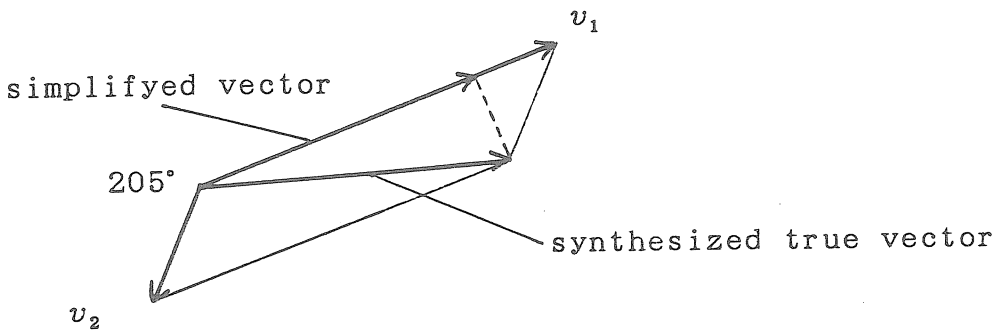


Figure 2. Synthesis of paired constituents whose angular velocities differ only by $2f_6$.

Appendix How to Calculate the Tidal Potential with the Harmonic Tables.

Following sequence, the tide-generating potential P_{nm} are calculated.

$$CV = \frac{3}{4}\mu GE\left(\frac{\sin \Pi}{3600} \cdot \frac{\pi}{180} \right)^3 \frac{1}{Re^2} \qquad \text{(A-1)}$$

$$Z_n = CV \cdot r\left(\frac{r}{Re}\right)^{n-1} \qquad for\ n = 2, 3, 4 \qquad \text{(A-2)}$$

$$P_{nm} = \sum^{i} amp_i \frac{g_{nm}(\phi)}{\max|g_{nm}(\phi)|} Z_n \cdot \cos(\omega_i \cdot t + \delta_{nm}) \quad for\ m = 0, 1, \cdots, n \qquad \text{(A-3)}$$

where r and ϕ is the geocentric radius and latitude of a site respectively. δ_{nm} is 0° if $n+m$ is even and -90° if $n+m$ is odd. The values amp_i and ω_i are given in the tables. The functions $g_{nm}(\phi)$ express the geographical coefficients. $\mathrm{Max}|g_{nm}(\phi)|$ ($= \Gamma_{nm}$) are called Doodson's normalization factors. They are denoted as

$$\left.\begin{aligned}
g_{20}(\phi) &= 1-3\sin^2\phi, & g_{21}(\phi) &= \sin 2\phi, \\
g_{22}(\phi) &= \cos^2\phi, & g_{30}(\phi) &= \sin\phi(3-5\sin^2\phi), \\
g_{31}(\phi) &= \cos\phi(1-5\sin^2\phi), & g_{32}(\phi) &= \sin\phi\cdot\cos^2\phi, \\
g_{33}(\phi) &= \cos^3\phi, & g_{40}(\phi) &= 3-30\sin^2\phi+35\sin^4\phi, \\
g_{41}(\phi) &= \sin 2\phi(3-7\sin^2\phi), & g_{42}(\phi) &= \cos^2\phi(1-7\sin^2\phi), \\
g_{43}(\phi) &= \sin\phi\cdot\cos^3\phi, & g_{44}(\phi) &= \cos^4\phi,
\end{aligned}\right\} \qquad \text{(A-4)}$$

$$
\left.
\begin{aligned}
&\Gamma_{20} = 2, \qquad \Gamma_{21} = 1, \qquad \Gamma_{22} = 1, \\
&\Gamma_{30} = 2, \qquad \Gamma_{31} = \frac{16}{3\sqrt{15}}, \\
&\Gamma_{32} = \frac{2}{3\sqrt{3}}, \qquad \Gamma_{33} = 1, \\
&\Gamma_{40} = 8, \qquad \Gamma_{41} = \frac{(3+\sqrt{393})\sqrt{390+2\sqrt{393}}}{224}, \\
&\Gamma_{42} = \frac{9}{7}, \qquad \Gamma_{43} = \frac{3\sqrt{3}}{16}, \qquad \Gamma_{44} = 1.
\end{aligned}
\right\} \quad \text{(A-5)}
$$

Doodson adopted nomalization factor $\Gamma_{30} = 2/\sqrt{5}$ in mistake. This scale is also adopted in this development to compare with his schedules.

If one wants to calculate the three component tidal accelerations in stead of potential, he can get them by differentiating the potential P_{nm}. The acceleration toward anti-geocentric direction is calculated by multiplying n/r to P_{nm}. The north direction component (not horizontal direction on ellipsoidal earth but tangential to a sphere of radius r) is obtained by differentiating the numerator $g_{nm}(\phi)$ in the equation (A-3) by geocentric latitude ϕ and multiplying $1/r$ to (A-3). The east one also calculated by adding 90° to the argument of cosine and multiplying $m/(r\cdot\cos\phi)$ to P_{nm}.

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An Introduction to the Tidal Analysis Program "BAYTAP"

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Abstract

The tidal analysis program "BAYTAP" (BAYesian Tidal Analysis Program) was developed to process complex tidal datasets, which have noobserbation periods, leaps and irregular data, and which should be determined the tidal factors and trend form precisely.

In simplified analysis model of BAYTAP, all parameters are determined by letting following function $J(d)$ minimum.

$$J(d) = \sum_{i=1}^{n} \left\{ (\text{irregular part})^2 + D^2 \cdot (\text{second degree difference of trend})^2 \right\}$$

where D is a *hyperparameter* to determine the rigidity of trend. The hyperparameter D is automatically determined by minimizing ABIC (a Bayesian information criterion), and indicates the quality of datasets. One of the advantages in BAYTAP is that it can handle a trend which drifts slowly in time, and which can not be expressed by polynomial or sine curves.

Following abilities can be listed in BAYTAP, (1) determination of tidal factors, (2) determination of trend and calculation of its power spectrum, (3) calculation of response

for associated datasets (for example, atmospheric pressure data), (4) interpolation of absent data and estimation of step magnitudes, (5) detection of irregular data (or abnomal phenomena), (6) calculation of ABIC to check the goodness of modeling. Adopting those abilities, BAYTAP is useful for the preprocessing of tidal dataset, and the precise analysis of tides and crustal movements.

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DETERMINATION AND CONSEQUENCES OF VARIABILITY OF S1-WAVE PARAMETERS

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The influence of temperature on the results of tidal instruments indications is usually revealed in two ways: 1. in the variations of the calibration factor, and 2. in the performance of physical mechanisms causing the quasi-tidal wave S1 interfering with the much smaller real tidal wave S1.

The influence of the calibration factor variations may be completely eliminated by correct calibrations of the instrument in the observation process and we will not discuss this problem here. This paper concerns the issue mentioned in point 2.

In the period from January 1980 till October 1984 at the tidal station in Warsaw the observations were realized using the gravimeter BN-17, that is the gravimeter Askania Gs-11 no 110 reconstructed by prof. M. Bonatz. However, at that time at the station there was no a thermostatic compartment with the accuracy of $\pm$ 0.°2 C which is indispensable for this type of gravimeters. A conventional analysis of thet observational material revealed that the results were very much distorted due to the temperature influence.

Therefore it was decided to elaborate that material in a special way with the following aims considered: 1. to free it of the temperature influence and to get more reliable results and 2. to learn the mechanism of tidal observations distortion due to the temperature variation which may be significant in correcting less perturbed observations than those in the case of the BN-type gravimeter.

The observations mentioned at the beginning obtained with the BN-17 gravimeter were especially useful, mainly in view of the second aim. They were under a great temperature influence which enabled more precise observation and investigation of this influence. At first the observational material of the two-year period from October 1982 till October 1984 underwent a detailed elaboration.

In order to determine the main effects of the distortion in the

results of the analysis caused by the disturbing influence of temperature variations, it is recommended to study Table 1 which gives the results of a typical analysis of the above mentioned two-year observational period. The following distortions result clearly from the table:

1. a very great amplitude factor of the wave S1 and its error,

2. a very high value of the mean error m_o,

3. unproportionally great value of M_D, ie. the mean error in the band of diurnal waves, in relation to m_o and M_{SD} $\left(M_D/M_{SD} = 4:1,\right.$ while it is usually of the order of $\left.2:1\right)$,

4. a false value of the amplitude factor of the wave P1.

Table 2 gives the values of parameters of the wave S1, ie. amplitude factor and phase difference, coming from the analysis of the period 1980-84 divided into three parts: a two-year part of 1980-82 and two one-year parts of 1982-83 and 1983-84. It results from the table that the parameters of the quasi-tidal wave S1 are variable in time, and especially its amplitude. If it is true in reality, it would explain all the reasons for the distortion in the results of a typical analysis which were mentioned in the points 1-4, namely:

1 and 2. adoption of the parameters of the wave S1 as constant in a typical analysis - while in reality they are variable - causes that the deviation of parameters have a form of accidental errors in the adjustment process, which increases the value of the mean error m_o as well as the errors in the determination of these parameters,

3. because the wave S1 lies in the band of diurnal waves, the deviations mentioned above will be revealed in this band in the first place,

4. if the parameters of the wave S1 are variable, its spectrum will be of the shape similar to the one showed in Fig. 1. Therefore, there is a great possibility that the waves of the near frequency to that of the wave S1, that is P1 and K1, will interfere with the corresponding part of the quasi-tidal S1-wave spectrum. Thus, they will both get distorted and the smaller one P1 will be distorted more.

In order to prove the thesis about the variability of parameters of the quasi-tidal wave S1, this variability must be determined, this wave must be eliminated from the observations, another analysis must be done, and finally, the results free of the lacks mentioned in points 1-4 must be obtained.

The main obstacle in determining the variability of the wave S1 is the fact that its frequency is close to the frequency of the waves P1 and K1, and thus, one-year observational period is needed to separate these three waves with the harmonic analysis method. Therefore, without

additional assumptions only the variability of the mean year parameters of the wave S1 can be investigated, which is definitely insufficient, because from the physical point of view this variability has probably the frequency of temperature variations at the station, ie. of the order of weeks or even days.

In order to form a two method of determining the variability of the wave S1 in time, a basic assumption was made that this variability is the main reason for the systematic error in the residuum after a typical analysis of the observations with the least squares method.

In the first method it is assumed that the amplitude of the wave S1 and a phase difference in relation to the theoretical wave S1 are variable. Thus it also shows frequency oscillations.

We adopt certain initial values for the parameters of all tidal waves, except for S1 (further it will be discussed which values are considered), and we subtract them from the observations. Then we obtain the residuum containing the wave S1. This residuum can be divided into optional sections, even of one-day length, and the factor of amplitude as well as the phase difference of the quasi-tidal wave S1 can be determined for each section. In this way we will obtain the variability of this wave parameters in time.

It is best to compute the initial values for the residuum determination as the most probable parameter values of tidal waves for a given station using the theoretical model, previous measurements, computation of the oceanic effects, etc. Also the values obtained from the first typical analysis of the elaborated material can be used as the initial values. However, it must be remembered that they are under influence of S1 wave variability. In such a case correct results of the analysis can be obtained only after the elimination of the wave S1 performed in a few iterations.

Fig. 2 shows the diagrams of S1-wave variability for the gravimeter BN-17 in the period 1982-84 determined with the above method. Table 3 gives the results of the repeated analysis of the discussed material carried out after the elimination of the wave S1 presented in Fig.2. Table 4 presents a compilation of the elements chosen from Tables 1 and 3 which are the most significant in confirmation of the assumption on the influence of S1-wave variability on the results of measurement with the BN-type gravimeter.

As it can be seen in Table 4, obtained results confirm the assumption that temperature distortions of the observational results mentioned at the beginnig in points 1-4 are caused by the variability of S1 wave parameters. Elimination of this wave removes all faults of distored

observations, namely:

1. A comparison of amplitude factor values from analysis before and after elimination of S1-wave illustrates the degree of this elimination. As it can be seen, it was eliminated in 95%. The error of determination of S1-wave considered as constant decreased by 58%.

2. The value of the mean square error m_o decreased by 36% and reached the value obtained from the observations with Gs-11 gravimeter at the Warsaw station.

3. The value of the mean square error M_D in the band of the diurnal waves decreased by nearly 2.5 times and reached the regular value in relation to the mean square error M_{SD} in the band of the semi-diurnal waves which is usually obtained in the analysis of tidal observations, ie. 2:1.

4. The value of the amplitude factor of the wave P1 was correct.

It should also be emphasized that the parameters of other waves with the frequencies distant from that of the wave S1 as well as the errors M_{SD} and M_{TD} did not change. It additionally confirms the assumption and the exactness of conducted correction because the variability of the wave S1 should not have any influence on these elements.

In the variability of the wave S1 presented in Fig. 2 two parts can be differentiated: a part changing more slowly with the period of the order of weeks or months and a short-periodical part of the order a few days. From the physical point of view such a short-periodical variability of the wave S1 is less probable and it may be caused by inaccuracy of the assumption made at the beginning, saying that the main (and practically the only one) reason for the systematic error in the residuum after a typical observational analysis is the variability only. Other physical reasons and the accidental error will also influence the determination of the wave S1 with the given method.

Due to that another analysis was made. Fig. 3 presents the variability of the wave S1 which is a modification of the curve from Fig. 2 obtained by its smoothing and graphical elimination of the short-periodical effects. Table 5 gives the analysis results of the same observations from the period 1982-84 from which the wave S1 presented in Fig. 3 was eliminated. It is seen (in Table 4) in the comparison of these results with the corresponding ones from table 3 that they are only slightly worse. It can be concluded that the disturbing variability of the wave S1 is of long-periodical character and the method of smoothing its curve variability determined with the suggested method still ought to be investigated.

In the second method of the determination of S1-wave variability it is assumed that the wave has a variable amplitude and a constant

frequency, which means that the phase fifference in relation to the theoretical wave is constant. If the residuum containing only the wave S1 - the way of obtaining this residuum is described above - undergoes an analysis in order to determine variation of the calibration factor in time (Chojnicki, 1984), this factor will denote the variability of S1 amplitude in time.

Let us remind: in this method the ratio of the tide value $P_o(t)$ before and after the adjustment is determined from the following formula:

$$K(t) = \frac{P_o(t) \cdot C_o(t) - r(t)}{P_o(t) \cdot C_o(t)}$$

therefore, in the case when there is only the wave S1 in the analysed tide, the factor $K(t)$ will denote exactly this wave variability.

