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Part I

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C o n t e n t s

I n h a l t s v e r z e i c h n i s

Part 1

Teil 1

Introduction

This 4th International Symposium "Geodesy and Physics of the Earth" was arranged jointly by the Central Earth Physics Institute Potsdam and the National Committee of Geodesy and Geophysics of the G.D.R. and co-sponsored by the International Association of Geodesy of the I.U.G.G. As to its tenor it continued the series of the symposia of 1970, 1973 and 1976 dealing with the same basic topic. Accordingly it was mainly devoted to the close links between geodetic and geophysical research studying the geodynamical behaviour of the Earth.

Taking place only short time after the XVII. General Assembly of I.U.G.G., Canberra 1979, the symposium also reflected the relevant highlights as well in papers as in a special evening session under the chair of the President of the I.A.G., Prof. H. Moritz. Reports were given by the General Secretary of the I.U.G.G., Prof. P. Melchior, and the Secretaries of the I.A.G. Sections IV (Theory) an V (Physical Interpretation), Prof. E. Grafarend and Prof. H. Kautzleben respectively.

The scientific programme prepared by members of the Scientific Committee - H. Kautzleben (G.D.R.), J.D. Boulanger (U.S.S.R.), E. Buschmann (G.D.R.), H. Moritz (Austria), R. Rapp (U.S.A.), Ya. Yatskiv (U.S.S.R.) - included contributions to the following items

- Global and Planetary Dynamics of the Earth,
- Figure and Gravity Field of the Earth,
- Geodynamical Processes,

which are kept in the structure of the Proceedings.

The Helmert commemorative lecture "Earth Rotation and Nutations in Regard to Liquid Core-Mantle and Ocean-Lithosphere Tidal Interactions" given by P. Melchior (Belgium) within the series of the annual Helmert-lectures of the Central Earth Physics Institute is also included in these Proceedings but will be distributed additionally together with the preceding ones in a special issue.

The symposium was attended by about 160 scientists from 17 countries. 59 papers were read and further 12 only distributed for want of time. All are included in these three volumes of the Proceedings.

It's a pleasent task to thank again very heartily all authors for their contributions and to thank also my colleagues engaged in the editorial and technical completion of this publication.

Potsdam, May 1981

H. Kautzleben

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4th International Symposium
Geodesy and Physics of the Earth
Karl Marx Stadt - 13 May-16 May 1980

"Helmert Lecture"

EARTH ROTATION AND NUTATIONS IN REGARO TO LIQUID CORE - MANTLE AND OCEAN - LITHOSPHERE TIDAL INTERACTIONS

by

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1. INTRODUCTION

When, in 1884, F.R. Helmert, at that time Professor at the Technischen Hochschule in Aachen, published the second part of his monumental treatise "Die mathematischen und Physikalischen theorieen der Höheren Geodäsie, he gave to it a sub title as follows :

"Die Physikalischen theorieen mit untersuchungen über die mathematische Erdgestalt auf Grund der Beobachtungen".

which shows that the great master fully realized how important for the development of advanced Geodesy were the physical aspects of the earth's internal constitution as well as the observations of related phenomena.

As a matter of fact 120 pages over 610 of the second part of the Helmert treatise were devoted to a discussion about earth tides, precession and nutations, the free Chandler motion and the internal distribution of densities.

To day Geodesy is at a turning point in its History. With experimental measurements reaching the centimeter level new interests - scientific, economic and, most important, humanitarian - appear with the possibility to control slow or sudden small surface motions resulting from internal thermodynamical processes which are dominated by dissipation effects.

Associated with a tectonic model such measurements seem to offer a way for predicting earthquakes, a difficult objective indeed, but so important for the safeguard of so many human lives that it justifies the efforts presently done in this direction.

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To correctly refer the time varying positions of their network points, Geodesists and Astronomers are presently in search for a well defined frame of reference, an extremely complicate task as, at this level of precision, every point fixed with respect to the Earth's crust is moving.

As long as we consider the Earth as made of a perfectly elastic mantle containing a perfect fluid core we have no serious difficulty to provide corrections for tidal movements and precession - nutations despite the existence of some paradox in the liquid core equations. The problem for this model may be considered as theoretically solved and sufficiently verified in view of the present still low experimental performances.

But such a crude model does not help to treat the new questions of major interest which are the plate tectonics motions, creep in the mantle, convection in the mantle and in the core, dissipation in the mantle and in the core, formation of the inner core by precipitation and crystallisation, all phenomena which influence the Earth's rotation characteristics.

All these movements are controlled by the viscosity internal distribution which unfortunately is still the less well know rheological parameter.

As a matter of fact we have to consider the planet Earth as composed with very high viscosity material like the lower mantle, low viscosity layers like the asthenosphere and extremely low viscosity mediums, the liquid outer core and the oceans.

The perturbations in the Earth's rotation - and consequently the deflections of our basic system of reference - are controlled by the interactions between these media. This raises formidable problems of elasticity and magneto-hydrodynamics.

The internal friction can be characterised either by the classical coefficient of kinematic viscosity ν expressed - as a diffusion - in $cm^2\ s^{-1}$ (stokes) or, more often in the recent litterature, by the quality factor Q which is defined as the ratio between the peak elastic potential energy W stored during one cycle and the power dissipated, dE/dt, by hysteresis into heat during this same cycle (fig. 1) :

$$Q^{-1} = \frac{1}{2\pi W} \oint \frac{dE}{dt}\, dt = \frac{T\Delta S}{2\pi W} = \sin \varepsilon = f/2\pi \qquad (1)$$

T is the Kelvin temperature

ΔS is the density of entropy generated in an irreversible way during one cycle

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ε is the phase angle of the deformation or loss angle

f is the internal friction.

Relation (1) is valid for viscoelastic bodies with small positive ε only. The linear relation between stress and strain rate which characterizes newtonian viscosity is valid if the deformation is produced by creep by diffusion of ions (oxygen ions) or vacancies through a crystal lattice.

There is of course a rapid variation of diffusion D with temperature as

$$D = D_o \exp(-H^*/kT) \qquad (2)$$

k being the Boltzmann constant and H^* the activation enthalpy for creep, $H^* = E^* + PV^*$, where E^* is the activation energy which is the energy required for a local rearrangement of atoms or vacancies to break the attractive bonds and pass through the barrier of repulsion. The dependence of creep on pressure is represented in terms of the activation volume V^*.

However an increase of density caused by crystallographic phase changes as it occurs at about 650 km depth - increases the activation energy (from 4 electron volts in the upper mantle to 6 electron volts in the lower mantle) and hence decreases the diffusion. This explains why the viscosity is about five orders of magnitude more in the lower mantle than in the upper mantle.

The quality factor then depends from temperature as

$$Q = Q_o \exp(H^*/kT) \qquad (3)$$

which shows that ideal elastic behavior is approached only at very low temperature. At temperatures approaching half the melting point or more, the creep plays a more and more important role.

As in viscous solids ν is inversely proportional to D, one can show, on thermodynamical grounds that νQ^{-1} is a constant. This of course does not apply to a perfect fluid (ν=0) which has a Q equal to infinite.

One has indeed

$$Q = 100 \quad \text{for} \quad \nu = 10^{22} \text{ stokes}$$
$$Q = 1000 \quad \text{for} \quad \nu = 10^{23} \text{ stokes}$$

As shown in the Table I there are many geophysical events which allow in principle to determine the quality factor which seems to be frequency dependent. However all these observable geophysical events do not penetrate the Earth's body to the same depth.

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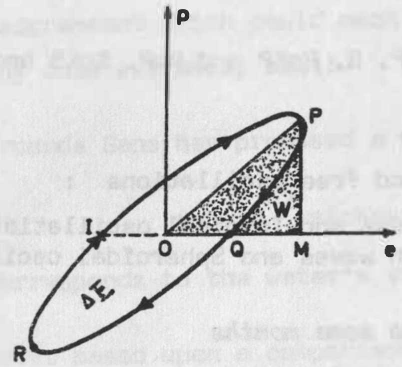

Fig.1 W: the elastic potential energy stored during one cycle

ΔE: the energy dissipated during one cycle

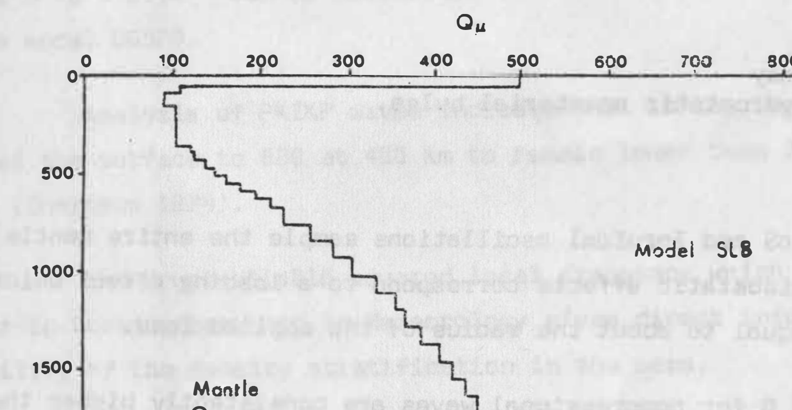

Fig.2 Q Model SL8 for the whole earth. (after Anderson and Hart, 1978).

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TABLE I

periods from about 1 to 20s

body waves : P, S, PnKP and PcP, SnKS and ScS

periods up to 54 min

surface waves and free oscillations :

Love waves and Toroïdal oscillations
Rayleigh waves and Spheroïdal oscillations

periods from several hours to some months

body tides and tidal loading

a period of 432 days

Chandler free nutation

secular effects

isostasy
non hydrostatic equatorial bulge.

For example ScS and Toroïdal oscillations sample the entire mantle and not the core while isostatic effects correspond to a loading effect which penetrates to a depth equal to about the radius of the applied load.

The values of Q for compressional waves are consistently higher than for shear waves. It appears therefore that attenuation is due virtually entirely to the shear component of strain, even in compressional waves.

Thus values of Q for fluids, including sea water, are exceedingly high, reflecting the fact that the stresses associated with wave motion in fluids are purely compressional.

Fig. 2 represents an estimation of Q in the Earth's Mantle.

2. PHYSICO-CHEMICAL STRUCTURE OF THE CORE

As the coupling mechanism between core and mantle is the key of the problem of many Earth rotation perturbations, the rheological behaviour of the core appears to be the most important topic for our purposes.

This behaviour can be described by three basic parameters : the modulus of rigidity μ, the coefficient of kinematic viscosity ν and the squared Brunt Väisälä frequency N^2.

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Diffracted waves require that the rigidity will be in any case less than 10^8 dynes cm^{-2}. A value $\mu=0$ would be equally satisfactory, however there is a small systematic disagreement which could mean that μ is not strictly zero (Sacks 1966) but in any case extremely small.

On atomic grounds Gans has proposed a viscosity

$$\nu \sim 10^{-2} \text{ stokes} \tag{4}$$

(which, by the way, corresponds to the water's viscosity).

Seismic results based upon a comparison of amplitudes of P7KP and P4KP rays indicates

$$5000 < Q < 10\ 000 \tag{5}$$

while a $Q \sim 3.10^6$ can be calculated for the fundamental spheroïdal mode of the Earth model DG579.

Analysis of PKIKP waves indicate that in the inner core Q raises from 200 at the surface to 600 at 400 km to remain lower than 2000 in the deepest part (Doornbos 1974).

The Brunt-Väisälä squared local frequency which is a well known parameter in Oceanography and in Meteorology gives direct information about the stability of the density stratification in the core.

Let us consider an infinitesimal element of mass in a fluid and let us displace it from the level r to the level $r + \xi$, the difference of hydrostatic pressure is $dp = -\rho\, g\, \xi$ from which results, by adiabatic dilatation, a change of density inside the element

$$(d\rho)_{int} = \rho\, dp/k = -\rho^2\, g\, \xi/k \tag{6}$$

while the density of the surrounding fluid has changed by

$$(d\rho)_{ext} = \xi\, d\rho/dr \tag{7}$$

the element is thus sollicitated by a restoring force

$$g\left[(d\rho)_{ext} - (d\rho)_{int}\right] = \xi\, g\left[\frac{d\rho}{dr} + \rho^2\,\frac{g}{k}\right] = -\rho\, \xi\, N^2 \tag{8}$$

Equating this restoring force to the inertial reaction of the element gives the equation of movement :

$$\rho\,\frac{d^2\xi}{dt^2} = -\,\rho\,\xi\,N^2 \tag{9}$$

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where

$$N^2(r) = -g(r)\,\rho^{-1}(r)\,\frac{d\rho(r)}{dr} - g^2(r)\,\rho(r)\,k^{-1}(r) \qquad (10)$$

is the square of the frequency called Brunt-Väisälä frequency. The equation of movement (9) shows that

	if $N^2(r) > 0$	the core is dynamically stable
	if $N^2(r) < 0$	the core is dynamically unstable
and	if $N^2(r) = 0$	Adams Williamson equation being satisfied, the core is in neutral equilibrium and in that case the restoring forces are only Coriolis and Lorentz forces.

The local Brunt Väisälä frequency is obviously a dominant factor in the spheroïdal gravitational modes of the liquid core. Some profiles of $N^2(r)$ for different models of the Earth's interior presented by M.L. Smith (1976) and by Crossley and Rochester (1980) are reproduced on Fig. 3. Irregularities are due to the problems in evaluating $d\rho/dr$.

To have a clear idea upon the limitations of the present investigations on the core-mantle interactions and their relations with astrogeodetical observations, it seems appropriate to summarize in a few words the present current status of speculations upon the outer core and inner core constitution and behaviour.

It is unanimously agreed that the outer core is made of a electrically conducting liquid binary alloy composed of a heavy metal (Fe) and a light non metal (S or Si). Density considerations show that this alloy is not far from its eutectic composition (fig. 4) but one can consider that it is slightly more metallic than the eutectic. In such a situation the core may be cooling, some part of the heavy metal crystallises to continually accrete the slightly more dense solid inner core. The mixture is enriched into its light non metal going slowly towards is eutectic composition while temperature decreases. This process requires rearrangement of the matter's distribution by buoyancy, which releases gravitational energy and leads directly to fluid motions which provide an efficient driving process for the geodynamo.

The gravitational energy is transformed into magnetic energy by dynamo action and then into internal heating by ohmic dissipation.

We should observe a slow growth of the inner core and we should have an unstably stratified outer core.

In this model the jump in density at the inner core-outer core boundary is an extremely important parameter as it determines the conditions of

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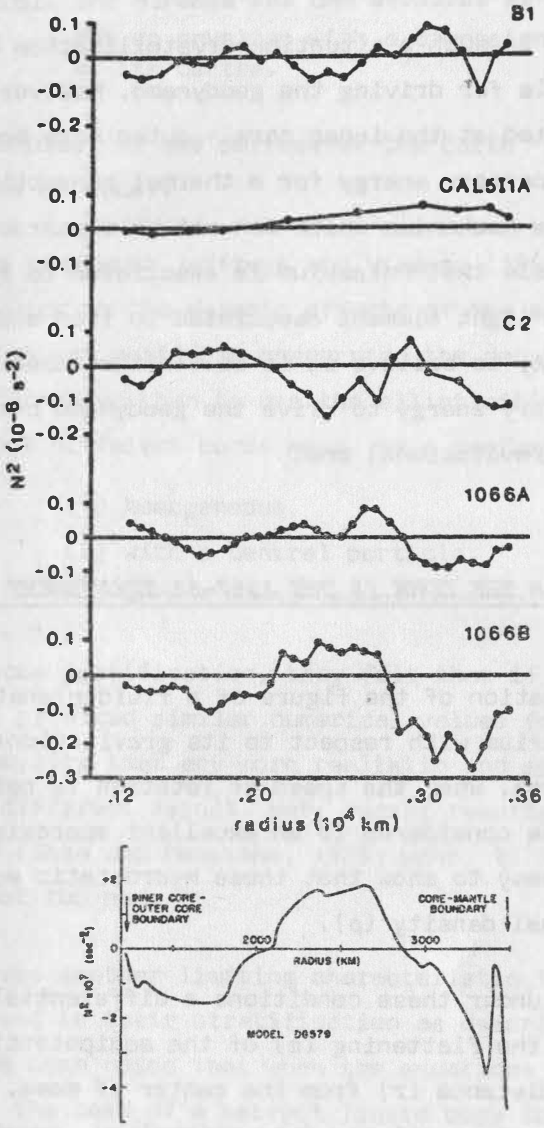

Fig.3 The local squared Brunt Väisälä frequency for six different models of the core according to Crossley and Rochester (1980) (upper five models) and M.L. Smith (1976) (lower graph).

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crystallisation. If there was no density jump we should have to consider that the composition of the alloy is eutectic and the same in the liquid outer core and in the solid inner core. In such a situation crystallisation do not make gravitational energy available for driving the geodynamo. However latent heat of crystallisation concentrated at the inner core - outer core boundary could perhaps still provide the necessary energy for a thermal convection. In this respect there is an alternate mechanism which can not be discarded. Geochemical arguments make it well possible that Potassium is associated to Sulfur in the outer core, if Sulfur is the light element associated to iron and not Silicium. There is now a marked tendency to believe it is so. In that case the radioactive K40 could provide the necessary energy to drive the geodynamo but this mechanism is less efficient than the gravitational one.

3. *ELEMENTARY MODELS USED FOR THE CORE IN THE 1957-61 TREATEMENT OF THE TIDAL AND NUTATION PROBLEMS.*

The first approximation of the figure of a fluid planet is obtained by assuming hydrostatic equilibrium with respect to its gravitational self-attraction and the centrifugal force. When the speed of rotation is not too fast, the equipotential surfaces may be considered to an excellent approximation as ellipsoids of revolution. It is easy to show that these hydrostatic equipotential surfaces are surfaces of equal density (ρ).

Clairaut obtained under these conditions a differential equation of the second order describing the flattening (e) of the equipotential surfaces as a function of their radial distance (r) from the center of mass. In the last century, when no information was available from seismology, great efforts were made to investigate the internal constitution of the Earth on the basis of the Clairaut equation. In particular, Roche showed that the equation was integrable if one chose a polynomial law for the distribution of density of the form

$$\rho = \rho_o (1 - a\, r^2) \quad (\rho_o \text{ : density at the centre}) \tag{11}$$

which evidently has no experimental basis.

Radau introduced a new parameter $|\eta = (r/e)\,(de/dr)|$ which proved to be useful in the analytical development of the Clairaut equation. One has indeed the relation

$$1 - \frac{2}{5}\sqrt{1+\eta} = \frac{C-A}{C}^{-1}\left(e - \frac{q}{2}\right) \tag{12}$$

with $q = \omega^2 a^3/GM$.

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This parameter varies between two limits :

$\eta = 0$ for a perfectly homogeneous fluid

$\eta = 3$ for an envelope with a dimensionless heavy particle at its centre.

As examples, at the surface of the Earth $\eta = 0.576$, while for Saturn $\eta = 1.711$ (at the surface).

At the time when Jeffreys and Vicente (1957a,b) and Molodensky (1961) published their work on the dynamic effects of the earth's liquid core, very little information was available concerning the density of the core. Thus they had no other alternative than to use the ellipticities derived from the Clairaut equation and adopt different cores made of a *perfect* fluid which was either

(1) homogeneous,

(2) with a central particle,

(3) with a Roche law of density.

With some justification, they felt that if these crude but totally different models provided similar numerical values for the Love numbers there was a good probability that any more realistic and sophisticated model should not give a much different result. Very recent results based upon much more realistic models (Shen and Mansinha, 1976; Wahr, 1979) seem to prove that this assumption was not too bad.

There was another limiting characteristic in the models used for the liquid core related to their stratification as described by the Brunt-Väisälä frequency. It has been noted that when the equations of elastic equilibrium where reduced to the case of a perfect liquid body (by putting the rigidity μ equal to zero as well as the viscosity ν), a relation between pressure changes and density was implied for the zero frequency case ($\omega_i = 0$) :

$$-\frac{g}{\rho}\frac{d\rho}{dr} - \frac{g^2\rho}{\lambda} = 0 \qquad (13)$$

($\lambda = k$ is incompressibility modulus when $\mu = 0$).

This relation, which had been assumed by Adams and Williamson in 1923, states that the change in density inside the core only depends upon the change of pressure with radial distance. It implies adiabaticity and chemical homogeneity inside the core and it expresses that the squared Brunt-Väisälä frequency (10) is zero everywhere in the core which has thus to be in neutral equilibrium.

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This artificial limitation with respect to all possibly more realistic core stratifications is an hydrodynamical paradox resulting from the fact that one has taken a zero viscosity which makes the boundary layer at the top of the core disappearing (see § 5).

The first distribution of density in the Earth constructed by Bullen in 1936 was based upon the fulfillment of the Adams-Williamson condition in the different regions of the mantle and a Roche law.

The cores in the Jeffreys-Vicente and Molodensky models are "Adams Williamson" cores.

4. *MODELS FOR THE MANTLE - THE CHOICE OF VARIABLES.*

Jeffreys and Vicente adopted for the mantle a solution obtained by Takeuchi in 1950. This was calculated with a spherical, non rotating, elastic isotropic (SNREI) model consisting of numerical values of the density (ρ) and the elastic moduli (λ,μ) given for 12 points in the mantle, the last nine being separated by 300 km in radial distance. For computing the displacements, Takeuchi had to calculate the first derivatives of the quantities ρ, λ and μ with respect to the radial distance, which was obviously a critical operation. A more suitable choice of variables (Molodensky, 1953; Alterman, Jarosch and Pekeris, 1960) made it possible to avoid this operation, but the Jeffreys and Vicente developments have not been recalculated with this new formulation. Molodensky, however, did use this approach. Note that the difference is wholly one of formulation; the two approaches are mathematically identical.

However because of the ellipticity, there is application of additional stresses at the bottom of the mantle and consequently the solution in the mantle should be changed in function of this coupling effect.

5. *INERTIAL CORE-MANTLE COUPLING.*

The coupling mechanism between core and mantle is the key of the problem of some Earth rotation anomalies which depend from internal processes. Three mechanisms of coupling are proposed : inertial and topographic, viscous, electromagnetic. The only informations we presently have to investigate the inertial and topographic couplings are from geodetic origin.

It is clear that if the core mantle boundary was perfectly spherical and the core material inviscid, no movement could be transmitted from the mantle

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to the core and vice versa. The two media could rotate independently. However the Clairaut-Radau theory allows us to calculate, by numerical integration the ellipticities of the equipotential surfaces inside the earth on the condition that the outside surface flattening as well as the density distribution are known. One finds in this way a flattening 1/392.15 (Denis (1979) for the core-mantle interface,a determination which rests on the hypothesis that the Earth is in hydrostatic equilibrium - which is not strictly true.

Such a flattening corresponds to a difference of 9 kilometers between the equatorial and polar radius of the core, a difference which the seismological technique has not yet allowed to measure. Evidently if a fluid is contained inside an elliptical cavity the motion of the mantle may be transmitted to it by pressure effects and *resonance* may happen when the oscillations of the boundary have a period very close to the period of free oscillations of the fluid in its container. However, and fortunately, there exists no perfect fluid : the mixture which constitutes the liquid core exhibits some viscosity which even if extremely low cannot be put equal to zero. We thus have to consider the existence of a boundary layer in the fluid at the core-mantle interface. Inside this layer there is a strong velocity gradient which allows the adjustment of the internal fluid flow to the movement of the lower mantle elastic boundary. *Dissipation* takes place inside this boundary layer, the thickness of which is proportional to the square root of the viscosity. For $\nu \sim 10^{-2}$ stoke, this boundary layer should be only 10 cm thick but this is comparable with the tidal deformations of the boundary. However if there is turbulence in the core the thickness of the boundary layer will increase and energy will be dissipated internally as well as in the boundary layer.

This possibility of a resonance has been suspected indeed since the time of the discovery of the polar motion and a number of beautiful mathematical analyses were constructed by Hough, Sludsky and Poincaré. The liquid core effects are therefore often called Poincaré effect. There is a narrow range of frequencies in which core-mantle pressure coupling efficiently connects the core rotation to the mantle rotation by the nearly resonant excitation of the fluid core's tilt-over mode. This range of frequencies falls inside the diurnal part of the earth tide spectrum.

This problem was considered again under the impulse given by Jeffreys and numerous papers by many distinguished authors have been published since the Geophysical Year which lead to the conclusion that such a resonance effect is indeed observable in the form of perturbations of the amplitudes of some earth tide waves having their period close to the resonance period (23 hours 56 minutes) and of the amplitudes of the associated astronomical nutations.

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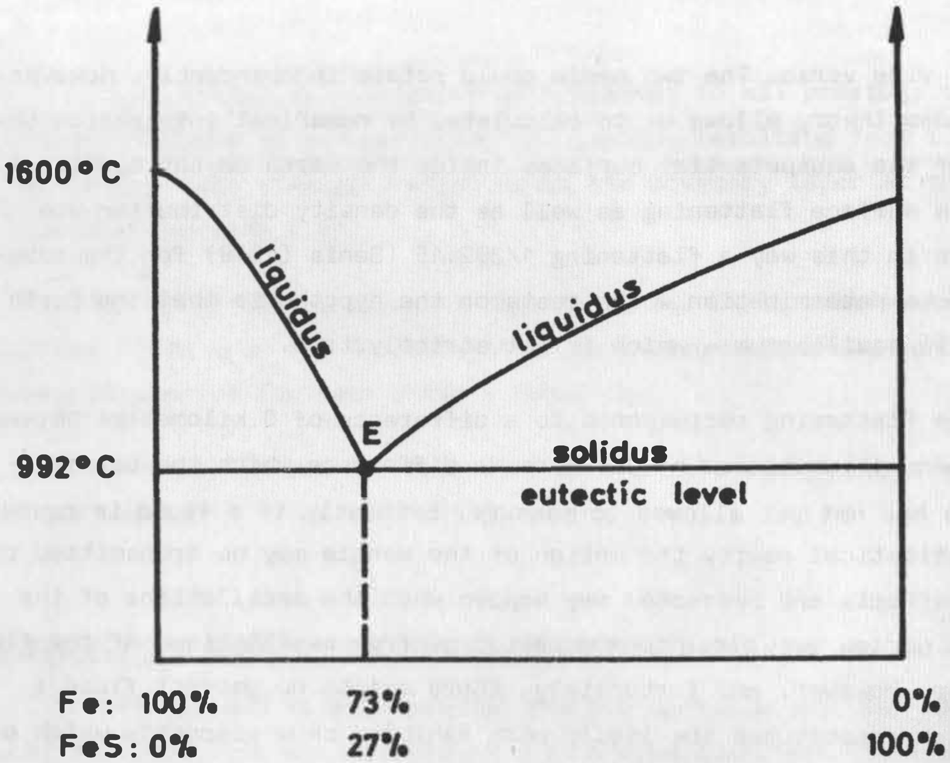

Fig.4 - Melting temperature of a Fe-Fe S mixture at normal pressure.
E is the eutectic point.

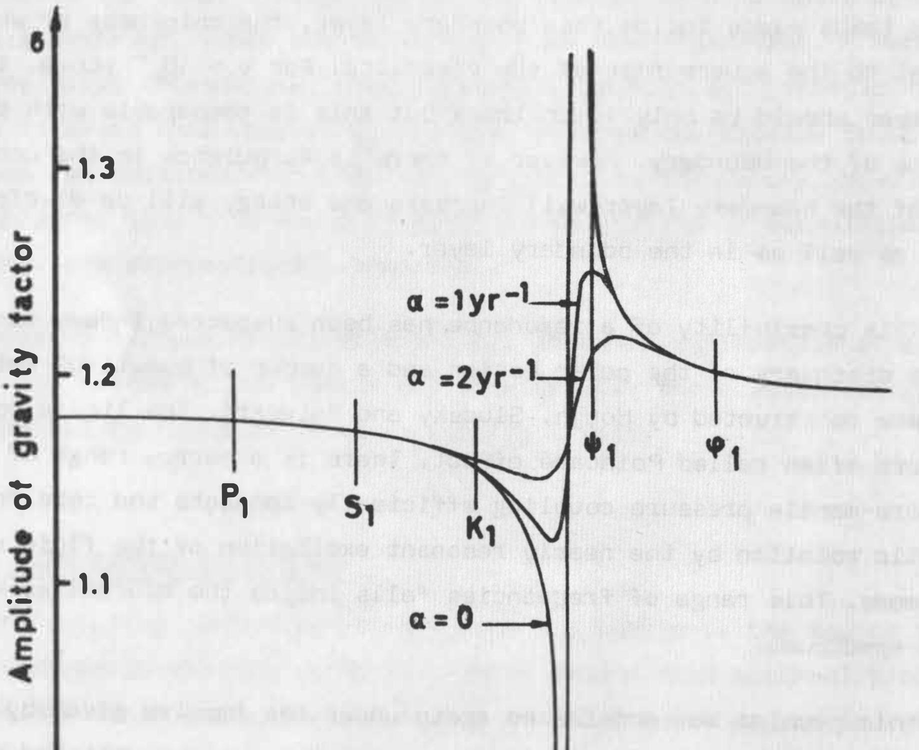

Fig.5 - Effect of dissipation in the core resonance acting on the diurnal
tidal waves.

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The value of the resonance period is of course essentially determined by the geometrical flattening of the core boundary which thus appears as one of the fundamental geodynamical parameters. On the other hand the dissipation of energy at the resonance frequency will produce a classical reduction of the peak amplitude as shown on the figure 5.

One obvious aim of tidal and nutation experimental determinations should be to estimate this reduction to derive direct informations upon the core viscosity.

6. *THE NUTATIONS AS DERIVED FROM THE TIDAL POTENTIAL.*

The relation between earth tides and nutations seems to have been pointed out for the first time by Jeffreys (1949) with only one short sentence : *"Precession nutation arise from diurnal components of the tidal potential".* Later on Jeffreys and Vicente (1957) again stated *"The forced nutations correspond to diurnal tides"* (page 171) and gave a short numerical table indicating the correspondance of four tidal waves 001, K1, P1 and O1 with precession and several nutations. But they did not made explicit this correspondence. On the other hand the numerical results obtained for the Love numbers in this paper are in rather strong conflict with the observed values.

Similarly Molodensky (1961) presented as a result of his theoretical investigations a numerical table where some of the principal diurnal tides were associated to some well known nutations but again without any detailed formulation of this correspondence.

In 1968 Melchior and Georis developed explicitly this relation from the expressions of the torques exerted by tidal forces deriving from the potential

$$W(A) = \sum_{\ell=2}^{\infty} \sum_{m=0}^{\ell} W_{\ell m}\, r^{\ell}\, P_{\ell}^{m}(\sin\delta)\, P_{\ell}^{m}(\sin\phi) \cos m.H(A) \qquad (14)$$

where

$$W_m = \frac{2\,(\ell-m)\,!\,GM}{(\ell+m)\,!\,d^{\ell+1}} \quad . \qquad (15)$$

In these expressions d, δ and α are very complicate functions of time. To obtain a purely harmonic development Doodson chose a set of variables which can be considered as linear functions of time during a sufficiently short

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interval (compatible with the duration of the observations).

The total torque exerted on the planet is

$$\underset{\sim}{N} = \iiint_v (\underset{\sim}{r} \wedge \underset{\sim}{\text{grad}}\, W)\, \rho\, dv. \tag{16}$$

This integral, extended to the entire volume of the planet, is transformed to

$$\underset{\sim}{N} = -\iiint_v \text{rot}\,(\rho\, W\underset{\sim}{r})\, dv - \iiint_v (\underset{\sim}{r} \wedge \underset{\sim}{\text{grad}}\, \rho)\, W\, dv \tag{17}$$

and, using the Ostrogradsky theorem :

$$\underset{\sim}{N} = -\oiint_s (\underset{\sim}{n} \wedge \underset{\sim}{R})\, \rho W\, dS - \iiint_v (\underset{\sim}{r} \wedge \underset{\sim}{\text{grad}}\, \rho)\, W\, dv, \tag{18}$$

where R is the vectorial radius at the external surface and n is the external normal. The first term is zero in the case of a spherical Earth ($\underset{\sim}{n}$, $\underset{\sim}{R}$ parallel) (geometrical ellipticity) while the second term is zero for a density distribution with spherical symmetry ($\underset{\sim}{r}$ parallel to $\underset{\sim}{\text{grad}}\, \rho$) (dynamical ellipticity). A surface integral term exists for every surface of discontinuity of ρ.