Fig. 4 shows the variability of the wave S1 determined in the above way and Table 6 presents the analysis results of the observational material from which the wave S1 was eliminated on the basis of Fig. 4. A general character of the variability in Figs. 4 and 2 is similar. However, because

- the results in Table 6 are much worse than the results presented in Tables 3 or 5 (the confrontation in Table 4),
- the amplitude of the wave S1 in Fig. 4 assumes negative values in some cases which corresponds to the phase difference by 180^o,
- the variability of the wave S1 in the short-periodical range in Fig. 4 is much greater than in Fig. 2,

it can be concluded that after all the phase difference variability of the quasi-tidal wave S1 exists. In other words the quasi-tidal wave S1 reveals frequency oscillations.

A physical interpretation of the described phenomenon is also worth mentioning. The occurence of the quasi-tidal wave S1 proves the reaction of the instrument to the diurnal temperature wave. This wave amplitude variability can be explained by the length variability of different metallic elements in the measurement system of the instrument. Because this phenomenon increases in the BN-type instrument with the capacitive output, it will probably concern a capacitor, which is the basic element of this output, and also other elements connected with it, like for example supply conduits, dielectric qualities of the air, etc.

The oscillations of S1-wave phase difference in relation to the theoretical equivalent of this wave can be also explained physically. A mean phase difference of this wave treated as a phase lag has a high va-

lue; it amounts about 270° which is equal to about 18^{h}. It is probably caused by the insulating material protecting the interior of the gravimeter against the external influence. Certain factors, like for example humidity variations, can change the conductivity of this insulant which will cause a phase lag of the wave S1. The influence of humidity variations on the tidal observations was alredy mentioned by Dittfeld (Dittfeld et al., 1983).

The idea presented here concerning the mechanism of the influence of temperature variations on the results of tidal observations obtained with the gravimeter with capacitive output is based on the initial results the work on which still has to be continued. The main disadvantage here is the laboriousness of computations. It would be especially interesting to check the usefulness of the applied method in the corrections of smaller temperature distortions of tidal observations performed with other instruments.

References

Chojnicki T., 1985, Determination of the shape of the calibration curve, B.I.M. no 94, 6312-6320.

Dittfeld H.-J., Elstner C., Harnisch M., Schwahn W., Simon D., 1983, Analysis and interpretation of Earth tide measurements at Potsdam and Tiefenort, Veröff. des Zentralinst. für Physik der Erde, no 71, 53-87.

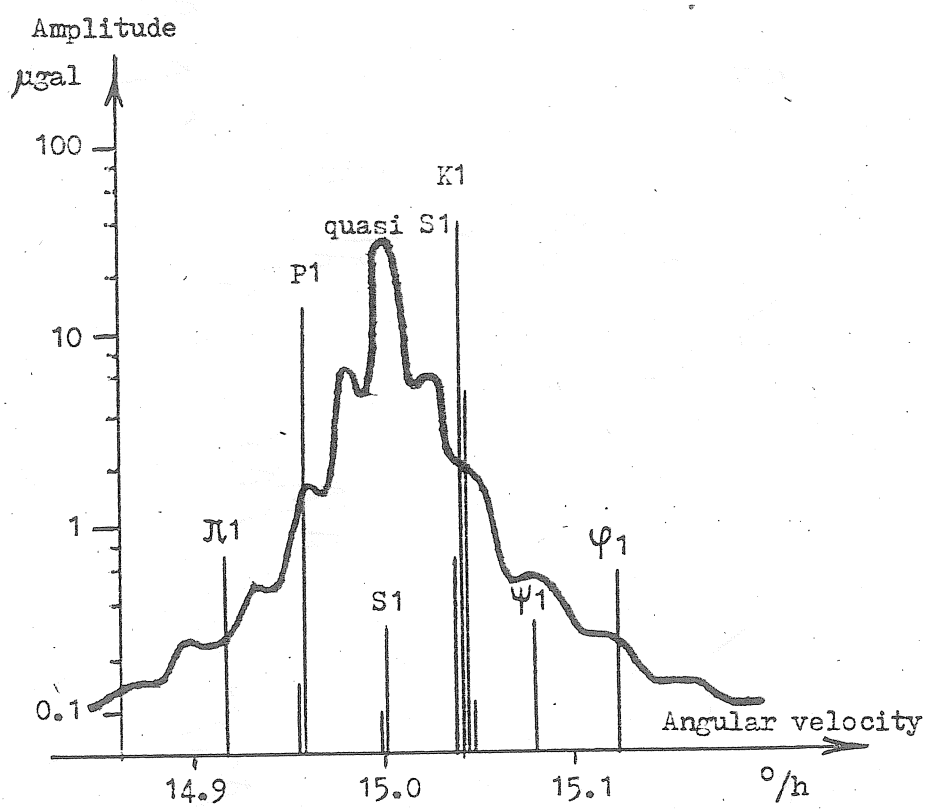


Fig.1. Spectrum of the quasi-tidal S1-wave

T a b l e I I

Parameters of S1-wave in different periods

Period	Amplitude factor	Phase difference
1980.I - 1982.IV	78.25	130°
1982.X - 1983.X	100.68	80
1983.X - 1984.X	55.43	84

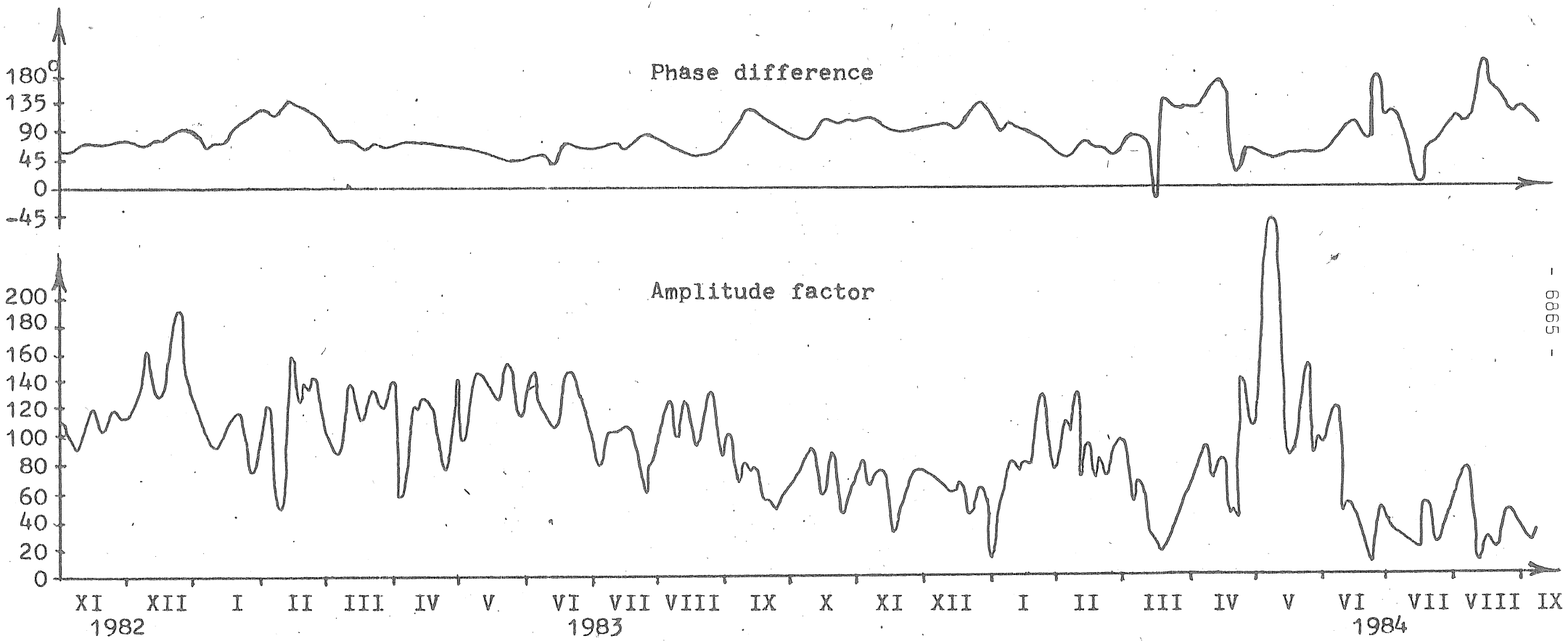


Fig. 2. Diagrams of S1-wave variability

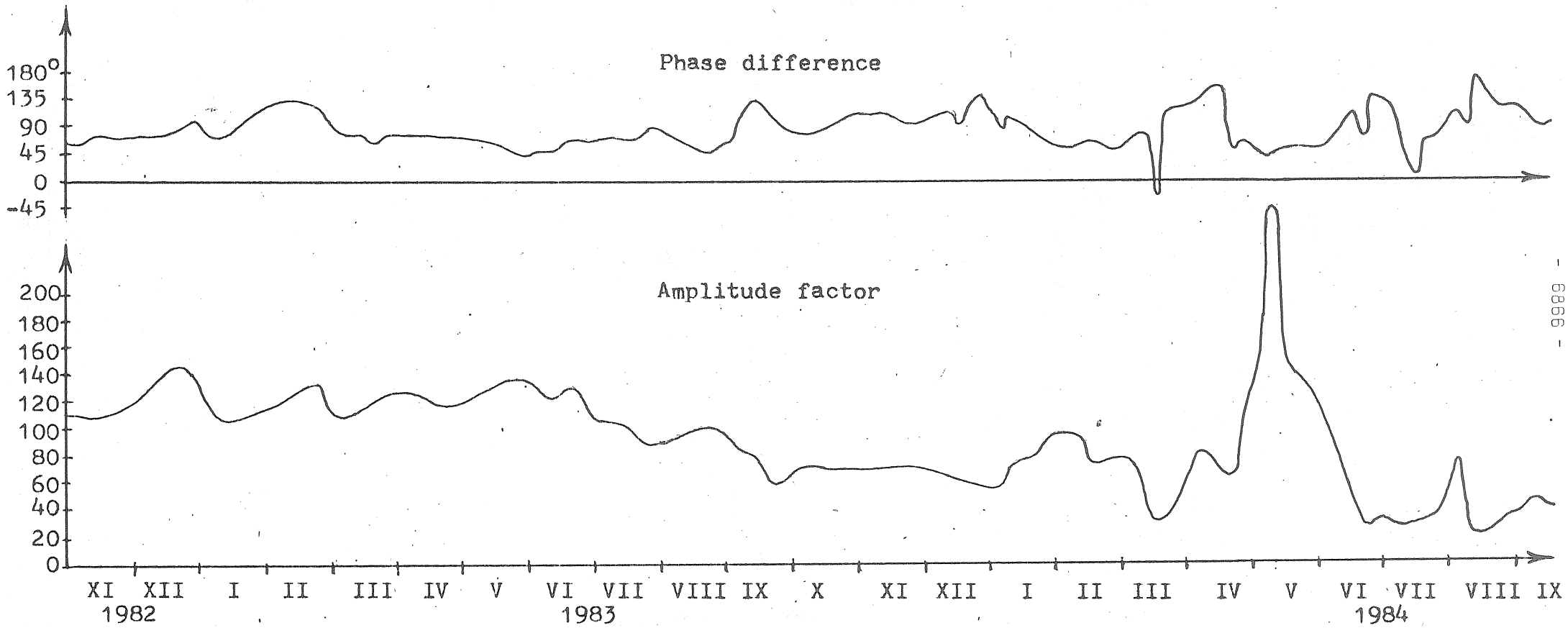


Fig. 3. Smoothed diagrams of S1-wave variability

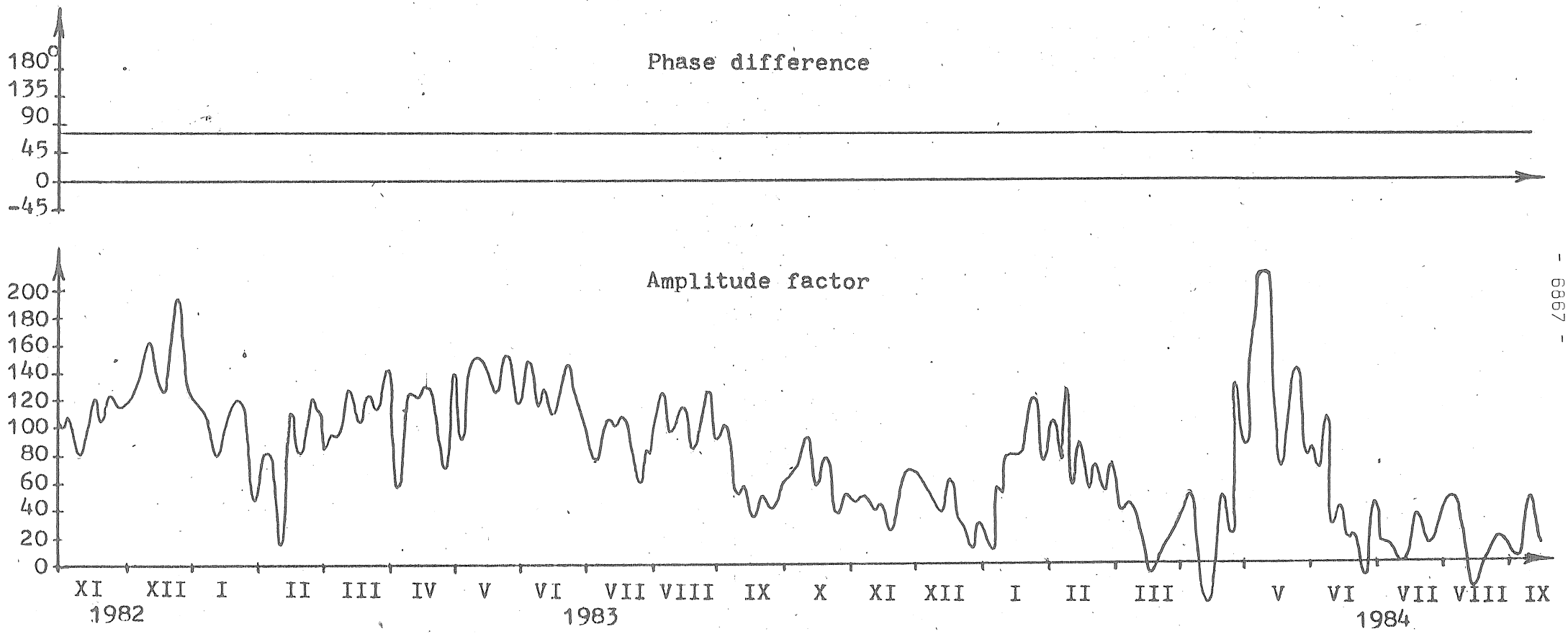


Fig. 4. Diàgram of S1-wave variability with constant phase differency

WYROWNANIE KONCOWE - FINAL ADJUSTMENT CHOJNICKI METHOD

KONCOWE WYNIKI OBLICZEN - OCENA DOKLADNOSCI NA PODSTAWIE RESIDUUM
FINAL RESULTS OF COMPUTATIONS - ESTIMATION OF ACCURACY BASED ON RESIDUAL

0.11701984 1 1 0 0 10001110 52.23 -21.01 110 0.0 981.245

STATION 0905 WARSZAWA VERTICAL COMPONENT POLAND

52 14 N 21 01 E H 110 M P 3 M D 260 KM
THE UNDERGROUND OF THE PALACE OF CULTURE QUATERNARY SANDS
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INSTALLATION M.BONATZ / T.CHOJNICKI / S.GADOMSKI
OPERATION T.CHOJNICKI / M.KACZOROWSKI / M.MALKOWSKI

LEAST SQUARE ANALYSIS IN CLASSICAL MANNER (CHOJNICKI)
FILTRATION OF OBSERVATIONS / FILTER 51/ 833
POTENTIAL CARTWRIGHT-EDDEN-(DOODSON) / EXPANSION REDUCED TO 65 WAVES
COMPUTATION - ZAKLAD GEODEZJI PLANETARNEJ CBK PAN - WARSZAWA - COMPUTER IBM/370

8210 2519-8211 1917/8211 22 6-8211 3021/8212 318-8212 2815/8212 3112-83 5 1010
83 5 1422-8310 2 4/8310 417-8311 2518/8312 817-84 3 2122/84 4 114-84 4 812
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84 9 14 9-8410 1413

TOTAL NUMBER OF DAYS 720 15919 READINGS

WAVE GROUP ARGUMENT	N	SYMBOL	ESTIM.AMPL. VALUE	R.M.S.	AMPLITUDE FACTOR VALUE	R.M.S.	PHASE DIFFERENCE VALUE	R.M.S.	RESIDUALS AMPL.	PHASE
117.-137.	10	Q1	6.27	0.56	1.18034	0.10516	-0.382	5.104	0.12	-20.7
145.-147.	6	O1	37.99	0.68	1.16985	0.02082	-0.388	1.019	0.43	-37.0
153.-157.	7	M1	2.31	0.59	1.00436	0.25673	-22.360	14.655	1.02	-121.0
162.-163.	3	P1	12.15	0.69	0.82094	0.04638	-3.367	3.238	5.00	-171.8
164.-164.	2	S1	17.96	0.65	77.49693	2.80295	82.280	2.073	17.93	83.1
165.-167.	6	K1	50.12	0.65	1.13812	0.01481	-1.229	0.745	1.08	-89.4
173.-175.	4	J1	2.34	0.61	0.92707	0.24381	-21.983	15.069	1.16	-131.0
183.-195.	7	OO1	1.75	0.52	1.38669	0.41018	12.946	16.944	0.46	58.4
227.-237.	4	2N2	1.15	0.14	1.19128	0.14502	-3.616	6.976	0.08	-69.0
245.-247.	4	N2	6.59	0.17	1.17433	0.02992	0.835	1.460	0.12	50.5
255.-255.	2	M2	32.16	0.17	1.14692	0.00616	0.340	0.308	0.42	152.7
263.-265.	4	L2	0.51	0.12	1.24251	0.28444	-40.755	13.115	0.34	-105.1
272.-273.	2	S2	17.03	0.18	1.22130	0.01316	0.151	0.617	0.85	3.0
275.-285.	3	K2	4.13	0.17	1.04893	0.04415	-6.145	2.412	0.64	-136.2
355.-355.	1	M3	0.28	0.07	0.80658	0.20073	8.413	14.258	0.10	156.3

R.M.S.ERROR M-ZERO 12.4781 MILISEC

R.M.S.ERROR FOR BANDS D 58.1940 SD 15.4642 TD 6.5780

O1/K1 1.0279 1-O1/1-K1 1.2297 M2/O1 0.9804

REFERENCE EPOCH 1984 1 1 0.0 JULIAN DATE 2445700.5

Table 1

Results of analysis of the rough observations

WYROWNANIE KONCOWE - FINAL ADJUSTMENT CHOJNICKI METHOD

KONCOWE WYNIKI OBLICZEN - OCENA DOKLADNOSCI NA PODSTAWIE RESIDUUM
FINAL RESULTS OF COMPUTATIONS - ESTIMATION OF ACCURACY BASED ON RESIDUAL

0.0 1984 1 1 0 0 10001110 52.23 -21.01 110 0.0 981.245

STATION 0905 WARSZAWA VERTICAL COMPONENT POLAND

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LEAST SQUARE ANALYSIS IN CLASSICAL MANNER (CHOJNICKI)
FILTRATION OF OBSERVATIONS / FILTER 51/ 833
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COMPUTATION - ZAKLAD GEODEZJI PLANETARNEJ CBK PAN - WARSZAWA - COMPUTER IBM/370

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105.-139.	65	Q1	6.22	0.23	1.16579	0.04330	0.999	2.128	0.11	73.3
143.-149.	26	O1	37.76	0.28	1.16233	0.00869	-0.002	0.428	0.10	-0.7
152.-158.	22	M1	2.45	0.23	1.13734	0.10740	-5.095	5.416	0.22	-104.4
161.-163.	10	P1	17.14	0.29	1.15660	0.01939	-0.463	0.961	0.14	-72.7
164.-164.	3	S1	0.90	0.27	3.90049	1.16940	168.430	17.176	1.17	171.1
165.-168.	20	K1	50.32	0.27	1.14383	0.00619	-0.012	0.310	0.28	-2.1
172.-177.	22	J1	3.09	0.27	1.13276	0.09767	0.113	4.940	0.08	175.5
181.-1E3.	37	OO1	1.37	0.20	1.18486	0.17093	3.279	8.265	0.08	71.8
207.-23X.	41	2N2	1.17	0.14	1.16521	0.13649	-3.723	6.713	0.08	-88.0
243.-248.	24	N2	6.67	0.16	1.16737	0.02856	-0.151	1.402	0.04	-23.0
252.-258.	26	M2	32.21	0.17	1.14753	0.00595	0.231	0.297	0.38	159.8
262.-267.	17	L2	0.57	0.12	1.39165	0.30335	-41.417	12.488	0.38	-97.2
271.-274.	9	S2	16.88	0.18	1.21908	0.01270	0.154	0.597	0.82	3.2
275.-2X5.	38	K2	4.05	0.17	1.06418	0.04369	-4.556	2.352	0.50	-139.6
327.-375.	17	M3	0.27	0.06	0.89216	0.19120	14.015	12.279	0.09	133.0

R.M.S.ERROR M-ZERO 7.9768 MILISEC

R.M.S.ERROR FOR BANDS D 24.3114 SD 14.9357 TD 6.5175

O1/K1 1.0162 1-O1/1-K1 1.1286 M2/O1 0.9873

REFERENCE EPOCH 1984 1 1 0.0 JULIAN DATE 2445700.5

Table 3

Results of analysis of the observations after elimination of variable S1-wave

Table 4

Confrontation of main results presented in Tables 1, 3, 5 and 6

Element	Values obtained			
	before	after		
		elimination of S1-wave		
	Table 1	Table 3	Table 5	Table 6
Amplit.fact. of S1-wave	77.497	3.900	3.655	0.795
m.s.e. of amplit.fact. of S1-wave	2.80	1.17	1.61	2.15
m.s.e. m_o	12.48	7.98	8.91	10.49
m.s.e. M_D	58.19	24.31	33.44	44.55
m.s.e. M_{SD}	15.46	14.94	15.34	15.42
M_D : M_{SD}	3.8 : 1	1.6 : 1	2.2 : 1	2.9 : 1
Amplit.fact. (resid.ampl.) of wave: P1	0.821 (5.00)	1.157 (0.14)	1.173 (0.31)	0.954 (2.95)
K1	1.138 (1.08)	1.144 (0.28)	1.135 (0.15)	1.095 (2.67)
O1	1.170 (0.43)	1.162 (0.10)	1.161 (0.18)	1.170 (0.45)
M2	1.147 (0.42)	1.148 (0.38)	1.147 (0.43)	1.146 (0.43)
S2	1.221 (0.85)	1.219 (0.82)	1.221 (0.85)	1.220 (0.84)

m.s.errors in μgal e.q. 10^{-8} m/sec^2

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0.11701984 1 1 0 0 10001110 52.23 -21.01 110 0.0 981.245

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117.-137.	10	Q1	6.24	0.32	1.17513	0.06042	2.049	2.946	0.24	70.5
145.-147.	6	O1	37.70	0.39	1.16098	0.01196	-0.252	0.590	0.18	-71.9
153.-157.	7	M1	2.37	0.34	1.03057	0.14751	-7.709	8.208	0.45	-134.8
162.-163.	3	P1	17.36	0.39	1.17287	0.02665	-0.443	1.302	0.31	-25.3
164.-164.	2	S1	0.85	0.37	3.65540	1.61068	-150.739	25.244	1.09	-157.6
165.-167.	6	K1	49.96	0.37	1.13458	0.00851	0.070	0.430	0.15	155.4
173.-175.	4	J1	2.82	0.35	1.11894	0.14005	0.996	7.172	0.12	155.4
183.-195.	7	OO1	1.77	0.30	1.39940	0.23569	6.053	9.647	0.35	32.6
227.-237.	4	2N2	1.18	0.14	1.21678	0.14390	-4.268	6.777	0.10	-59.5
245.-247.	4	N2	6.63	0.17	1.18174	0.02969	0.783	1.439	0.15	36.9
255.-255.	2	M2	32.16	0.17	1.14659	0.00612	0.363	0.306	0.43	151.8
263.-265.	4	L2	0.50	0.11	1.21880	0.28224	-40.200	13.267	0.33	-106.2
272.-273.	2	S2	17.02	0.18	1.22071	0.01306	0.207	0.613	0.85	4.2
275.-285.	3	K2	4.12	0.17	1.04832	0.04381	-6.223	2.395	0.64	-136.1
355.-355.	1	M3	0.29	0.07	0.84271	0.19952	10.491	13.564	0.10	147.3

R.M.S.ERROR M-ZERO 8.9124 MILISEC

R.M.S.ERROR FOR BANDS D 33.4362 SD 15.3446 TD 6.5383

O1/K1 1.0233 1-O1/1-K1 1.1962 M2/O1 0.9876

REFERENCE EPOCH 1984 1 1 0.0 JULIAN DATE 2445700.5

Table 5

Results of analysis of the observations after elimination of smoothed variable S1-wave

WYROWNANIE KONCOWE - FINAL ADJUSTMENT CHOJNICKI METHOD

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GRAVIMETER BN-17 (ASKANIA GS-11 NO 110)
CALIBRATION - GRAVIMETRIC BASIS
INSTALLATION M.BONATZ / T.CHOJNICKI / S.GADOMSKI
OPERATION T.CHOJNICKI / M.KACZOROWSKI / M.MALKOWSKI

LEAST SQUARE ANALYSIS IN CLASSICAL MANNER (CHOJNICKI)
FILTRATION OF OBSERVATIONS / FILTER 51/ 833
POTENTIAL CARTWRIGHT-EDDEN-(DOODSON) / EXPANSION REDUCED TO 65 WAVES
COMPUTATION - ZAKLAD GEODEZJI PLANETARNEJ CBK PAN - WARSZAWA - COMPUTER IBM/370

8210 2519-8211 1917/8211 22 6-8211 3021/8212 318-8212 2815/8212 3112-83 5 1010
83 5 1422-8310 2 4/8310 417-8311 2518/8312 817-84 3 2122/84 4 114-84 4 812
84 4 1112-84 7 6 5/84 7 10 9-84 7 2315/84 7 2615-84 8 26 9/84 8 3013-84 9 1016
84 9 14 9-8410 1413

TOTAL NUMBER OF DAYS 720 15919 READINGS

WAVE GROUP ARGUMENT	N	SYMBOL	ESTIM.AMPL. VALUE	R.M.S.	AMPLITUDE FACTOR VALUE	R.M.S.	PHASE DIFFERENCE VALUE	R.M.S.	RESIDUALS AMPL.	PHASE
117.-137.	10	Q1	6.27	0.43	1.17931	0.08051	0.650	3.911	0.13	34.1
145.-147.	6	O1	38.02	0.52	1.17055	0.01594	-0.407	0.780	0.45	-36.5
153.-157.	7	M1	2.64	0.45	1.14765	0.19654	-9.101	9.820	0.42	-98.0
162.-163.	3	P1	14.13	0.53	0.95431	0.03551	0.075	2.133	2.95	179.6
164.-164.	2	S1	0.18	0.50	0.79457	2.14583	78.052	154.754	0.29	141.7
165.-167.	6	K1	48.21	0.50	1.09467	0.01134	-2.201	0.593	2.67	-136.1
173.-175.	4	J1	2.58	0.47	1.02256	0.18664	-15.082	10.458	0.80	-123.2
183.-195.	7	OO1	1.74	0.40	1.37720	0.31403	9.803	13.061	0.39	50.0
227.-237.	4	2N2	1.18	0.14	1.21631	0.14458	-2.930	6.812	0.08	-48.7
245.-247.	4	N2	6.62	0.17	1.17991	0.02983	0.939	1.448	0.15	44.5
255.-255.	2	M2	32.15	0.17	1.14636	0.00615	0.351	0.307	0.43	153.0
263.-265.	4	L2	0.50	0.12	1.21710	0.28358	-40.319	13.348	0.33	-106.4
272.-273.	2	S2	17.01	0.18	1.22048	0.01312	0.154	0.616	0.84	3.1
275.-285.	3	K2	4.12	0.17	1.04758	0.04402	-6.366	2.408	0.65	-135.7
355.-355.	1	M3	0.28	0.07	0.81342	0.19985	9.751	14.076	0.10	152.6

R.M.S.ERROR M-ZERO 10.4930 MILISEC

R.M.S.ERROR FOR BANDS D 44.5507 SD 15.4173 TD 6.5490

O1/K1 1.0693 1-O1/1-K1 1.8015 M2/O1 0.9793

REFERENCE EPOCH 1984 1 1 0.0 JULIAN DATE 2445700.5

Table 6

Results of analysis of the observations after elimination of variable S1-wave with constant phase difference

Noise levels of less than 20 ngal - consequences for tidal analyses

by

G. Jentzsch *

1. Introduction

The comparison of the analyses of gravity variations recorded at two stations only 21 km apart yielded to some interesting results. At the tidal Observatory in Potsdam (GDR) the Askania gravimeter GS-15/222 is recording since April 1974, and in parallel, the LaCoste-Romberg gravimeter ET-18 recorded at the Tidal Observatory Berlin (West), covering a period of nearly two years (May 1980 untill March 1981).