The tidal potential has to be introduced into the expression for the torque. Choosing as system of axes the direction of the vernal equinox (Ox_o), the direction of the North pole of the Earth (Oz_o) and the axis perpendicular to the plane $x_o\, Oz_o$ (Oy_o), Melchior and Georis demonstrated that the projections of this torque are

$$\begin{aligned} N_{xo} &= +\sum_{\ell} J'_{\ell}\, W_{\ell 1}\, P^1_{\ell}\,(\sin\delta)\, \sin\alpha\ , \\ N_{yo} &= -\sum_{\ell} J'_{\ell}\, W_{\ell 1}\, P^1_{\ell}\,(\sin\delta)\, \cos\alpha\ , \end{aligned} \tag{19}$$

where

$$J'_{\ell} = \frac{1}{2}\,\ell(\ell+1)\, a^{\ell}\, J_{\ell}\ . \tag{20}$$

The torque is zero if $m \neq 1$ and the J_{ℓ} are the zonal coefficients in the Earth's gravity field. In particular

$$J'_2 = 3\, a^2\, J_2 = 3\, a^2\, (C-A)\, /\, Ma^2 \tag{21}$$

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Introducing the variations of distance, declination and right ascension of the external body with time, we develop the perturbing potential in the form of a sum of simple periodic terms

$$W_{\ell m} P_{\ell}^{m} (\sin \delta) \cos mH = K_{\ell} \sum_{i} A_{\ell mi} \cos \left[\omega_i t + \frac{1}{2} (\ell - m) \pi\right] , \qquad (22)$$

with

$$K_2 = GM/2c^3 . \qquad (23)$$

The tesseral tidal frequency spectrum is *symmetric with respect to the central sidereal frequency* ω : there are n lines on the left and n lines on the right of ω. Thus we may put

$$\boxed{\Delta\omega_i = -\Delta\omega_{-i} = \omega_i - \omega = \omega_i - 15^{\circ}041\ 069} \qquad (24)$$

This leads to the very simple expressions (for $\ell = 2$, $m = 1$)

$$N_{xo} = - \sum_{i=-n}^{i=+n} K\ J'\ A_i \cos (\Delta\omega_i t)$$

$$N_{yo} = + \sum_{i=-n}^{i=+n} K\ J'\ A_i \sin (\Delta\omega_i t) \qquad (25)$$

A first important remark can be made now : precession and nutations are movements of the axis of figure of the Earth described in an inertial system of fixed axes, while tides are observed at points fixed with respect to the Earth, rotating with the angular velocity

$$\omega = \frac{2\pi}{t'} = 15^{\circ}041\ 069 \text{ per hour} . \qquad (26)$$

Thus, *the frequency of a nutation* $(\Delta\omega_i)$ *can be directly deduced from the frequency of the corresponding tide by simple subtraction of the "sidereal frequency" (15°041 per hour of universal time) :* $\omega_i - \omega = \Delta\omega_i$ *as is obvious in formulas (25).*

But these formulas permit a second statement : *Two waves of symmetric frequency with respect to the sidereal frequency form only one and the same wave of nutation; the sum of their amplitudes (major axis) appears in* N_{xo} *and their difference (minor axis) in* N_{yo} ,

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$$N_{xo} = - \sum_{i=0}^{i=+n} K\,J'\,(A_i + A_{-i}) \cos (\Delta\omega_i t) \,,$$

$$N_{yo} = + \sum_{i=0}^{i=+n} K\,J'\,(A_i - A_{-i}) \sin (\Delta\omega_i t) \,. \tag{27}$$

Conversely we may consider an elliptic nutation as equivalent to two circular nutations of equal and opposite velocity corresponding to the two symmetrical tidal waves.

The rotations of the system of axes are given by

$$\boxed{\dot\theta = + \frac{N_{yo}}{C\omega} \,, \quad (\sin\theta)\,.\,\dot\psi = + \frac{N_{xo}}{C\omega}} \tag{28}$$

and using (27) we obtain the nutations in terms of the development in tidal waves :

$$\dot\theta = \sum_i \frac{K}{C\omega} J'\,(A_i - A_{-i}) \sin (\Delta\omega_i\,.\,t) \,,$$

$$\sin\theta\,.\,\dot\psi = - \sum_i \frac{K}{C\omega} J'\,(A_i + A_{-i}) \cos (\Delta\omega_i\,.\,t) \,. \tag{29}$$

Let us introduce a dimensionless constant :

$$E = \frac{3}{2} \frac{GM}{c^3} \frac{C-A}{C\omega^2} = \frac{KJ'}{C\omega^2} \,. \tag{30}$$

Its value, expressed in seconds of arc, is for the Moon

$$\boxed{E = 0''016\,442\,7} \tag{31}$$

Then

$$\dot\theta = +E_{☾}\,\omega \sum_i (A_i - A_{-i}) \sin (\Delta\omega_i t) \,,$$

$$\dot\psi \sin\theta = -E_{☾}\,\omega \sum_i (A_i - A_{-i}) \cos (\Delta\omega_i t) \,. \tag{32}$$

The K_1 *tidal field of force* is distributed according to the $\cos(\tau + s)$ function, i.e., the cosine of the sidereal time or hour angle of the vernal equinox. It therefore *permanently points towards the vernal equinox ($\dot\theta$ axis),*

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and the torques produced have no resultant component along the $\dot{\theta}$ *axis. Obliquity remains constant.* Instead, they act along the direction 90° away; i.e., $\dot{\psi} \sin \theta$.

The equations for K_1 give

$$\dot{\psi} = -E_{☾} \frac{\omega A(K_1)}{\sin \theta} , \quad \dot{\theta} = 0 , \tag{33}$$

and from

$$E = 0''.016\,4427 , \quad \omega = 7.292 \times 10^{-5}\ s^{-1} ,$$

$$\sin^{-1} \theta = 2.512 , \quad A = 0.530\,5 ,$$

we obtain

$$\dot{\psi} = -50''.38 \text{ per year, the luni-solar precession constant.}$$

The nutations are obtained by integration of equations (32) :

$$\boxed{\begin{aligned} \Delta\theta &= -E_{☾} \sum_i \frac{\omega}{\Delta\omega_i} (A_i - A_{-i}) \cos (\Delta\omega_i t) , \\ \sin \theta \quad \Delta\psi &= -E_{☾} \sum_i \frac{\omega}{\Delta\omega_i} (A_i + A_{-i}) \sin (\Delta\omega_i t) . \end{aligned}} \tag{34}$$

The presence of $\Delta\omega_i$ in the denominator shows that the waves give rise to nutations of an amplitude which becomes lower as their frequency diverges from that of the sidereal day (wave K_1), even when the amplitude of the tide is comparable to that of K_1 (this is the case with O_1 versus P_1).

We observe that tidal waves symmetrical with respect to K_1 and of equal amplitude ($A_i = A_{-i}$) do not cause nutations in obliquity ($\Delta\theta = 0$) but only nutations in longitude. This is the case for waves generated by the ellipticity of the orbits :

NO_1 and J_1 for the Moon,

S_1 and ψ_1 for the Sun.

The periods of the nutations associated with the ellipticity of the orbits are evidently a month and a year. In the sense of mechanics it seems unsuitable to classify these components among the "short-period nutations", as they do not practically alter the angle θ and show only a variation of ψ, that is a precession. The two components produced by the ellipticity of the orbits should logically have been named "short-period precessions".

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The forced diurnal nutations described inside the Earth and associated with the precession-nutations in space (often called Oppolzer terms) may be deduced as a function of the tidal components by introducing the expressions (32) in the Euler kinematic relations. It is found that they have the same frequencies as the corresponding tidal waves and amplitudes equal to those of these tidal waves multiplied by the factor $(\omega^2 a^3/GM) / \left[(C-A)/C\right]$, which is nearly unity.

7. *THE NEW NUTATION TABLES.*

Formula (34) shows in a very simple way how the magnitudes of the axis of every elliptic nutation are directly related to the magnitude of one pair of diurnal tidal waves having their frequencies symetric with respect to ω.

On the basis of these formulas, Melchior (1971) constructed a detailed table of nutations (see Table II) taking into account the experimental results he had derived from very precise earth tide measurements.

This table published in Celestial Mechanics, was used at the Jet Propulsion Laboratory for the reduction of Lunar Laser Ranging by Williams (1976), Harris and Williams (1976) King, Counselman and Shapiro (1978) as well as for the reduction of VLBI measurements at the NASA by Chopo Ma (1978).

Chopo Ma gives some details about the improvement of the VLBI results : he states that when using this table for the recent observations (since 1973) the root of weighted mean square delay residual always decrease, the improvement in the most recent data (1976-77) being *"quite startling, 37 %"*.

Simultaneously "the diurnal polar motion scale factor is reduced in every data set when the nutation corrections are applied ... the phase angle is also changed by nutation corrections and the scatter in phase is reduced.

But even the classical techniques of Astrometry clearly indicate that the IAU nutation tables are not satisfactory. McCarthy, Seidelmann and Van Flandern (1977) have shown that *"discrepancies with observations can accumulate to 0"1 in right ascension and significantly affect the determination of UT1 and materially influence the derivation of the new fundamental catalogue of star positions and proper motions FK5"*.

These authors suggested that in the absence of a non-rigid-Earth model which can satisfy all requirements, the coefficients found from the investigation of solid-Earth-tides should be adopted as a working standard and they

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concluded : *"Statistically, there is no significant difference in the fit of Melchior's coefficients, Molodensky I, Jeffreys Vicente I or Pedersen models to the astronomical observational results, although the Melchior coefficients are the best overall"*.

One has been therefore very disturbed by the fact that in august 1979 IAU choose the Molodensky model II (1961), a model with inner core, but against which the following theoretical criticism has been raised by Jeffreys and Vicente : *"For the diurnal waves, the differential equations are hyperbolic. With an inner core there are new boundary conditions and the complementary functions needed are of a totally different form. For this reason, Molodensky solution for Model II may not be so reliable"*.

More critical even is the fact pointed out by Pariiskii (1978) that the Model II of Molodensky has been calculated with an earth flattening equal to 1/297 which makes it particularly unsuitable for nutation problems. Model I was calculated with 1/298.3 flattening.

For these reasons the International Centre for Earth Tides (ICET) had chosen since several years the Molodensky model I as a *provisional* standard of comparison for earth tide analysis. This model I slightly better fits the earth tide measurements, typically for the fundamental wave O1 (model I : δ = 1.160; model II : δ = 1.164).

It also appears that Molodensky model II nutations diverge from the more recent theories by up to 0"002 at six months period and 18.6 years period. Such differences will be significant with the new astrometric techniques (VLBI, Lunar Laser).

Therefore IAU would have been wise to consult IUGG or simply carefully look at more recent models as those presented by Po Yu-Shen and Mansinha (1976), Sasao Okamoto and Sakai (1977) and principally those of Wahr (1979). Po Yu-Shen and Mansinha, Sasao et al have considered other structural models of the core than the Adams Williamson one but still use a spherical non-rotating mantle.

Wahr considers for the first time a rotating slightly elliptical mantle.

Rotation and deformation are computed simultaneously. Elliptical and rotational effects are considered throughout both the core and mantle and at each internal boundary.

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TABLE II

Nutation coefficients (units are arcseconds)

Term	Woolard	Astronomical Observations	Rigid Earth with N=9.2050 (1)	Melchior 1971 (6)	Wahr 1979
Principal					
Obliquity	9.2100	9.2050 ± 0.0017 (1) 9.1990 ± 0.0035 (2)	9.2050	9.2014	9.2035
Longitude	6.8584	6.8409 ± 0.0025 (1) 6.8360 ± 0.0035 (2)	6.8547	6.8386	6.8430
Annual					
Obliquity	0.0000	—	0.0000	0.0056	0.0055
Longitude	-0.0502	—	-0.0503	-0.0580	-0.0567
Semi-Annual					
Obliquity	0.5522	0.578 ± 0.002 (1)	0.5528	0.5724	0.5708
Longitude	0.5066	0.533 ± 0.002 (1)	0.5072	0.5237	0.5215
Semi-Monthly					
Obliquity	0.0884	0.0925 ± 0.0014 (1) 0.0897 ± 0.0007 (3) 0.0893 ± 0.0022 (4) 0.0898 ± 0.0016 (5)	0.0844	0.0910	0.0910
Longitude	0.0811	0.0853 ± 0.0010 (1) 0.0818 ± 0.0022 (4) 0.0824 ± 0.0016 (5)	0.0811	0.0831	0.0834

(1) Mc Carthy, Seidelmann, Van Flandern (1977)
(2) Yumi, Yokoyama, Ishii (1978)
(3) Gubanov, Yagudin, (1978)
(4) Iijima, Fujii, Niimi, (1978)
(5) Mc Carthy (1976) : results of Washington and Herstmonceux PZTs
(6) four models were given in my 1971 paper. I should have selected this one in 1979.

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The Coriolis term and the boundary conditions on an elliptical interface have as a consequence a coupling between the toroidal (T_n^m) and spheroidal (S_n^m) modes of deformation of different degree n but same order m which involves an infinite system to be solved. Thus truncature is unavoidable to obtain a numerical solution.

In the Wahr model the solution is truncated to

$$T_1^1 + S_2^1 + T_3^1$$

in the mantle as well as in the core. (x).

Wahr has used five different recent (1975) models of the Earth's interior of course with liquid outer core and solid inner core. The first three models have squared Brunt-Väisälä frequency fluctuating rapidly around a zero mean (because of the $\partial\rho/\partial r$ which is not well determined - see fig. 3). He has also slightly modified one of the original models to produce a neutral core and a stably stratified core.

The numerical results for these five models are so similar that it leaves unfortunately no hope to improve our knowledge of the core μ, ν, N^2 parameters with the commonly available instruments. As an exemple we should point out here that M.L. Smith found a difference of 1.4 sidereal day in the Chandler period predicted from a neutral core or a stable core.

It is thus clear that only completely new techniques (VLBI, Laser, Cryoscopic gravimeter) could allow us to infer these properties from nutations and tides.

One can also conclude with Wahr that with such coherent results from the models, one can remove almost perfectly the body tide from the observations and study with more confidence the other geophysical phenomena affecting tilt, strain and gravity.

(x) T_1^1 mode is a rigid rotation of the whole core. Its associated centrifugal potential produces a deformation which results in a displacement field of S_2^1 form. On the other hand, in an elliptical body S_2^1 torques produce a T_1^1 mode.

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8. EARTH TIDE EXPERIMENTAL RESULTS.

The first decisive experimental proof of the existence of the Poincaré effect was obtained around 1965 with four quartz VM pendulums installed in two mines in Belgium (Melchior, 1966) from the following amplitude factors of the three main tesseral diurnal waves measured in the East West horizontal component :

TABLE III

First experimental result (1965)	Theoretical models Mol. I	Mol. II	Wahr
$\gamma(O_1) = 0.666 \pm 0.005$	0.687	0.686	0.689
$\gamma(P_1) = 0.712 \pm 0.005$	0.700	0.697	0.700
$\gamma(K_1) = 0.745 \pm 0.004$	0.733	0.726	0.730

In the vertical component, it has long been difficult indeed to obtain good results for the P_1 wave because the at that time widely used Askania GS11 gravimeters were seriously disturbed by barometric effects in the diurnal band frequencies.

Since 1966 the number of experimental results has considerably increased, all of them only reconfirming this first dermination.

We will therefore refer here only to some series of high quality which allow to determine the more critical wave ψ_1 which is the nearest to the resonance frequency but which, very unfortunately, has a very small amplitude.

These series are those for which the spurious component S_1 has a very low amplitude. These are the series obtained by Abours and Lecolazet (1977) (gravity), Levine (1977) (strain), Melchior (1977) (gravity, strain, tilt), Warburton and Goodkind (1978) (gravity).

One of the most important points in tidal observations is the calibration of the instruments. What we are doing indeed is to compare amplitudes and phases measured by dynamometers (pendulums and gravimeters) with a model of tidal forces which basically depends upon the value given to the mass of the Moon.

The calibration of the Verbaandert-Melchior quartz horizontal pendulums is presently achieved to 0.5 % by the use of the special device which allows to tie the instrument's sensitivity to a well known spectral line.

When calibrating the gravimeters it is more difficult to avoid systematic errors and they may be more important than the accidental errors.

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Nevertheless we compared in Bruxelles some 35 instruments from different makers (Geodynamics, LaCoste Romberg and Askania) calibrated in different ways and we defined for each instrument a frequency dependent rheological model which is then used for all the reduction operations. (Ducarme 1975)

Another important point for the separation of the critical diurnal tidal waves is that the instrument must be made independent of the barometric effects. The gravimeters are more or less free from that effect because there is a compensating capsul fixed on the beam (opposite to the mass with respect to the rotating point). Of course they must always remain sealed.

The pendulums however are very sensitive to deformations of their support. To avoid the spurious tilts due to the effect of pressure changes on their base, the instrument's box should not be sealed which is erroneously often the case. The VM pendulums are constructed in such a way that this barometric effect is completely avoided which appears indeed in their very small S_1 component.

Moreover experience shows that pendulums must be installed at a minimum depth of 50 meters. Unsatisfactory installations are obvious when the results of analysis exhibit a large spurious atmospheric component (called wave S_1). When this is the case all diurnal components are spoiled and can not be used for our purpose. Topography and cavity effects may also spoil the measured tilts but this does not appear for the diurnal components observed in our stations Dourbes and Walferdange equipped with VM quartz pendulums where very long series are available. Anyway cavity and topography must affect in the same way O_1, P_1, K_1, ψ_1 and the other diurnal waves.

Finally, it is clear that to separate very narrow tidal frequencies, longer and longer series of observations are needed.

We present in the Table IV the results of the analysis of the longest series obtained with tiltmeters and gravimeters. They fit very well the theoretical models but the error bars are far too large to allow us to make precise quantitative evaluation of the dissipation effects which should be the most interesting feature to try to observe and measure : phase lags, damping of the core free nutation and reduction of the resonance effect mainly on the ψ_1 wave, the nearest to the resonance frequency.

We have presently no real possibility to measure phase lags with sufficient precision but the amplitude factors observed, particularly $\gamma(\psi_1)$, show no reduction with respect to the models.

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This should mean that the viscosity of the core is very low and that there should be no observable deviations of the nutation amplitudes from the dissipationless values.

The damping factor introduced by Sasao Okamoto and Sakai (1977) is probably much less than what they propose (0.2 year^{-1} instead of 1 year^{-1}).

But, as said before only completely new techniques could allow us to measure these effects with the needed precision.

TABLE IV

Conclusion from experimental results according to ICET

	δ	γ	
Q_1	1.1532 ± 0.0112	0.6182 ± 0.0153	
O_1	1.1570 ± 0.0063	0.6603 ± 0.0088	
NO_1		0.7210 ± 0.0236	
P_1	1.1600 ± 0.0091	0.7227 ± 0.0113	
K_1	1.1467 ± 0.0098	0.7530 ± 0.0079	
- - - - -	- - - - -	- - - - -	(x)
ψ_1	1.2606 ± 0.1570	0.5515 ± 0.0324	
ϕ_1	1.1888 ± 0.1189	0.6346 ± 0.0643	
J_1	1.1682 ± 0.0325	0.6792 ± 0.0330	
OO_1	1.1587 ± 0.0473	0.6086 ± 0.0748	
	10 SERIES	3 SERIES	
	201.972 READINGS	242.256 READINGS	

(x) position of the resonance line

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9. *Ocean-Lithosphere tidal interactions*

The main obstacle encountered in our search for the liquid core effects in the observed tidal amplitudes and phases comes from the interaction between oceanic tides and body tides.

It was known since Hecker's work that the oceanic tides were producing the so called "indirect effects" (attraction, load, change of potential) which the instruments were measuring simultaneously with the pure body tide. Much more recently it was realized (Hendershott 1972) that the oceanic tides also can not be correctly calculated if the tidal vertical displacements of the bottom of the sea are not introduced as a second member in the Laplace tidal equations.

At about the same time J.T. Kuo expressed the idea that tidal gravity measurements on the continents provide efficient constraints for the construction of improved oceanic cotidal maps. With this objective in mind Kuo has installed a number of Geodynamics gravimeters along profiles in the USA and Canada, in Europe and more recently in South America.

Since 1973 the International Centre for Earth Tides (ICET) has initiated Trans World Tidal Gravity Profiles to fullfil the gaps in the observations of earth tides.

There is indeed no problem actually to produce the correction for the global solid earth tide to a precision better than one microgal by using a sufficiently good earth-tide model and taking into account the hydrodynamical effects of the liquid core. However, we are less sure by far about the interaction effect of the oceanic tides upon the earth tide, which are acting by their direct attraction on the instrument itself and by their loading effect upon the crust which is additionally deformed by it. A procedure allowing the calculation of these effects has been developed by Farrell (1972) by using Green functions but it evidently rests upon the precise knowledge of the distribution of the tides in the open oceans and seas all around the world.

Something like eight world maps describing the tidal oscillations of the water masses in the oceans have recently been constructed by different authors by numerical integration of the famous Laplace tidal equations but their solutions diverge considerably from each other because of the introduction of different boundary conditions, friction laws or simply grid interval (1°, 4° or even 6°). One of the objectives of the Trans World tidal gravity profiles is to check if one of these cotidal charts permits adequate correction of the observed data (Ducarme and Melchior, 1978). Such a chart could then be used as a working standard for every kind of tidal correction (Laser, VLBI, ...).

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It is already clear that amongst the existing maps two (the Schwiderski and Parke maps) are satisfactory for the European gravity net while another one (Hendershott map) is more satisfactory for Australia and the South Pacific. What is surely remarkable is that all the obtained loading vectors (defined as the difference between the observed tide and the computed solid earth tide -see figure 6) are of the same order of magnitude over very large areas and that this magnitude fits very well with the loading computed from the oceanic tidal maps. The discrepancies with oceanic maps is in general in the phases.

The world cotidal maps do not give a sufficiently detailed description of the tides in the nearby sea or ocean for the stations which are very near to a coast. These stations therefore need additional corrections but unfortunately detailed tidal maps are not yet available in most of the concerned areas.

To-day ICET has completed the measurements in 48 stations for a duration of about six months at each place, using seven different equipments (three Geodynamics and four LaCoste Romberg, each one being associated to a quartz clock). The structure of this network is shown on figure 7. It may appear as not optimum but it is not difficult to imagine the nature of the practical problems to overcome and that in the tropical countries there are few places where such equipments can be properly installed.

In the Tables VI and VII, we give two examples of our results obtained for the main tidal wave M_2 (period 12 hours 23 minutes) which concern two very widely separated areas: Western Europe where the amplitudes are around 3 microgals and East Australia - New Zealand - South Pacific where the amplitudes reach 10 microgals.

The coherency of the phases for such small vectors give an impressive idea of the performances of the gravimeters used (Geodynamics and LaCoste-Romberg). This demonstrates that these instruments, which have not a sufficient precision for making new progresses in the investigations about the Earth's deep interior, can still make an useful contribution if they are installed at places where the oceanic interaction has an amplitude larger than one microgal.

Fig.7 The ICET Trans World Tidal Gravity Profiles 1973 - 1980.
(can not be printed)

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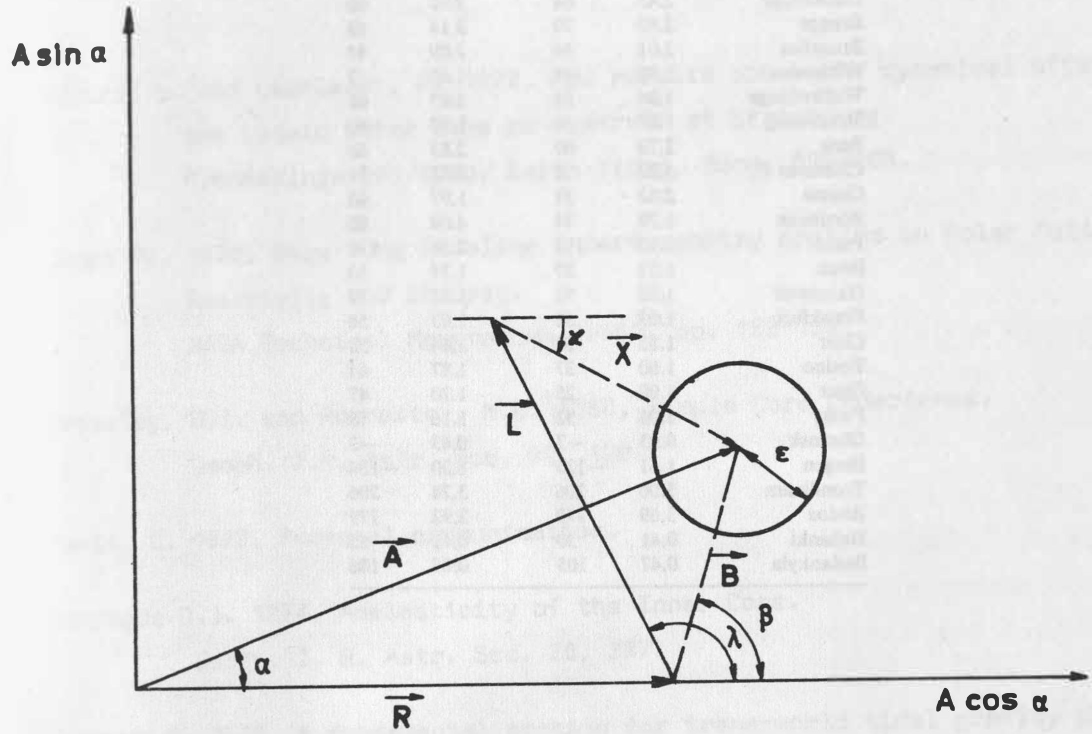

Fig. 6 $\vec{R}$ is the theoretical elastic body tide of frequency ω_i

$\vec{A}$ is the observed corresponding tide

then

$$B_i \cos(\omega_i t + \beta_i) = A_i \cos(\omega_i t + \alpha_i) - R_i \cos \omega_i t$$

$\vec{L}$ is the calculated oceanic load and attraction

$\vec{X}$ is the unexplained part and ε the estimated error of measurements.

In the Tables VI and VII we compare $\vec{B}$ to $\vec{L}$.

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Table V-M_2 tidal load vector

station	observed B	observed β	calculated L	calculated λ
Cambridge	2.45	68	2.93	60
Brugge	2.65	70	2.14	69
Bruxelles	2.01	64	2.09	63
Witteveen	1.90	41	1.48	57
Walferdange	1.84	56	1.95	61
Strasbourg	1.37	50	1.78	60
Paris	2.73	60	2.83	66
Clermont F.	3.22	58	2.72	71
Grasse	2.02	58	1.97	66
Bordeaux	5.79	74	4.08	80
Porto	5.10	110	7.26	110
Bonn	1.52	57	1.74	59
Hannover	1.28	51	1.31	57
Frankfurt	1.09	52	1.63	58
Chur	1.83	52	1.64	58
Torino	1.60	37	1.87	64
Graz	1.98	25	1.20	47
Pecny	1.06	32	1.16	48
Obninsk	0.95	−7	0.43	−3
Bergen	1.61	−133	1.30	−134
Trondheim	5.00	206	3.24	206
Bodoe	3.69	179	2.92	179
Helsinki	0.41	30	0.45	55
Sodankyla	0.47	105	0.65	106

Table VI - M_2 tidal load vector

	station	observed B	observed β	calculated L	calculated λ
Java	Bandung	6.63	−17	5.51	− 3
Celebes	Ujung Pandang	4.69	−26	3.12	10
	Manado	6.47	− 2	5.63	8
N. Guinea	Jaya Pura	5.57	−17	5.82	−15
Papua	Port Moresby	4.93	− 6	3.55	− 8
Australia	Darwin	3.55	24	3.03	3
	Charters T.	4.02	−57	3.27	−11
	Armidale	3.62	−51	5.85	−43
	Canberra	3.42	−43	5.54	−43
Tasmania	Hobart	3.96	−65	3.12	−42
N. Zealand (S)	Lauder	1.68	−62	2.29	−88
N. Zealand (N)	Hamilton	8.28	−42	9.63	−59
N. Caledonia	Noumea	13.06	−36	8.91	−27
Fiji	Suva	11.66	− 5	11.03	−22
Samoa	Apia	14.42	−27	7.80	−22

The "observed vector" (B, amplitude; β, phase) is obtained by subtracting from the observed tidal component a "theoretical" component calculated for a model earth composed by an elastic mantle and a liquid core (Molodensky model).

The "calculated vector" (L: amplitude; λ: phase) is obtained by the Farrell method on the basis of the Parke cotidal map for the European stations but on the basis of the Hendershott map for the Pacific area.

In these tables B and L are given in microgals, β and λ in degrees, the minus sign corresponding to a lag.

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Variations of the Geographical Latitude at Józefosław - Observatory and their Comparison with Gravimetrical Determinations

by

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Abstract

Permanent astronomical determinations of the geographical latitude have been made by Horrebov-Talcott method at Józefosław since 1959 using VZT. Periodical gravity measurements have been made since June 1976 along the observatory meridian. Our gravimetrical base-line contains 7 gravity points. Central one is situated at Józefosław. The others are situated symmetrically from observatory to the North and the South, separated about 3,6 and 12 kms. Between gravity stations, good stabilized, the gravity differences using some quartz gravity meters have been measured. We used Worden, Sharpe CG-2 and Scintrex instruments. Every time they are calibrated by laboratory apparatus using method of inclination to determine the coefficient of gravity meters. Results of gravity observations point out that the plumb line direction has periodical and secular variations. The comparison between the results obtained by astronomical and gravimetrical way will be presented in our paper.

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1. Introduction

The permanent observations of the latitude variations have been executed at the Józefosław - Observatory since 1959. The 12-th group programme of Horrebov-Talcott pairs [1] is the background of the latitude determinations at Józefosław. The observations are carried out by means of Vizual Zenith Telescope /VZT/. The results of the observations are used by BIH and IPMS. System of declination corrections had been determined by the use of the chain method of observations adjustment from the period of 1961-1969 consisting 1010 H-T pairs [3] . In 1972 about 30 H-T pair were substitute by new ones because of precession effect.

That way the new 12-th group programme, foreseen for operation from 1972 up to 1984 has been formed [4] . The declination corrections of star - pairs of the new programme have been determined using observations of 44 H-T pairs common for both programme in the period 1972-76 [5] .

For geophysical interpretion of the latitude variations starting from 1976 the gravimetric measurements along meridian base - line have been done.

2. Gravimetrical works

Variations of the plumb line direction connected with the mass dislocations inside the Earth's crust can be estimated by permament gravimetric observations. Such determinations have been performed since June 1976. Variations of the horizontal gravity gradient at Józefosław - Observatory have been determined. The total length of our gravimetric base line is of 30 kms. It consists of six points; three points to the North and three points to the South along the meridian of Józefosław. Gravity stations are located on

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$r_3 = 2{,}8$ kms, $r_2 = 6{,}3$ kms, $r_1 = 13{,}2$ kms from the observatory. Each pair of points situated at the same distance allows to estimate some mass displacements occuring at different depths. Utilising Vening Meinesz formula for meridional component of the absolute deflection we can put as follows

$$\Delta\varphi = (1 + k - l) \frac{\partial T}{\partial \varphi} \cdot \frac{1}{g \cdot r} = \frac{\Lambda}{g \cdot r} \frac{\partial T}{\partial \varphi} \qquad (1)$$

where k, l are the Love's numbers. Value $\Lambda = 1 + k - l = 1{,}13$ we can take first as constant.

For the gravity changes one can obtain

$$\Delta g = (1 + h - \frac{3}{2} k) \frac{\partial T}{\partial r} = G \cdot \frac{\partial T}{\partial r} = 1{,}20 \frac{\partial T}{\partial r} \qquad (2)$$

Next relation between Δg and $\Delta\varphi$ can be found. This way the periodical gravimetric measurements can be used for the latitude changes determination.

Taking into account our meridian base-line we could utilize Gauss - Czebyszew formula to calculate the Vening Meinesz integral value up to 15 kms for meridional component. Radii of rings in that zone are equal to the distances of gravimetrical stations from astronomical observatory. In that case the common formula has a shape

$$\Delta\xi = \Delta\varphi = -\frac{\varrho''}{2\gamma} \frac{15\,\text{kms}}{3} \left(\frac{\delta\Delta g_{r_1}}{13{,}2\,\text{kms}} + \frac{\delta\Delta g_{r_2}}{6{,}3\,\text{kms}} + \frac{\delta\Delta g_{r_3}}{2{,}8\,\text{kms}} \right) \frac{\Lambda}{G} \qquad (3)$$

where $\delta\Delta g_{r_i}$ meen the gravity differences changes during the time interval between two stations separated of r_i from Józefosław. Introtucing the Love's numbers value we can obtain at last the formula

$$\Delta\varphi = -0{,}''247 \left(0{,}0758\, \delta\Delta g_{r_1} + 0{,}161\, \delta\Delta g_{r_2} + 0{,}357\, \delta\Delta g_{r_3} \right) \qquad (4)$$

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The mean error of the local latitude changes obtained by that method from gravimetric measurements up to 15 kms from observatory we can get from formula

$$m_{\Delta\varphi} = \pm 0\overset{''}{,}247 \left(0{,}0051\ m^2 \delta\Delta g_1 + 0{,}028\ m^2 \delta\Delta g_2 + 0{,}111\ m^2 \delta\Delta g_3 \right)^{1/2} \qquad (5)$$

Both in (4) and (5) formula $\delta\Delta g_i$ must be expressed in miliGals.

The gravity changes determinations have been already done several times and the precise Worden, Sharpe and Scintrex gravity meters were used. Each serie of our measurements was preceded by an examination of gravity meters in the laboratory. Using the inclination method of calibration the coefficients of their equations were determined with an error of the order $\pm 1 \cdot 10^{-4}$. Each result of Δg measurement consists of three independent rides and it is characterised by mean error of the arithmetical mean about $\pm 10\ \mu$Gls. The obtained results of measurements and calcutions are presented on the graph /Fig.1/ showing $\Delta\varphi$ changes. To get actual situation in the regional gravity field we have calculated average value of the gravity gradient and its changes /$D\delta g$/. Those values we can transform to the changes of meridional component of vertical deflection /$D\xi$/ using formula

$$D\xi = 0\overset{''}{,}0525\ \frac{\Lambda}{G}\ D\delta g = 0\overset{''}{,}0494\ D\delta g \qquad (6)$$

Figure 1 shows both $\Delta\varphi$ and $D\xi$ graphs.

3. Comparison of the latitude variations with the gravimetrical results

On the basis of the observational material, normal points of a latitude were determined under following assumptions:

a/ desirable number of star poirs for one normal point - 45

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b/ time interval between two successive normal points should be not longer than 35 days,

c/ time interva between the last and last but one star pairs in normal point should be not greater than 15 days,

d/ the greatest number of groups in one normal point should be less than 10.

These normal points were smoothed in behalf of determination of mean latitude variation. We took adventage of the Vondrak algorithm [7] with optimum value of the smoothing coefficient $\varepsilon = 0.2$. This coefficient was choosen according to assumption that mean error , estimated from differences between smoothed and observed values of latitude, should be equal to unity RMS error of normal point, which amounts about $0\overset{''}{.}03$. Next values of latitude for equal intervals of $0\overset{y}{.}1$ were interpolated using the third order Lagrange polynomal. Obtained this way Orlov's mean latitude curve is plotted on Fig. 2.

In an earlier author's paper [6] some disadvantages of the Orlov's filter were discussed and a new approach of the determination of mean latitude was suggested. In present paper we give another third way of the evaluation of filtered latitude so that comparison between variations of the plumb line obtained by latitude observations and gravimetrical ones will be succesful. This simple method it is filtering by use of the Vondrak smoothing procedure /see [8] /. For this purpose, a value of the coefficient $\varepsilon = 10^{-8}$ was addopted in accordance to the frequency characteristics presented on Fig. 1 in [8] . On the base of that figure we can expect that all short periodical terms doesn't appear in the filtered latitude curve obtained in such a way. We hope, this filtered latitude curve can be also interpreted as variation of the plumb line direction at the station.

It can be easily noticed from Fig. 2 that two collapses occured. The first appeared in the moment of $1965\overset{y}{.}5$, and another one,

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something smaller, in 1975.^{y} Therefore, we have expected that these collapses could bring a deformational effect to filtered latitude obtained by use of Vondrak's algorithm. To avoid this our observations only from time interval 1975.^{y}05 - 1980.^{y}3 have been accepted for determination of filtered latitude. In the same interval our gravimetrical measurement have been done. The past of mean latitude curve, filtered latitude as well as the curves of plumb line variations are presented on Fig. 1.

4. Conclusion

Obtained results of gravimetrical measurements and calculations give clearly one conclusion that the plumb line direction deviates towards the equator, which is in accordance to the astronomically obtained results. Gravimetrical determinations don't explain the 1978 - collapse, unfortunatly. We don't exclude a possibility to the coincidence with the earthquaces. To find the sources of other variations we need to take into account geological and hydrological conditions around the astronomical observatory. It was given by J.Byl [2] that the mostly influence have the ground water level changes, the air pressure and other meteorological conditions /rain, snow/.

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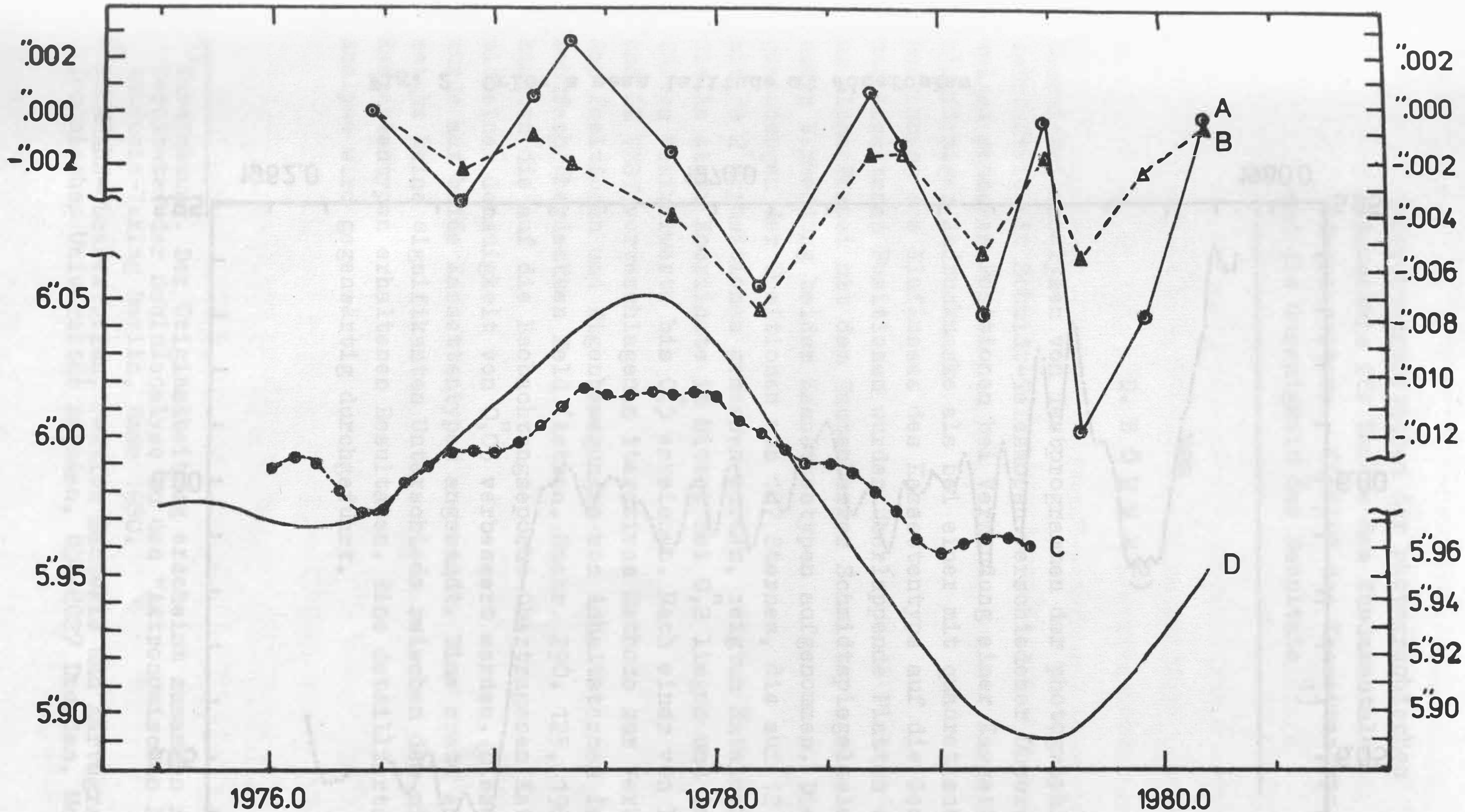

Fig. 1 Changes of the plumb line

A - derived by the gravimetrical method using formula /4/,
B - derived by the gravimetrical method using formula /6/,
C - mean latitude obtained by the use of OR2 filter,
D - filtered latitude

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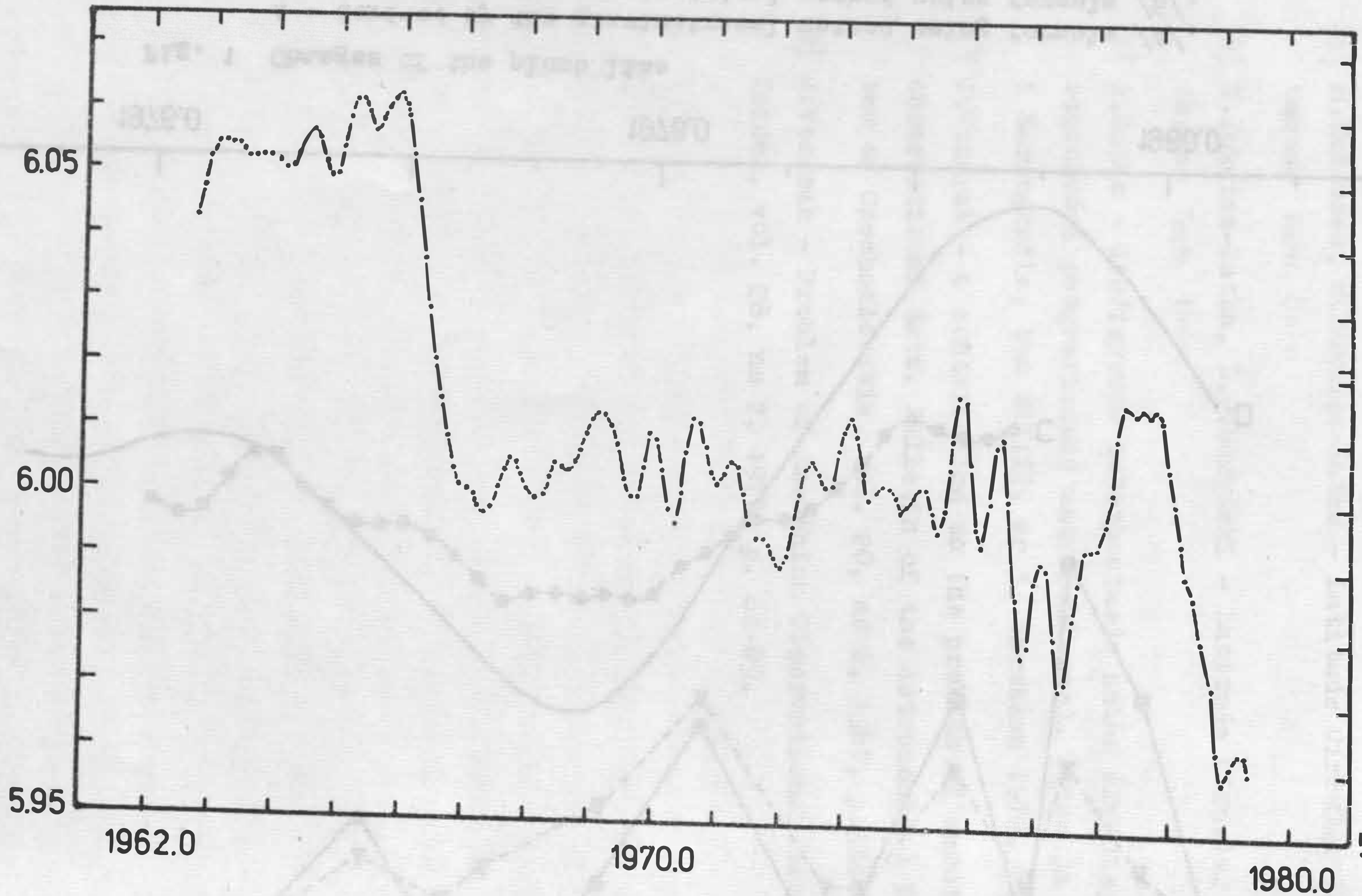

Fig. 2 Orlov's mean latitude at Józefosław

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Beobachtungsmethoden der photographischen Astrometrie für Zwecke des fundamentalen Referenzsystems - Einfluß des Kassettentyps auf die Genauigkeit der Resultate [1]

von

D. B Ö H M E [2]

Genauigkeitsanalysen von Testprogrammen der photographischen Astrometrie mit Schmidt-Teleskopen verschiedener Observatorien zeigen genauere Positionen bei Verwendung einer Kassette mit ringförmiger Andruckmaske als bei einer mit quadratischer. Zur Bestimmung des Einflusses des Kassettentyps auf die Genauigkeit der erhaltenen Positionen wurden überlappende Platten des Feldes um Alpha Persei mit dem Tautenburger Schmidtspiegelteleskop unter Verwendung beider Kassettentypen aufgenommen. Die Ausgleichungen der Positionen von 187 Sternen, die auf 12 Platten mit je 2 Expositionen gemessen wurden, zeigten Katalogfehler, die in einer Koordinate im Mittel bei $0\overset{''}{,}2$ liegen und in einigen Fällen Maximalwerte bis $0\overset{''}{,}5$ erreichen. Nach einer von DIECKVOSS und DE VEGT vorgeschlagenen iterativen Methode zur Verbesserung der Positionen und Eigenbewegungen von Anhaltsternen in einem mehrfach überdeckten Feld (Astron. Nachr. 290. 125, 1967) konnten die auf die Beobachtungsepoche übertragenen Katalogörter mit einer Genauigkeit von $0\overset{''}{,}05$ verbessert werden. Diese Methode wurde auf beide Kassettentypen angewandt. Eine erste Analyse zeigte keine signifikanten Unterschiede zwischen den mit beiden Kassettentypen erhaltenen Resultaten. Eine detailliertere Analyse wird gegenwärtig durchgeführt.

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1) Kurzfassung. Der Originalbeitrag erscheint zusammen mit den Resultaten der Schlußanalyse in den "Astronomischen Nachrichten", Akademie-Verlag Berlin, Ende 1980.

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Spectral Analysis of Modeled Latitude Variations

by

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Summary

In the paper application of the MAXIMUM ENTROPY spectral analysis to investigation of latitude variations is tested on the base of model functions. Functions including main periodical terms of latitude variations together with changes of parameters of these terms, it means periods, amplitudes and phases were used.

Parameters of periodical terms in the polar motion /Chandler and annual mainly/ change in time /Jeffreys 1970 [3], Iijima 1971 [4], Rochester 1975 [7]/. Besides, secular and irregular variations occur. In this connexion both polar coordinates and variations of a station latitude do not fulfil the assumptions of spectral analysis. Many tests of theoretical models approximating latitude variations have been done in order to establish the best conditions of the use of the Maximum Entropy spectral analysis /McDonough 1974 [2], Andersen 1974 [1], Emec and Jackiv 1976 [8]/ for studies of the above-mentioned processes as well as the influence of changes of an amplitude, phase and period of some terms on results. Two modeled functions have been used in investigations /Table 1/, model II containing periodical terms of variations of the Józefosław latitude determined with the use of the harmonic analysis method /Kołaczek et al. 1977 [5]/. Data have been generated in 5-day intervals.

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1. Testing Number of Data

The number of data necessary for the analysis depends on a period of a harmonic in demand as well as on the spectrum image, and on an occurence of harmonics with a nearing frequency and similar energy especially and on an accuracy in demand. For the model of Józefosław latitude variations at 450 observations 8 among from 14 given periodical terms at most were determinable, whereas at 900 observations /13.85 years/ it is impossible to determine only one low-energy term with a period approaching the annual /T=1.05 year, A=0.016/. Numbers of data cannot increase freely because effects occur connected with variation of parameters of particular harmonics.

If we want to obtain good results of MESA analysis for latitude variations or similar time functions, data including at least 12 years should be investigated /see Iijima 1971 [4], too/.

2. Testing Filter Length

The best filter length depends on many factors, namely on a number of harmonics occuring in the model, energy and proximity of periods of these harmonics as well as on a noise level. The filter has been tested on modeled variations of the Józefosław latitude /Fig. 1/.

The filters of length 33% and 50% have not allowed to detected low-energy frequencies. Only the filter of the length 66% enabled determination of all modeled periodical terms except one /T=1.05/ of a small energy and a period approaching one year. A further enlargement of the filter length does not improve results. From these investigations it results that for the analysis of real observational data a filter should be used of a length not less than 60%. A length $K=4\sqrt{N}$, proposed by Emec and Jackiv /1976 [8]/, where K denotes a number of iterations and N a number of data, is lowered significantly.

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3. Testing Accuracy of Determinations with MESA Method

The accuracy of determination of particular periods depends mainly on what multiple of them is comprised by data, and next on their amplitude and proximity of other periods. A number of data being properly great, even periodical terms below the noise can be determined /Fig. 1, T=0.909 A=0.010/. In the model containing three basic periodical terms with a noise on the level of 0.025 /50% of the amplitude of the semiannual term/ having 300 data /4.61 years/ the maximal accuracy of 0.5 a day for the semiannual term and about 10 days for the annual and Chandler terms was obtained. Having 450 observations /6.92 years/ these values were 0.5 a day and 2 days respectively. For the model of Józefosław latitude variations at 900 data /13.85 years/ the accuracy of determinations of particular periods was 0-2.2 days for T<1.2 a year, 3 days for the Chandler period /1.2 a year/ and to 10 days for periods 1.2-2.5 years. The Józefosław model is the closest to a real situation wich we have analysing observational data, thus similar accuracies can be expected when using MESA method in investigations of latitude variations.

4. Testing Effects of Phase Changes

Abrupt changes of a phase of the Chandler term by 15^o, 30^o and 45^o have been investigated as well as a linear change by 45^o during 0.5 a year for the model containing terms with the period 183, 366, 440 and 660 days at 900 data, and for the model of Józefosław latitude variations with the same number of data. This disturbance has not influenced very much the accuracy of determinations of particular periods. In the first case a low-energy term with a period approaching the Chandler term has been created /Fig. 2/. In the second model a similar phenomen has not been observed. Only if a phase changes by 30^o and 45^o a term with T=0.951 and A=0.031 cannot be determined, that is with a period approaching the assumed

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Chandler period what results from a peak broadening.

5. Testing Period Changes

An effect of a linear change of the Chandler period by 10 and 20 days /in the range 1.193-1.221 a year and 1.193-1.248 a year/ during 13.83 years /900 data/ was investigated basing on the model of Józefosław latitude variations. A strong spectrum broadening occured and a number of determined periods decreased from 13 to 12 and 11 respectively. The determined Chandler period is the result of averaging its changes /Fig. 3/.

6. Amplitude Modulation

A change of the amplitude causes effects like a change of the period. Still stronger spectrum broadening and decrease of a number of determined periods is observed. At the abrupt change of the amplitude of the Chandler term from 0.131 to 0.231, 10 among from 14 assumed periods were obtained in the model of Józefosław latitude variations. The spectrum image in this disturbance is presented in Figure 3.

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TABLE 1. Models of latitude variations.

	Period-Amplitude	Noise Mean-Standard value dev.	Considered perturbations	N	K
I	183D - 0".03	0.0 - 0.025	-	450	150
	366D - 0".10	0.0 - 0.025	-	900	300-500
	440D - 0".15	0.0 - 0.025	Changes of phase and amplitude	900	500
	660D - 0".025				
II	1.193Y - 0".131	0.0 - 0.025	Changes of phase period and amplitude	900	500-700
	1.005Y - 0".162				
	0.609Y - 0".029				
	0.427Y - 0".013				
	0.473Y - 0".013				
	0.568Y - 0".011				
	0.692Y - 0".015				
	0.767Y - 0".016				
	0.909Y - 0".010				
	0.951Y - 0".031				
	1.050Y - 0".016				
	1.312Y - 0".027				
	1.939Y - 0".014				
	2.444Y - 0".009				

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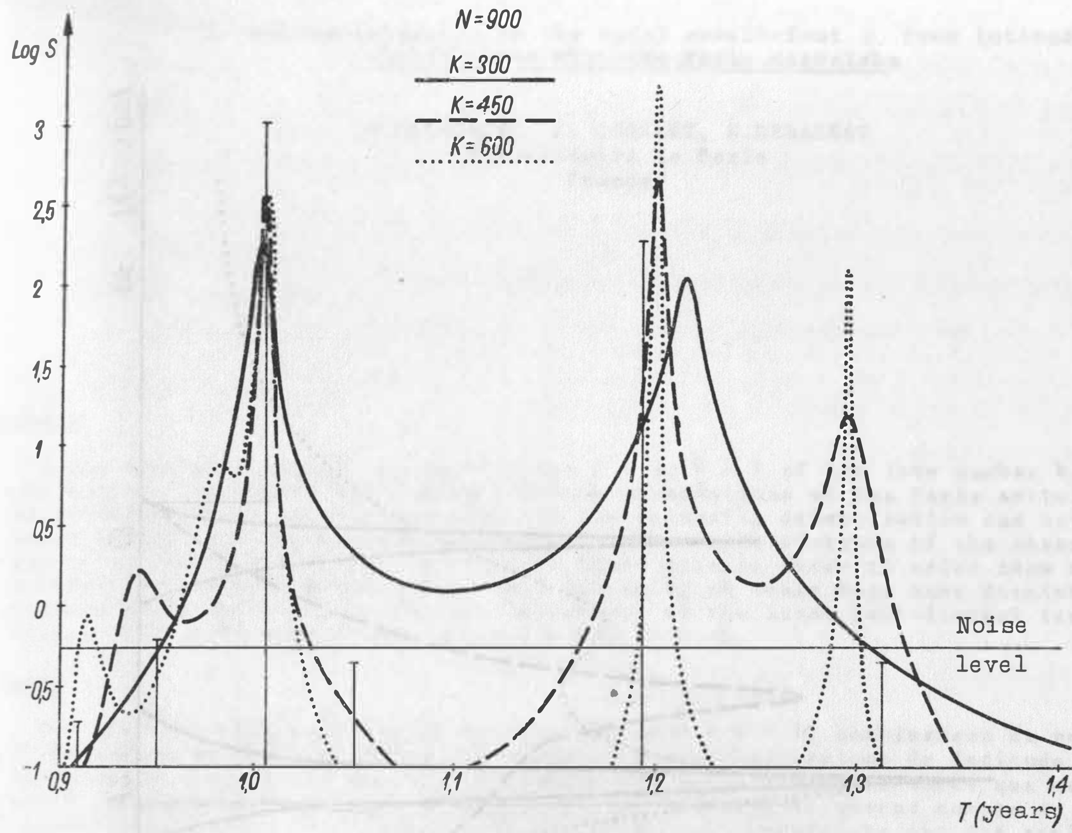

Fig.1

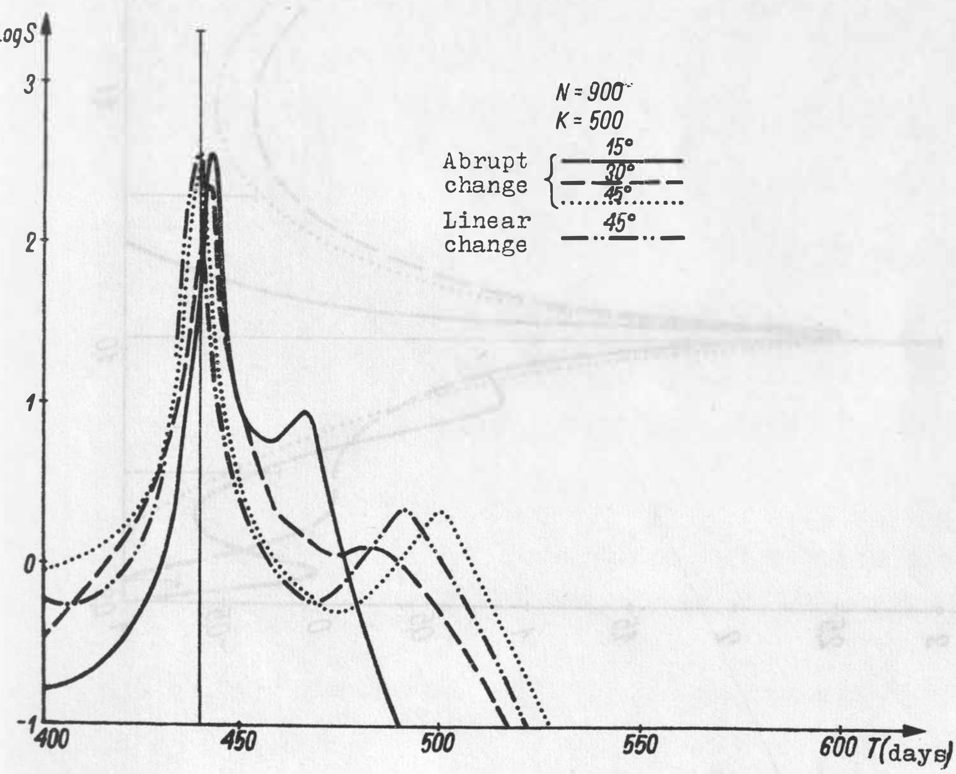

Fig.2

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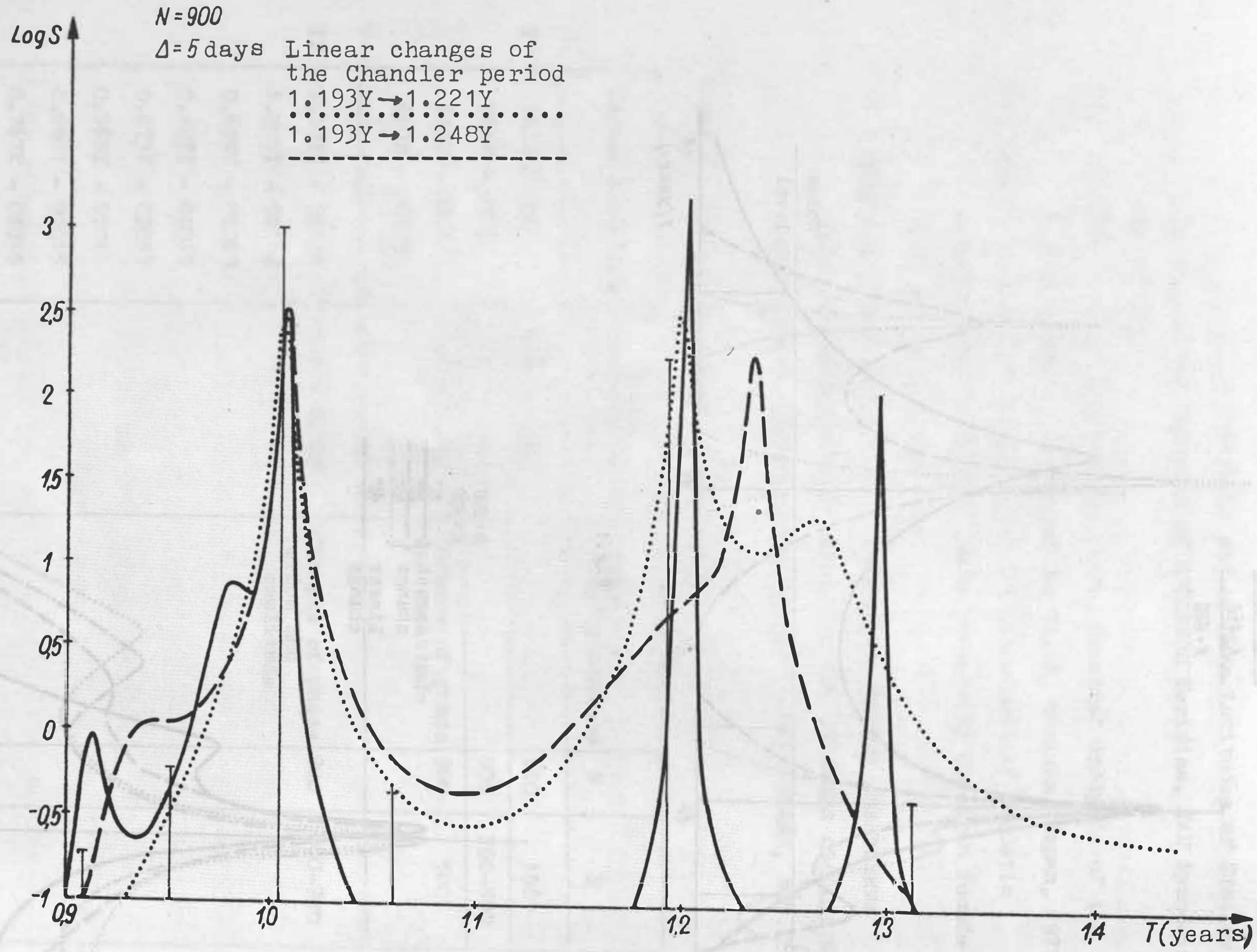

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Fig.3

A new determination of the tidal coefficient Λ from latitude observations with the Paris astrolabe

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France

Summary

A new determination of the combination $\Lambda = 1 + k - l$ of the love number k and the Shida number l have been made using latitude observations of the Paris astrolabe. The data extend over a longer period than for the preceding determination and have been re-reduced taking into account the variation in the zenith distance of the observations. Moreover corrections have been applied to these data in order to refer them to the new IAU nutational coefficients. A Vondrak's smoothing of these data have furnished latitude residuals among which a least-square adjustment of the lunar semi-diurnal term of the theoretical tidal latitude variation gives: $\Lambda = 1.05 \pm 0.15$.

Résumé

Une nouvelle détermination du coefficient $\Lambda = 1 + k - l$, combinaison du nombre de love k et du nombre de Shida l, a été faite à partir des observations de latitude effectuées à l'astrolabe de Paris. Ces données s'étendent sur une plus longue durée que celle utilisée pour la précédente détermination, et on été re-réduites en tenant compte de la variation de la distance zénithale d'observation. De plus, des corrections ont été appliquées afin de se rapporter aux nouveaux coefficients UAI de nutation. Un lissage de Vondrak des données a fourni des résidus de latitude à partir desquels un ajustement par moindres carrés du terme lunaire semi-diurne de la variation théorique de la latitude, due aux marées terrestres, a donné la valeur: $\Lambda = 1.05 \pm 0.15$.

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The combination 1+k-l of the love number k and the Shida number l appears as a multiplying factor, denoted Λ , in the deviation of the vertical due to the global body tide measured with astronomical instruments (Melchior 1978).

A previous determination of this coefficient given at the 8th International Symposium on Earth Tides (Capitaine and al. 1979), from the Paris latitude observations, from 1956.6 to 1976.5, obtained by the usual method and using 1964-IAU nutational coefficients was: $\Lambda = 1.24 \pm 0.21$.

Such astronomical determination of the coefficient Λ , in spite of its weak precision, seems to be useful because of its wholly independence of the classical earth-tides analyses and because of its indirect access to the number l.

The Paris latitude observations have been re-reduced taking into account the variations in the zenith distance of the observations (Chollet 1979). Moreover, new nutational coefficients, especially two ones with fortnightly periods,have been adopted at the IAU General Assembly in August 1979.

Therefore it was interesting to recompute the Λ coefficient with those re-reduced data that extend over a longer period (1956.6 - 1979.1), and taking into account the amelioration of the nutational coefficients, which lessens the noise-level.

The homogeneous serie of latitude observations used comprises 6770 groups of stars. Each value of latitude given by the observation of a group has been corected by the corresponding group correction.

In order to remove the variations of periods greater than 60 days, we have computed latitude residuals with respect to smoothed values obtained by the Vondrak's method using a smoothing factor of $\varepsilon = 10^{-7}$ (Vondrak 1977).

The 6770 equations considered were such that their first members are the theoretical lunar tidal latitude variations (Melchior 1978) at the date of the observation with one unknown multiplying factor for each term (the long period one, the diurnal one, the semi-diurnal one), and the second members are the corresponding latitude residuals.

The least-squares method was then applied to these equations and the value of Λ , derived from the multiplying factor of the semi-diurnal term, was: $\Lambda = 1.05 \pm 0.15$, the phase-lag being of 5°.

This value of Λ is consistent with other computed and theoretical values, the computed ones being included between 0.40 and 1.70, and the theoretical ones between 1.20 and 1.22 (Melchior 1978).

The slightly too low value so otained can be due to the diminution of the observed effect of the semi-diurnal earth-tide, due to the non-negligeable indirect oceanic effect at the Paris station.

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INFLUENCE OF SOME INSTRUMENT ERRORS ON TIME OBSERVATIONS WITH TRANSIT INSTRUMENTS AND THEIR DETERMINATION

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(Abstract)

Two instrument errors are subject of the study - ellipticity and inequality of transit instrument horizontal axis bearing working sections.

The influence of ellipticity and inequality of bearing working sections on time observations with transit instruments is defined, and it is also shown that their finding out means to determine the value of one parameter N' which may be done by astronomical observations specially carried out for this purpose, i.e. observations of star passing over a meridian. Parameter N' thus determined is free from random errors or star right ascensions and, to a great extent, from systematical catalogue errors of the type $\Delta\alpha_\delta$ and $\Delta\alpha_\alpha$.

The problem related to selection of stars and to N' determination is studied, and some indications related to carrying out and treatment of the observations are given.

ВЛИЯНИЕ НЕКОТОРЫХ ИНСТРУМЕНТАЛЬНЫХ ОШИБОК ПРИ ОПРЕДЕЛЕНИИ ВРЕМЕНИ ПАССАЖНЫМ ИНСТРУМЕНТОМ В МЕРИДИАНЕ И ИХ ОПРЕДЕЛЕНИЕ

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/Резюме/

Объектом исследования являются две инструментальные ошибки - эллиптичность и неравенство рабочих сечений цапф горизонтальной оси пассажного инструмента.

Определяется влияние, которое эллиптичность и неравенство рабочих сечений цапф оказывают на наблюдения для времени пассажным инструментом в меридиане. Показано, что вывод эллиптичности и неравенства рабочих сечений сводится к определению значения инструментального параметра N'. Это можно сделать посредством специально проведенных астрономических наблюдений - наблюдений звезд через меридиан.

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Определенный таким образом параметр N' свободен от случайных ошибок прямых восхождений звезд и в значительной мере свободен от систематических каталожных ошибок вида $\Delta\alpha_\delta$ и $\Delta\alpha_\alpha$.

Разработан также вопрос о выборе звезд, связанный с выводом N' и даны некоторые указания в связи с проведением и обработкой наблюдений.

Ellipticity is the most frequent form of first approximation of the working seotions of astronomical instruments horizontal axis bearing acquired during their manufacture (7). Further, ellipticity is the most dangerous form of such sections, since its influence on observation results has a marked systematical character (3, 8) as opposed to working section corrugation which is fortuitous.