The common periods of both records were analyzed as well as the long series from Potsdam. The results of these investigations were published by Asch et al. (1986a/b). Therefore, in the following these results are only summarized and extended to the purpose of the Working Group for 'High Precision Tidal Data Processing'.

1. Calibration

Both instruments were calibrated independently. It turned out that the observed amplitudes of the ET-18 are slightly bigger than those provided by the GS-15/222; but the mean difference of the main tidal constituents is less than 1%.

3. Errors and residuals

The error bars provided by the analyses (based upon the Fourier spectrum of the residuals) are almost identical (comp. tab. 1). Comparing these error bars with the spectrums of the residuals (see fig. 1) we realize, that the errors are overestimated due

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Table 1: Error bars obtained from the analyses of the common period of 400 days of the LCR ET-18 and the Askania GS-15/222 (in microgal).

	ET - 18	GS - 15/222
diurnal	.0730	.0666
semidiurnal	.0305	.0265
terdiurnal	.0203	.0187

to harmonics still present in the residuals. The ambient noise levels are about half of these values. Although the spectral amplitudes are about 0.1 μgal or less the peaks are significant.

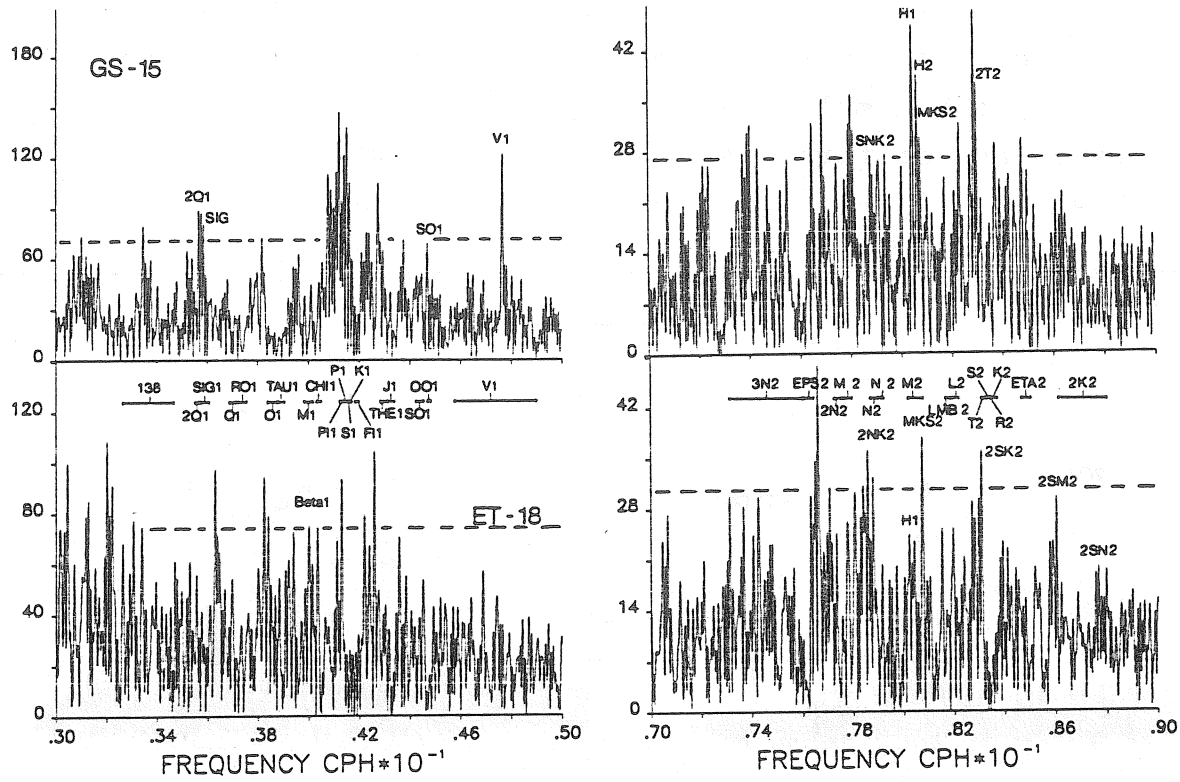


Figure 1. Spectrums of the filtered residuals for diurnal (left) and semidiurnal (right) tidal bands; upper: GS-15/222, lower: LCR ET-18. The broken horizontal lines indicate the calculated mean noise levels. Main tidal frequencies and the wave grouping used in the analyses are marked. Amplitudes are in nanogal (from Asch et al., 1986a).

These small harmonics are close to tidal frequencies, and they most likely result from temporal variations of the tidal parameters due to indirect tidal signals, e.g. of meteorological origin. This has been confirmed by analyzing wind speed and air pressure.

The spectrums of the residuals of the 10-years record from Potsdam (see fig. 2) provide a more distinct picture: The ambient noise levels of the diurnal and semidiurnal tidal bands are reduced to less than 20 ngal and 10 ngal, respectively. Spectral peaks are found close to 2Q1, P1, S1, and within the groups of O1, M, PI1 and V1, as well as close to 2N2, N2, H1, H2, Delta2, and within the groups of N2, GAM2, M2, L2 and K2. Some peaks are between tidal groups N2 and NI2, as well as between T2, S2, R2 and K2.

Asch et al. (1986a) have shown, that the analyses of overlapping yearly subintervals indicate temporal variations of most of these peaks with amplitudes of up to 0.3 μgal (P1S1K1) in the diurnal band, and differences of up to 0.1 μgal in the semidiurnal band.

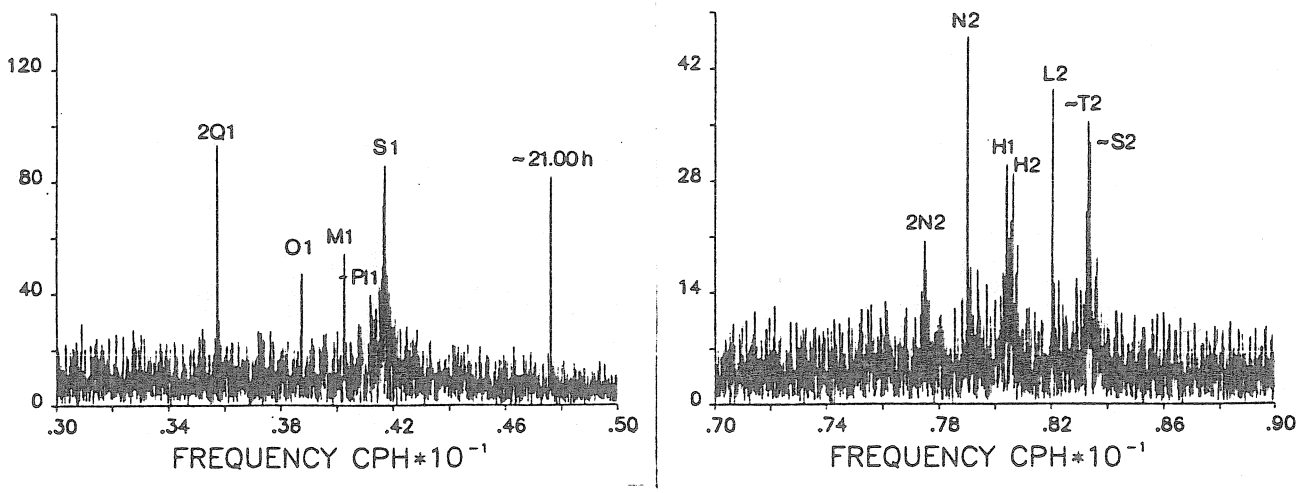


Figure 2. Diurnal and semidiurnal spectrums of the filtered residuals of the 10-years record Potsdam, GS-15/222). Amplitudes are in nanogal (from Asch et al., 1986a).

4. Conclusions and consequences

At first it must be noted, that the ambient noise levels of less than 20 ngal are of physical meaning. Of course it is not possible here to distinguish between instrumental and other physical origins.

The peaks in the spectrums of the residuals can be allocated to

- varying meteorological influences of tidal frequencies;
- tidal constituents not contained in the tidal development;
- non-linearities of the sensors, as well as variations in the calibration function and problems with the time base.

Regarding meteorology we ought to find more appropriate regression models which may also be time dependent. Furthermore, the analyses of both records show, that the instruments react differently to local air pressure. Therefore we must distinguish different effects from local and distant air pressure variations.

According to the contributions of Xi and Tamura (this issue) the extension of the tidal development to the forth order for the moon and to the third order for the sun provides an accuracy of each tidal constituent on the 1 ngal level. Since for some constituents the relation of the amplitudes of forth order to second order is about 10^{-3}, modulation effects are to be expected when applying the old development.

Finally, without suitable regression models to meteorology it is hardly possible to define the noise level of the sensor. This also influences the interpretation of non-linearities of the instruments. On the other hand, the corresponding phase errors for O1 and M2 of about 0.10^{o} and 0.05^{o} are equivalent to some 25 seconds. This defines the requirements to the stability of the calibration a well as to the stability of the time base over the whole recording period.

4. References

Asch, G., Elstner, C., Jentzsch, G., and Plag, H.-P., 1986: On the estimation of significant periodic and aperiodic gravity variations in the time series of neighbouring stations - part I. -Proc. Tenth Int. Symp. Earth Tides, Madrid, 1985.

Asch, G., Elstner, C., Jentzsch, G., and Plag, H.-P., 1986: On the estimation of significant periodic and aperiodic gravity variations in the time series of neighbouring stations - part II. -Proc. Tenth Int. Symp. Earth Tides, Madrid, 1985.

Tamura, Y.: A harmonic development of the tide-generating potential. (this issue).

Xi, Q.: A new complete development of the tide-generating potential for the epoch J2000.0. (this issue).

COMPARISON BETWEEN THE THEORETICAL AND OBSERVED TIDAL GRAVIMETRIC FACTORS

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SUMMARY

According to the conventions used for tidal data analysis, we adopt here the following definition of the gravimetric factor δ : "In the frequency domain, the tidal gravimetric factor is the transfer function between the tidal force exerted along the vertical and the tidal gravity changes measured by a gravimeter". We assume that the local vertical coincides with the normal to the ellipsoid.

This definition differs significantly from what J. Wahr has assumed when he developped his theory. We have thus to recompute the theoretical values of δ. The constant term δ_0 in the representation of δ is only slightly reduced while the latitude dependant term δ_1 is divided by a factor of two (table 1).

Using the data bank of the International Center for Earth Tides we recomputed by linear regression δ_0 and δ_1 from all the available observations. We may conclude that the new value of the latitude dependant coefficient δ_1 fits very well the observations. However the computed constant part δ_0 is still lower than the one deduced from the observations, but the discrepancy has been reduced by a factor of two and reaches now only 0.6 %.

Tidal Gravity factor $\delta = 1 + h - \frac{3}{2} k$

Liquid Core Resonance effects, Coriolis force and flattening effects

Theoretical formulas

Semi diurnal waves $\quad \delta = \delta_0 - \delta_1 \frac{\sqrt{3}}{2} (7 \sin^2 \phi - 1)$

Diurnal waves $\quad \delta(\omega_i) = \delta_0(\omega_i) - \delta_1(\omega_i) \frac{\sqrt{5}}{4} (7 \sin^2 \phi - 3)$

Numerical coefficients

Semi diurnal wave

		Wahr (1)	Dehant (1)	Dehant (2)	Observations
M_2	δ_0	1.1599	1.1629	1.1617	1.1707
	δ_1	-0.0045	-0.0023	-0.0025	-0.0024

Diurnal waves

O_1	δ_0	1.1520	1.1543	1.1534	1.1611
	δ_1	-0.0063	-0.0033	-0.0035	-0.0026
P_1	δ_0	1.1470	1.1493		1.1545
	δ_1	-0.0063	-0.0032		-0.0033
K_1	δ_0	1.1320	1.1344		1.1440
	δ_1	-0.0062	-0.0030		-0.0034

(1) model 1066A

(2) model PREM inelastic (Zschau model for μ, calculated on the basis of PREM - Zschau and Wang 1985).

ERROR ESTIMATION OF GRAVITY LOADING CORRECTION

H.T. HSU

Some authors are recently trying to interpret the geophysical problem by means of tide observation data. For example, S.M. Molodensky studied the relation between the tide anomalies and the lateral heterogenity of the crust and upper mantle, P. Melchior et al found that, there would be certain correlation between gravity tide anomalies and the distribution of heat flow. In these researches, we always define the tide anomaly as such a residual, which is obtained after substructing the theoretical tide of a model earth and loading correction of ocean tides from the observations. But, it is well known that, the reliability of those residuals is not only influenced by the observation error, but also affected by the choice theoretical model and the accuracy of loading correction. Therefore, to study the obtainable precision of loading correction is very important for the further usage of tide data.

The theory and method of loading correction of ocean tides had been improved by Longman and Farrell several years ago. Usually, the loading corrections can be obtained from the cotidal maps by using the convolution of tide height with a certain Green function. Later on, a combined procedure of convolution and harmonic expansion is applied. Here we plan to estimate the possible error and obtainable precision of gravity loading correction according to these two computation procedures.

I. Fundamental formulas of gravity loading correction

In general, we always decompose both of earth and ocean tides in the frequency domain and then discuss them. Thus, the tide height can be expressed as follows:

$$H(\varphi,\lambda,t)=\sum_{p}\zeta_{p}(\varphi,\lambda)\cos(\omega_{p}t+\chi_{p}-\delta_{p}(\varphi,\lambda)) \qquad (1)$$

and the corresponding gravity loading correction will be:

$$\delta g(\varphi,\lambda,t)=\sum_{p}L_{p}(\varphi,\lambda)\cos(\omega_{p}t+\chi_{p}-\alpha_{p}(\varphi,\lambda)) \qquad (2)$$

In which:

p	total number of tide components in consideration
ω_p, χ_p	frequency and initial phase of tide component considered
t	universal time

L_ϕ, α_ϕ amplitude and phase lag of gravity loading correction for ϕ wave

ζ_ϕ, δ_ϕ amplitude and phase of tide height for ϕ wave

For sake of simplification, we will omit the subscript ϕ, it means that we are now only discussing the effect of the individual tide component and the tidal error can be simply calculated by superposing all the effects of individual component.

Introducing new variables

$$\left.\begin{aligned} LC(\varphi,\lambda) &= L(\varphi,\lambda)\cos\alpha(\varphi,\lambda) \\ LS(\varphi,\lambda) &= L(\varphi,\lambda)\sin\alpha(\varphi,\lambda) \end{aligned}\right\} \qquad (3)$$

We have

$$L = (LC + LS)^{1/2} \qquad \alpha = tg^{-1} LS/LC \qquad (4)$$

Two methods are able to be used in practical computation

Convolution integration

According to Farrell, the relations hold

$$\left.\begin{aligned} LC(\varphi,\lambda) &= \int_\Sigma \mu H_c(\varphi',\lambda') G(\psi)\, dS' \\ LS(\varphi,\lambda) &= \int_\Sigma \mu H_s(\varphi',\lambda') G(\psi)\, dS' \end{aligned}\right\} \qquad (5)$$

where

$H_c = \zeta\cos\delta$ and $H_s = \zeta\sin\delta$: cosine and sine components of tide height

μ: density of sea water

ψ: spherical distance between source point (φ',λ') and field point (φ,λ), obviously

$$\psi = \cos^{-1}(\sin\varphi\sin\varphi' + \cos\varphi\cos\varphi'\cos(\lambda-\lambda'))$$

$G(\psi)$: gravity Green function, the unit of which is $cm\,g^{-1}sec^{-2}$.

$$G(\psi) = -\frac{f}{\mu R^2 \sin\frac{\psi}{2}} + g^E(\psi) \qquad (6)$$

$$g^E(\psi) = \frac{f}{R^2}\sum_{n=0}^{\infty}(2h_n' - (n+1)k_n')P_n(\cos\psi) \qquad (7)$$

in which the first term represents the direct attraction of sea water and second term is the contribution due to the deformation of crust under the action of loading mass and potential change caused by mass redistribution.

f, R: Newton's constant and mean radius of the earth

μ: density of sea water and supposed to be $1.03\ g/cm^3$

dS': spherical element, comvolution are performed on the whole sphere Σ

$P_n(\cos\psi)$: Legendre polynomials

Combination procedure

According to paper [2], the fundamental idea of this method is to divide

the whole integral area into two parts by using a boundary spherical cap with radius ψ_0, and then, use the convolution to take into account of the local effect in the inner zone within the cap, elsewhere use the spherical harmonic expansion to consider the global effect. Then the gravity loading correction can be written as follows

$$\left.\begin{aligned} LC(\varphi,\lambda) &= \int_0^{2\pi}\int_0^{\psi_0} \mu H_c(\varphi',\lambda') G(\psi)\, dS' + \sum_{r=0}^{m} \mu Q_r(\psi_0) H_{rc}(\varphi,\lambda) \\ LS(\varphi,\lambda) &= \int_0^{2\pi}\int_0^{\psi_0} \mu H_s(\varphi',\lambda') G(\psi)\, dS' + \sum_{r=0}^{m} \mu Q_r(\psi_0) H_{rs}(\varphi,\lambda) \end{aligned}\right\} \quad (8)$$

Here

Q_r is so-called truncation coefficient, the unit is $cm^3 g^{-1} sec^{-2}$, m is the degree of expansion.

$$\begin{aligned} Q_r(\psi_0) &= 2\pi R^2 \int_{\psi_0}^{\pi} G(\psi)\sin\psi\, d\psi \\ &= -\frac{\pi f}{2}\int_{\psi_0}^{\pi} \frac{P_r(\cos\psi)}{\sin\frac{\psi}{2}}\sin\psi\, d\psi + 2\pi R^2 \int_{\psi_0}^{\pi} g^E(\psi) P_r(\cos\psi)\sin\psi\, d\psi \end{aligned} \quad (9)$$

H_{rc}, H_{rs} are cosine and sine components of r-degree harmonic term in the expansion of tide height.

$$\left.\begin{aligned} H_{rc}(\varphi,\lambda) &= \sum_{k=0}^{r} (\bar{a}_{rk}\cos m\lambda + \bar{b}_{rk}\sin m\lambda)\bar{P}_{rk}(\sin\varphi) \\ H_{rs}(\varphi,\lambda) &= \sum_{k=0}^{r} (\bar{a}'_{rk}\cos m\lambda + \bar{b}'_{rk}\sin m\lambda)\bar{P}_{rk}(\sin\varphi) \end{aligned}\right\} \quad (10)$$

$\bar{P}_{rk}(\sin\varphi)$ is the normalized associated Legendre polynomial and $\bar{a}_{rk}$, $\bar{b}_{rk}$, $\bar{a}'_{rk}$, $\bar{b}'_{rk}$ are expansion coefficients. The advantage of the combination procedure is greatly saving computer time.

Some remarks:

a. The formula given here does not consider the height of station (field point), because it is found from many authors that this effect is very small. Especially in China, the heights of station along the coast are almost zero and the mountain area in western part is far away from the sea

b. In respect of the Green function, Pekeris (1978) derived from the limit of extenal potential, that is

$$G(\psi) = \frac{f}{R^2}\sum_{n=0}^{\infty}[2h'_n - (n+1)(1+k'_n)]P_n(\cos\psi)$$

At the same time, the result by Farrell (1972) through internal potential approach is

$$G(\psi) = \frac{f}{R^2}\sum_{n=0}^{\infty}[2h'_n - (n+1)k'_n + n]P_n(\cos\psi)$$

since

$$\sum_{n=0}^{\infty} n P_n(\cos\psi) = -\sum_{n=0}^{\infty}(n+1)P_n(\cos\psi)$$

the both formulas are equivalent if the heights of stations are not to take

into account.

c. Recently, many tide solution of a visco-elastic earth have been derived (Zachau and so on), in which, the real and imaginary parts of Green function have to be considered, that means, we should determine the corresponding phase lag effect, but in present paper we are limited in case of an elastic earth model.

II. Error estimation of gravity loading correction

In fact, it does not matter which method is used, since the tide height will be taken from cotidal map and Green function depends on choice earth model, the loading correction obtained should include two kinds of main error sources:

a. Error caused from interior structure of the earth.

b. Error due to the cotidal map.

If we carry out the analysis more in detail, in the convolution method, there are the following types of errors:

a. error from different earth model;

b. error in the mean block tide height;

c. discretization error due to the loss of information by using finite block size.

As to the combination procedure, the other two types of errors have to be added:

d. error in the applied set of harmonic coefficients;

e. truncation error coming from the limit of finite terms in the spherical expansion.

It is well known that, by using different earth models, we can obtain different Green functions so the convolution term implies an error:

$$\varepsilon_1 = \int_0^{2\pi}\int_0^{\psi_0} \mu H(\varphi', \lambda') \Delta G(\psi) \, ds'$$

Here we use H to denote H_c or H_s. Obviously, for the convolution method. $\psi_0 = 180^\circ$ is necessary and for the combination procedure, different values of are possible. Thus

$$\sigma_1^2 = M\{\varepsilon_1^2\} = 2\pi R^2 \mu^2 \sum_j E_{\psi_j} \int_{\psi_j}^{\psi_{j+1}} \{\Delta G(\psi)\}^2 \sin\psi \, d\psi$$

E_ψ is the so-called error constant defined by Moritz [8], it is a variable that strongly depends on the size of the chosen block. Because when ψ is very small, ΔG has very big value, in order to have necessary precision, different block sizes should be used according to the distance

from computed station. We have applied two sets of tide height block:

$15' \times 15'$ blocks if $\psi \leq 1^\circ$

$1^\circ \times 1^\circ$ blocks if $\psi > 1^\circ$

Besides, as $\Delta G(\psi)$ becomes infinite when $\psi = 0$, therefore a small area surrounding the station ($\psi \leq S_0$) is considered separately. We suppose that within this area, the tide height H remains a constant, thus

$$\sigma_1^2 = \sigma_{10}^2 + 2\pi\mu^2 E_{15'\times 15'} \int_{S_0}^{1} R^4 \{\Delta G(\psi)\}^2 \sin\psi \, d\psi + 2\pi\mu^2 E_{1^\circ\times 1^\circ} \int_{1}^{\psi_0} R^4 \{\Delta G(\psi)\}^2 \sin\psi \, d\psi \tag{11}$$

As an approximate estimation, we soppose that there is no correlation between the mean values of tide height, we have:

$$E = \iint_{\Delta\sigma} \sigma_{H_i H_k} \, d\sigma = H_m^2 \, \Delta\sigma$$

Here $\sigma_{H_i H_k}$ means the covariance of tide height, $\Delta\sigma$ is area of small block, H_m reprensents the variance of tide height.

$$H_{mc}^2 = \sum_{r=0}^{\infty} C_{rc} \qquad H_{ms}^2 = \sum_{r=0}^{\infty} C_{rs} \tag{12}$$

where C_{rc}, C_{rs} are rth degree-variance of H_c and H_s, respectively,

$$\left.\begin{aligned} C_{rc} &= \sum_{k=0}^{r} (\bar{a}_{rk}^2 + \bar{b}_{rk}^2) \\ C_{rs} &= \sum_{k=0}^{r} (\bar{a}_{rk}'^2 + \bar{b}_{rk}'^2) \end{aligned}\right\} \tag{13}$$

for Schwiderski $1^\circ \times 1^\circ$ cotidal maps, we have

$H_m^2 = 600 \ cm^2$ for M_2 wave

$H_m^2 = 50 \ cm^2$ for O_1 wave

then

$E_{1^\circ\times 1^\circ}(M_2) = 0.1815$ $\qquad$ $E_{1^\circ\times 1^\circ}(O_1) = 0.01512$

$E_{15'\times 15'}(M_2) = 0.0113$ $\qquad$ $E_{15'\times 15'}(O_1) = 0.000945$

in addition,

$$\sigma_{10}^2 = 2\pi\mu^2 H_m^2 \left\{ \int_0^{S_0} R^2 G(\psi) \sin\psi \, d\psi \right\}^2$$

and $\Delta G(\psi)$ is the difference of Green functions for different earth models. In this paper, we estimate it based on the Gutenberg-Bullen and 1066A models [1][4]. From Fig. 1 we can see that, when $\psi \leq 1^\circ$ ($\lg\psi \leq 0$), the discrepancies between these two models are very large, but it turns to almost zero when ψ gradually increases. So it can be judged that model ermor mainly occurs in the vicinity of station.

Table 1 shows the results obtained for different S_0 value. It could be seen that the choice of S_0 has only small influence on results, afterwards we shall use $S_0 = 0.1°$. On the other hand, the effection of model to convolution are nearly no change when ψ_0 varies from $5°$ to $180°$

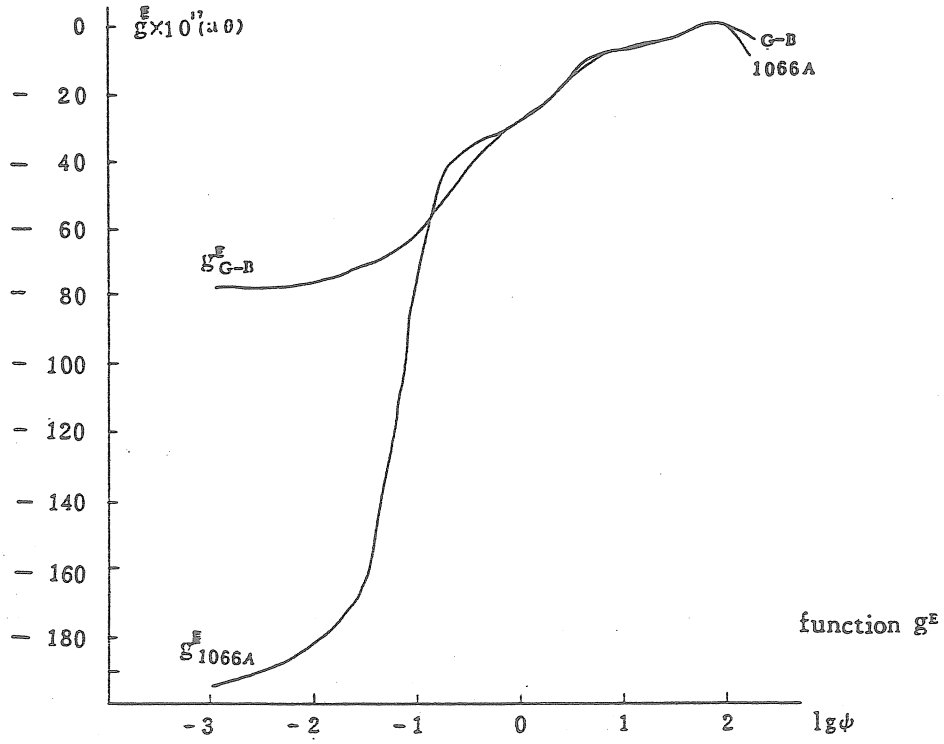


Fig. 1: Function g^E

Table 1 The effect of model error on convolution (unit: μgal)

S_0 / ψ_0	0.02		0.06		0.10		0.25	
	M_2	O_1	M_2	O_1	M_2	O_1	M_2	O_1
5°	0.183	0.053	0.148	0.043	0.179	0.052	0.173	0.050
8°	0.183	0.053	0.148	0.043	0.179	0.052	0.173	0.050
10°	0.183	0.053	0.148	0.043	0.179	0.052	0.173	0.050
16°	0.183	0.053	0.148	0.043	0.180	0.052	0.173	0.050
20°	0.183	0.053	0.148	0.043	0.180	0.052	0.173	0.050
180°	0.184	0.053	0.148	0.043	0.180	0.052	0.173	0.050

As far as the combination procedure is concerned, besides the convolution term there is an additional term for the effect of remote area, which relates to $Q_r(\psi_0)$. Due to the adoption of various earth models, we can generate different truncation coefficients $Q_r(\psi_0)$, therefore, the influence of different earth model to remote area term will be:

$$\varepsilon_2 = \mu \sum_{r=0}^{m} \Delta Q_r(\psi_0) \begin{matrix} H_{rc} \\ H_{rs} \end{matrix}$$

It is easily to obtain

$$\sigma_2^2 = M\{\varepsilon_2^2\} = \mu^2 \sum_{r=0}^{m} \Delta Q_r^2(\psi_0) \begin{matrix} C_{rc} \\ C_{rs} \end{matrix} \qquad (14)$$

According to GB and 1066A model, we have computed the values of $\Delta Q_r(\psi_0)$ for different ψ_0, and shown it in Table 2. To obtain the necessary-degree-variances of C_{rc}, C_{rs} , we expand the tide height of Schwiderski M_2 and O_1 cotidal maps into spherical harmonics to $r=30$ respectively, the the results obtained are shown in Fig.2. Further, fitting the degree-variances of r=15-30 by use of formula $C_r = A/\eta^n$, we get the values of the degree-variance C_{rc} and C_{rs} as the function of r:[5]

$$\begin{aligned} C_{rc} = C_{rs} &= 200/\eta^{1.3} \quad cm^2 \qquad \text{for } M_2 \text{ wave} \\ C_{rc} = C_{rs} &= 20/\eta^{1.4} \quad cm^2 \qquad \text{for } O_1 \text{ wave} \end{aligned} \qquad (15)$$

with this the σ_2^2 can be easily computed by (14). For different truncation degrees m , the results obtained are listed in Table 3. It can be seen from the table, σ_2^2 plays an important role in the error estimation too, on the other hand, it seems that there are no changes as m from 15 to 30, i.e, for the harmonic expansion m =15 is enough in the case of present accuracy.