The influence of ellipticity and inequality on the working section is expressed in a direct horizontal (azimuthal) deviation of instrument horizontal axis, when moving its telescope in elevation which will cause, if it is not taken into consideration, a deviation from the results of the azimuthal astronomical observations, i.e. the results of observation on a vertical line. In case of modern portable transit instruments, the influence of ellipticity and inequality of bearing working sections is of the order of the relative corrections of observations as a result of their treatment as per the method of the least squares (4).

Equation (3) is drawn up for the influence of ellipticity on bearing working sections of an astronomical instrument having 90° V-sheped bearing, when observing a vertical line

(1) $$\Delta A = M.\sin 2z + N.\cos 2z$$

where

ΔA is azimuthal rotation of instrument horizontal axis due to working section ellipticity

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z is instrument zenith distance considered as positive from one side of zenith and as negative from other side of zenith

M and N are equal to

$$M = \frac{\varrho\sqrt{2}\,(a-b)}{L}\sin\Delta\varphi \cdot \sin(\Delta\varphi - 2\psi)$$

(2)

$$N = \frac{\varrho\sqrt{2}\,(a-b)}{L}\sin\Delta\varphi \cdot \cos(\Delta\varphi - 2\psi)$$

Here "a" and "b" are the large and small semi-axes of the working sections which are accepted in this case that they are ellipses of equal dimensions, but of a random mutual position. The straight line connecting the centres of these ellipses represent instrument horizontal axis.

L is the distance between the working sections, i.e. ellipses

ψ is the angle between instrument aiming axis and ellipse large semi-axis

$\Delta\varphi$ is the angle between equal axes of both ellipses

ϱ is second in an angle of 1 radian

The equations of M and N may be written down in the following way too:

$$M = \frac{\varrho a e^2}{L\sqrt{2}}\sin\Delta\varphi \cdot \sin(\Delta\varphi - 2\psi)$$

(3)

$$N = \frac{\varrho a e^2}{L\sqrt{2}}\sin\Delta\varphi \cdot \cos(\Delta\varphi - 2\psi)$$

where "e" is ellipse eccentricity.

M and N are parameters connected with bearing working section eccentricity. They are maintained as instrument constant values for a prolonged period of time, since the values participating in their equations are also maintained for a prolonged period of time.

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The number of M and N are equal to the azimuthal deviation ΔA of the horizontal axis for given instrument zenith distance, namely

$$(4)\qquad M = \pm \Delta A \quad \begin{array}{|l} + \text{ for } z = +45^{\circ} \\ - \text{ for } z = -45^{\circ} \end{array}$$

$$N = \pm \Delta A \quad \begin{array}{|l} + \text{ for } z = 0^{\circ} \\ - \text{ for } z = \pm 90^{\circ} \end{array}$$

ΔA and z are co-ordinates in the modified astronomical spherical co-ordinate system used by the author and connected with the instrument itself. Celestial horizon is accepted as the basic circle of this system, and the points of intersection of instrument vertical withe celestial horizon are accepted to be the initial points. In this case instrument vertical is connected with the line connecting journal bearing top. Equation (1) represents actually the equation of the line traced by instrument aiming axis on celestial sphere, when moving the telescope in elevation in this co-ordinate system.

On the basis of (1) and tracing the mechanism of carrying out observations, it is obtained, for ellipticity influence of working sections on time-longitude observations by means of transit instruments (4)

$$(5)\qquad \Delta A_e = N . \cos 2z$$

$$(6)\qquad \Delta u_e = N . \sin(\varphi \mp \delta) . \cos 2(\varphi \mp \delta) . \sec \delta \quad \begin{array}{|l} - \text{ star u.c.} \\ + \text{ star l.c.} \end{array}$$

where

ΔA_e is the mean of both position of instrument azimuthal deviation, i.e. horizontal axis deviation from perpendicular

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to the plane including instrument vertical at which the star is observed

Δu_e is the correction to be added algebraically to the average moment of star observation

δ is star declination

φ is observation place latitude

Equation (6) is valid for an observation place located in the Northern hemisphere. Here, contrary to equation (1), star zenith distance, i.e. instrument zenith distance, is always a positive figure.

Contrary to circular working sections, the inequality of the elliptical ones is influencing the observations with a transit instrument (5, 8). Moreover, elliptiicty influence and inequality influence and the joint influence of ellipticity and inequality of bearing working sections on the observations are manifested in the same law and are expressed in a direct instrument horizontal axis deviation horizontaly, when moving its telescope in elevation. In this case, the deduction of inequality influence and of joint ellipticity and inequality influence of working sections on observations means a formal substitution to parameter N in (5) and (6) of parameter ΔN and N' for which we have (5)

(7) $$\Delta N = \frac{\varrho(\Delta b - \Delta a)}{L\sqrt{2}} \sin 2\varphi \quad \text{or}$$

(8) $$\Delta N = \frac{\varrho(a_2 e_2^2 - a_1 e_1^2)}{L\,2\sqrt{2}} \sin 2\varphi$$

(9) $$N' = N + \Delta N$$

where

(10) $$\Delta a = a_1 - a_2$$
$$\Delta b = b_1 - b_2$$

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Here, when considering the problem of working sections inequality, it is accepted that such sections are ellipses of different dimensions and of a random mutual position, their semi-axes and eccentricities being marked by a_1, b_1, a_2, b_2, e_1, e_2.

Working section ellipticity and inequality are determined by defined the values of parameters N and ΔN which should be done by special astronomical observations made for this purpose. However, by means of these observations, it is possible to find out only parameter N' connected with the joint influence of working section ellipticity and inequality, but not N and ΔN what is actually necessary. The definition of N' by observations of stars in a meridian is oonneoted first of all with the selection of stars so that it is possible to find out the most accurate possible N' by their observation.

We shall deal here with the problem of star selection, when determining ellipticity and inequality of bearing working sections of transit instruments by observations in meridian, and we shall give certain indications related to carrying out and treatment of the observations. We shall determine star zenith and respectively declinations that should be included in the star groups so that N' of the highest accurary could be found out or in other words we shall define the oomposition of the best star group.

Proceeding from the observation equations of the type

(11) $\Delta u + K_i k_j + n_i N' = l_i + v_i$ of a weight $p_i = f_\delta \cos^2\delta_i$ or $p_i = \cos^2\delta_i$

where $n_i N'$ is the correction for bearing working section elliptioity and inequality written down in this way

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(12) $$\Delta u_{e.H._i} = N' \sin(\varphi \mp \delta_i) . \cos 2(\varphi \mp \delta_i) . \sec \delta_i \quad \left| \begin{array}{l} - \text{ star u.c.} \\ + \text{ star l.c.} \end{array} \right.$$

Δu is chronometer correction

k_j is instrument azimuth obtained from star group bearing the number „j"

K_i is the so-called star azimuthal coefficient of a catalogue number i equal to

(13) $$K_i = \sin(\varphi \mp \delta_i) \sec \delta \quad \left| \begin{array}{l} - \text{ star in upper culmination} \\ + \text{ star in lower culmination} \end{array} \right.$$

l_i is the constant term of observation equation equal to the difference between star right ascension and the corrected average moment of star observation because of different instrument errors and constant chronometer errors

v_i is observation relative correction

The first weight is valid for observations with visual transit instrument, and the second one - with photoelectric transit instrument.

Taking into consideration that $p_{N'} = \frac{1}{Q_{33}}$ the weight $p_{N'}$, of parameter N' is

(14) $$p_{N'} = \frac{1}{[p][pKK] - [pK]^2} \Big([p][pKK][pnn] + 2[pK][pn][pKn] - [pK]^2[pnn] - [pn]^2[pKK] - [p][pKn]^2 \Big)$$

where

$$[p] = \sum_{t=1}^{g} f_\delta \cos^2 \delta_t$$

$$[pK] = \sum_{t=1}^{g} f_\delta \sin(\varphi \mp \delta_t) . \cos \delta_t$$

(15) $$[pKK] = \sum_{t=1}^{g} f_\delta \sin^2(\varphi \mp \delta_t)$$

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$$[pn] = \sum_{t=1}^{g} f_\delta \sin(\varphi \mp \delta_t) \cos 2(\varphi \mp \delta_t) \cos \delta_t$$

$$[pnn] = \sum_{t=1}^{g} f_\delta \sin^2(\varphi \mp \delta_t) \cos^2 2(\varphi \mp \delta_t)$$

$$[pKn] = \sum_{t=1}^{g} f_\delta \sin^2(\varphi \mp \delta_t) \cos 2(\varphi \mp \delta_t)$$

"t" indicates the number of the star in the group, and "g" is star quantity in the group.

It is difficult, even impossible to establish analytically by means of (14) for which values of δ at a given φ the weight $p_{N'}$ will be the maximum one, and how the composition of the best star group will be defined. Moreover, equation (14) does not take into account the influence of systematical catalogue errors of the type $\Delta\alpha_\delta$ on the observations, therefore, the weight calculated as per (14) becomes a fictitious one. Thus the composition of the best star group may be establish only empirically by calculations, but this would be very difficult, if we had to use only equation (14).

One of our assumptions could help, but we have to verify its veracity experimentally. It consists in the following: first to deduct a value from the observations, it is necessary that this value has an influence on them, and second, the greater its influence on the observations, i.e. the greater correction expressed as a module because of the influence of this value, the more accurate this value. In the practice, it means that parameter N' will be deducted most accurately from the observations of stars for which the correction for bearing working section ellipticity and inequality adopts extreme values of a function which are not zero. This would be true, if only one value had an influence on the observations, i.e. if only one correction participated in observation equations, and namely the

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correction for working section ellipticity and inequality. However, two more corrections are included in them (11) - chronometer correction and instrument azimuth correction which represent another condition, namely that when selecting star groups, stars for which there is a proportionality between coefficients preceding N' and k on the one hand, and N' and Δu on the other hand, should be avoided, and in any case no groups should be formed of stars for which there is a proportionality between such coefficients. This would be also true, if star right ascensions had not been charged with systematical catalogue errors being a function of " δ ", i.e. errors of the type $\Delta\alpha_\delta$. So the assumption put forward by us is approximate in a sense, and therefore it should be complied with approximately.

The problem of finding out the extreme values of the correction of bearing working section ellipticity and inequality with respect to " δ " is actually the problem of finding out the extreme value of the function

$$F = \sin(\varphi \mp \delta) \cdot \cos 2(\varphi \mp \delta) \quad \begin{array}{|l} - \text{ star in upper culmination} \\ + \text{ star in lower culmination} \end{array} \tag{16}$$

which may be made analytically or graphically. The results of the graphical solution are shown on fig. 1. They relate to $\varphi = +43^\circ$. Fig. 1 shows that, in the area of star observation, F has four extreme values - one maximum and three minimums located near $z_s = 25^\circ$, $z_s = 90^\circ$, $z_N = 25^\circ$ and $z_N = 90^\circ$ or near $\delta = +18^\circ$, -47° and $+68^\circ$ for stars in upper culmination and $\delta = +47^\circ$ for stars in lower culmination.

To verify the veracity of our assumption and to determine the composition of the best star group, we form different variants of star groups including stars of declinations located near and far

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from the extreme values of F for which we calculate $p_{N'}$ as per (14) accepting that $f_\delta = 1$. The results are shown on table 1.

Taking into consideration arguments related to instrument azimuth constancy during observation of the star group, we accepted that the group consists of 12 stars. Such a group is observed for one hour during which it may be assumed that instrument azimuth is practically unchanged.

For further understandable reasons connected with lateral refraction, we limited our observations to stars of zenith distance up to 80°.

The results shown in table 1 confirm completely our assumptions and prove that the groups should consist of stars located approximately uniformly in the whole zenith interval (from 80° North to 80° South of zenith) and at the same time grouped around extreme values of F. Such a location of stars in the groups is to be preferred, and it is easier to be realized in comparison with a concentrated location of stars in extreme values of F. Only in this case, it is possible to consider that the parameter N' thus obtained will be of a high accuracy and at the same time free to a great extent from the systematical catalogue errors $\Delta\alpha_\delta$. Variants Nos. 11, 18, 23, 30 shown in table 1 turned out to be the most suitable of the variants studied. Their star group consists of stars of the following zenith intervals and declinations:

No. 11 - $z_N = 80^\circ, 70^\circ, 35^\circ, 30^\circ, 25^\circ, 20^\circ$ and $z_S = 20^\circ, 25^\circ, 30^\circ, 35^\circ, 70^\circ, 80^\circ$ or $\delta = +57^\circ, +67^\circ$ in lower culmination and $\delta = +78^\circ, +73^\circ, +68^\circ, +63^\circ, +23^\circ, +18^\circ, +13^\circ, +8^\circ, -27^\circ, -37^\circ$ in upper culmination; No. 18 - $z_N = 80^\circ, 35^\circ, 30^\circ, 25^\circ, 20^\circ, 10^\circ$ and $z_S = 10^\circ, 20^\circ, 25^\circ, 30^\circ, 35^\circ, 80^\circ$ or $\delta = +57^\circ$ in lower culmination and $\delta = +78^\circ, +73^\circ, +68^\circ, +63^\circ, +53^\circ, +33^\circ, +23^\circ, +18^\circ, +13^\circ, +8^\circ, -37^\circ$ in upper

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culmination; No.23 - $z_N = 80^\circ, 70^\circ, 35^\circ, 30^\circ, 25^\circ, 15^\circ$ and $z_s =$ $15^\circ, 25^\circ, 30^\circ, 35^\circ, 70^\circ, 80^\circ$ or $\delta = +57^\circ, +67^\circ$ in lower culmination and $\delta = +78^\circ, +73^\circ, +68^\circ, +58^\circ, +28^\circ, +18^\circ, +13^\circ, +8^\circ, -27^\circ,$ -37° in upper culmination; No.30 - $z_N = 80^\circ, 40^\circ, 30^\circ, 25^\circ, 20^\circ,$ 10° and $z_s = 10^\circ, 20^\circ, 25^\circ, 30^\circ, 40^\circ, 80^\circ$ or $\delta = +57^\circ$ in lower culmination and $\delta = +83^\circ, +73^\circ, +68^\circ, +63^\circ, +53^\circ, +33^\circ, +23^\circ, +18^\circ,$ $+13^\circ, +3^\circ, -37^\circ$ in upper culmination.

A special programme of observation (in groups) has been established to obtain N'. Every group consisted of about 12 stars located at an interval of about $1^h - 1^h15^m$ along right ascension. An interval of about $10^m - 15^m$ has been left between the groups. Several groups have been observed every evening.

The treatment of the observations of all nights has been made simultaneously by adjustment by the method of the least squares. One observation equation of the type

(17) $\Delta u + K_i k + n_i N' = l_{iq} + v_{iq}$ of a weight $p_i = f\delta \cos^2\delta_i$ or $p_i = \cos^2\delta_i$

where q = 1, 2 ... m is the number, and "m" is the number of nights of observation, has been established for every night of observation.

To minimize the number of parasitic unknowns and to improve in this way parameter N' accuracy, first it is necessary to have an accurate chronometer of a stable operation which will allow to reduce the observations of the different nights to a given epoch selected about the middle of the period of observation. As a result thereof we shall have only one unknown value of chronometer correction, namely Δu for this epoch. In this way the number of unko will be reduced by (m-1). Second, it is necessary to have at least one stable mark placed at a sufficient distance from the instrument which will allow to control instrument azimuth change during

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the night of observation and during the total period of observation. Therefore, before and after observation of every star group, the instrument should be directed to the mark, and the relevant measurements should be made with the micrometer. The observations of the stars of the whole group are corrected with the results obtained and reduced to a determined value of instrument azimuth, i.e. of mark azimuth. It is this value "k" of instrument azimuth that is obtained from the treatment of the observations. Thus the number of unknowns is reduced by (r-1) where "r" is the number of all observations expressed in groups or the number of the so-called goups of nights.

On the basis of (17) are drawn up 3 normal equations of 3 unknowns, where N' is looked for and Δu and "k" are parasitic values.

The parameter N' thus obtained will be free from random errors of star right ascension and, to a great extent, from the systematical catalogue errors of the type $\Delta\alpha_\delta$ and $\Delta\alpha_\alpha$.

By determination of N' it is possible to correct the current latitude-time observations carried out with transit instruments, when the correction (12) is written down in figures in the mean moment of star observation.

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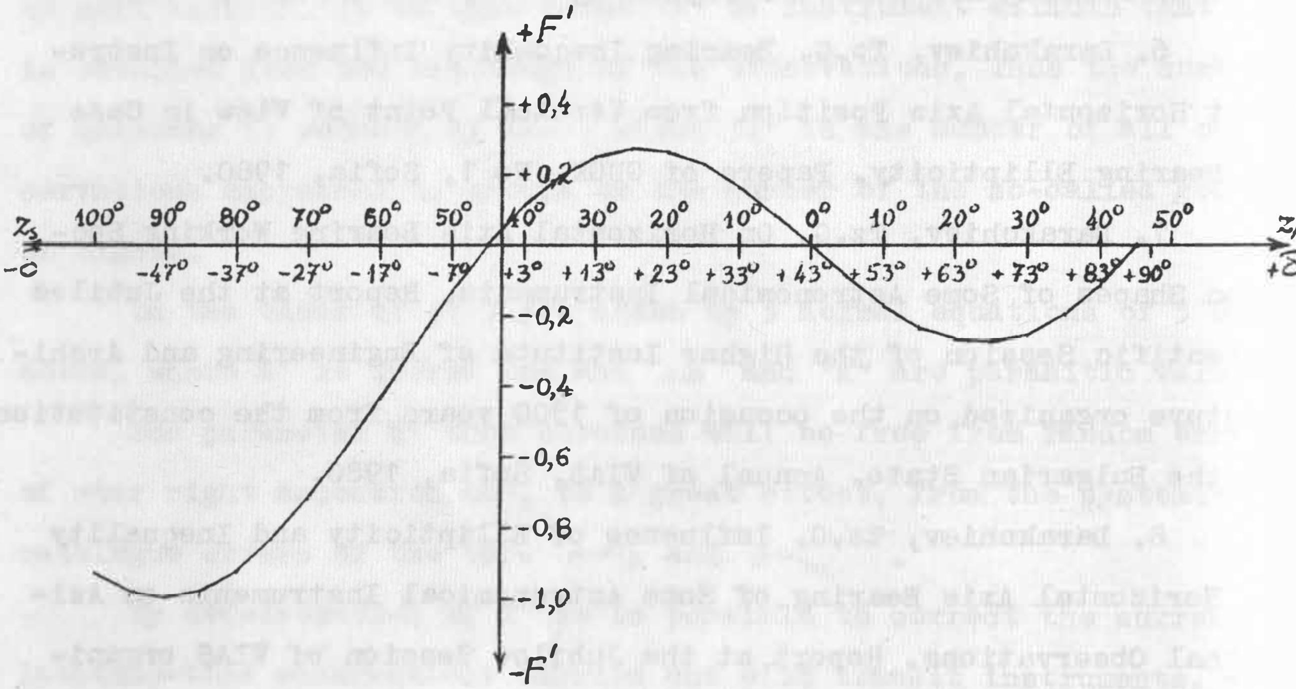
G R A F

OF THE FUNCTION $F=\sin(\varphi\mp\delta)\cos2(\varphi\mp\delta)$ — star u.c. / + star l.c.

FOR $\varphi = +43^{\circ}$

a) $F'=\sin(\varphi-\delta)\cos2(\varphi-\delta)$



b) $F''=\sin(\varphi+\delta)\cos2(\varphi+\delta)$

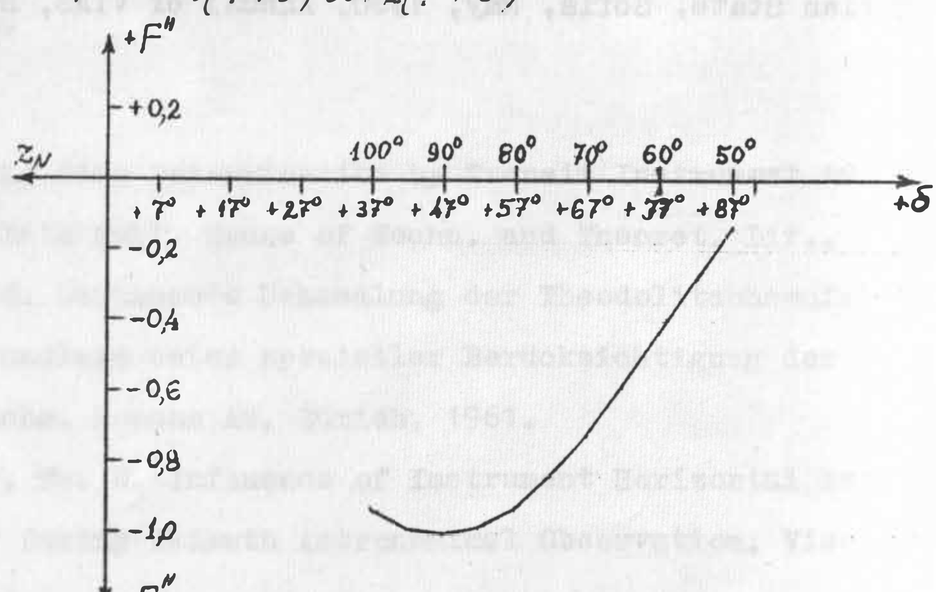


FIGURE 1

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Table 1

	Variants			
	1	2	3	4
	The group consists of star having zenith distances			
	80^0_N, 65^0_N, 50^0_N, 35^0_N, 20^0_N, 5^0_N, 5^0_S, 20^0_S, 35^0_S, 50^0_S, 65^0_S, 80^0_S,	80^0_N, 80^0_N, 75^0_N, 75^0_N, 60^0_N, 60^0_N, 60^0_S, 60^0_S, 75^0_S, 75^0_S, 80^0_S, 80^0_S,	80^0_N, 80^0_N, 80^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_S, 25^0_S, 25^0_S, 80^0_S, 80^0_S, 80^0_S,	80^0_N, 80^0_N, 80^0_N, 80^0_N, 25^0_N, 25^0_N, 25^0_S, 25^0_S, 80^0_S, 80^0_S, 80^0_S, 80^0_S,
$p_{N'}$	1,41	0,46	2,27	1,64

	Variants			
	5	6	7	8
	The group consists of star having zenith distances			
	15^0_N, 15^0_N, 10^0_N, 10^0_N, 5^0_N, 5^0_N, 5^0_S, 5^0_S, 10^0_S, 10^0_S, 15^0_S, 15^0_S,	55^0_N, 50^0_N, 45^0_N, 40^0_N, 35^0_N, 30^0_N, 30^0_S, 35^0_S, 40^0_S, 45^0_S, 50^0_S, 55^0_S,	90^0_N, 90^0_N, 35^0_N, 35^0_N, 35^0_N, 35^0_N, 35^0_S, 35^0_S, 35^0_S, 35^0_S, 90^0_S, 90^0_S,	80^0_N, 80^0_N, 35^0_N, 35^0_N, 35^0_N, 35^0_N, 35^0_S, 35^0_S, 35^0_S, 35^0_S, 80^0_S, 80^0_S,
$p_{N'}$	0,03	0,42	2,86	2,58

	Variants			
	9	10	11	12
	80^0_N, 80^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_S, 25^0_S, 25^0_S, 25^0_S, 80^0_S, 80^0_S,	80^0_N, 70^0_N, 60^0_N, 30^0_N, 25^0_N, 20^0_N, 20^0_S, 25^0_S, 30^0_S, 60^0_S, 70^0_S, 80^0_S,	80^0_N, 70^0_N, 35^0_N, 30^0_N, 25^0_N, 20^0_N, 20^0_S, 25^0_S, 30^0_S, 35^0_S, 70^0_S, 80^0_S,	80^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_S, 25^0_S, 25^0_S, 25^0_S, 25^0_S, 80^0_S,
$p_{N'}$	2,61	1,84	2,27	2,33

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	Variants			
	13	14	15	16
	25^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_S, 25^0_S, 25^0_S, 25^0_S, 25^0_S, 25^0_S,	80^0_N, 80^0_N, 80^0_N, 80^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_N,	80^0_N, 80^0_N, 30^0_N, 30^0_N, 30^0_N, 30^0_N, 30^0_S, 30^0_S, 30^0_S, 30^0_S, 80^0_S, 80^0_S,	80^0_N, 70^0_N, 60^0_N, 35^0_N, 25^0_N, 10^0_N, 10^0_S, 25^0_S, 35^0_S, 60^0_S, 70^0_S, 80^0_S,
$p_{N'}$	0,00	0,00	2,74	1,55

	Variants			
	17	18	19	20
	55^0_N, 50^0_N, 45^0_N, 40^0_N, 5^0_N, 0^0, 0^0, 5^0_S, 40^0_S, 45^0_S, 50^0_S, 55^0_S,	80^0_N, 35^0_N, 30^0_N, 25^0_N, 20^0_N, 10^0_N, 10^0_S, 20^0_S, 25^0_S, 30^0_S, 35^0_S, 80^0_S,	70^0_N, 35^0_N, 30^0_N, 25^0_N, 20^0_N, 10^0_N, 10^0_S, 20^0_S, 25^0_S, 30^0_S, 35^0_S, 70^0_S,	45^0_N, 45^0_N, 45^0_N, 45^0_N, 0^0, 0^0, 0^0, 0^0, 45^0_S, 45^0_S, 45^0_S, 45^0_S,
$p_{N'}$	0,15	2,05	1,53	0,00

	Variants			
	21	22	23	24
	70^0_N, 60^0_N, 35^0_N, 30^0_N, 25^0_N, 15^0_N, 15^0_S, 25^0_S, 30^0_S, 35^0_S, 60^0_S, 70^0_S,	80^0_N, 70^0_N, 40^0_N, 30^0_N, 20^0_N, 10^0_N, 10^0_S, 20^0_S, 30^0_S, 40^0_S, 70^0_S, 80^0_S,	80^0_N, 70^0_N, 35^0_N, 30^0_N, 25^0_N, 15^0_N, 15^0_S, 25^0_S, 30^0_S, 35^0_S, 70^0_S, 80^0_S,	90^0_N, 50^0_N, 50^0_N, 45^0_N, 35^0_N, 24^0_N, 24^0_N, 0^0, 24^0_S, 24^0_S, 45^0_S, 90^0_S,
$p_{N'}$	1,53	1,87	2,16	1,81

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	Variants			
	25	26	27	28
	90^0_N, 90^0_N, 50^0_N, 50^0_N, 24^0_N, 24^0_N, 0^0, 0^0, 24^0_S, 24^0_S, 90^0_S, 90^0_S,	90^0_N, 90^0_N, 80^0_N, 50^0_N, 35^0_N, 35^0_N, 35^0_N, 24^0_S, 24^0_S, 24^0_S, 90^0_S, 90^0_S,	90^0_N, 90^0_N, 35^0_N, 35^0_N, 35^0_N, 35^0_N, 35^0_S, 35^0_S, 35^0_S, 35^0_S, 90^0_S, 90^0_S,	90^0_N, 90^0_N, 35^0_N, 35^0_N, 35^0_N, 35^0_N, 24^0_S, 24^0_S, 24^0_S, 24^0_S, 90^0_S, 90^0_S,
p_N	1,87	2,48	2,86	2,83

	Variants			
	29	30	31	32
	90^0_N, 90^0_N, 30^0_N, 25^0_N, 25^0_N, 20^0_N, 20^0_S, 25^0_S, 25^0_S, 30^0_S, 90^0_S, 90^0_S,	80^0_N, 40^0_N, 30^0_N, 25^0_N, 20^0_N, 10^0_N, 10^0_S, 20^0_S, 25^0_S, 30^0_S, 40^0_S, 80^0_S,	80^0_N, 70^0_N, 60^0_N, 35^0_N, 25^0_N, 15^0_N, 15^0_S, 25^0_S, 35^0_S, 60^0_S, 70^0_S, 80^0_S,	80^0_N, 80^0_N, 24^0_N 24^0_N, 24^0_N, 24^0_N 24^0_S, 24^0_S, 24^0_S, 24^0_S, 80^0_S, 80^0_S,
p_N	2,78	1,96	1,68	2,55

	Variants			
	33	34	35	36
	90^0_N, 90^0_N, 24^0_N, 24^0_N, 24^0_N, 24^0_N, 24^0_S, 24^0_S, 24^0_S, 24^0_S, 90^0_S, 90^0_S,	90^0_N, 90^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_N, 25^0_S, 25^0_S, 25^0_S, 25^0_S, 90^0_S, 90^0_S,	90^0_N, 90^0_N, 90^0_N, 24^0_N, 24^0_N, 24^0_N, 24^0_N, 24^0_N, 24^0_S, 90^0_S, 90^0_S, 90^0_S,	90^0_N, 90^0_N, 30^0_N, 30^0_N, 30^0_N, 30^0_N, 30^0_S, 30^0_S, 30^0_S, 30^0_S, 90^0_S, 90^0_S,
p_N	2,77	2,84	2,37	3,00

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Investigations on the Effect of the Resonance of the Liquid Outer Core of the Earth in Gravimetric Tidal Variations

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Summary

Analysis results from GS-15 Earth tide registrations during 1974 - 1979 (1686 registrations days) at Potsdam represent generally the effect of the resonance of the liquid outer core in correspondence to the Earth model MOLODENSKY II.

Existing deviations agree with those determined at other European stations.

The results are reported and discussed especially with respect to the observed temporal variations of the diurnal Earth tide parameters inside the resonance range.

Introduction

Assuming the validity of the Earth models given by MOLODENSKY, one can expect a significant frequency dependence of the amplitude in the diurnal range of the tidal potential. Analysis results of long time Earth tide records with modern gravimeters are showing mostly a general agreement with the predicted fine structure of the diurnal part of the tidal spectrum.
But only a very few measured series have a quality, sufficient for an interpretation in this direction. To get a resolution of all the waves near the frequency of resonance ($\omega_R = 15.073^o/h$), there are needed series longer than one year, and their inner accuracy must be better than characterized by the mean square error of 0.1 % for the δ-factors of the main tidal waves, corresponding to $m_o \leq \pm 1 \cdot 10^{-8}\ m{\cdot}s^{-2}$ for standard CHOJNICKI-analysises. To exclude the calibration problems, the results of different instruments installed at the same or at different stations shall be normalized for comparison with one another.

Results recieved at the Gravimetrical Observatory Potsdam

The digital Earth tide registration with the gravimeter GS 15 No. 222, performed between March 1974 and June 1979 may be charakterized by the results

$$\delta O1 = 1.1511 \pm 0.0002 \; ; \qquad \delta K1 = 1.1400 \pm 0.0001 \; ;$$

$$\delta M2 = 1.1839 \pm 0.0001 \; ; \qquad m_o = \pm 0.58 \cdot 10^{-8}\ m{\cdot}s^{-2} ,$$

obtained by the aid of CHOJNICKIs programme employing a data volume of 40 464 hourly readings. This data set and its residuals after the analysis are the basis for a number

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of investigations, reported also in other contributions during the symposium. The full analysis result, printed in the standardisized form, is represented in table I.
For the discussion of the resonance of the liquid core of the Earth a very interesting parameter is $\delta\psi_1$, because the frequency of the ψ1-wave is the nearest to the resonance frequency. But its amplitude is very small - 0.34 • 10^{-8} $m \cdot s^{-2}$ at Potsdam - and therefore the mean square error remains greater than for the most other constituents.
As estimated by WENZEL (1976) there are needed 27 years of registration for a 1 % - security. At Potsdam we found:

duration of series years	evaluated hrs.	$\delta\psi_1$	$3 \cdot m(\delta\psi 1)$ ±	$\frac{3m(\delta\psi 1)}{\delta\psi 1}$ ± %
1.0	7 990	1.3042	0.0877	6.72
1.4	12 454	1.2627	0.0747	5.92
3	18 543	1.1920	0.0576	4.83
4	26 533	1.2227	0.0485	3.96
4	31 130	1.2315	0.0447	3.63
5	39 914	1.2241	0.0376	3.07

The stability as well as the confidence interval of three times the error given by CHOJNICKI-analysises are showing distinctly the difficulties of a experimental estimation of the ψ1-parameter.

While in the last years the similarity of the results of the measurements with the theory of MOLODENSKY essentially was shown, now we have reached in the results a level of accuracy, sufficient for the first steps in the direction of quantitative decisions.

Comparison with other results

In spite of the sufficient inner accuracy of the measurements and of the similarity of the shape of the diurnal spectrum to the theoretical predictions, there are significant differences between theory and experiment as shown at fig. 1. To check our result for regional specialities, it was compared with those of 12 series from other European stations containing more than 10 000 readings: Sevres, Bruxelles (2 series), Walferdange, Frankfurt/M. (3 series), Hannover given by DUCARME and MELCHIOR/1977; Strasbourg (ABOURS, LECOLAZET 1977/79); Pecny (ŠIMON 1979) and Zürich (GERSTENECKER 1979).
According to the mean square error of the normalized factors weighted mean values were calculated. For a better comparableness with the results, which were computed at the ICET by the aid of DUCARMEs programme, the errors of the results of CHOJNICKIs standard analysis were multiplied by three for Strasbourg and Potsdam.

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At fig. 1 these European mean values were compared with the result at Potsdam and there are only very small differences between the single results but some characteristical deviations against the curve calculated for the model. These deviations are obtained for the majority of the stations in Western and Central Europe.