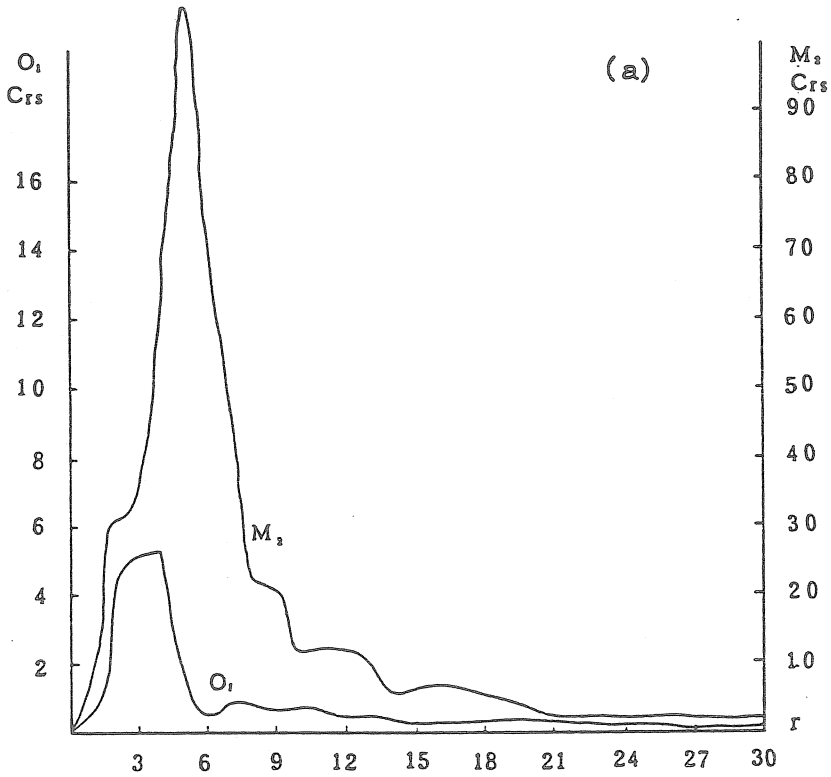


Fig. 2a: Degree-Variance of H_s

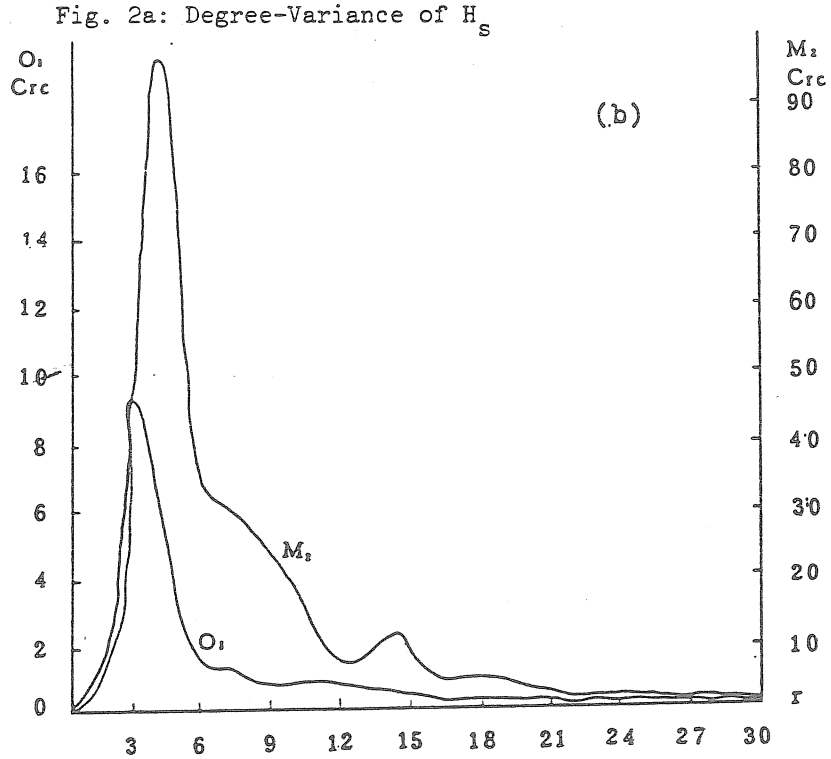


Fig. 2b: Degree-Variance of H_c

Table 2 $\Delta Q_r(\psi_0)$

r \ ψ_0	5°	8°	10°	16°	20°
1	3.903	4.119	4.599	7.188	9.369
2	32.087	31.855	31.42	28.925	27.01
3	10.041	9.834	9.377	7.136	5.480
4	2.145	1.926	1.509	0.506	1.757
5	1.048	1.240	1.668	3.335	4.223
6	1.103	1.301	1.680	3.046	3.486
7	1.041	1.213	1.580	2.567	2.644
8	1.108	1.279	1.591	2.253	1.956
9	1.074	1.222	1.504	1.809	1.251
10	0.960	1.102	1.330	1.336	0.565
11	0.869	0.969	1.156	0.873	0.005
12	0.744	0.850	0.993	0.474	0.412
13	0.674	0.763	0.862	0.154	0.665
14	0.590	0.662	0.730	0.125	0.794
15	0.535	0.594	0.615	0.310	0.798
16	0.468	0.507	0.504	0.462	0.710
17	0.426	0.454	0.401	0.522	0.552
18	0.366	0.376	0.296	0.563	0.361
19	0.322	0.321	0.197	0.536	0.159
20	0.266	0.252	0.104	0.491	0.028
21	0.226	0.199	0.026	0.407	0.188
22	0.180	0.145	0.042	0.308	0.303
23	0.145	0.098	0.010	0.201	0.370
24	0.107	0.056	0.146	0.089	0.384
25	0.080	0.020	0.185	0.013	0.355
26	0.050	0.012	0.218	0.104	0.285
27	0.031	0.037	0.242	0.178	0.193
28	0.006	0.062	0.260	0.228	0.085
29	0.006	0.075	0.267	0.482	0.019
30	0.025	0.093	0.266	0.265	0.112

Table 3 Model effect in spherical expansion term of combination procedure

ψ	wave \ m	15	20	30	50
5°	M_{2c}	0.152	0.1522	0.1522	0.1522
	M_{2s}	0.195	0.195	0195	0.195
	O_{1c}	0.086	0.086	0.086	0.086
	O_{1s}	0.074	0.074	0.074	0.074
8°	M_{2c}	0.151	0.151	0.151	0.151
	M_{2s}	0.194	0.194	0.194	0.194
	O_{1c}	0.085	0.085	0.085	0.085
	O_{1s}	0.074	0.074	0.074	0.074
10°	M_{2c}	0.148	0.148	0.148	0.148
	M_{2s}	0.190	0.190	0.190	0.190
	O_{1c}	0.084	0.084	0.084	0.084
	O_{1s}	0.072	0.072	0.072	0.072
16°	M_{2c}	0.136	0.136	0.136	0.136
	M_{2s}	0178	0.178	0.178	0.178
	O_{1c}	0.076	0.076	0.076	0.076
	O_{1s}	0.066	0.066	0.066	0.066
20°	M_{2c}	0.128	0.128	0.128	0.128
	M_{2s}	0.170	0.170	0.170	0.170
	O_{1c}	0.070	0 070	0 .070	0.070
	O_{1s}	0.061	0.061	0.061	0.061

Error in the mean tide height

If there is a error of δH to the block mean tide height H , the consquent error to convolution term will be:

$$\varepsilon_3 = \int_0^{2\pi} \int_0^{\psi_0} \mu \, \delta H(\varphi', \lambda') G(\psi) \, dS'$$

Suppose the mean square error of mean tide height is m_H^2 , then similarly to formula (11) we have:

$$\sigma_3^2 = M\{\varepsilon_3^2\} = \sigma_{30}^2 + 2\pi\mu^2 \Delta\sigma_{15'\times 15'} m_H^2 \int_{S_0}^{1} R^4 G^2(\psi) \sin\psi \, d\psi + 2\pi\mu^2 \Delta\sigma_{1^\circ\times 1^\circ} m_H^2 \int_{1}^{\psi_0} R^4 G^2(\psi) \sin\psi \, d\psi \quad (16)$$

Here

$$\Delta\sigma_{15'\times 15'} = 0.00001904 \qquad \Delta\sigma_{1^\circ\times 1^\circ} = 0.00030446$$

$$\sigma_{30}^2 = 2\pi\mu^2 m_H^2 \left\{ \int_0^{S_0} R^2 G(\psi) \sin\psi \, d\psi \right\}^2$$

The calculated results are shown in Table 4, where m_H value is supposed to be ± 5cm according to the estimation by Schwiderski with his cotidal map. $G(\psi)$ are obtained from GB model by Farrell. We can see that when so changes from 0.02^0–0.1^0, the influence to the result is very small, therefore we shall take the value corresponding to $S_0 = 0.1$ in the final error estimation.

Table 4 Error due to inaccuracy of tide height

(unit μgal)

ψ° \ S_0	0.02	0.06	0.10	0.25
5	0.0659	0.0622	0.0641	0.0821
8	0.0676	0.0640	0.0658	0.0834
10	0.0682	0.0646	0.0644	0.0839
16	0.0692	0.0656	0.0674	0.0847
20	0.0695	0.0660	0.0678	0.0850
180	0.0708	0.0673	0.0691	0.0860

Error in the used set of harmonic coefficients in the calculation of remote area

From formula (8) (10), the errors of gravity loading correction for the remote region are obtained as follows:

For cosine component $$\sigma_{4,C}^2 = \mu^2 \sum_{r=0}^{m} Q_r^2 \sum_{k=0}^{r} \left(m_{\bar{a}_{rk}}^2 + m_{\bar{b}_{rk}}^2 \right)$$

For sine component $$\sigma_{4,S}^2 = \mu^2 \sum_{r=0}^{m} Q_r^2 \sum_{k=0}^{r} \left(m_{\bar{a}'_{rk}}^2 + m_{\bar{b}'_{rk}}^2 \right)$$

But the coefficients $\bar{a}_{rk}$, $\bar{b}_{rk}$, $\bar{a}'_{rk}$, $\bar{b}'_{rk}$ are derived from the cosine and sine components of tide height respectively, we have

$$\begin{matrix}\bar{a}_{rk}\\ \bar{b}_{rk}\end{matrix} = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} H_c(\varphi',\lambda')\,\bar{P}_{rk}(\sin\varphi') \begin{matrix}\cos k\lambda'\\ \sin k\lambda'\end{matrix} \cos\varphi'\,d\varphi'\,d\lambda'$$

and the same expression for the coefficients $\bar{a}'_{rk}$, $\bar{b}'_{rk}$ only by substituting H_c with H_s. For the whole cotidal map is divided into $1^0 \times 1^0$ blocks $\Delta\sigma$ with mean square error m_H, so the coefficient errors will be

$$m^2_{\bar{a}_{rk}} = m^2_{\bar{b}_{rk}} = m^2_{\bar{a}'_{rk}} = m^2_{\bar{b}'_{rk}} = \frac{1}{4\pi} m_H^2 \Delta\sigma$$

and

$$\sigma_4^2 = \frac{1}{4\pi}\mu^2 m_H^2 \Delta\sigma \sum_{r=0}^{m} Q_r^2 \cdot (2r+1) \qquad (17)$$

Let $\Delta\sigma = {}^{1}/_{57.2985^2}$, $m_H = \pm 5$ cm, we get the value σ_4 for different truncation degree m and cap radius ψ and list it in Table 5.

Table5 Error due to inaccuracy of harmonic coefficients

unit: μgal

ψ \ m	15	20	30	50
5	0.0235	0.0236	0.0244	0.0248
8	0.0194	0.0199	0.0201	0.0204
10	0.0179	0.0182	0.0183	0.0185
16	0.0143	0.0145	0.0146	0.0147
20	0.0127	0.0128	0.0129	0.0130

Obviously, this error is very small and can be neglected completely.