Comparison with theoretical predictions

At table II the most important parameters for investigations of the resonance are compared with the corresponding values calculated by the formulas of MOLODENSKY. There are only very small differences between both the models. On the other hand results at Potsdam are much more close to the European mean than to the values of the models. The measured results for $\delta\varphi 1/\delta 01$ are about four percent higher than expected by the theory and the most significant parameter ($\delta 01 - \delta K1$) amounts to less than 60 % of the calculated value.

Symbol (i)	$\delta_i/\delta 01$ - Theory		$\delta_i/\delta 01$ - Analysis result	
	Mo. II	Mo. I	Potsdam	European mean
P1	0.9953	0.9951	1.0019 ± .0009	1.0015 ± .0009
K1	0.9822	0.9813	0.9903 ± .0006	0.9897 ± .0003
$\psi 1$	1.0706	1.0704	1.0634 ± .0327	1.0524 ± .0284
$\varphi 1$	1.0126	1.0129	1.0484 ± .0177	1.0513 ± .0142
$\delta 01 - \delta K1$	0.0207	0.0217	0.0111 ± .0006	0.0120 ± .0004

Table II: Comparison between normalized analysis results and model predictions

Using the δ-factors without normalisation, the differences between the models are enlarged by a factor of about ten. So we can better compare the single results with the predictions (table III).

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Symbol	δ - theoretically		δ - analysis result	
	Mo. II	Mo. I	Potsdam	European mean
O1	1.1640	1.1593	1.1511	1.1517
P1	1.1585	1.1537	1.1533	1.1534
K1	1.1433	1.1376	1.1400	1.1398
ψ1	1.2461	1.2409	1.2241	1.2121
φ1	1.1786	1.1743	1.2069	1.2108
δO1/δK1	1.0181	1.0190	1.0098	1.0104

Table III: Not normalized analysis results and model predictions

Also table III shows that the agreement between Potsdam and the mean result of the other stations is much better than between the measured values and the models. Therefore the deviation against the theory is not local or a peculiarity of a single measurement, but it is valid for the West European region.

At first we have to assume that the indirect effect of the oceans is the reason for the deviations. At our disposal are corrections calculated by PERTZEV for two of the upper mentioned stations (Pecny - ŠIMON 1979; Potsdam - DITTFELD 1980). After the corrections towards the ellipsoide, the inertial correction and the correction because of the indirect effect we get the values listed at table IV but there remain again deviations to the theory.

Symbol	Mo. II	Mo. I	Potsdam	Pecny
δO1	1.1640	1.1593	1.1573	1.1566
δK1	1.1433	1.1376	1.1419	1.1377
δM2	1.1647	1.1601	1.1579	1.1542
δO1 - δK1	0.0207	0.0217	0.0153	0.0189
δM2 - δO1	0.0007	0.0008	0.0006	- 0.0024
δO1 / δK1	1.0181	1.0190	1.0134	1.0166

Table IV: Comparison between model predictions and fully corrected results at Pecny and Potsdam

With these results it is also not possible to decide between the models. The difference δO1 - δK1 is clearly nearer to the theoretical value, but to small

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again. The same can be said for δO1 and δM2. The normalized factor for K1 after correction

$$\delta K1 / \delta O1 = 0.9868 \quad \text{(Potsdam)}$$
$$= 0.9837 \quad \text{(Pecny)},$$

is situated nearer to the curve of resonance (see fig. 1) but yet greater than expected for both the models (0.9822 and 0.9813 respectively). But because δO1 equals δM2 practically PERTZEVs correction of the indirect effect seems to fit the conditions of the model better than the corrections offered by other authors.

Temporal variations of the characteristical parameters

In general there are temporal variations not expected by the model. Using a registration of more than five years under nearly constant conditions, we have the possibility to check the time stability of the analysis results. Fig. 2 shows the results of overlapping shifted periods each lasting about one and a half year (6400 ... 12 900 hourly readings; $m_o = \pm\ 0.50 \ldots 0.63 \cdot 10^{-8}\ m \cdot s^{-2}$). In each analysis we used a resolution of 19 wave groups, so K1 is fully separated. The temporal variation of (δO1 - δK1) seems to be significant. Analysing disjunct monthly registration periods with the VENEDIKOV programme M65 we found a periodical variation of δO1 - δ(P1 S1 K1) with an amplitude of 0.0056 ± 0.0015, corresponding to about 37 % of the mean difference δO1 - δK1. The period of these fluctuation is 365.0 d, as represented at fig. 3. The nature of these variations, mostly caused perhaps by S1-type disturbances, is discussed by ELSTNER/SCHWAHN 1980. For our aim the conclusion is important that the results, charakterizing the resonance of the liquid outer core, at a given station are variing also with time - seasonal as well as with a long-term temporal trend. These variations very exceed the differences between the models. - So we also can not expect the desired decision, because we will get different results for different registration periods at the same station.

Conclusion

Pictures like fig. 1 were often discussed as a experimental confirmation of MOLODENSKYs theory. It should be remarked, that already the visibility of the effect of resonance in the diurnal spectrum is a sign for very accurate and small disturbed measurements. But looking carefully at the results of the European stations one can find any contradictions which shall be summed up in the following.

1. In general the δ-factors are less than expected by the model. The clearest expeption is φ1 with about plus three percent.
2. Also by introduction of the at present known corrections, one can not avoid significant deviations against the theory of MOLODENSKY.
3. The usual representation of the results (normalized δ-factors δ_i/ δO1 or differences δO1 - δK1) leads to a more optimistic view than the direct

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comparison of the theoretical and the measured δ-factors.

4. From the configuration of the measured points at fig. 1 may be concluded also, that the resonance is not so sharp as expected by the model and possibly other effects influencing the diurnal spectrum are acting in Western and Central Europe. Looking at the painting <u>without</u> the curve of resonance - extremely - one may be tempted to fit the datas with a curve like the frequency dependence of forced vibrations or with curves having more than one singularity.
5. For a final discussion corrections of the indirect effect of the oceans are needed for all the waves around the frequency of resonance. For a global comparison these corrections are to calculate in a similar way for all the stations having series of sufficient quality.
6. Time variations of the tidal parameters inside the resonance range must be checked carefully in the next future.
   Especially is to clear, whether these effects are regional or instrumental or of global character. In the latter case the whole theory must be improved.

At present it seems to be improbable that the results concerning the resonance of the liquid outer core will come closer to the model values only by prolonging the measurements with instruments of the same generation. On the other hand one may expect a better fitting with the experiment by a more detailed theory, which perhaps will be worked out in the future. At present we are not able to explain whether the reason for the distinctions between model and experiment is founded in the uncompleteness of the measurements, in the insecure corrections or in the model itself.

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WYROWNANIV KONCOWE - COMPENSATION FINALE METHODE DE CHOJNICKI

KONCOWE WYNIKI OBLICZEN - RESULTATS FINALS DES CALCULS

0.0 1976 5 1 0 0 1000111 52.3807 -13.0667 82 0.0 981.261400

STATION POTSDAM 0764 COMPOSANTE VERTICALE REP.DEMOCR.ALLEMANDE

52 23 N 13 4 E H 82 M P 3 M D 250 KM
ZENTRALINSTITUT FUER PHYSIK DER ERDE POTSDAM H.J. DITTFELD
GRAVIMETER ASKANIA GS-15 NO. 222 DIGITAL
CALIBRATION ELECTROMAGNETIQUE
INSTALLATION H.J. DITTFELD
MAINTENANCE H.J. DITTFELD, W. ALTMANN
DEVELOPPEMENT DU POTENTIEL SUIVANT CARTWRIGHT-EDDEN
METHODE MOINDRES CARRES / MOYEN DE CHOJNICKI / FILTRE PERTSEV
CALCUL ZENTRALINSTITUT FUER ASTROPHYSIK, K. ARLT. ES 1040

1974 3 22 0 - 1974 4 13 21 / 1974 4 18 0 - 1974 6 19 21 / 1974 6 25 0 - 1974 7 13 21
1974 7 19 0 - 1974 11 4 21 / 1974 11 12 0 - 1974 12 14 21 / 1975 6 22 0 - 1975 10 27 21
1975 11 5 0 - 1976 1 6 21 / 1976 1 12 0 - 1976 9 17 21 / 1976 9 22 0 - 1976 11 1 21
1976 12 2 0 - 1978 5 4 21 / 1978 5 10 0 - 1979 6 29 21

NOMBRE TOTAL DE HEURES 39714

GROUPE	SYMBOLE	AMPLITUDE	PHASE EPOQUE DE REFERANCE	FACT.AMPL.	EQM	corr.	DEPHASAGE	EQM	SOMME D*AMPLIT.
128-141	SMQ1	0.2017	104.149	1.14202	0.02290	-5.41	-5.536	1.149	0.5334
142-148	2Q1	0.6387	283.190	1.29597	0.00693	-1.16	-1.286	0.307	1.0204
149-162	SIG1	0.7989	328.249	1.15327	0.00562	-0.89	-1.026	0.279	1.2717
163-177	Q1	4.9140	146.423	1.15231	0.00087	-0.26	-0.394	0.043	7.3724
178-192	RO1	0.9257	186.102	1.16471	0.00446	+0.11	-0.030	0.219	1.5975
193-210	O1	26.1271	9.572	1.15114	0.00016	+0.03	-0.110	0.008	36.6771
211-218	TAU1	0.4797	276.020	1.14079	0.00874	-0.36	-0.499	0.439	0.5713
219-233	M1	2.7074	110.615	1.13292	0.00158	-0.06	-0.207	0.080	3.2269
234-240	CHI1	0.4072	152.194	1.11197	0.01064	-0.59	-0.735	0.548	0.6162
241-243	PI1	0.3107	305.683	1.16781	0.00502	-0.14	-0.293	0.246	0.8605
244-250	P1	14.1162	64.418	1.15329	0.00029	+0.33	0.178	0.015	14.2105
251-253	S1	0.2363	216.268	0.63548	0.01748	80.86	80.711	1.577	0.4582
254-254	K1	38.9978	328.976	1.14002	0.00011	+0.18	0.030	0.005	49.1021
265-266	PSI1	0.3322	79.386	1.22408	0.01252	-5.12	-5.278	0.586	0.3452
267-273	PHI1	0.6114	42.386	1.20685	0.00682	+2.37	2.219	0.324	0.7072
274-279	THE1	0.3832	155.344	1.20586	0.01033	+0.32	0.163	0.491	0.5992
280-295	J1	1.9953	198.108	1.16603	0.00210	-0.40	-0.557	0.103	3.4588
296-303	SO1	0.3269	10.993	1.12844	0.01322	+2.07	1.906	0.671	0.5370
304-313	OO1	0.9231	107.407	1.14730	0.00512	+0.40	0.238	0.256	2.6169
314-332	NY1	0.1695	297.934	1.14111	0.02641	+0.43	0.261	1.326	0.7871
333-353	EPS2	0.2336	254.947	1.14090	0.02013	+1.62	1.340	1.011	0.5106
354-363	2N2	0.6731	71.910	1.17244	0.00628	+2.87	2.586	0.307	0.9611
364-373	MY2	0.8659	119.813	1.15852	0.00489	+2.33	2.040	0.262	1.0177
374-390	N2	5.2924	297.308	1.17841	0.00078	+2.09	1.800	0.038	6.4211
391-397	NY2	1.0333	344.455	1.18391	0.00399	+1.70	1.411	0.193	1.1392
398-423	M2	28.8130	162.843	1.18388	0.00014	+1.21	0.912	0.007	29.7315
424-428	LMB2	0.2152	163.505	1.14947	0.01923	-0.35	-0.649	0.959	0.2347
429-440	L2	1.1171	173.921	1.14054	0.00356	+0.86	0.555	0.179	1.8092
441-442	T2	0.7532	87.486	1.15493	0.00540	-0.35	-0.659	0.268	0.7980
443-446	S2	13.0601	206.071	1.18753	0.00032	+0.38	0.074	0.015	13.1179
447-458	K2	2.7918	296.982	1.18973	0.00144	+0.15	-0.157	0.069	3.0059
459-473	ETA2	0.1571	169.397	1.15836	0.02948	-0.55	-0.863	1.458	0.4496
474-487	2K2	0.0476	44.886	1.02842	0.09796	+7.50	7.185	5.457	0.2203
488-504	M3	0.2767	348.065	0.98828	0.01104	-0.89	-1.338	0.640	0.6127

ERREUR Q.M 0.58 MIKROGAL

O1/K1 1.0078 1-O1/1-K1 1.0794 M2/O1 1.0284

EPOQUE DE REFERENCE 1976 5 1 0.0

Table I: GS 15 No. 222 - Potsdam, March 1974/June 1979
Analysis result of the digital registration

DOI: https://doi.org/10.2312/zipe.1981.063.01

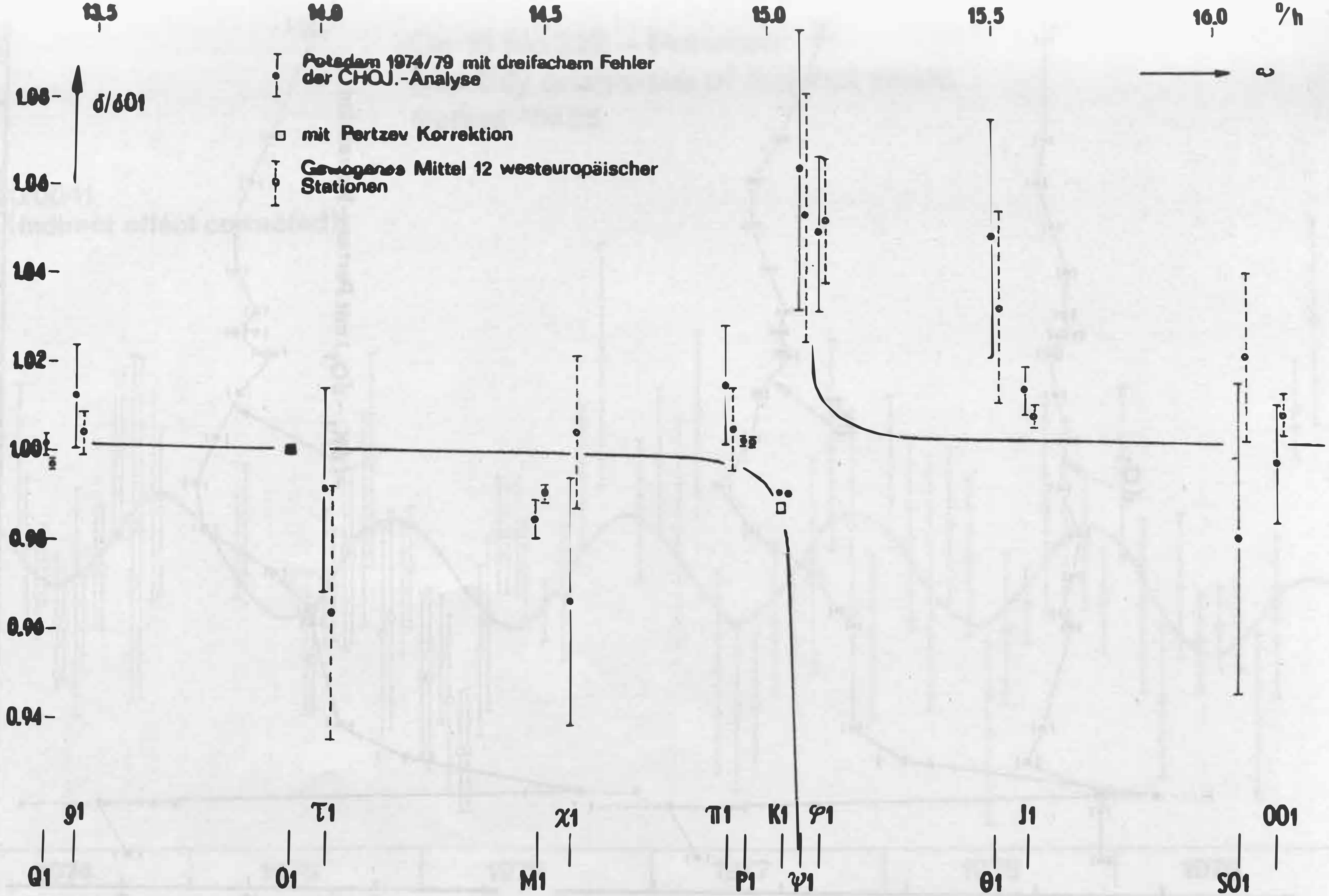

Fig. 1: Gravimeter Gs 15 No. 222 - Potsdam, March 1974 / June 1979
Distribution of normalized δ-factors around the frequency of resonance

DOI: https://doi.org/10.2312/zipe.1981.063.01

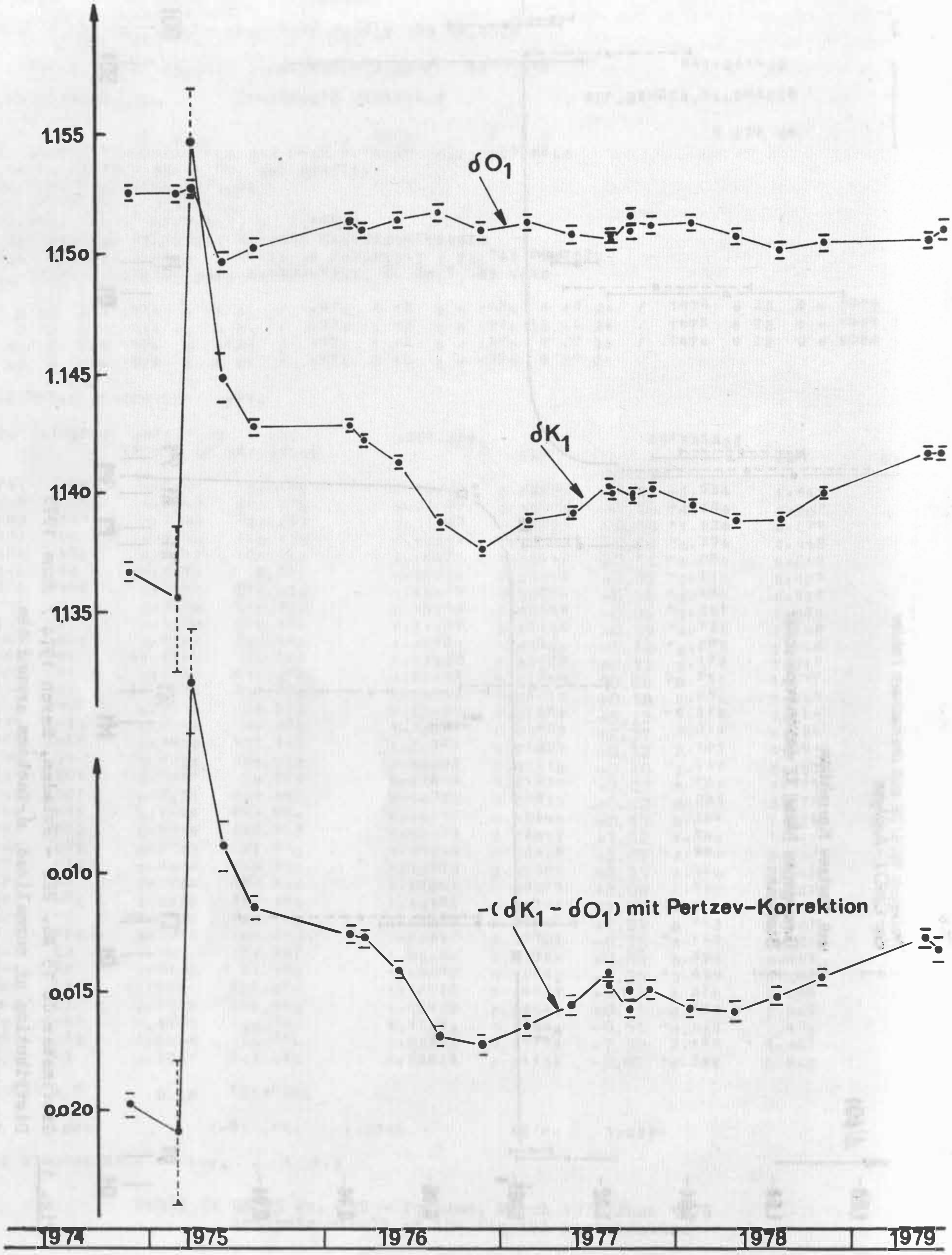

Fig. 2: Gravimeter Gs 15 No. 222 - Potsdam, March 1974 / December 1979
Temporal variation of results, characterizing the resonance of the liquid outer core -
Overlapping CHOJNICKI analysises of registration periods, each lasting 12.....18 monthes

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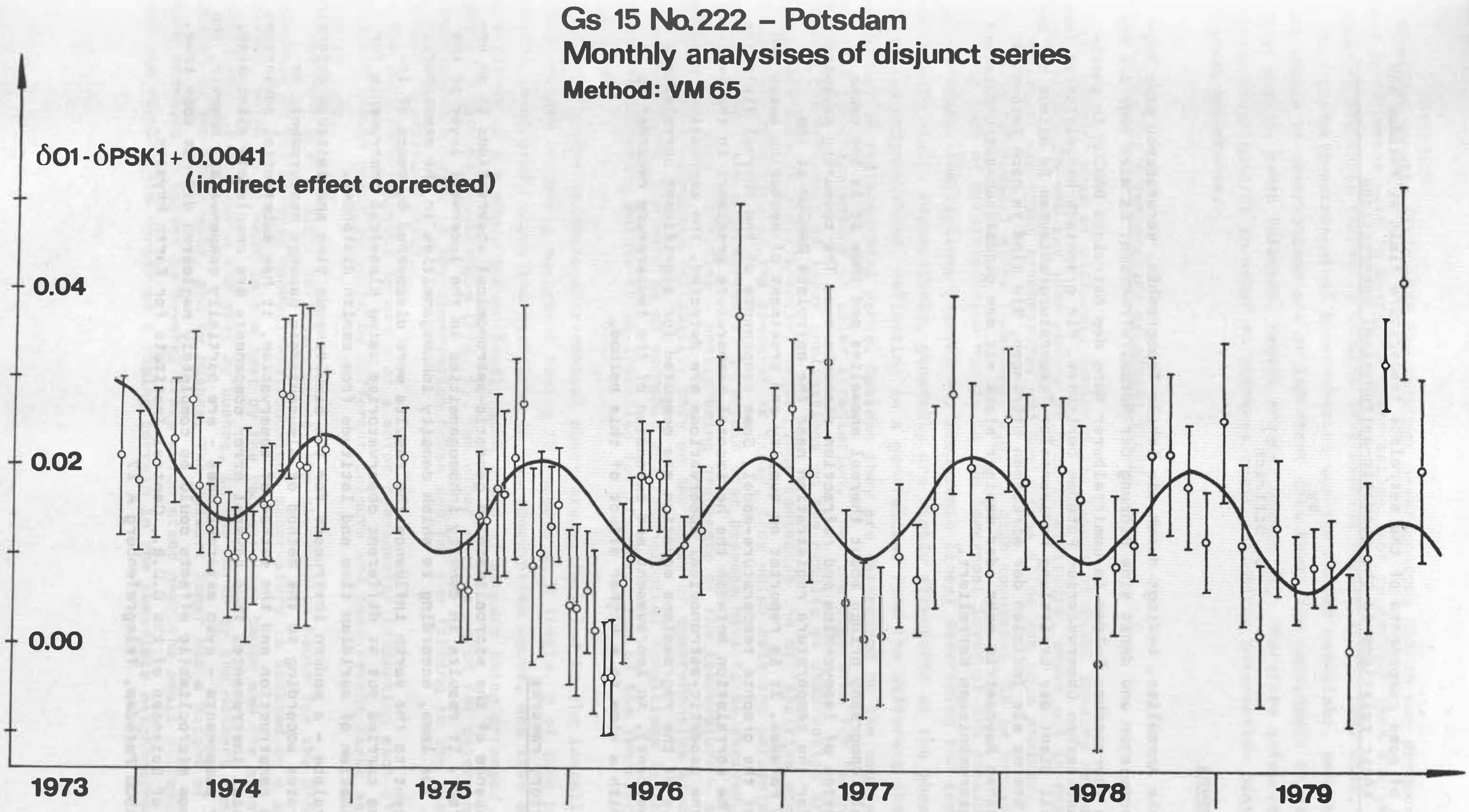

Fig. 3: Gravimeter Gs 15 No. 222 - Potsdam, Nov. 1973 / December 1979
Temporal variation of the difference between the amplitude factors of the main diurnal waves for disjunct monthly registration periods calculated by the programme VM65 and adjusted for 59 monthly results by the equation $D(t) = x_1+x_2t+x_3t^2+x_4t^3+x_5\sin\omega t+x_6\cos\omega t$

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Examination of some componente of the aetrolabe temperature field at Potsdam and their relations to the geodetic-astronomical observations

by

J. Dittrich[1])

Zusammenfassung

Thermische Anomalien, bedingt durch die lokale Topographie, verursachen eine Neigung der Ieopykenen und damit eine Störung der Normalrefraktion. Es wird über die Erfassung des thermischen Feldes in unmittelbarer Nähe des Astrolabs DANJON im geodätisch-astronomischen Observatorium Potsdam berichtet. Ein graphisch hergeleitetes Temperaturmodell dient der Ermittlung horizontaler Temperaturgradienten im Azimut der beobachteten Sterne als Indizien der wirksamen Störungen. Sie sind je nach Intensität der thermischen Asymmetrie mehr oder weniger stark mit den geodätisch-astronomischen Beobachtungsergebnissen korreliert.

Summary

The local topography brings about thermal anomalies and thus it is the cause of the inclination of isopycenics and refraction disturbances. The measuring equipment is described for the temperature registration near the astrolabe DANJON at the observatory Potsdam. It is reportet on quelity and treatment of measuring dates and on design of the graphic temperature-model. Some components of the thermal field are analysed. The correlation between the horizontal temperature gradients in the 6-meter-plane and the geodetic-astronomical observations are detected. The corrections produced on the baeie of the regreesions equation are computed for significant correlations (about 30 percent). An improvement and extension of the temperature recorder is discussed with a view to a higher effect of this method.

1. Introductory remarks

The influence of the microclimate on geodetic-astronomical observations is an unconteeted fact. It resulte in density inhomogeneities in the lowermost layer of the atmosphere. The laws, according to which density inhomogeneities in the atmospheric layer adjacent to the earth influence the results were discovered by means of investigations carried out at different observatories using classical instruments for the determination of meridian time and latitude from zenith distances.

The astrolabe - a modern instrument for the simultaneous time and latitude determination - operates according to the method of almucantarate passage measurement. As regards the construction and the method of observation, it has substantial advantages over claseical instruments. Thus several error components are completely eliminated, while other componente - even external ones - are partially compensated. However, the hope that now microclimatic effects could be completely neglected did not come true.

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A disturbed density field with its inherent heterogeneous optics may produce refraction disturbances also in astrolabe observations, not to mention that the thermal asymmetry may cause thermally induced instrumental errors at the same time.

Many geodetic-astronomical observatories use the DANJON astrolabe, and their long-term series of observations are an important data basis for geodynamic investigations (polar motion, earth rotation, recent crustal movements); therefore attempts to improve their quality in order to increase their scientific information content are of great importance.

2. Establishing a temperature measuring field

The "simple" case of uniformly inclined air layers of equal density as described in the literature now and then occurs at greater altitudes, above all in cases where air masses of different temperatures and humidities slide one upon another. It is also found for typical slope locations, e.g. in high mountains. It is however rarely that this type of stratification occurs in the lowermost layer of the atmosphere at observatories. The isolines (isotherms, isopycenic lines) describing the temperature and density field, respectively, generally are highly structured at the observatory and in its neighbourhood, reflecting in a generalized form the different thermal capacities of its essential parts. Besides they are determined by the vegetation, the wind and the daily amount of solar irradiation. Thus the algorithm for taking into account the influence of layer inclinations on the results of observation are applicable only in a differential sense. This indicates the difficulties occurring in an adequate detection of the temperature field, from which relevant parameters for the influence upon the observation of a certain star passage have to be derived. It is obvious that such quantities - mostly being gradients of the temperature - can be derived with an adequate reliability only on the basis of comorehensive studies and a great experience, the more so as economic and technological conditions limit the number of measuring points to be installed for the detection of the temperature field.

At the Potsdam geodetic-astronomical observatory, they led to the installation of a temperature measuring equipment having 12 sensors at 2 levels, 5 of them being located immediately above the astrolabe in the observation house, and five others, at an altitude of 6 m above ground level, each group of sensors being arranged in the form of a diagonal quadrangle (Fig. 1). Two other sensors serve for detecting the temperatures outside of the observation house and for the fitting to the thermodynamic temperature scale.

The data were recorded by means of a motor compensator indicating each of 12 measured values point by point by different colours and measurement marks as a function of time.

Together with 2 older meridian houses, the observation house for the DANJON astrolabe at the Potsdam geodetic-astronomical observatory is located on a small plateau, which is bounded in the east by the registration house and the measuring laboratory, in the south and west by bushes, in the north by the Helmert tower located in the north-east, and by bushes. The Helmert tower has a height of 19 m, being excelled in height by several trees which stand near the amall plateau. In the west the timber gets denser on a rising terrain in the immediate neighbourhood. The

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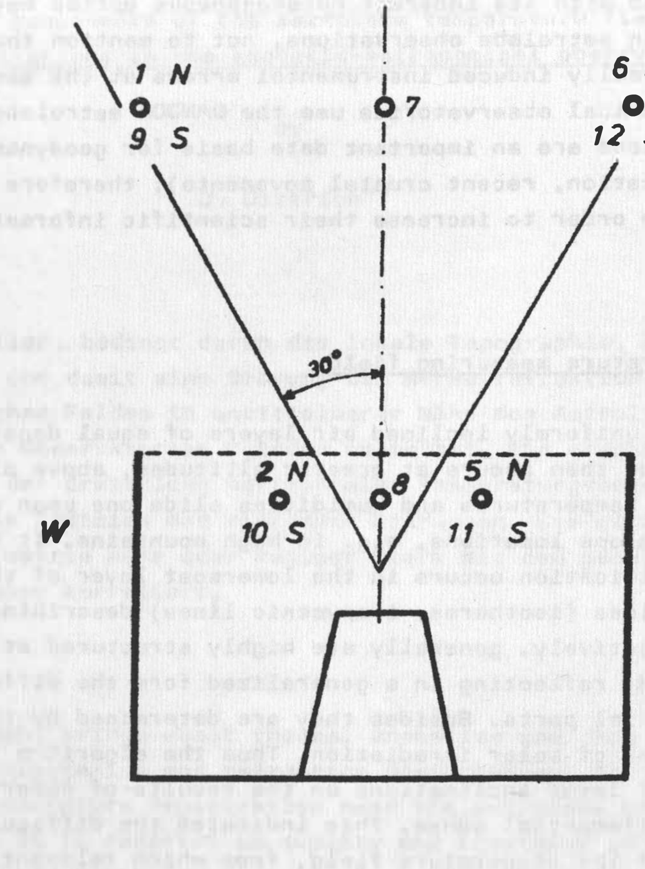

<u>Fig. 1:</u> Position of the thermal sensors

terrain slightly slopes towards the south and east. At night an intensive radiation of the heat-accumulating west walls of the registration house and the measuring laboratory - which in the daytime are irradiated by the sun - must be expected. The hight broadleaf trees likewise influence the microclimate of the small clearing. Meteorological effects on the observations must by all means be expected.

3. Influence of the slope of the layers of equal density

Although the lowermost 10 m of the earth's atmosphere yield only 1.3 ‰ of the normal refraction, layer inclinations in this zone may reach considerable values, thus also inducing considerable disturbances. They have to be considered like a shift of the refraction zenith, i.e. the zenith point will have to be reduced because of refraction, while the piercing point of the normal to the inclined layers will be free of the influence of refraction. According to ZVEREV (1946) and KUNTZ (1975), respectively, one has

(1) $\zeta' - z' = - \varepsilon \cos (a - i)$,

where ζ' denotes the apparent zenith distance of the celestial body for a layer

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inclination as referred to the refraction zenith Z'; z' denotes the apparent zenith distance without the layer inclination, ε the angular distance of the refraction zenith Z' from the zenith Z, a the azimuth of the observed star and i that of the refraction zenith (Fig. 2).

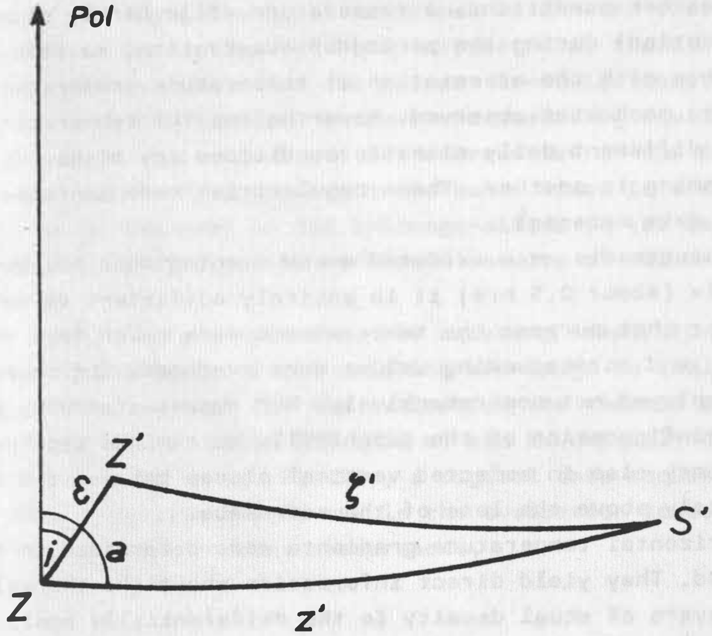

Fig. 2: Spherical triangle: zenith, refraction zenith, apparent place

The influence of the layer inclination (refraction difference) is given by

$$R\left\{\zeta' - z'\right\} = m \cos(a - i), \quad (2)$$

where $\alpha = 60''.1$ and $m = \alpha\,\varepsilon \sec^2 z$.