Discretization error

This error comes from the loss of information by the substitution of point values for mean tide heights. We follow the idea of smooth factor in physical geodesy and estimate and effects based on the spherical expansion. For point tide height H, its mean value being $\bar{H}$, the discretization error equals

$$\varepsilon_5 = \mu\int_0^{2\pi}\int_0^{\pi}(H-\bar{H})\,G(\psi)\,dS'$$

It is well-known that by expanding H and $\bar{H}$ into spherical harmonics, we get:

$$H=\sum_{r=0}^{\infty} H_r \qquad \bar{H}=\sum_{r=0}^{\infty}\beta_r H_r$$

Here β_r are called smoothing factors; we have

$$\beta_r=\frac{1}{1-\cos\eta}\cdot\frac{1}{2n+1}\left\{P_{n-1}(\cos\eta)-P_{n+1}(\cos\eta)\right\}$$

varies from 1 to zero as r increases to infinite, η is the radius of equivalent circle, if the area of mean block is $\Delta\sigma$, obviously

$$\pi\eta^2=\Delta\sigma \quad , \qquad \eta=\sqrt{\frac{\Delta\sigma}{\pi}}$$

then,

$$\begin{matrix}\varepsilon_{5,c}\\ \varepsilon_{5,s}\end{matrix}=\mu\sum_{r=0}^{\infty}(1-\beta_r)Q'_r\begin{matrix}H_{rc}\\ H_{rs}\end{matrix}$$

$$Q'_r=2\pi R^2\int_0^{\psi_0}G(\psi)\sin\psi\,d\psi$$

Taking its expectation, we have

$$\sigma_5^2=M\{\varepsilon_5^2\}=\mu^2\sum_{r=0}^{\infty}(1-\beta_r)^2 Q_r'^2\begin{matrix}C_{rc}\\ C_{rs}\end{matrix} \qquad (18)$$

The calculating results are shown in Table 6.

Truncation error

This error is caused by the finite degree of spherical harmonic expansion of tide height in the calculation of the remote region. From formula (8), it is wasy to verify the truncation error;

Table 6 Discretization error

(unit: μgal)

ψ \ wave	M_2	O_1
5	0.0871	0.0207
8	0.0872	0.0207
10	0.0874	0.0207
16	0.0890	0.0211
20	0.0897	0.0213

For cosine component $\quad \sigma_{6,c}^2=\mu^2\sum_{r=m+1}^{\infty}Q_r^2 C_{rc}$

For sine component $\quad \sigma_{6,s}^2=\mu^2\sum_{r=m+1}^{\infty}Q_r^2 C_{rs}$ $\qquad (19)$

Using formulas (9) (15) given above , the truncation errors obtained are listed in-table 7. Apparently, this error decreases as the degree of truncation m is enlarged and cap radius, too. But since its value seems so small comparing with other error sources, it makes no sense to increase the truncation degree and cap radius.

III. Final result and discussion

The final errors after taking into account of all the error sources are as follows

$$m_{Lc}^2 = \sum_{i=1}^{5} \sigma_{i,c}^2 \quad , \qquad m_{Ls}^2 = \sum_{i=1}^{5} \sigma_{i,s}^2 \tag{20}$$

Table 8 and Table 9 show the final error estimation of the convolution method and combination method for M_2, O_1 respectively. According to formula

$$\delta g = L\cos(\omega t + \chi - \alpha) \tag{21}$$

it is able to derive

$$m_L \leq m \,, \qquad m_\alpha \leq m/L \tag{22}$$

$$m = \max\{m_{Lc}, m_{Ls}\}$$

Table 7 Truncation error
(unit: μgal)

ψ	wave \ m	15	20	30	50
5°	M_{2C}	0.0654	0.0575	0.0349	0.0145
	M_{2S}	0.0723	0.0646	0.0349	0.0145
	O_{1C}	0.0196	0.0174	0.0092	0.0037
	O_{1S}	0.0189	0.0167	0.0092	0.0037
8°	M_{2C}	0.0660	0.0344	0.0216	0.0088
	M_{2S}	0.0741	0.0372	0.0216	0.0088
	O_{1C}	0.0195	0.0103	0.0057	0.0022
	O_{1S}	0.0186	0.0100	0.0057	0.0022
10°	M_{2C}	0.0480	0.0247	0.0198	0.0077
	M_{2S}	0.0544	0.0269	0.0198	0.0077
	O_{1C}	0.0141	0.0071	0.0052	0.0020
	O_{1S}	0.0133	0.0069	0.0052	0.0020
16°	M_{2C}	0.0343	0.0202	0.0129	0.0056
	M_{2S}	0.0374	0.0222	0.0129	0.0056
	O_{1C}	0.0100	0.0061	0.0034	0.0013
	O_{1S}	0.0097	0.0058	0.0034	0.0013
20°	M_{2C}	0.0281	0.0172	0.0108	0.0044
	M_{2S}	0.0311	0.0190	0.0108	0.0044
	O_{1C}	0.0084	0.0051	0.0028	0.0011
	O_{1S}	0.0079	0.0050	0.0028	0.0011

Thus, we can calculate the amplitude error m_1 and phase error of m_α loading correction from the errors of cosine and sine components. From the final estimation we can see:

a. The available precision of the gravity loading correction are

M_2 $\pm 0.22\mu gal$, O_1 $\pm 0.09\mu gal$ by convolution alone

M_2 $\pm$ $0.29\mu gal$, O_1 $\pm 0.13\mu gal$ by use of convolution and harmonic expansion ($m=15$, $\psi=15^\circ$)

Table 8

Radius of cap	Map error		Model error				Total amount			
	M_2	O_1	M_{2c}	M_{2s}	O_{1c}	O_{1s}	M_{2c}	M_{2s}	O_{1c}	O_{1s}
5	0.123	0.073	0.235	0.265	0.101	0.091	0.265	0.291	0.124	0.116
8	0.117	0.072	0.234	0.264	0.100	0.090	0.262	0.287	0.123	0.115
10	0.114	0.072	0.232	0.261	0.098	0.089	0.258	0.285	0.122	0.114
16	0.114	0.072	0.226	0.253	0.092	0.084	0.252	0.278	0.117	0.111
20	0.114	0.072	0.219	0.244	0.086	0.079	0.247	0.269	0.112	0.107

** Error estimation of combination procedure (μgal)

Table 9

Map error		Model error		Total amount	
M_2	O_1	M_2	O_1	M_2	O_1
0.117	0.073	0.180	0.052	0.215	0.090

** Error estimation of convolution method (μgal)

The differences are mainly due to the fact that the model errors increase when spherical harmonics up to finite degree are used to represent the effect of remote ocean, while the effect of inaccuracy of cotidal map are the same for both methods.

b. In view of tidal error estimation, the dominating factor is the error effect in the vicinity of station. Therefore, it is necessary to have a precise

local cotidal map in the sea coast area and it is better to choose the Green functions obtained directly from the physical parameters of the crust of upper mantle in the area. This is why the residuals in some near-coast station of China, such as Chuanzhou, Yulin, were still larger than that in other stations [10] .

c. In the combination procedure, it is unsuitable to adopt higher degree of truncation and larger cap radius for increasing the accuracy of method, usually, the adoption of m =15, $\psi = 5^\circ$ is recommended to gain a similar accuracy and increase the computing efficiency.

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Tidal Loading Computations for Tilt in Europe

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We have adapted the program used to compute tidal gravity loading and attraction effects (Melchior & alii, 1980) for the horizontal components. We use the Green's functions tabulated by Farrell (1972) for tilt and the Schwiderski maps (1980).

The amplitudes are expressed in milleseconds of arc (mseca) and the phases in degrees (lead positive) with respect to the corresponding horizontal tidal tilt. For this reason we have to add ninety degrees to the east-west component of the loading.

Figures 1 and 2 show a general picture of the M_2 indirect effects on tilt in Europe.

In the EW component as big amplitudes as 20 mseca are observed around the Gulf of Biscaye. Phases are rotating around the British Isles.

In the NS component the amplitudes are more or less four times smaller while the phases are shifting from South to North.

We did compare our results with those of several authors (Table 1). The general agreement is rather good even in the vicinity of the North Sea.

The differences are due to different procedures of computation. Baker (1979) is using the Hendershott (1972) map with a refined model for the North Sea and the Irish Sea (Flather, 1976). Souriau (1979) also uses Hendershott map with a special model for the Gulf of Biscaye. Bower (1970) uses British admiralty chart for North Sea, Hansen (1949) for the Atlantic and Bogdanov (1961) for the Pacific Oceans.

Goad (1980) adopted the Schwiderski maps but his numerical procedure is different from Farrell approach.

Complete results of the waves Q_1, O_1, P_1, K_1, N_2, M_2, S_2, K_2 and M_f are already stored for 180 clinometric stations in the Data Bank at the International Center for Earth Tides and are available on request.

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Table 1

Tidal Loading Computations
Horizontal Components

TILT EW COMPONENT WAVE M2 RESIDUES UNIT: MILLISECOND OF ARC

STATION	OBSERVED		BAKER*		GOAD*		BOWER		SOURIAU		DUCARME	
0203 DOURBES 1	1.81	10	1.22	7	1.27	19	2.05	46	1.62	332	2.08	27
0203 DOURBES 2	1.51	31										
0204 SCLAIGN.1	2.89	49	1.61	11	1.74	-18	2.01	37	1.93	32	1.89	13
0204 SCLAIGN.2	2.06	54										
0204 SCLAIGN.3	1.53	49										
0207 WARMIF.1	1.36	-53	1.76	-27	1.58	-16	2.74	49	1.77	-6	1.98	-6
0207 WARMIF.2	1.62	-27										
0209 REMOUCH.	2.21	-58									1.81	-13
0211 VIELSALM	1.55	53	1.83	-25	1.75	-33	2.61	45			1.86	-16
0216 KANNE	2.19	3	1.91	-11							1.77	-17
0243 MEMBACH	2.71	-28									1.81	-22
0252 WALFERD.1	2.27	-38	2.00	-34	1.80	-41	2.93	47	1.96	-19	2.03	-20
0252 WALFERD.2	2.63	-33										
0252 WALFERD.3	2.31	11										
0252 WALFERD.4	1.71	-19										
0906 KSIAZ	1.46	-70	0.98	-55							0.90	-50
0927 PRIBRAM	2.23	-46			0.80	-60					1.11	-45
0951 SOPRON	0.51	-18			0.80	-32					0.93	-42

TILT NS COMPONENT WAVE M2 RESIDUES UNIT: MILLISECOND OF ARC

STATION	OBSERVED		BAKER		GOAD		BOWER		SOURIAU		DUCARME	
0203 DOURBES 1	2.02	-165	1.55	-151	2.02	-72	1.31	-46	1.41	-146	1.84	-81
0203 DOURBES 2	1.89	-168										
0204 SCLAIGN.1	2.35	6	0.84	-147	2.02	-57	0.72	-59	0.64	-132	2.16	-60
0204 SCLAIGN.2	1.42	-58										
0207 WARMIF.1	0.68	-89	1.10	-130	1.04	-82	0.93	-62	0.94	-125	1.66	-77
0207 WARMIF.2	0.64	-58										
0209 REMOUCH.	2.38	-171									2.04	-62
0211 VIELSALM	2.18	-139	0.82	-118	1.63	-63	0.98	-91			1.82	-66
0216 KANNE	2.09	-4									2.42	-56
0243 MEMBACH	2.93	18									2.09	-61
0252 WALFERD.1	0.70	-126	0.90	-118	1.48	-60	0.77	-68	0.70	-110	1.46	-75
0252 WALFERD.2	0.43	-139										
0906 KSIAZ	0.56	-105	0.45	-147							0.40	-110
0927 PRIBRAM	0.41	-19			0.60	-95					0.46	-92
0951 SOPRON	0.57	-51			0.22	-88					0.27	-81