The thermally induced portion of the correction due to a layer inclination can be calculated for a known compensation altitude from the horizontal temperature gradient. According to ZVEREV (1946) one may start from the fact that temperature differences measured in an optimum way indicate density differences and that refraction disturbances determined through the former ones almost compensate the effects of the air layer near the ground.

All attempts to determine the slope and the azimuth of the disturbed air layers from the geodetic-astronomical observational data have a practical chance of success only for the "simple" case.

For being able to take into account the room refraction, local refraction disturbances and the influence of the temperature difference between the instrument and the compensation altitude in the normal refraction, the compensation altitude together with its temperature must be known. While for the compensation altitude

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plausible assumptions can be made on the basis of empirical values and theoretical studies, in most cases its temperature is unknown unless it lies within the range of direct temperature measurem nt.

4. Preparation and processing of the data material

For stable large-scale weather conditions, a temperature field hardly changes its character (typical stratification) during the period of observation, so that it will not be detrimental to dispense with the association of temperature measurements being as synchronous as possible to each star observed. Nevertheless the temperature conditions as a function of different daily climatic conditions may highly differ in their character from one evening to another. These regularities were confirmed a posteriori by the available data material.

Two schedules of star measurements were executed every evening when the sky was clear. For each star schedule (about 2.5 hrs) it is entirely sufficient to determine a mean temperature model. For that purpose the temperatures were taken from the recordings every 20 minutes, and corresponding values were averaged. The character of the temperature field is displayed not comprehensively, but representatively for the given possibilities by the configuration of the graphically determined isotherms in the 6-metre plane, if necessary also in selected vertical planes between the 6-metre level and the level immediately above the lens of the astrolabe.

In the 6-metre plane, horizontal temperature gradients were determined in the azimuth of all stars observed. They yield direct information about the thermally caused inclination of the layers of equal density in the differentially small region which is passed by the beam of light coming from the star.

For about 50 % of the observations these temperature gradients exhibit correlations to the results of measurement. For 30 % of the observation schedules it was possible to derive significant and even highly significant correlation coefficients, while for 20 % the coefficients are close to the limit of significance.

For observations with significant correlation coefficients, corrections were determined by the method of regression analysis, the values of which reach $0\overset{''}{.}2$ for the latitude and 20 ms for the clock correction.

The application of ZVEREV's method of calculation fails due to uncertainties in the determination of the compensation altitude. Computations were carried out with different plausible compensation altitudes, but in all cases the corrections obtained were too small.

The values obtained by the regression analysis can be explained only by inversions which at least temporarily extend to higher altitudes. Thus there is reason to suppose that the temperature gradients in the 6-metre plane are not always representative of the dependence of the results of observation on the temperature field. Above all that is true when the correlation coefficients are close to the limit of significance end their magnitudes are already markedly influenced by one or two inaccurate star observations for only 20 - 25 degrees of freedom.

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5. Evaluation of the investigations and conclusions

Significant correlation coefficients between astronomical results of observation and temperature gradients are the only criterion for their correction, which cen be carried out by the method of regression analysis. This work meets the objective requirements for improving the quality of the series of observations. However, it cannot satisfy to correct only those observations whose correlations to the tempereture coefficients are significant, if it cannot be ensured thet in the other ceses the observations are not influenced by an asymmetrical thermal or density field. This situation is determinative for the present investigetions. The number of values detected by means of the given temperature meesuring equipment is not great enough to detect possible effects which are not represented et the 6-metre level. Their existence must however be taken into account. Since in this way, for the time being, there will be an increase in the inhomogeneities in the seriee of observations, a decision on the quality of the corrected results of observation is made more difficult.

To get a satisfactory solution, the existing temperature measuring equipment should be extended on the basis of the existing knowledge to include et least 25 to 30 measuring points, so that for the evaluation the thermal conditions of a second, possibly also a third, level (12 m/18 m) can be uniquely detected in addition to those of the 6-metre level. Finally, a digital data acquisition end a suitable preliminary data reduction should enable the evaluation to be combined with that of the geodetic-astronomical routine measurement.

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On the State of the Inner Core

by

S. Franck [1) and U. Schmit [1)

Summary

We explain theoretically the distribution of the seismic wave attenuation coefficient in the Earth's core which was found with help of seismic data. It is shown that slow relaxation processes near to the melting transition at the inner core boundary may explain high values of anelasticity very well.
The inner core material should be very close to its melting point. In the deep inner core also other mechanisms of seismic wave attenuation, suggesting a quasi-polycristalline structure of the material, may be important.

Zusammenfassung

Wir erklären theoretisch die mit Hilfe von seismischen Daten gefundene Verteilung des Dämpfungskoeffizienten seismischer Wellen im Erdkern. Es wird gezeigt, wie die starke Anelastizität auf langsame Relaxationsprozesse am Schmelzübergang an der Grenze des Innenkerns zurückgeführt werden kann.
Das Material im Innenkern sollte sich sehr nahe am Schmelzpunkt befinden. Im tiefen Innenkern können auch andere Dämpfungsmechanismen, die von einer quasi-polykristallinen Struktur des Materials herrühren, von Bedeutung sein.

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1. Introduction

According to our general view the Earth's core may be divided into a liquid outer core and a solid inner core. This fact results from the observation that transverse seismic waves vanish in the outer core but not in the inner one. Besides such basic knowledge derived from the distribution of seismic velocities also data of seismic wave attenuation may provide us information on the state of matter in the core of the Earth.

The seismic wave attenuation coefficient Q^{-1} describes the dissipating part of mechanical wave energy per wave length.

From seismological observations Doornbos /1/ found the distribution of the seismic P - wave attenuation coefficient in the Earth's core.

His results are shown in figure 1, curve 1.

It is interesting that there is an appreciable asymmetric peak at the inner core boundary (ICB) and that the attenuation is higher in the solid inner core than in the liquid outer core. In this paper we look for explanations of such a behaviour.

2. Attenuation mechanisms in the inner core

We use the common idea that at the ICB an isochemical melting transition from the solid inner core to the liquid outer core takes place. Up to now the microscopic mechanism of the melting transition is not completely understood. Therefore we apply phenomenological Landau theory of phase transitions /2/. In this model short-range order and long-range order are taken into account simultaneously. Melting is then characterized by the vanishing of the long range order parameter η.

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For illustration we recall that in the framework of Born's theory of melting the order parameter η could be identified with the shear modulus that goes to zero at the melting point. In the melting theory of Frenkel η is related to a certain critical concentration of defects.
For the explanation of elastic wave attenuation we use the phenomenon of order parameter relaxation :

A P - wave, running through the inner core, leads to periodic compressions and dilatations. So the order parameter comes from its equilibrium value to non-equilibrium states and relaxes back. Usually the processes of relaxation are so quickly that the thermodynamical equilibrium turns up immediately and the effect is without any significanse.

As follows from extension of Landau theory /3/, near to the phase transition point the order parameter relaxes very slowly. The relaxation time τ is proportional to $(T_m - T)^{-1}$, where T_m is the melting point.
Every relaxation process to the thermodynamical equilibrium is an irreversible process with increase of entropy and consequently energy dissipation. In this way mechanical wave energy, needed for bringing the order parameter into the non-equilibrium state, dissipates.

A quantitative analysis with help of the relaxation model of attenuation was given in a paper of Stiller et.al. /4/. In such calculations you need a certain distribution of temperature and melting temperature within the inner core. Curve 2 of figure 1 was computed with help of the Higgins-Kennedy /5/ temperature distribution while curve 3 refers to the thermal model of Stacey /6/. According to Higgins and Kennedy the temperature in the centre of the Earth is only about 15 deg below the corresponding melting temperature. We see that the corresponding curve 2 approximates the data of Doornbos very well.

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In the outer core the mechnaism of order parameter relaxation does not work because in the liquid state η is identical to zero (no long-range order, vanishing shear modulus).
In this way we many also account for the low Q^{-1}-values in the outer core.
In the paper of Stiller et al. /4/ also a further mechanism of wave attenuation has been discussed. The effect is based on energy loss due to thermal conduction when elastic waves propagate in inhomogeneous matter (quasi-polycristalline, grained, impurities etc.). A detailed analysis gives highest values of Q^{-1} ($\approx 10^{-3}$) when the inhomogeneous matter has a characteristic size of about 10^{-3} m. This effect of wave attenuation can never explain the peak-structure at the ICB but may be important in the deep inner core.

3. Concluding remarks

From our investigations we may conclude that the whole inner core is in a thermodynamical state very near to its melting point. The inner core is so to say already "soft" and therefore seismic wave attenuation is so high.
Another mechanism of wave attenuation may play an important role in the deep inner core far away from the ICB. This effect hints to an inhomogeneous structure of the inner core.
We want to recall that such a state is the usual state of planetary matter. Especially "dirty" matter, like the matter in the Earth's interior, is expected to have such a struture.

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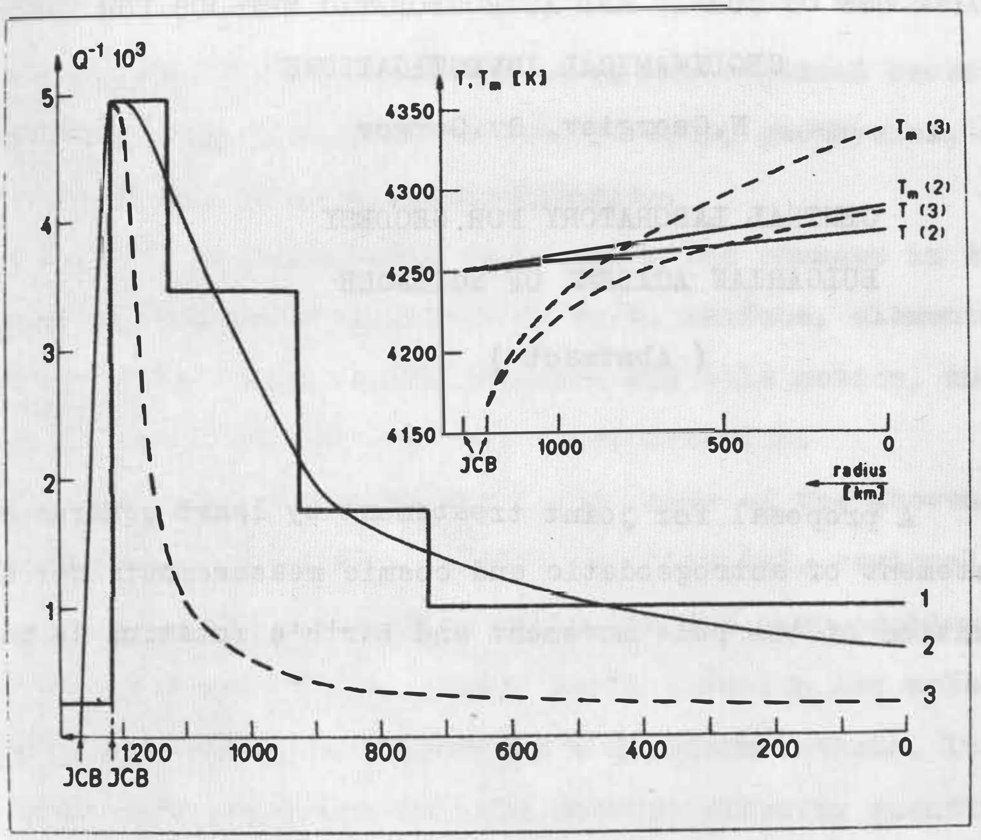

figure 1

Attenuation coefficient of seismic P - waves in the Earth's core.

1 - data of Doornbos

2 - present model with temperature distribution of Higgins and Kennedy

3 - present model with temperature distribution of Stacey

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JOINT USE OF COSMIC AND ASTROGEODETIC METHODS FOR GEODYNAMICAL INVESTIGATIONS

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(Abstract)

A proposal for joint treatement by least squares adjustement of astrogeodetic and cosmic measurements for determination of the pole movement and Earth's rotation is made.

СОВМЕСТНОЕ ИСПОЛЬЗОВАНИЕ КОСМИЧЕСКИХ И АСТРОНОМО-ГЕОДЕЗИЧЕСКИХ МЕТОДОВ ПРИ ГЕОДИНАМИЧЕСКИХ ИССЛЕДОВАНИЯХ

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Болгарской академии наук-София

(Резюме)

Дана методика совместной обработки по методу наименьших квадратов астрономо-геодезических и космических измерений для определения движения полюса и вращения Земли.

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1. Introduction

A new branch of science of the Earth has appeared recently as an interdisciplinary science between geodesy, geophysics, astronomy and oceanology. This is the geodynamics.

The subject of geodynamics is to study the changes in time and space of the location of points on earth surface, elements of earth gravitational field, Earth rotation and pole motion, and their respective mathematical and physical interpretation.

Taking into consideration the large range of the abovementioned geodynamical phenomena - global, continental, regional and local - we would point out that we shall discuss here problems related to the Earth as a whole, namely Earth rotation and pole motion by using classical, astrogeodetic and modern methods. It should be also noted that these are the only methods offering quantitative characteristics of geodynamical research work having one or another degree of accuracy. At present the accuracy of the astrogeodetic observations is of the order of 0."01, when determining the latitude, and $0\overset{s}{.}001$ (0,"015) during time observation obtained after averaging 5-day observations. This accuracy depends mainly on the equipment used in observation which will not be capable to provide for better results in the near future.

Using modern methods and equipment in satellite geodesy is an innovation in studying the global geodynamical phenomena. The results obtained represent a ground that allows to believe that the cosmic methods will increase the accuracy of the values determined by one order and will allow to study some special influences and influences of short periods, as well as their modifications.

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Specific systematic errors, the sources of which are not yet completely studied and defined, are inherent not only of the astrogeodetical methods, but of the cosmic methods too. This circumstance and the requirement for an increase of the accuracy of the elements to be determined impose to proceed to the study of the possibility to use jointly astrogeodetic and cosmic observations.

2. Joint use of latitude and time observations to determine pole co-ordinates

As it is well known, since 1967 the International Time Service (BIH) has started joint treatment of latitude and time measurements to determine pole co-ordinates (x, y) and uneven Earth rotation T = UT1 - UTC, by using the set of observation equations for the epoch T [1] .

$$(1)\quad \begin{cases} x(T)\cos\lambda_{0i} + y(T)\sin\lambda_{0i} + z(T) = \varphi(T) - \varphi_{0i}, \\ [x(T)\sin\lambda_{0i} - y(T)\cos\lambda_{0i}]\,\mathrm{tg}\,\varphi_{0i} + t(T) = [UT0_i - UTC], \end{cases}$$

where

$\lambda_{0i}, \varphi_{0i}$ - are the geographical co-ordinates of the observation station for the adopted initial epoch To

$\varphi(T)$ is the latitude obtained from observation during the epoch T

$z(T)$ and $t(T)$ are terms including the systematical influences and are equal for all stations

The solution of the set of observation equations (1) is made by respecting the condition.

$$(2)\quad \sum_{i=1}^{N_\varphi} (\varphi_i - \varphi_{0i})^2 + \sum_{i=1}^{N_\lambda} (\lambda_i - \lambda_{0i})\cos^2\varphi_{0i} = \min .$$

Taking into consideration the method of treatment of latitude

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and time astrogeodetic observations adopted by BIH, we have made model investigations to determine pole co-ordinates by separate and joint application of the relevant latitude and time observations. The observation equations of type (1) in which the materials of the five stations determining pole motion - Mitzuzawa, Kitab, Carloforte, Geitersberg and Yukia - were used for this purpose. Table 1 shows the mean square errors m_x, m_y of pole co-ordinates x, y determined by adjustment using the method of the least suqares and the mean square errors m_z, m_t of the additional unknown values z and t.

Table 1

Mean square errors observations	m_x/m/	m_y/m/	m_z". 10^{-2}	m_t^s. 10^{-3}
Latitude	0,22	0,18	0,45	-
Time	0,43	0,52	-	0,58
Latitude and time (jointly)	0,19	0,17	0,45	0,58

Taking into consideration the well-known circumstance that it is not suitable to use only time observations, when determining pole co-ordinates, the common treatment of latitude and time observations leads to a slightly noticeable increase of pole co-ordinate accuracy and to a reduction of the influence of the systematical errors on the values determined, as illustrated by the mean square errors obtained and shown in Table 1.

3. Study of pole motion and Earth rotation by artificial satellites of the Earth

It is not possible to improve at present the astrogeodetic observation accuracy as mentioned above because of the systematical

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and probable errors of observation, errors in star catalogues, anomalies in atmospheric refraction, etc. This is an obstacle to the study of important geodynamical phenomena such as modifications in short periods of Earth rotation velocity, diurnal nutation provoked by Earth's liquid core, establishment of a relationship between seismic activity and pole Chandler's motion, drift of the continents, etc.

The results obtained by means of the new technical equipment and methods such as laser and Doppler observations by artificial satellites of the Earth, optical laser location of the Moon, very long base line interferometry represent a ground to consider that much more accurate and detailed data may be obtained in the near future for the above geodynamical phenomena. This is confirmed also by the accuracies of $\pm$ 0.02 m in distance determination by means of laser range finders and by Doppler measurements of the order of $\pm$ 0.20 m published in some papers.

It should be taken into consideration further that, when determining the characteristics of global geodynamical phenomena by observation by artificial satellites of the Earth, it is necessary to predict satellite co-ordinates at any moment with an accuracy corresponding to the accuracy of the measuring apparatus. It is possible to ensure the use with good results of the artificial satellites of the Earth, when studying geodynamical phenomena, only by establishing a correspondence between observation accuracy and prediction.

When using laser measurements of the distance to the artificial satellites of the Earth and of pole motion, equations of type [2] are used usually.

$$D_o - D_c = \frac{1}{D_c}\Big\{\left[(X_s \cos\psi + Y_s \sin\psi) z_p - Z_s x_p\right] x -$$

(3)

$$-\left[(X_s \sin\psi - Y_s \cos\psi) z_p + Z_s y_p\right] y - \left[(x_p X_s + y_p Y_s)\sin\psi + \right.$$

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$$+(y_p X_s - x_p y_s)\cos\psi\Big]\omega ,$$

where

D_c - measured distance from the station to the satellite

D_0 - distance calculated on the basis of ephemerides

X_s, y_s, Z_s - co-ordinates of the artificial satellite of the Earth at the moment t in inertial system of co-ordinates

x_p, y_p, z_p - co-ordinates of stations in the Earth's co-ordinate system

x, y - pole co-ordinates

ω - angular rotation velocity of the Earth

ψ - angle between axes of true star system of axes and inertial system

When Doppler observations of the artificial satellites of the Earth to be used also for determination of pole co-ordinates are available, it will be possible to use different methods and mathematical models. Here, we shall use the equation [3] .

$$N_{ij} = \frac{f_0}{c}\Big\{\Big[((\xi_j - x) - X)^2 + ((\eta_j - y) - Y)^2 + (\zeta_j - Z)^2\Big]^{\frac{1}{2}} - \tag{4}$$

$$-\Big[((\xi_i - x) - X)^2 + ((\eta_i - y) - Y)^2 + (\zeta_i - Z)^2\Big]^{\frac{1}{2}}\Big\} + \Delta f \Delta t ,$$

where

N_{ij} - is a Doppler integral number

$\Delta f = f - f_0$ - is the difference between received and emitted frequencies

Δt - is the time interval in which Doppler shifting integration is made

ξ, η, ζ - are satellite co-ordinates at different moments i and j

X, Y, Z - are co-ordinates of Earth's station

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In this case we have connected pole co-ordinates x , y with satellite co-ordinates, accepting that, when determining satellite orbit, pole motion influence has not been taken into account.

4. Joint use of astrogeodetic and cosmic measurements in pole motion and Earth rotation determination

Here, we shall discuss the possibility of a joint treatment, on the basis of the least suqares, of results obtained by using different methods of measurement. We think that this method is most suitable for use for the time being, since we have a heterogeneous information available on which some unknown and not completely studied systematical factors have a certain influence. It should be expected that such a joint treatment will reduce the influence of the systematical errors on the geodynamical values determined.

By using equations (1), (3) and (4) and after the relevant linearization, we obtain the observation equations of every station i , and of k or l satellite observations recorded in a matrix:

a) equations for latitude

$$(5) \qquad \underset{1.3}{A_{\varphi_i}} \begin{pmatrix} dx \\ dy \\ dw \end{pmatrix} + z + f_{\varphi_i} = V_{\varphi_i} \ , \qquad p_{\varphi_i}$$

b) equations for time

$$(6) \qquad \underset{1.3}{A_{\lambda_i}} \begin{pmatrix} dx \\ dy \\ dw \end{pmatrix} + t + f_{\lambda_i} = V_{\lambda_i} \ , \qquad p_{\lambda_i}$$

c) equations for laser measurements to a satellite

$$(7) \qquad \underset{k.3}{A_{\varrho_i}} \begin{pmatrix} dx \\ dy \\ dw \end{pmatrix} + \underset{k.3}{B_{\varrho_i}} \underset{3.1}{dR_i} + \underset{k.6}{C_{\varrho_i}} dS + \underset{k.1}{I_k} u + f_{\varrho_i} = \underset{k.1}{V_{\varrho_i}} \ , \qquad \underset{k.k}{P_{\varrho k_i}}$$

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d) equations for Doppler measurements to a satellite

$$(8)\qquad \underset{l.3}{A_{\Delta\varrho_i}}\begin{pmatrix} dx \\ dy \\ dw \end{pmatrix} + \underset{l.3}{B_{\Delta\varrho_i}}\underset{3.1}{dR_i} + \underset{l.6}{C_{\Delta\varrho_i}}\underset{6.1}{dS} + \underset{k.1}{I_l V} + \underset{l.1}{f_{\Delta\varrho_i}} = \underset{l.1}{V_{\Delta\varrho_i}}\,, \quad \underset{l.l}{P_{\Delta\varrho_i}}$$

In the equations (5) - (8) are used the following significations:

A - is the matrix of the coefficients preceding the corrections dx, dy, dw of pole co-ordinates and Earth rotation which are looked for ; z, t, u, v - are unknown values including systematical influences; B - is the matrix of the coefficients preceding the corrections dR (dX, dY, dZ) of the co-ordinates of Earth's stations that are looked for; C - is the matrix of the coefficients preceding the unknown corrections dS_j of satellite orbit elements; f - is constant terms; V - is the corrections of the relevant measurements; p - is their weights.

The observation equations (5) - (8) will be written down in short as follows:

$$(9)\qquad \bar{A}_i \Delta + F_i = V_i\,,$$

where we have as to the matrix of the coefficients preceding the unknowns

$$(10)\qquad \underset{z.5}{\bar{A}_i} = \begin{vmatrix} \underset{1.3}{A_{\varphi_i}} & 0 & 0 & 1 \\ \underset{1.3}{A_{\lambda_i}} & 0 & 0 & 1 \\ \underset{k.3}{A_{\varrho_i}} & \underset{k.3}{B_{\varrho_i}} & \underset{k.6}{C_{\varrho_i}} & I_k \\ \underset{l.3}{A_{\Delta\varrho_i}} & \underset{l.3}{B_{\Delta\varrho_i}} & \underset{l.6}{C_{\Delta\varrho_i}} & \underset{l,1}{I_l} \end{vmatrix},$$

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where $r = k + l + 2$, $s = 3n + 13$, n - number of stations on the Earth

Vector of constant terms

(11) $$F_i^* = |f_\varphi , f_\lambda , f_\rho , f_{\Delta\rho}| ,$$

Vector of corrections

(12) $$V_i^* = |V_\varphi , V_\lambda , V_\rho , V_{\Delta\rho}| ,$$

Matrix of weights

(13) $$P_i = \{ p_\varphi , p_\lambda , P_\rho , P_{\Delta\rho} \} ,$$

Vector of unknowns

(14) $$\Delta^* = |dp , dR , dS , C| .$$

As to the symbols in (14) we have

(15)
$$dp^* = |dx , dy , dw| ,$$
$$dR^* = |dR_1 , dR_2 , \dots dR_n| ,$$
$$dS^* = |du , d\Omega , di , da_x , da_y , dn| ,$$
$$C^* = |z, t, u, v| .$$

From (9) we obtain the normal equations by means of which we define the unknowns Δ

(16) $$N\Delta + W = 0 ,$$

where

(17)
$$N = \sum_{i=1}^{n} \bar{A}_i^* P_i \bar{A}_i ,$$
$$W = \sum_{i=1}^{n} \bar{A}_i^* P_i F_i .$$

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The system (16) may be solved by different methods depending on which group of unknowns in (14) should be determined. Since in this case it is the unknowns dP (dx, dy , $d\omega$), characterizing pole motion and Earth rotation that are essential, they may be written down in the last place in the system (16), and during the solution it is possible to obtain only these values together with the relevant estimates of their average errors.

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Problems in Defining a Standard Tidal Correction Model

by

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Zusammenfassung

Die Definition eines einfachen Standardmodells zur Gezeiten-korrektion enthält Probleme, von denen einige erörtert werden. Die Genauigkeit der LONGMANschen Formeln wird diskutiert.

Abstract

The paper summarizes a number of problems which have to be dealt with when creating a simple standard tidal correction model. The accuracy of Longman's formulas is discussed.

1. General

A standard tidal correction model is a set of formulas and rules which are accurate enough to cover most of the applications and which, at the same time, are relatively simple to implement. An inaccurate model has little use, and if the formulas and rules are exceedingly complicated, hard to use or too subjectively chosen, people will simply not use them.

The tidal correction can be thought to consist of two separate parts. First, we have the direct tidal effect, which can easily be defined in simple mathematical terms. The direct effect is all we would have if the earth were totally rigid. Second, we have the indirect effect of the yielding of the earth and the displaced water masses.

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Principally, the direct effect is straightforward to calculate. If we have the coordinates of the Sun and the Moon, the rest is simple mathematics. Nevertheless, the computational procedures have to be well chosen to make a fit standard. For our purposes the coordinates of the Moon and the Sun cannot be obtained by observational procedures. They have to be computed or taken from a list of precomputed values. The most logical choice for the ephemeris (a set of coordinates for the Moon and the Sun) is to use the coordinates published in the current edition of the Almanac. At present these coordinates are based on Brown's and Newcomb's well-known theories.

The real problem with the direct tidal effect is the amount of approximation that can be allowed. The coordinates in the Almanac are printed only at regular time intervals and their computation for an exact epoch involves interpolation. This kind of manual reading is also laborious and it is often preferable to calculate the coordinates independently. However, the formulas in Brown's and Newcomb's theories are complicated, and simplified computational procedures have definite advantages. Both the interpolation and the simplification of the formulas introduce approximation into the computed tidal correction. An upper limit for this approximation is essential for a standard tidal correction model; the specification of an actual interpolation formula or a certain type of computational method is of lesser importance. In Chapter 2 we summarize a number of factors which affect the accuracy of the tidal model. It is shown that an accuracy of 0.05 - 0.01 μGal (10^{-8} m/s^2) can be achieved relatively easily.

The indirect tidal effect is a great deal more difficult to standardize. About all that can be done is to give factors (e.g. 1.16 for the vertical component) by which the direct tidal force is multiplied in order to get the correction. The actual indirect effect depends largely on local geophysical features and the proximity of the oceans. The use of a single multiplying factor, on the other hand, seems to leave residuals of several microgals (e.g. Ducarme, Poitevin, Loodts, 1978) when compared with actual observations. Even the inertial effect which is felt by the gravimeter when the earth's crust moves up and down can reach

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0.5 μGal if we assume that a tidal force of 100 μGal causes a displacement of 20 cm. The accuracy of the indirect part in the tidal model cannot reach the high precision to which the tidal force is computed for a rigid earth. A standard tidal correction model can include a certain multiplying factor. On the other hand, the standard may allow the separation of the indirect part from the direct one; i.e. observers would use the direct standard tidal model and, if necessary, formulate the indirect effect as they see fit.

2. Smaller effects in the direct tidal force

2.1. How accurate should the astronomical data be in order to achieve an accuracy of 0.10 or 0.01 μGal

Let us use the simple approximate formula

$$F = G M_B \frac{r}{R^3} (3 \cos^2 z - 1) \qquad (1)$$

for the vertical component F of the tidal force.

Here

$G M_B$ is the gravitational constant of the celestial body, $0.01230002 \times 3.986005 \times 10^{14}$ m^3/s^2 for the Moon, $1.32712438 \times 10^{20}$ m^3/s^2 for the Sun,

r is the radius of the earth, approximately 6370 km,

R is the distance between the center of the earth and the celestial body, and

z is the zenith angle of the celestial body.

Differentiating formula (1) with respect to z we have

$$dF = - G M_B \frac{r}{R^3} 6 \sin z \cos z \, dz$$

$$= - G M_B \frac{r}{R^3} 3 \sin 2z \, dz$$

This has a maximum value at $z = 45^\circ$ of

$$dF_{max} = - 3 G M_B \frac{r}{R^3} dz$$

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By taking $R = 3.565\times10^{8}$ m for the minimum distance of the Moon and $R = 1.47\times10^{11}$ m for that of the Sun we have

$$dF_{max} = -210\ \mu\text{Gal}\ dz \qquad \text{for the Moon, and}$$

$$dF_{max} = -80\ \mu\text{Gal}\ dz \qquad \text{for the Sun.}$$

This means that an error of 10" ($= 4.848\times10^{-5}$ rad) in the angular position of the Moon causes a discrepancy of 0.01 μGal in the vertical component of the tidal force. For the Sun the discrepancy would be 0.004 μGal.

We next keep the angle z constant and differentiate with respect to the distance R.

We have

$$dF = -3\ G\ M_B \frac{r}{R^4} (3\cos^2 z - 1)\ dR$$

$$= -3 \frac{F}{R} dR \quad .$$

Using the approximate formula $R = \frac{r}{\Pi}$ between the parallax Π of the Moon and the distance R, we get

$$\frac{dR}{R} = -\frac{d\Pi}{\Pi} \quad , \text{ and}$$

$$dF = 3 \frac{F}{\Pi} d\Pi \quad .$$

We have

$$dF_{max} = 23000\ \mu\text{Gal}\ d\Pi \qquad \text{for the Moon, and}$$

$$dF_{max} = -160\ \mu\text{Gal/AU}\ dR \qquad \text{for the Sun.}$$

An accuracy of 0.01 μGal thus requires that Π (for the Moon) be known to within $\pm$ 0".1 and R (for the Sun) be known to within $\pm 6.3\times10^{-5}$ AU (Astronomical Units, 1.49597870×10^{11} m).

It follows from the linearity of the differential formulas that the limits for an accuracy of 0.10 μGal are ten times larger.

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2.2. The effect of the planets

Venus causes a maximum effect of 0.007 μGal, and Jupiter an effect of 0.0008 μGal (Heikkinen, 1978, p. 11).

2.3. The effect of the ellipsoidal shape of the earth

This effect is detailed in Heikkinen, 1978 (pp. 12-20).

The linear acceleration of the center of mass of the earth is affected by the ellipsoidal shape of the earth to the extent of 0.002 μGal.

Considerably greater, however, is the effect of the angular acceleration. The attraction of a celestial body on the equatorial bulge of the earth gives the earth angular acceleration, gives rise to precession and nutation, and causes a plumbline to tilt, as seen in Fig. 1.

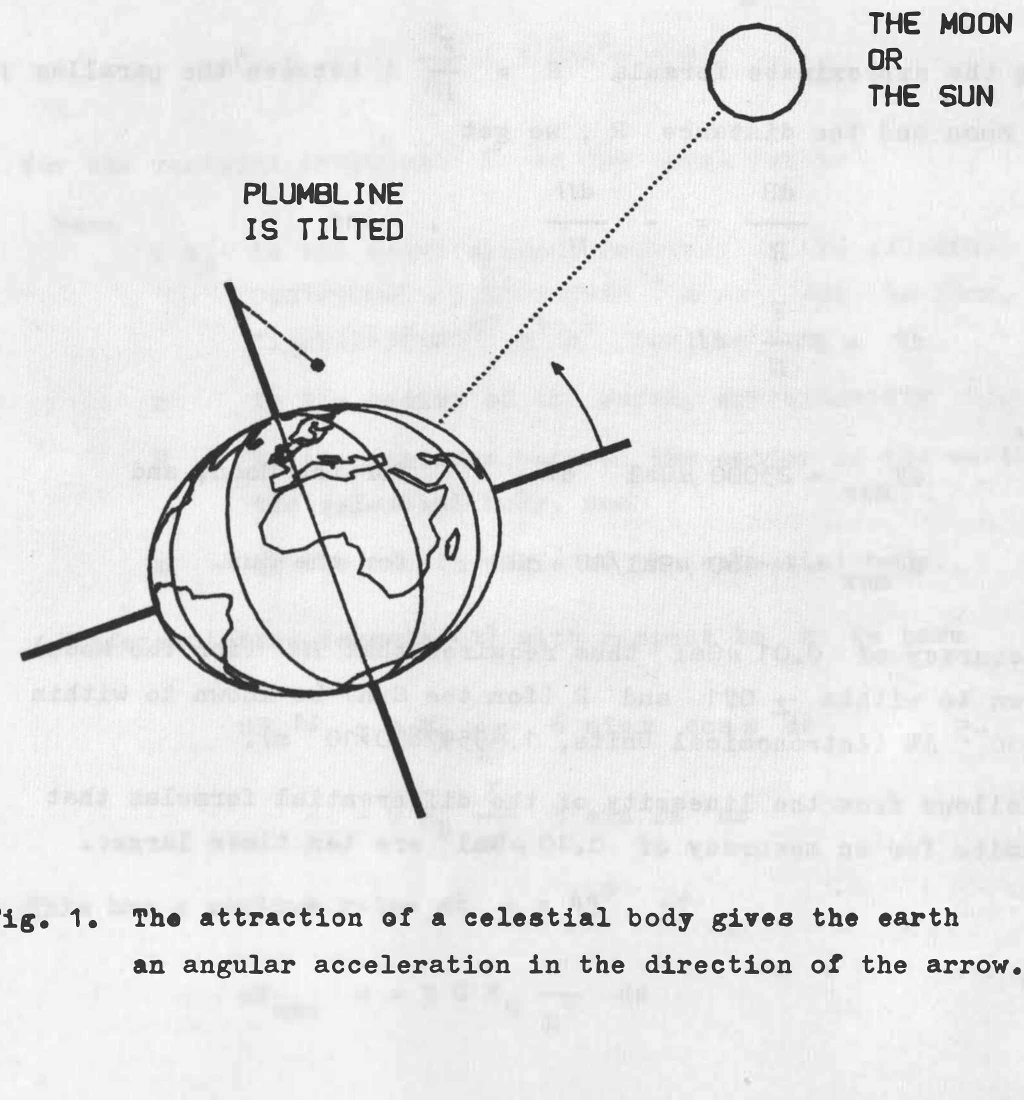

Fig. 1. The attraction of a celestial body gives the earth an angular acceleration in the direction of the arrow.

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This can affect the horizontal components of the tidal force by 0.3 μGal and the vertical component by 0.001 μGal.

The ellipsoidal effect cannot be calculated from tidal potential expressions, which are all based on a spherical earth model, and its inclusion into a standard tidal model requires special attention.

2.4. The effect of a change in IAU constants

A standard tidal model will preferably use the latest IAU approved astronomical constants. Among the changed constants from the system of 1964 to that of 1976 are (e.g. Groten, 1979, Appendix E) (SI units)

	1964	1976	(1976-1964)/1964
$G\,M_{Moon}$	$3.98603\times10^{14}/81.30$	$3.986005\times10^{14}\times 0.01230002$	-1.46×10^{-5}
$G\,M_{Sun}$	1.32718×10^{20}	1.32712438×10^{20}	-4.19×10^{-5}
Unit Distance	1.496×10^{11}	1.49597870×10^{11}	-1.42×10^{-5}

Based on the considerations of 2.1 these three changes can have a maximum effect of 0.002 μGal each.

2.5. Geometrical or apparent coordinates

Apparent coordinates are published in the Almanac. They are thus corrected for aberration, which is approximately 20".5 for the Sun and 0".7 for the Moon. The Sun's aberration causes a maximum difference of 0.008 μGal, using the formulas of 2.1.

This question arises in connection with the theories stating that the gravitational attraction advances at the speed of light.

2.6. Nutation

The coefficient of the largest nutational term (which affects longitude) has the value 17" . The possible omission of this term causes an effect of 0.017 μGal in the tidal force.

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2.7. Ephemeris Time, Universal Time

Ephemeris Time is the argument of Newcomb's Tables of the Sun. It is the time that has to be given as starting data for the Tables in order to get correct solar coordinates. The difference between Ephemeris Time and Universal Time is about 50 seconds for 1980, and as the Moon travels a maximum of $15\overset{\circ}{.}4$ in 24 hours, this difference has an effect of 32" in the longitude of the Moon. This again (formulas of 2.1) causes a difference of 0.03 μGal in the vertical component of the tidal force. As the Sun moves only about one degree a day, its effect is smaller.

2.8. How many terms should be taken from Brown's series

The current lunar ephemeris is based on Brown's series, which have over 2500 terms. They are not all necessary when computing tidal forces. Table 1 shows the number of terms which have coefficients larger (in absolute terms) than 0".01, 0".1, 1", 10" or 100".

We have also truncated the series at these points and then computed the lunar coordinates once every 24 hours for five years. The maximum discrepancies between these results and the 'true' coordinates given by the complete series are also given in Table 1. It can be seen (referring to the results of 2.1) that in order to obtain an even and equal truncation effect from all three series, it is advisable to include an approximately equal number of terms in each series. For example, taking the 60 largest terms in longitude, 45 in latitude and 56 in sine parallax gives us a total of 161 terms and maximum errors of 0.011 μGal, 0.009 μGal and 0.010 μGal , respectively.

2.9. Longman's formulas

Longman's formulas (Longman, 1959) have long served as the basis for the tidal correction used in practice all over the world. These formulas have a very small number of terms and the error caused by the approximations can exceed $\pm$ 3 μGal.

Fig. 2 shows for 24 hours the difference between Longman's

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	LONGITUDE						LATITUDE						SINE PARALLAX					
	number	1970	1972	1974	1976	1978	number	1970	1972	1974	1976	1978	number	1970	1972	1974	1976	1978
100"	13	240	330	300	200	270	7	170	220	190	190	200	2	77	81	80	76	76
10"	27	52	82	74	67	53	14	61	90	82	71	61	5	9.4	10	9.1	11	7.5
1"	60	7.8	11	9.5	7.3	7.9	45	5.8	9.1	7.1	6.9	5.1	9	4.4	4.4	4.3	5.2	5.3
0.1"	143	1.3	1.6	1.9	1.3	1.3	94	1.2	1.6	1.2	1.0	0.8	28	0.46	0.56	0.51	0.61	0.44
0.01"	386	0.22	0.23	0.21	0.19	0.20	221	0.18	0.18	0.19	0.18	0.21	56	0.09	0.09	0.07	0.08	0.07
All	1113						839						643					

Table 1. The table shows the number of terms in Brown's series, when the series are truncated at 100", 10", 1", 0".1 or 0".01 . For instance, the latitude series has 45 terms with a coefficient larger than 1". The table also shows the maximum truncation errors which occurred in the years indicated. The truncation errors are expressed in seconds of arc.

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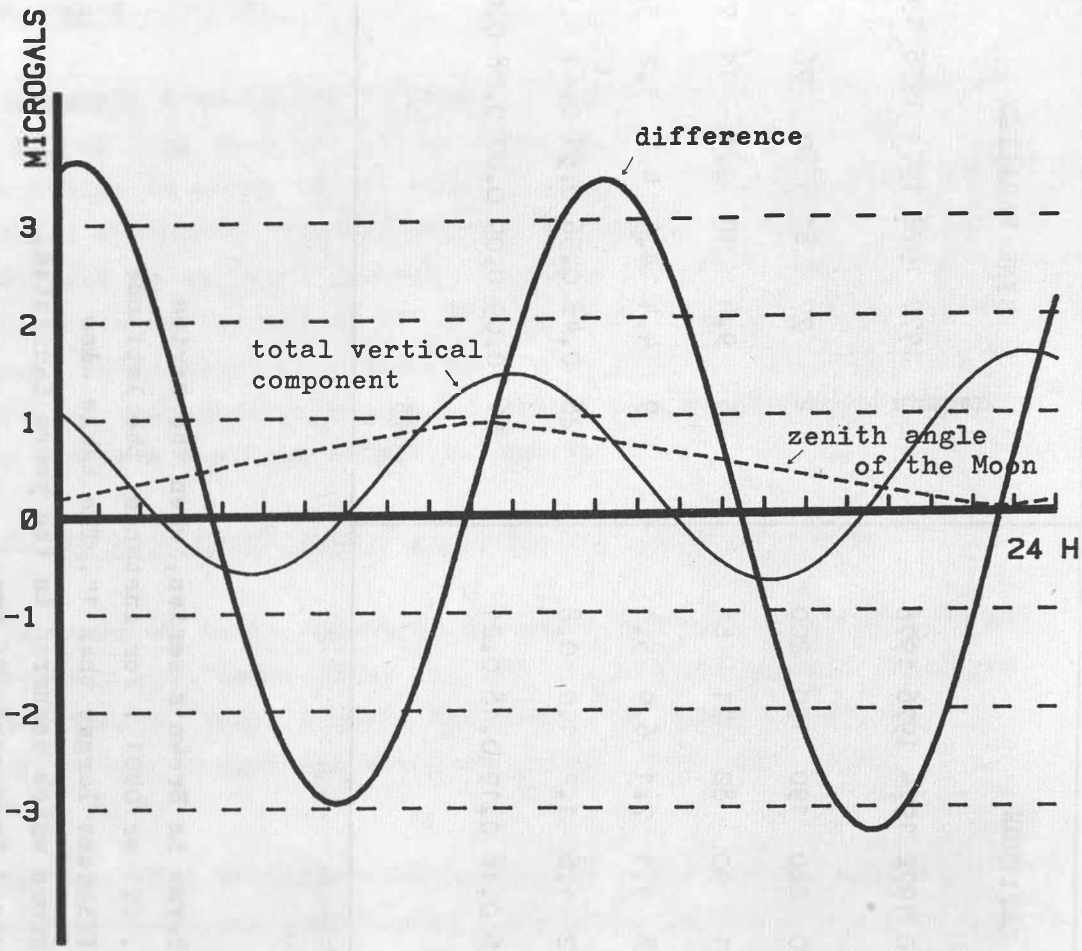

Fig 2. The approximation error of Longman's vertical component for latitude = 0^{o}, longitude = 0^{o}, from April 11, 1980 at 11 o'clock GMT to April 12, 1980 at 11.
The total vertical component and the zenith angle of the Moon are also shown in the figure. The one microgal line corresponds to 100 microgals in the total component and to 180^{o} in the zenith angle. The maximum error shown is 3.6 microgals.

vertical tidal component and the component given by the ephemerides of the Almanac. The computation place is 0^{o} longitude, 0^{o} latitude; the whole of 1980 was examined for maximum discrepancy (using an interval of 2.4 hours); the limit of 3 μGal was exceeded several times, and Fig. 2 shows the discrepancy for a day in April 1980.

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3. Conclusions

It has been seen that the theoretical tidal force includes a number of small effects within the range 0.001 to 0.03 μGal, and while the accuracy of 0.01 μGal can easily be achieved, the limit of 0.05 μGal might give an opportunity for a few significant simplifications. Among them is the possibility to ignore the difference between Ephemeris Time and Universal Time.

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Variation of the CHANDLER period derived from latitudes observed at Potsdam Observatory

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Summary

Previously the latitudes observed at the Potsdam Geodetic-Astronomical Observatory had been investigated by the harmonic analysis with respect to the temporal variations of the mean latitude as well as of the amplitude and phase of the CHANDLER, annual and semiannual wobbles, the CHANDLER period taking constantly as 1.200 years. On the base of the significantly obtained variation of the phase of the CHANDLER wobble, further studies were to be made with consideration being given to a variable CHANDLER period. - Using the simple and the modified harmonic analyses, the results were derived for periods of treatment of six years at intervals of three months. According to this, the CHANDLER period varies between 1.185 and 1.193 years from 1957.8 to 1978.0.

Резюме

Прежние исследования широт, наблюдаемых в геодезическо-астрономической обсерватории Потсдама, в отношении временных изменений средней широты, а также амплитуды и фазы чандлеровской, годовой и полугодовой волн были произведены по способу гармонического анализа с принятым чандлеровским периодом в I,200 года. На основании значительной вариации фазы чандлеровской волны дальнейшие исследования должны быть сделаны, принимая во внимание переменный чандлеровский период. - Определены результаты для периодов обработки в 6 лет при интервалах в четверть года с помощью простого и модифицированного гармонического анализов. Соответственно этому чандлеровский период изменяется между I,I85 и I,I93 годами с I957.8 по I978.0 гг.

1. Introduction

Several papers [2 - 4] have been published on the studies of the latitudes observed at the Potsdam Geodetic-Astronomical Observatory, which refer to temporal variations of the mean latitude and the amplitude and phase of the CHANDLER, annual, and semiannual wobbles. The results were determined by harmonic analysis and a fixed CHANDLER period of 1.200 years. As far as the phase of the CHANDLER wobble is concerned, its temporal variation was found to be significant (see Fig. 4 in [2] and Fig. 2b in [4]). This means that the actual CHANDLER period deviates somewhat from the assumed value and should be variable to a limited extent. It was thought desirable therefore to conduct further studies including temporal variation of the CHANDLER period.

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2. Further improvement of letitude values

Previous investigations [2 - 4] were based on the latitude valuee from 1957.8 to 1977.0 homogenized and improved by group corrections. It had been shown that the DANJON astrolabe employed for astronomical time and latitude determination was not an impersonal instrument. Aiming at further improving the latitude values, corrections for personal equations in latitude were derived and applied. These corrections turned out to vary temporally, between -0.099" and +0.102". From then the studies were based on homogenized latitude values improved by group corrections and for personal equations, particularly for the period from 1957.8 to 1978.0.

3. Simple and modified harmonic analyses

With the aim of obtaining also the length of the CHANDLER period it was proposed to use a modified harmonic analysis method. In the case of simple harmonic analysis the functional model for adjustment with the mean latitude and the pairs of coefficients for the CHANDLER, annual, and semi-annual wobbles has 7 unknowns. If modified harmonic analysis is used the CHANDLER period becomes the 8th unknown. This means that there is no longer a linear connection between tha unknowns. Approximate values for the unknowns are therefore required in order to solve the equation systems which have been linearized with the aid of a TAYLOR series. Thesa must be sufficiently close to the actual values to avoid any pronounced inaccuracy which might be caused by the neglected terms of second and higher order of the TAYLOR series.

4. Derivation of results

4.1. General procedure

The variability of the CHANDLER period was investigated as described in [2], i.e. treatments covered a period of six years with time displacements of three months. The zero point for time metering is the epoch 1958.0. The 58 treatments have the median epochs from September/October 1960 to December 1974/January 1975 at three-month intervals. They were based on latitude values which varied in number between 1,329 and 705. Their results were derived by simple and modified harmonic analyses.

4.2. Special procedure

Simple harmonic analysis was ueed to determine the approximate values of the unknowns for modified harmonic analysis, with adjuetments performed using a fixed CHANDLER period between 1.200 and 1.182 yeara and an interval of 0.002 years. The criterion for the adjustment results that give the best approximate values together with the CHANDLER period introduced into the specific calculation, should be that the mean square error ie minimal, i.e.

m_o = min. within the treatmente.

Decisions, however, were possible only in the case of nine treatments, and the latitude values were either unfavourably distributed or ineufficient in number in the other cases.

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It can be assumed that the phase of the CHANDLER wobble changes at shorter intervals than its period. The treatments for six-year periods give smoothed results, and a direct phase change in the CHANDLER wobble is therefore unreal, but what is indicated is a change in period. The second criterion therefore was that the phase of the CHANDLER wobble must be constant with time,

α_{CH} = const. between the treatments.

Modified harmonic analysis was carried out using the approximate values found by applying the two criteria. The calculations were repeated with the results obtained, the purpose being confirmation. It turned out that the results were in agreement with the approximate values only in those treatments where m_o = min. Only the results of four treatments were eventually assumed to be definitive. In one case the result was implausible, and in four others better results were obtained using the criterin α_{CH} = const. This indicates that modified harmonic analysis requires very good data material as far as quantity and distribution are concerned.

Then the question arose what agreement there was between the final results obtained from modified harmonic analysis and those from simple harmonic analysis using a fixed definitive CHANDLER period. As a first step, therefore, those treatments that were suitable were checked to see whether the adjustment results were available for the definitive value of the CHANDLER period rounded to three decimals. Where this was not the case, a supplementary calculation was made using that value. The results from the two analysis methods were then compared, and it was found that they were in agreement and thus confirmed one another.

Concerning the final results from the other treatments, the only way to determine them was according to the criterion α_{CH} = const., from the adjustment results obtained from simple harmonic analysis. In order to define these results, the four phase angles of the CHANDLER wobble which were already definitive, served as reference values. In this connection it was necessary, mostly as a supplement to the adjustments with a CHANDLER period interval of 0.002 years, to determine one or two intermediate values for the latter.

Of the definitive results derived for the eight quantities - the mean latitude of Potsdam, the amplitude, phase and period of the CHANDLER wobble and the amplitude and phase of the annual and semi-annual wobbles - only those relating to the CHANDLER period will be discussed here.

5. Results relating to the CHANDLER period

The latitudes observed at the Potsdam Observatory between 1957.8 and 1978.0 gave values of the CHANDLER period from 1.185 to 1.193 years. Fig. 1 shows its temporal variation. The mean square errors related to the results obtained by adjustment are also indicated and amount to ±0.002 years.

According to these investigations, the actual average value of the CHANDLER period is 1.189 years. More studies must be made to find out in how far the associated temporal variation is real. CHOLLET and DÉBARBAT /1/ determined a CHANDLER period of 1.192 years from the amplitude spectrum of latitudes observed at Paris from 1956.5 to 1970.8. As can be seen from Fig. 1 the comparable own values, or their average which is 1.191 years, are in good agreement with that result.

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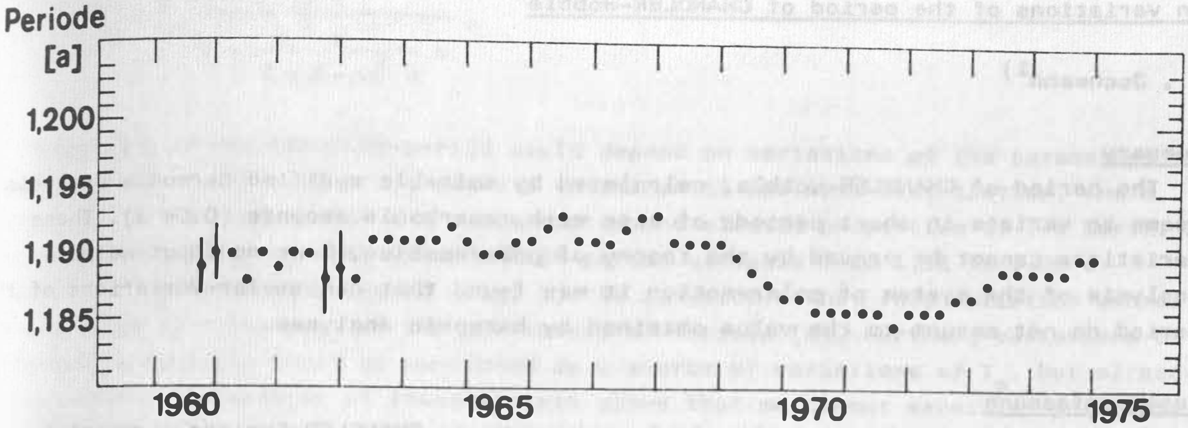

Fig. 1. Temporal variation of the CHANDLER period;
♦ Adjustment result from modified harmonic analysis,
• Result from simple harmonic analysis

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On variations of the period of CHANDLER-wobble

H . Jochmann[1)]

Summary

The period of CHANDLER-wobble, calculated by suitable modified harmonic analysis, seems to variate in short periods of time with remarkable amounts (0.04 a). These variations cannot be proved by the theory of polar-motion. From an input-output-analysis of the system of polar-motion it was found that nonsecular-variations of the period do not amount to the value obtained by harmonic analyses.

Zusammenfassung

Die mit Hilfe der harmonischen Analyse berechnete CHANDLER-Periode variiert in relativ kurzen Zeiträumen um bemerkenswerte Beträge (0,04 a). Diese Variationen sind auf Grund der Theorie der Polbewegung nicht erklärbar. Durch eine Eingangs-Ausgangs-Analyse des Systems der Polbewegung wurde festgestellt, daß nichtsäkulare Variationen dieser Periode die mittels harmonischer Analyse berechneten Beträge nicht erreichen können.

1. Phanomenon and possibility of a variation of the period of CHANDLER-wobble

Several publications concerned with the harmonic analysis of polar-motion express a variation with time of the period of CHANDLER-wobble. This variation can be accepted being real only if we can state a natural cause for it. The model of polar-motion is given by the differential-equation

$$\dot{u} + \lambda u = i\beta\,(u - \psi) \tag{1}$$

referring to a plane pole-coordinate-system. The origin of this system is the mean position of the pole of inertia. In (1) are

u the vector of the pole of rotation

ψ the vector of the excitation-function

$\lambda \approx 0.05$ the damping parameter,

and

$$\beta = \frac{2\pi}{T_o} \tag{2}$$

is the circular frequency of CHANDLER-wobble.

According to LOVE and LARMOR (1909) the CHANDLER-period is related to the EULERian-period

$$T_r = \frac{A}{C - A}\,\frac{2\pi}{\omega} \quad . \tag{3}$$

by the equation

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$$(4) \qquad T_o = T_r \frac{1}{1 - \dfrac{\omega^2 a}{2 g \varepsilon - \omega^2 a} k} .$$

Variations of the CHANDLER-period could depend on variations of the parameters of equation (4). A variation of T_r means a variation of the mass-distribution, and a variation of the LOVE-number k a variation of the elastic properties of the Earth. In the period from 1930 to 1960 the CHANDLER-period variates from 1.16 to 1.20 a according to a harmonic analysis (Fig. 1). It is evident that this variation cannot be explained by variations of the parameters of formula (4). Further, variations of core-mantle-coupling could be mentioned as a source of variations of T_o, but already an approximate estimation of these effects shows that we cannot expect an influence on variations of T_o which explains an amount of 0.04 a.

We must consider that harmonic analysis is not suited to determine T_o on certain circumstances. Especially it is not suited to determine a variation of T_o since it is impossible to differ period-variations from phase-variations. Therefore a mathematical model to determine T_o must be choosen which is in closer connection to the mechanics of polar-motion.

2. An input-output-analysis of the system of polar-motion.

Polar-motion is represented by equation (1). The input of this equation is the excitation-function ψ. Since the circular-frequency of the CHANDLER-wobble is a parameter of differential-equation (1) its value can be determined if an excitation-function and its corresponding part of polar-motion is known.

We used the annual period of polar-motion and its excitation-function which is caused by meteorological events. In our case it comprises seasonal air-mass-mations and variations of ground-water-storage. The excitation-function was calculated by the following relation:

$$(5) \qquad \psi(t) = - \frac{1}{C - A} \int_S \frac{D(\varphi, \lambda, t)}{2} \sin 2\varphi \exp(i\lambda) \, ds.$$

By this equation mass-motion is represented as density-variation of a layer at the Earth's surface. $D(\varphi, \lambda, t)$ involves the local density-variations and parameters depending on the Earth's shape. From monthly mean values of $\psi(t)$ the mean values of the annual periods for 1930.0 - 1939.9, 1940.0 - 1949.9, 1950.0 - 1959.9 were derived. Introducing this excitation-function in (1) a particular solution is obtained, expressing the polar-motion with annual period

$$(6) \qquad u_M = u_M(t, T_o).$$

(6) has to be in accordance with the annual period calculated by pole-coordinates of the IPMS (u_A) provided that the circular-frequency of CHANDLER-wobble is correct. Supposing that the differences $u_M - u_A$ depend on an error of T_o, a correction of its value can be calculated by minimizing the functional

$$(7) \qquad \int_0^{2\pi} (u_M(t, T_o) - u_A(t))^2 \, dt.$$

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From (7) the following values of the CHANDLER-period were obtained:

Period	T_o	Accuracy	Precision	T'_o
1930 - 39.9	1.197 a	0.002 a	0.017 a	1.163 a
1940 - 49.9	1.203	0.002	0.013	1.203
1950 - 59.9	1.187	0.002	0.039	1.187
1930 - 59.9	1.190	0.001	0.013	1.190

T'_o are the values, obtained from harmonic analyses. The accuracy represents the errors of pole-coordinates and air-pressure-values. The precision is a measure for the knowledge of natural excitation-functions with annual period.

The values T_o must be considered as better approximations to the real value of the CHANDLER-period, since the mathematical model, used for its calculation, is in closer connection to the physical model of polar-motion. It is proved by the obtained results that determinable nonsecular-variations of T_o do not exist.

The variations obtained from harmonic analyses are induced by variations of the phase-angle of CHANDLER-wobble. The values T_o and T'_o obtained for the period 1930 - 59.9 agree very well. From this ensues that the mean of the phases vanishes for long time-series.

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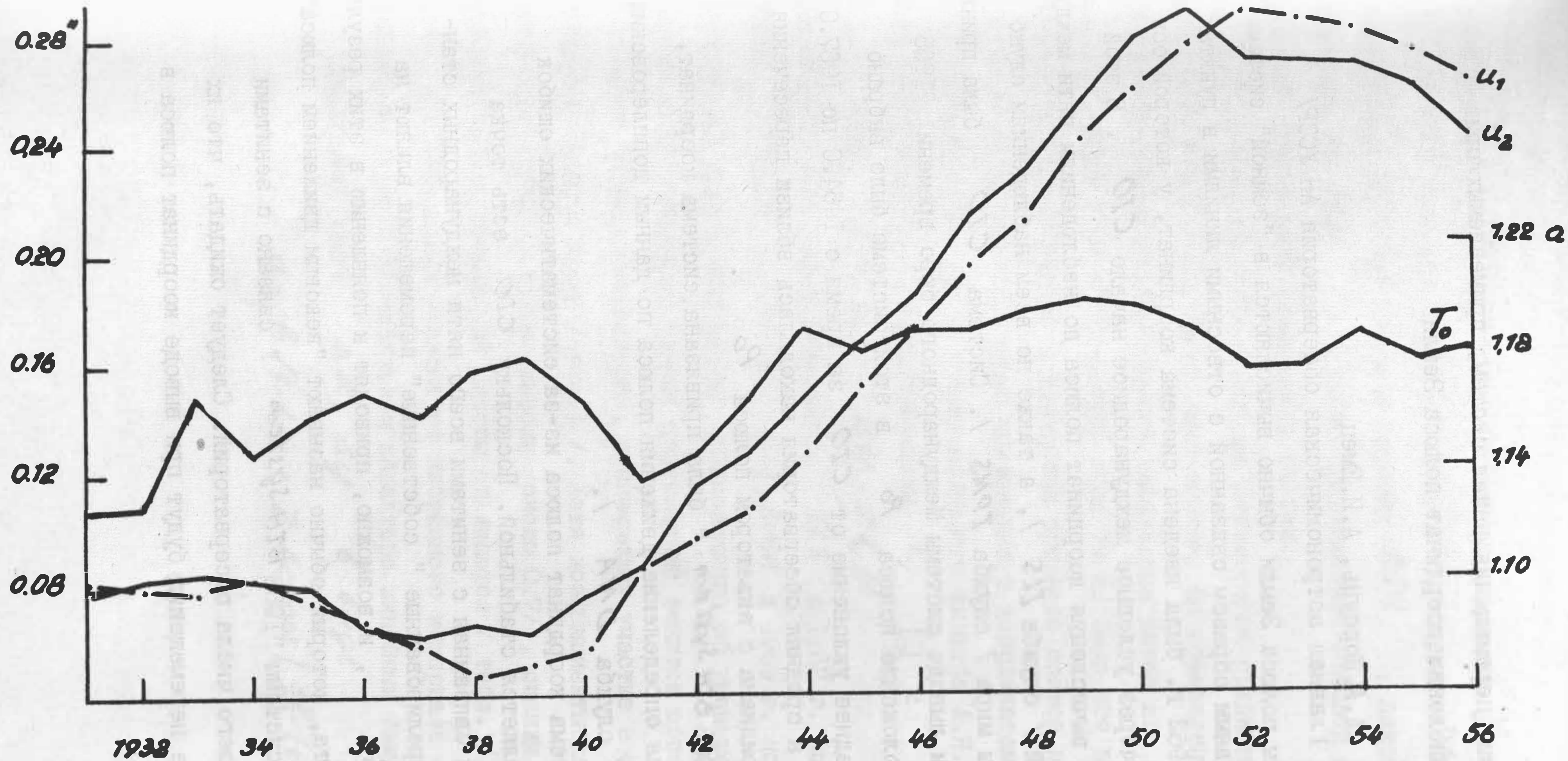

Fig. 1 Amplitudes and periods of the CHANDLER-wobble (1931 - 1956)

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Относительные перемещения начал систем, применяемых при вычислении координат полюса Земли

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I. Координаты полюса Земли обычно вычисляются в "земной" системе координат, условным образом связанной с отвесными линиями в пунктах наблюдений. С 1962 г. была введена система координат, у которой ось OZ проходит через условное международное начало CIO. В этой системе ведутся вычисления координат полюса по наблюдениям пяти международных станций / служба ILS /, а также по всем наблюдениям служб времени и широты мира / служба IPMS /. Система CIO была принята за основу при выводе системы Международного бюро времени "1968 BIH System ". Положение полюса P_0 в этой системе было выбрано так, что его среднее уклонение от CIO за время с 1964.0 по 1967.0 равнялось нулю, а средняя обсерватория находилась вблизи пересечения Гринвичского меридиана с экватором полюса P_0.

К системе "1968 BIH System " была привязана система координат, в которой ведется определение движения полюса по данным допплеровских наблюдений ИСЗ / служба DMA /.

Условная система координат полюса из-за систематических ошибок наблюдений не является стабильной. Поскольку CIO есть точка условным образом связанная с зенитами всего пяти международных станций, то их некоррелированные " собственные" перемещения влияют на результаты ILS , и возможно, приводят к появлению в этих результатах того эффекта, который обычно называют "вековым движением полюса". Начало отсчета системы "1968 BIH System " связано с зенитами значительно большего числа обсерваторий. Следует ожидать, что их некоррелированные перемещения будут при выводе координат полюса в

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значительной степени взаимно уничтожаться, так что указанный эффект будет заметно слабее. Координаты полюса в системе DMA, хотя первоначально были привязаны к системе BIH, далее вычислялись независимо от BIH и поэтому представляют большой интерес при сравнении стабильности различных систем.

Были рассмотрены относительные перемещения среднего полюса эпохи наблюдения и начал указанных выше систем. По определению А.Я.Орлова средним полюсом эпохи наблюдений называется такое его положение, какое он занимал бы в эту эпоху, если бы не было его периодических колебаний. Относительные перемещения среднего полюса и начал условных систем легко определить путем применения к координатам в i-той условной системе / x_i, y_i / низкочастотного фильтра А.Я.Орлова - линейного преобразования с коэффициентами K_j [I] :

$$\Delta x_i = \sum_j K_j x_i , \quad \Delta y_i = \sum_j K_j y_i$$

для анализа были взяты результаты ILS с I962 г. по I976 г. [2], BIH с I962 г. по I978 г. [3], DMA с I969 г. по I978 г [3].

Проведенный анализ подтвердил предположение об уменьшении влияния собственных некоррелированных перемещений зенитов обсерваторий при увеличении числа обсерваторий, принимающих участие в определении координат полюса Земли / рис.I /. Хотя коэффициенты корреляции соответствующих кривых довольно высоки /около 0.7/, оценки линейных трендов относительных перемещений систем отличаются / табл.I/. Следует отметить, что эти оценки зависят от избранного интервала осреднения, что свидетельствует о нестабильном характере линейных изменений.

Представив далее Δx, Δy в виде

$$a + b(t - t_0) + \sum A_k \cos\left[\frac{2\pi}{T_k}(t - t_0) + \alpha_k\right],$$

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мы оценили T_k методом спектрального анализа с максимальной энтропией / при числе отбеливающих коэффициентов $M=4\sqrt{n}$ /, и A_k, α_k по методу наименьших квадратов / табл.I /. Общих долгопериодических колебаний в интервале времени до IO лет не обнаружено.

2. С 1979 г. BIH вычисляет координаты полюса в новой условной системе "1979 BIH System", которая отличается от системы "1968 BIH System" следующими поправками:

$$x : C_x = 0.''024 \sin 2\pi(t-0.158) + 0.''007 \sin 4\pi(t-0.289),$$

$$y : C_y = 0$$

$$UT1 : C_u = 0.^s0007 \sin 2\pi(t-0.477) + 0.^s0007 \sin 4\pi(t-0.387).$$

Эти поправки были получены на основании сравнения координат полюса систем BIH и DMA. Проведенный нами спектральный анализ разностей $X_{BIH}-X_{DMA}$, $Y_{BIH}-Y_{DMA}$ за время с I969 по I978 гг. показал, что помимо указанных выше систематических расхождений по координате x, имеются периодические вариации разностей $Y_{BIH}-Y_{DMA}$ с периодами 2.5 и 7.5 лет и амплитудами, соответственно, равными: $0.''018$ и $0.''014$.

Одной из возможных причин систематических расхождений координат полюса по данным BIH и DMA с годовым и полугодовым периодами может быть несовершентсво методики вычисления, применяемой BIH. Эта методика включает как алгоритм вычисления координат полюса так и геометрию сети служб времени и широты, по наблюдениям которых ведутся вычисления.