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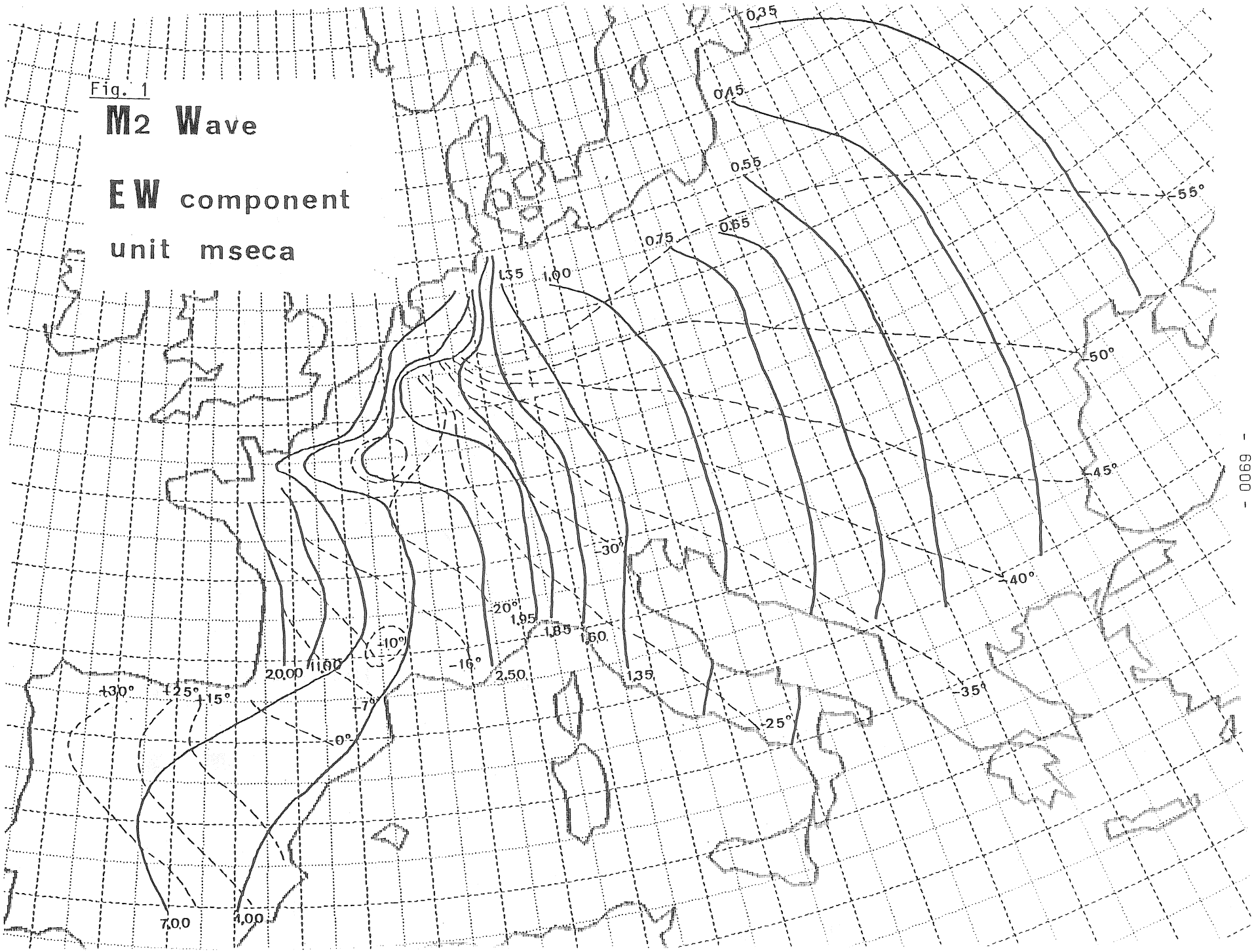
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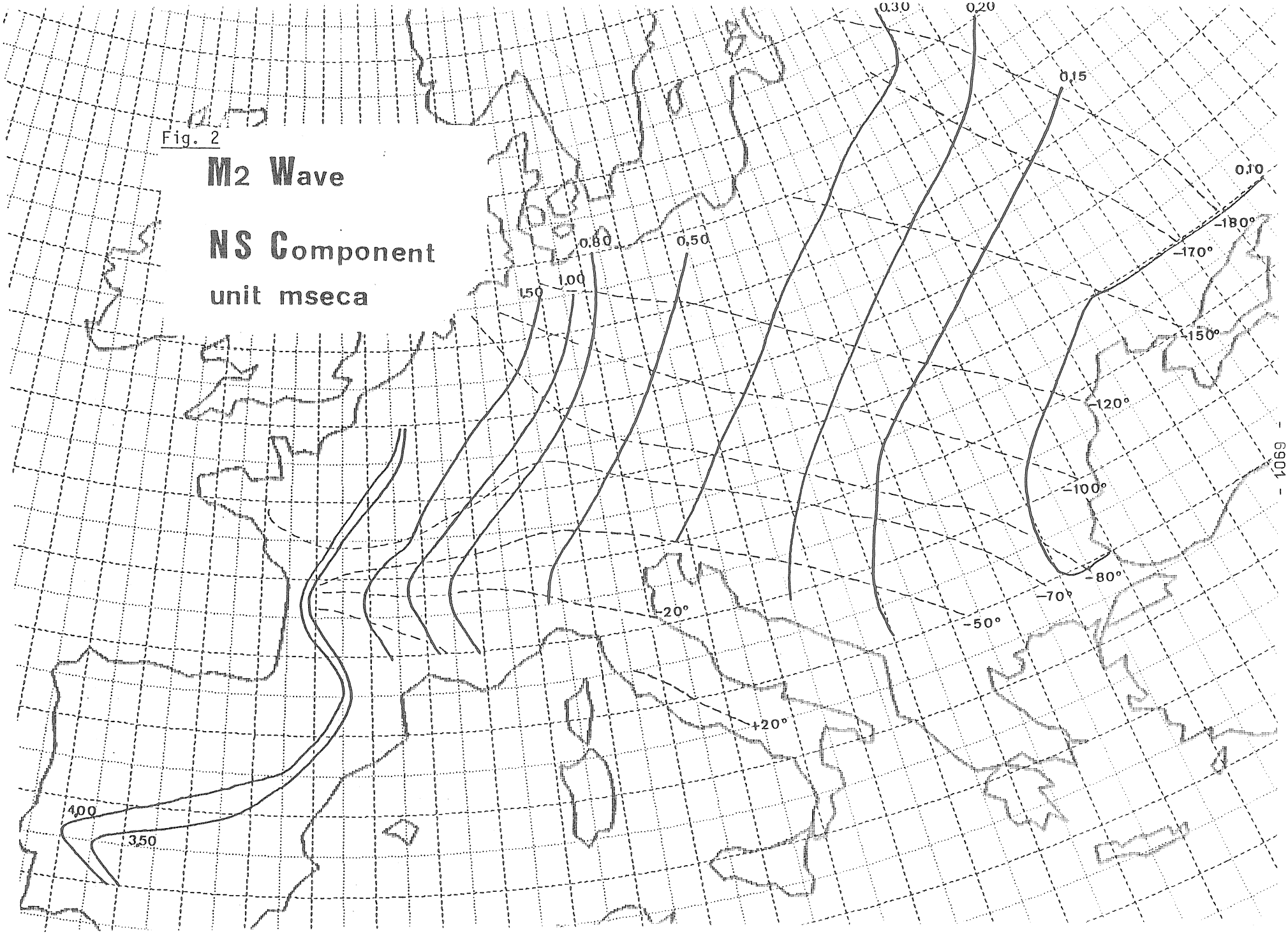
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Fig. 1
M2 Wave
EW component
unit mseca
0.35
0.45
0.55
0.65
0.75
1.00
1.35
1.60
1.85
1.95
2.50
20.00
11.00
7.00
1.00
-55°
-50°
-45°
-40°
-35°
-30°
-25°
-20°
-16°
-10°
-7°
-0°
+30°
+25°
+15°


Fig. 2
M2 Wave
NS Component
unit mseca
0.30
0.20
0.15
0.10
-180°
-170°
-150°
-120°
-100°
-80°
-70°
-50°
-20°
+20°
0.80
0.50
1.00
1.50
4.00
3.50
- 6901 -

LONG TERM PERIODICAL GRAVITY CHANGES OBSERVED WITH A SUPERCONDUCTING GRAVIMETER

F. DE MEYER*, B. DUCARME**

SUMMARY :

From a four years registration period with a Superconducting gravity meter installed at the Royal Observatory of Belgium we were able to modelize the instrumental drift in order to study long period gravity changes. By instrumental drift we mean apparent gravity changes that we can physically explain by some instrumental properties. The initial drift rate was of the order of 0.15 µgal day^{-1} and is slowly decreasing.

We then introduced the long period tides, the polar motion effects and an annual component and we finally obtain residues exhibiting a white noise structure. The origin of the annual term is not yet clearly understood and could also have an instrumental origin.

These steps are shown in figures 1, 2 and 3.

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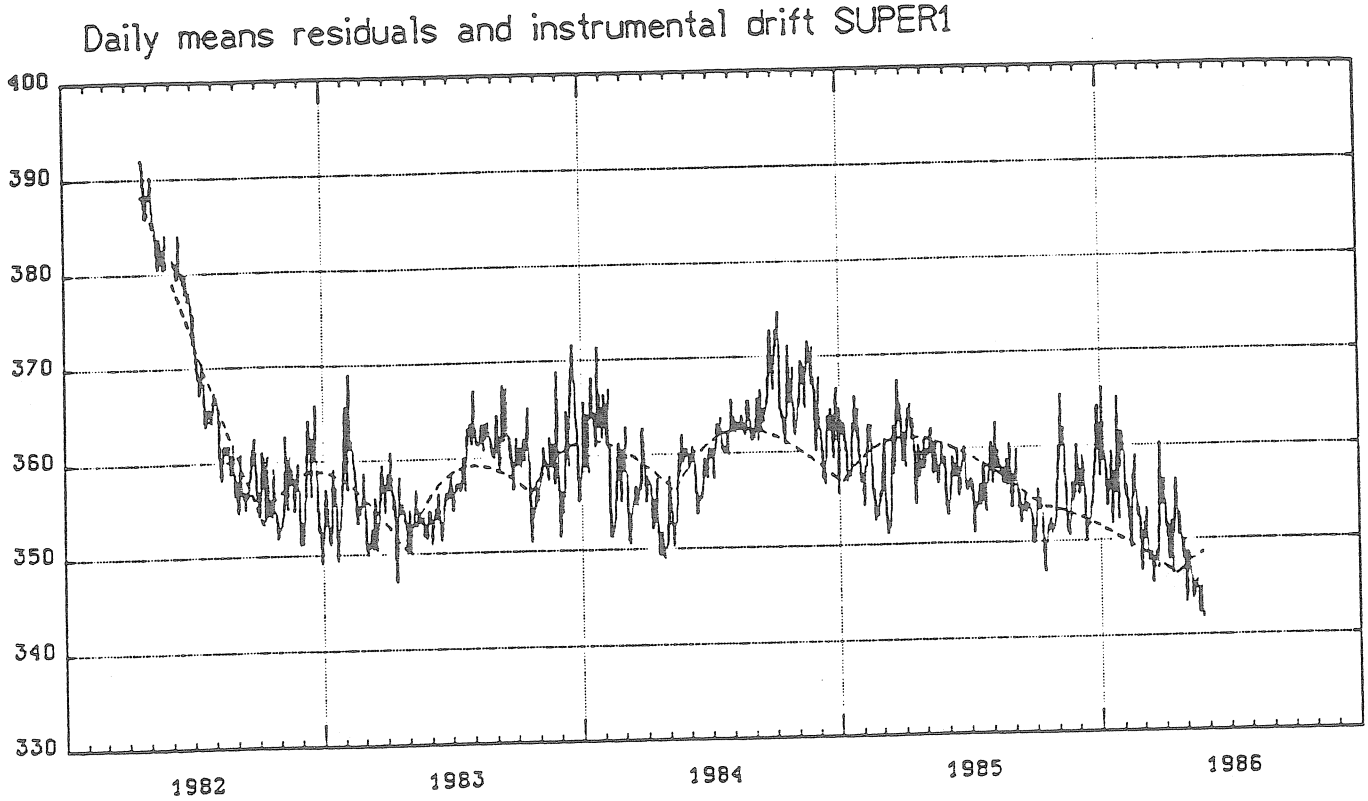


Figure 1 : Raw drift (pressure effects still included).
The dashed line shows the modelized instrumental effects.

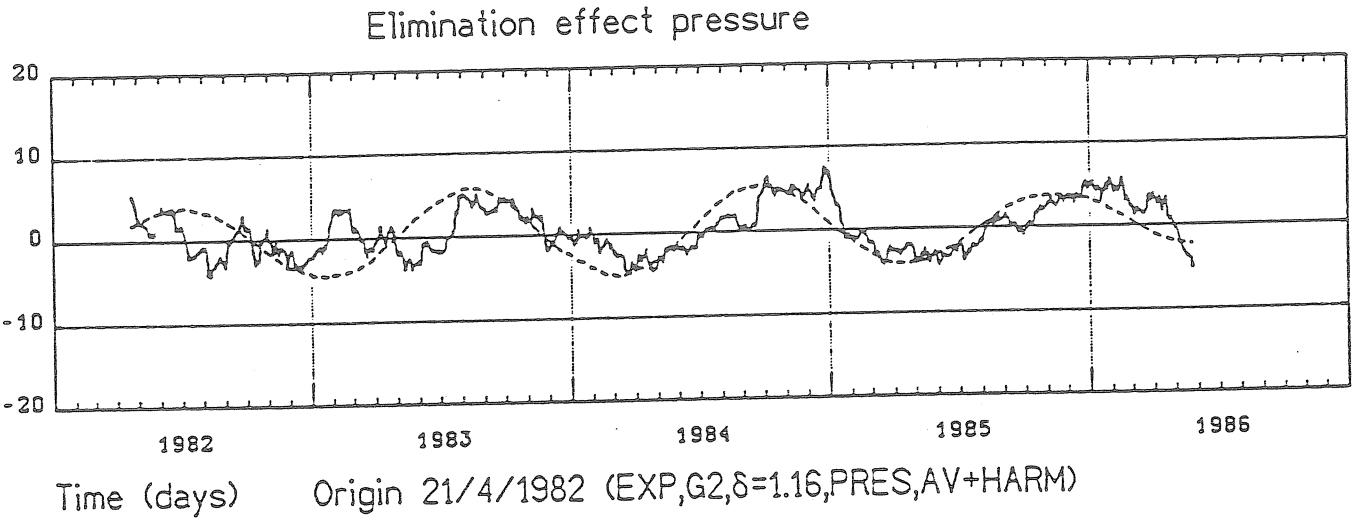


Figure 2 : Observed long term gravity changes (pressure and instrumental effects removed).
The dashed line shows the theoretical amplitude of the polar motion induced tide (δ = 1.16).

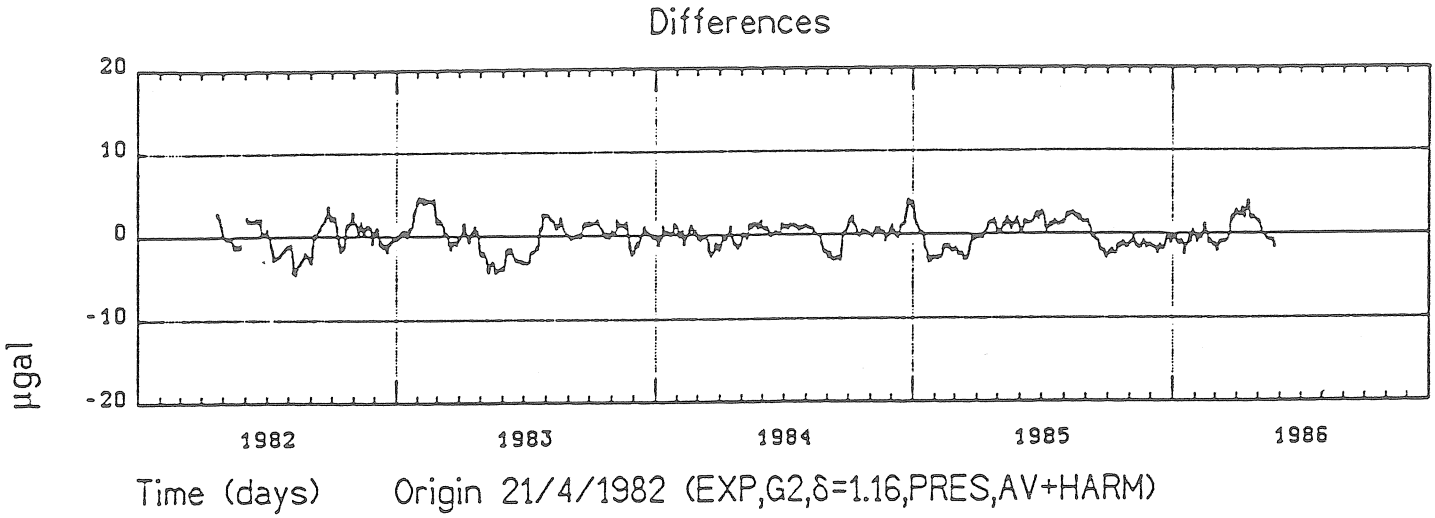


Figure 3 : Final residues after subtracting the polar motion induced tide (δ = 1.16) and an annual term (A = 4 microgal).