BIH определяет x, y, z, t из решения систем условных уравнений вида

$$\begin{aligned} x\cos\lambda_i + y\sin\lambda_i + z &= \varphi_i - \varphi_{i0} \\ -x\sin\lambda_i \operatorname{tg}\varphi_i + y\cos\lambda_i \operatorname{tg}\varphi_i + t &= UT0_i - UTC \end{aligned} \qquad (1)$$

Судить о корректном решении системы, а следовательно, о хорошем разделении неизвестных x, y, z, t можно по корреляционной матрице, элементы которой равны

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$$r_{ik} = \alpha_{ik} / \sqrt{\alpha_{ik}\alpha_{kk}}$$

где α_{ik} элементы обратной матрицы системы нормальных уравнений. Корреляционная матрица для системы вида (I), которая решается в BIH приведена в табл.2. Слева и внизу от главной диагонали приведены r_{ik} для случая, когда условным уравнениям приписываются веса, согласно определениям BIH, справа и вверху - с единичным весом, соответственно. Из табл.2 видно, что из всех неизвестных наименее полно разделяются неизвестные x и z; введение весов формально улучшает это разделение, однако, повидимому, не полностью освобождает определяемые координаты x от влияния общего неполярного z -члена.

Проведенный анализ общего z -члена за время с 1968 г. по 1978 г. позволяет представить его в виде:

$$z = 0.''004 - 0.0005(t-t_0) - 0.''027\cos[2\pi(t-t_0)+100^\circ] + $$
$$+ 0.''003\cos[4\pi(t-t_0)+165^\circ] + 0.''003\cos\left[\frac{2\pi}{1.7}(t-t_0)+302^\circ\right] + $$
$$+ 0.''004\cos[2\pi/7.0(t-t_0)+193^\circ]$$
$$t_0 = 1973.0$$

Обращает на себя внимание тот факт, что оценки амплитуд годовой и полугодовой волн z - члена близки к соответствующим оценкам поправки C_x. Присутствие общего z -члена в уравнениях вида (I) свидетельствует о том, что экватор мгновенного полюса P смещен на величину z, периодически изменяющуюся во времени, относительно условного экватора полюса P_0 и является малым кругом. Решение системы вида (I) не позволяет полностью исключить этот эффект, и происходит это из-за неравномерного распределения служб времени и широты по земному шару / преимущественное распределение их в Европейской части/.

При сравнении координат в системах BIH и DMA смещение экватора мгновенного полюса относительно условного проявляется в основном как смещение по оси OX, т.е. смещение средней обсерватории или начала отсчета долгот.

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Таблица I

T в годах	TLS 1962-1976 x	TLS 1962-1976 y	BIH 1962-1978 x	BIH 1962-1978 y	DMA 1969-1978 x	DMA 1969-1978 y
a	0.″04I	0.″24I	0.″015	0.″249	0.″004	0.″253
b	0.0038	0.0020	0.0028	0.00I3	0.0009	0.0022
2.5	-	-	-	-	0.0I0	0.008
3.0	0.004	0.0I0	-	-	-	-
7.5	-	-	-	-	0.0II	0.0I4
9.6	0.027	0.0II	-	-	-	-
			1972-1978		1972-1978	
a			0.″025	0.″252	0.″009	0.″254
b			0.00I4	0.0020	0.000I	0.0030

Таблица 2

	x	y	z	t
x	-	-0.05	-0.53	-0.I4
y	-0.I4	-	-0.II	0.22
z	-0.26	0.04	-	0.I0
t	0.07	0.04	0.02	-

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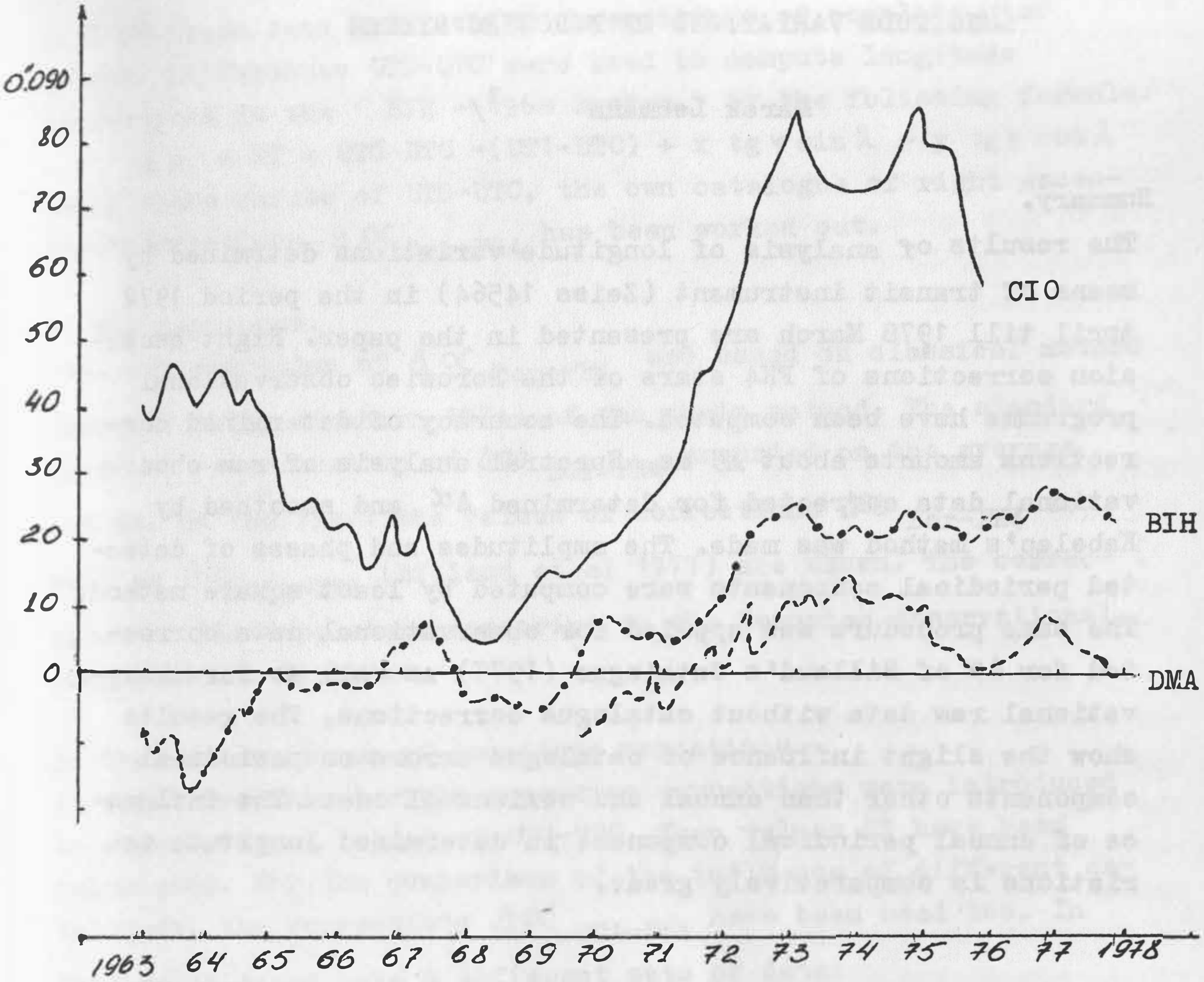

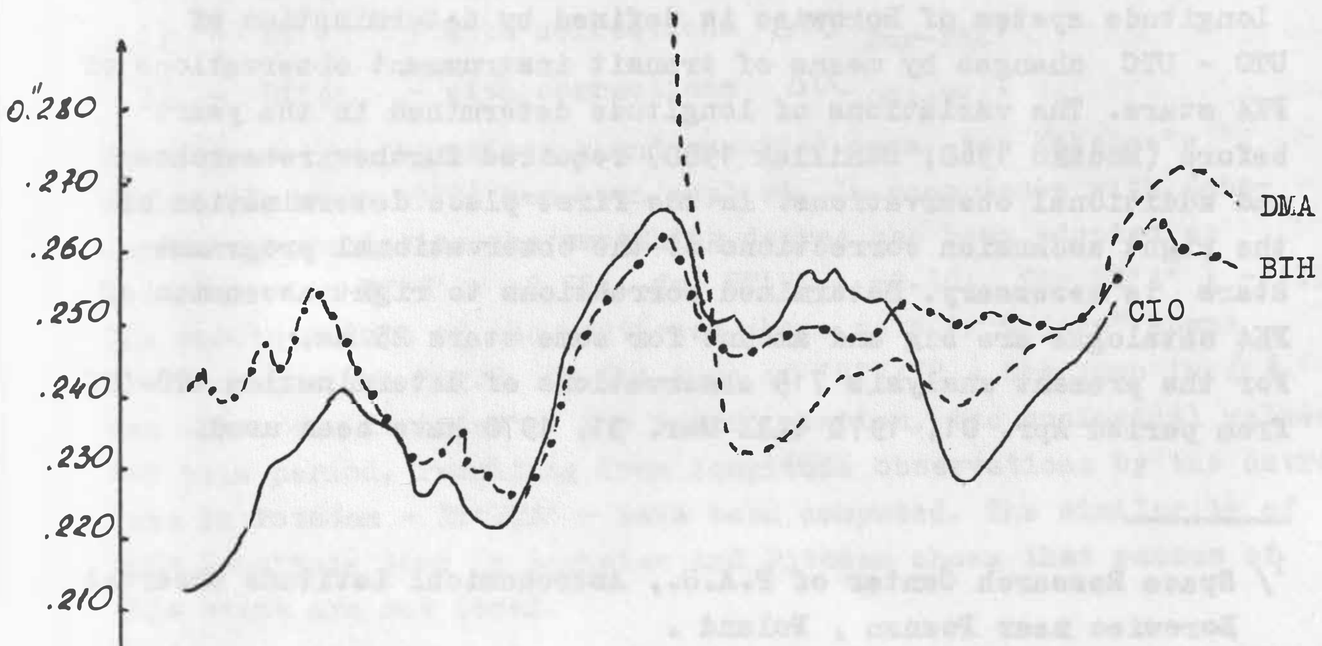

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LONGITUDE VARIATIONS OF BOROWIEC SYSTEM

Marek Lehmann [1]

Summary.

The results of analysis of longitude variations detrmined by means of transit instrument (Zeiss 14564) in the period 1972 April till 1978 March are presented in the paper. Right ascension corrections of FK4 stars of the Borowiec observational programme have been computed. The accuracy of determined corrections amounts about ±5 ms. Spectral analysis of raw observational data corrected for determined $\Delta\alpha$ and smoothed by Kabelac's method was made. The amplitudes and phases of detected periodical components were computed by least square method. The same procedure was applied for observational data corrected for $\Delta\alpha$ of Billaud's Catalogue (1977) as well as for observational raw data without catalogue corrections. The results show the slight influence of catalogue errors on periodical components other than annual and semiannual ones. The influence of annual periodical component in determined longitude variations is comparatively great.

1. Introduction.

Longitude system of Borowiec is defined by determination of UT0 - UTC changes by means of transit instrumment observations of FK4 stars. The variations of longitude determined in the years before (Moczko 1968, Schillak 1980) required further researches and additional observations. In the first place determination of the right ascension corrections of the observational programme stars is necessary. Determined corrections to right ascension of FK4 catalogue are big and amount for some stars 25 ms.

For the present analysis 715 observations of determination UT0-UTC from period Apr. 01, 1972 till Mar. 31, 1978 have been used.

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90 % of these data consists of observations of complete star groups. Differences UTO-UTC were used to compute longitude corrections in the ' BIH - 1968 System ' by the following formula:

$$\Delta\lambda = RT = UT0-UTC - (UT1-UTC) + x\ tg\varphi \sin\lambda - y\ tg\varphi \cos\lambda$$

Using these values of UTO-UTC, the own catalogue of right ascension corrections $\Delta\alpha_{Bor-FK4}$ has been worked out.

2. The catalogue.

The determination of $\Delta\alpha_{Bor-FK4}$ are based on classical method (Podobed 1975, Eichhorn 1974) of the chain method. The standard error of determination of $\Delta\alpha_{Bor-FK4}$ amounted on the average $\pm$ 5 ms. On the Fig.1 the values of corrections $\Delta\alpha_{Bor-FK4}$ as well as $\Delta\alpha_{GCA-FK4}$ (Billaud et al 1977) are shown. The corrections of FK4 Supp stars appearing in the Borowiec observational programme are framed.

3. The determination of longitude variations.

At first determined right ascension corrections were introduced to observational values of UTO-UTC. Then values RT have been calculated. For the comparison of the influence of different catalogues, the corrections $\Delta\alpha_{GCA-FK4}$ have been used too. In this solution we have 3 different sets of data:

1) - RT'S' - without catalogue corrections,
2) - RT'V' - with corrections $\Delta\alpha_{Bor-FK4}$'
3) - RT'A' - with corrections $\Delta\alpha_{GCA-FK4}$'

In order to get equidistant and smoothed data, the Kabelac's method (Kabelac 1977) has been applied. In accordance with Kabelac's recommendation the smoothing degree has been adopted as follows: for RT'S' : -2.55; for RT'V' : -2.10; for RT'A' : -2.05. The smoothed data of the mentioned above sets in 5 days' spans are shown on the Fig.2. In the turn of 1977/78 a big jump in $\Delta\lambda$ was observed. In order of its interpretation, the analogical values for this period, resulting from longitude observations by the astrolabe in Potsdam - RT'PTA' - have been computed. The similarity of this longitude jump in Borowiec and Potsdam shows that causes of this event are not local.

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4. The analysis of longitude variations.

In order to determine the periodical components in observations of longitude, the spectral analysis by the use of MESA (Maximum Entropy Spectral Analysis) - method (Smylie et al 1973, Jaks, Lehmann 1980) has been applied. A 25 % and 50 % point prediction-filters were used in the estimate. Received spectra from sequencies RT'S', RT'V', RT'A' are presented on the Figures 3 , 4 , 5. Computations of values P maximum entropy spectral power density has been carried out for frequencies from 0.1 to 10.0 CPY. The mentioned above Figures shows clear decrease of the value of spectral density function P begining from the argument of about 3.2 CPY. Periods shorter than 100 days cannot be analysed due to following causes:

1) described above decreasing of function P,
2) existing of gaps of observations of order of 30 days and more,
3) low accuracy of TI observations.

In the purpose of finding of amplitudes and phases of periodical components by the MESA-method, the method of least squares has been applied. The results are given in the tab. 1. Taking into account the existence of the annual and semiannual components in these variations, the annual and semiannual periods were added to the set of periods of RT'A' data determined by MESA. They are denoted by parantheses. The differences of amplitudes of annual and semi-annual components of different sets is clearly seen. It is worth to note that introduction of $\Delta\alpha_{Bor-FK4}$ the annual wave in variations of Borowiec longitude increased. In the order to determine reality and appreciation of influence of catalogue errors as well as accepted periodicity, the statisical tests have been applied. Statistical analysis were used for every of sequencies RT'S', RT'A', RT'V' before and after removing from these sequencies respective periodical components given in the tab.1 . The Fig.6 and 7 presents 30 - class distributive series of mentioned above sequencies. Compendium of descriptive characters of these sequencies from performed tests of randomness on the significance level 5 % as well as Pearson's χ^2 is given in the tab.2 .

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5. Conclusions.

A. Right ascension corrections of the Borowiec Catalogue are in accordance with the corrections of the astrolabe catalogue.

B. Introduction of catalogue corrections has not explained the longitude variations.

C. Differnces of amplitudes and phases of annual waves between RT'V' and RT'A' indicate that own right ascension catalogue are closly connected with local source influences having annual period. Separation of them is wery complicated and should require special geophysical examinations.

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Smylie D.E., Clarke G.K.C., Ulrych T.J. - Analysis of Irregularities in the Earth's Rotation - Methods in computational Physic, Acad. Press, New York 1973, 391-430.

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Period |in days|			Amplitude |in ms|			Phase |in degrees|		
RT'S'	RT'V'	RT'A'	RT'S'	RT'V'	RT'A'	RT'S'	RT'V'	RT'A'
1353	1405	1353	6.2	5.9	6.1	232.4 ± 3.1	235.2 ± 4.0	225.5 ± 4.1
435	425	425	4.1	4.7	4.8	246.0 4.6	250.4 5.0	244.9 5.3
(345)	(362)							
[365.24]	[365.24]	[365.24]	6.2	8.5	2.7	230.6 3.1	125.5 2.8	257.4 9.5
252	254	254	3.5	2.7	3.1	327.5 5.5	339.1 8.3	339.8 8.1
230	225	227	3.7	3.9	3.6	334.5 5.1	299.9 5.8	337.3 7.0
(183)	(181)							
[182.6]	[182.6]	[182.6]	4.4	3.9	1.9	289.2 4.3	327.0 5.8	291.4 13.2
123	119	118	2.1	2.1	2.3	77.2 8.5	25.0 10.5	21.3 10.7
noise for amplitudes:			±.3	±.4	±.4			

Table 1. Amplitudes and phases from MESA-method detected periodicitics.

[ ] - received period; ( ) - detected period.

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	RT'S'	RT'V'	RT'A'	RT'S'	RT'V'	RT'A'
	before removal			after removal		
	test of randomness					
median	-13.9	-14.0	-14.1	.0	.1	-.1 [ms]
let. A	12	17	22	18	28	31
let. B	12	17	22	18	28	31
series	24	34	44	36	56	62
statist.	-2.14	-2.03	-1.93	-2.01	-1.80	-1.73
test limit:		1.96			1.96	
randomnity	-	-	+	-	+	+
	Pearson's χ^2 test					
max.val.	15.8	22.5	15.7	14.5	14.8	18.4 [ms]
min.val.	-43.3	-40.5	-38.6	-14.2	-15.5	-16.6 [ms]
max-min	59.1	63.0	54.3	28.7	30.3	35.0 [ms]
lenght	2.0	2.2	1.9	1.0	1.1	1.2 [ms]
mean	-13.3	-13.4	-13.0	.0	.0	.0 [ms]
sigma	10.1	10.8	9.5	4.7	5.7	6.2 [ms]
statist.	75.20	48.88	90.46	26.91	39.60	30.28
test limit:		37.67			37.67	
normality	-	-	-	+	-	+

Table 2. Some results of hypothesis testings.

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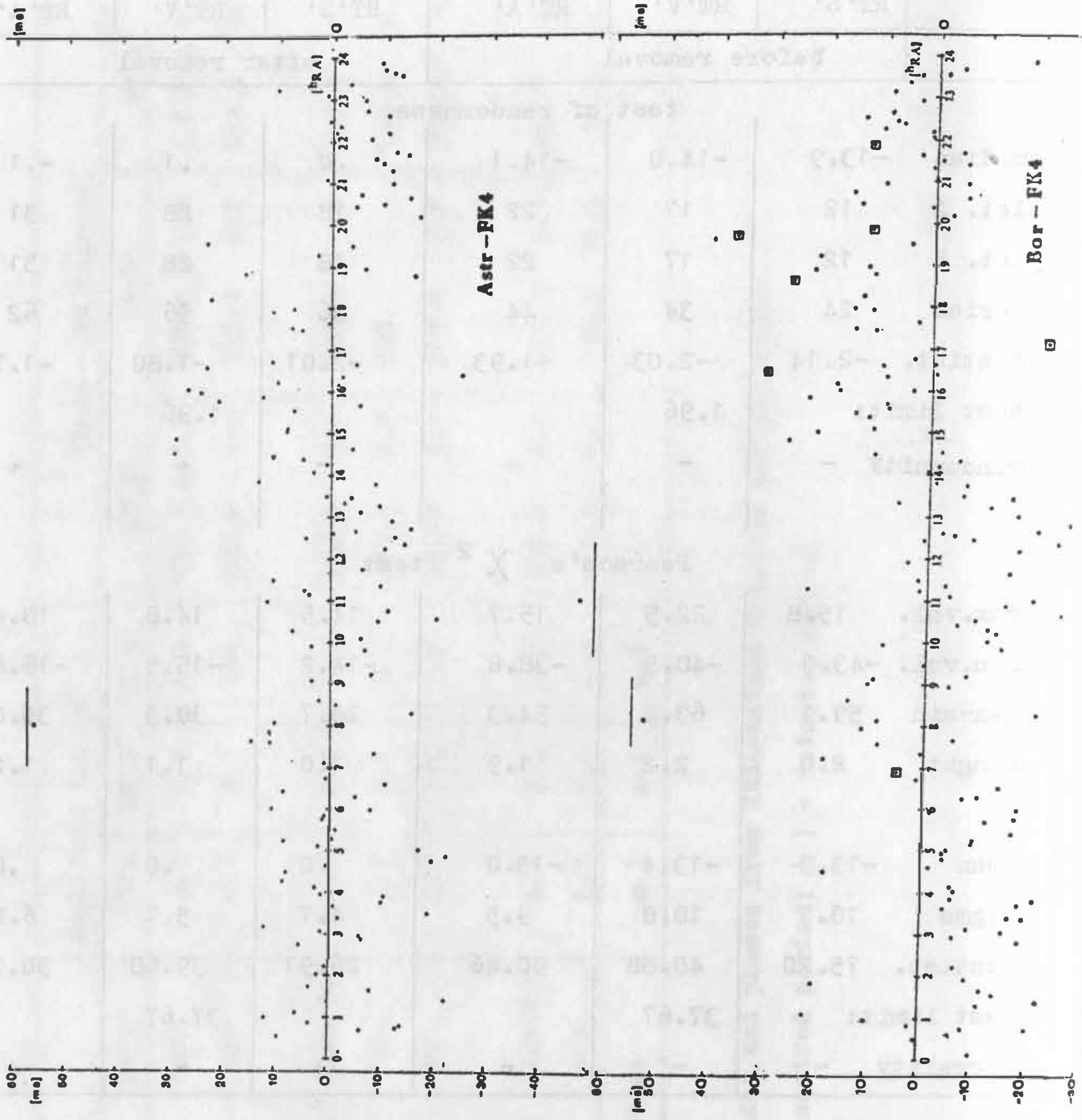

Fig. 1. Right ascension corrections of Borowiec observational programme stars.

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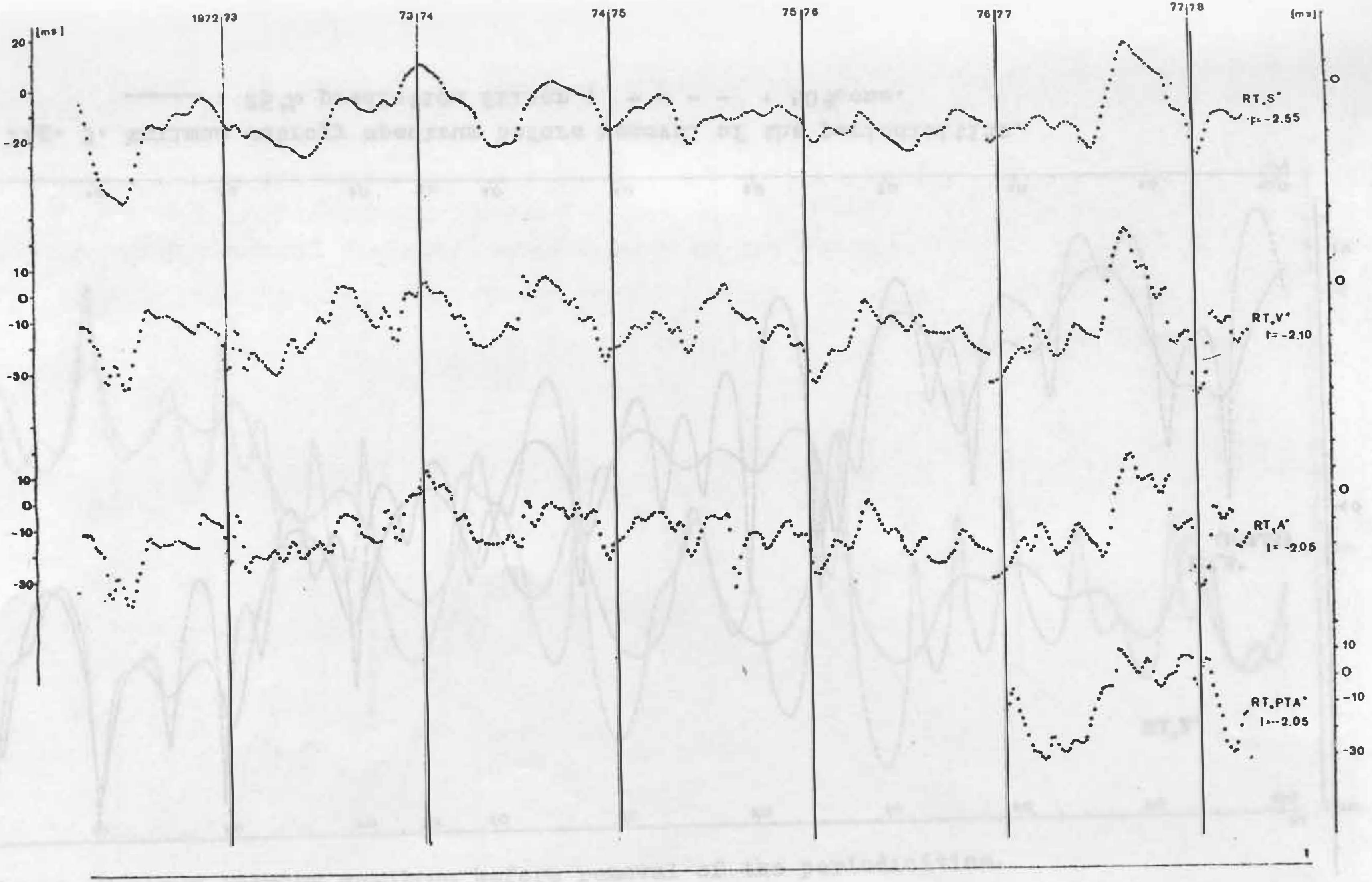

Fig. 2. Smoothed sequencies of longitude corrections.

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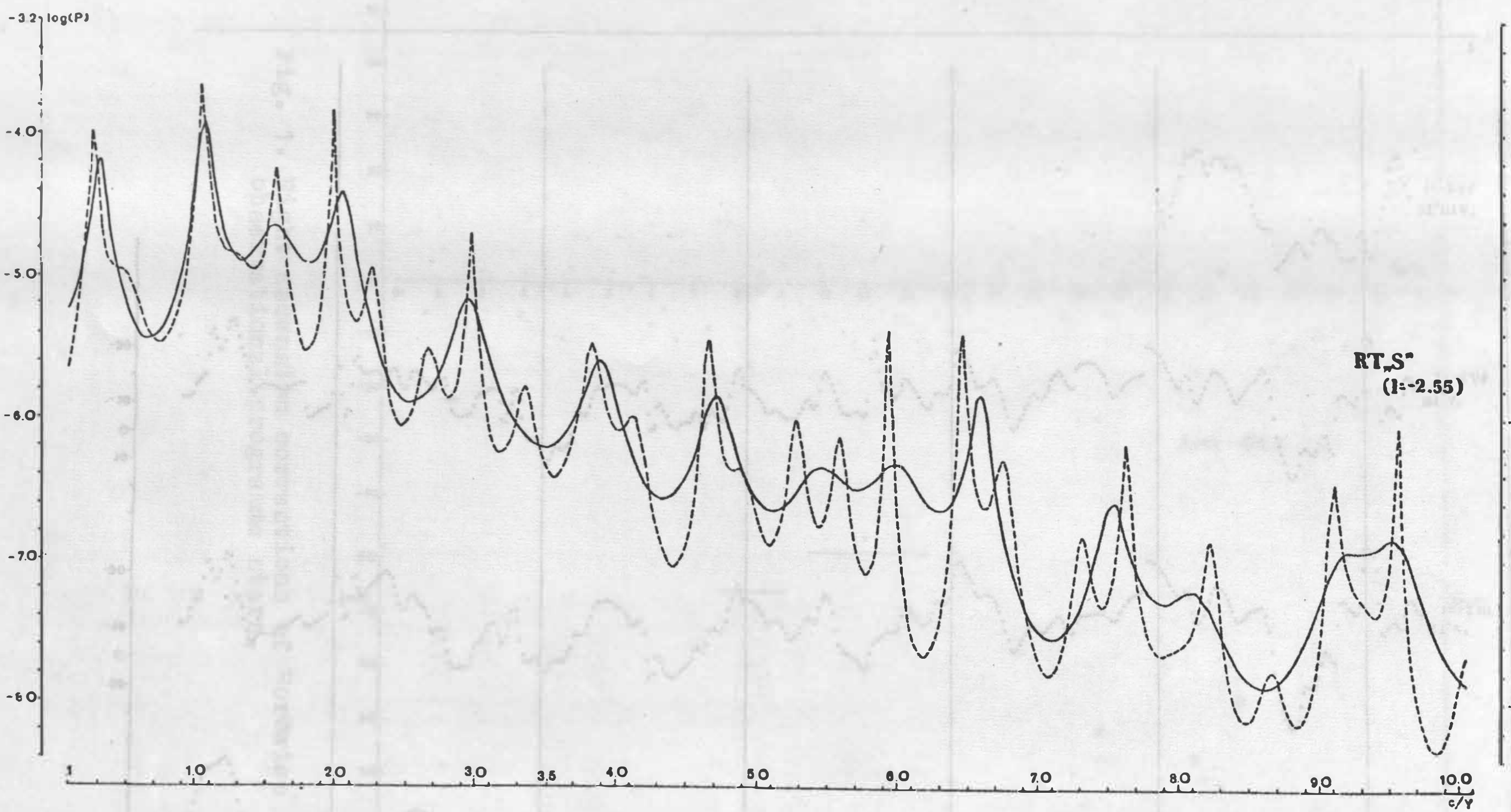

Fig. 3. Maximum entropy spectrum before removal of the periodicitics.
——— : 25 % prediction filter ; - - - - : 50 % one.

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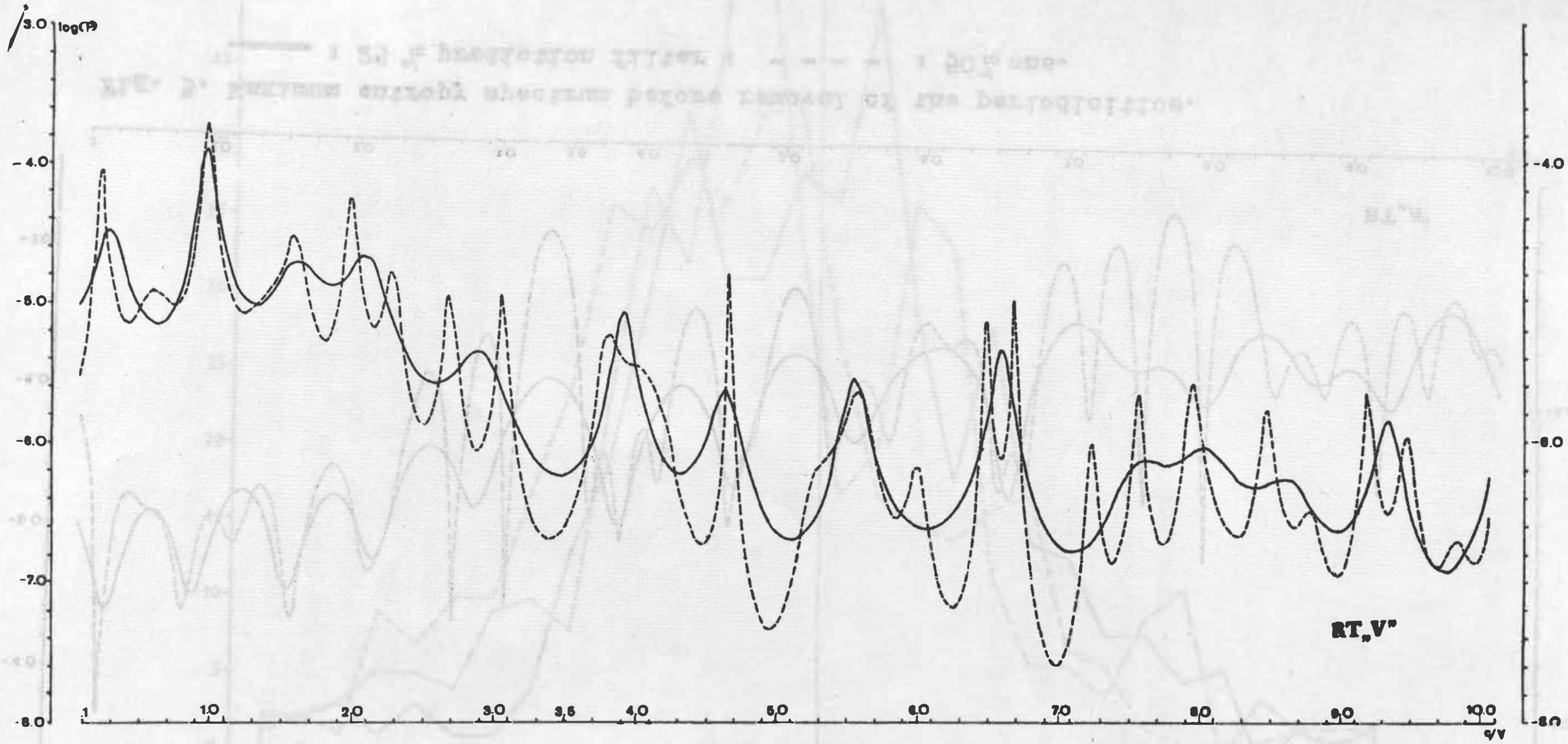

Fig. 4. Maximum entropy spectrum before removal of the periodicitics.
——— : 25 % prediction filter ; - - - - : 50 % one.

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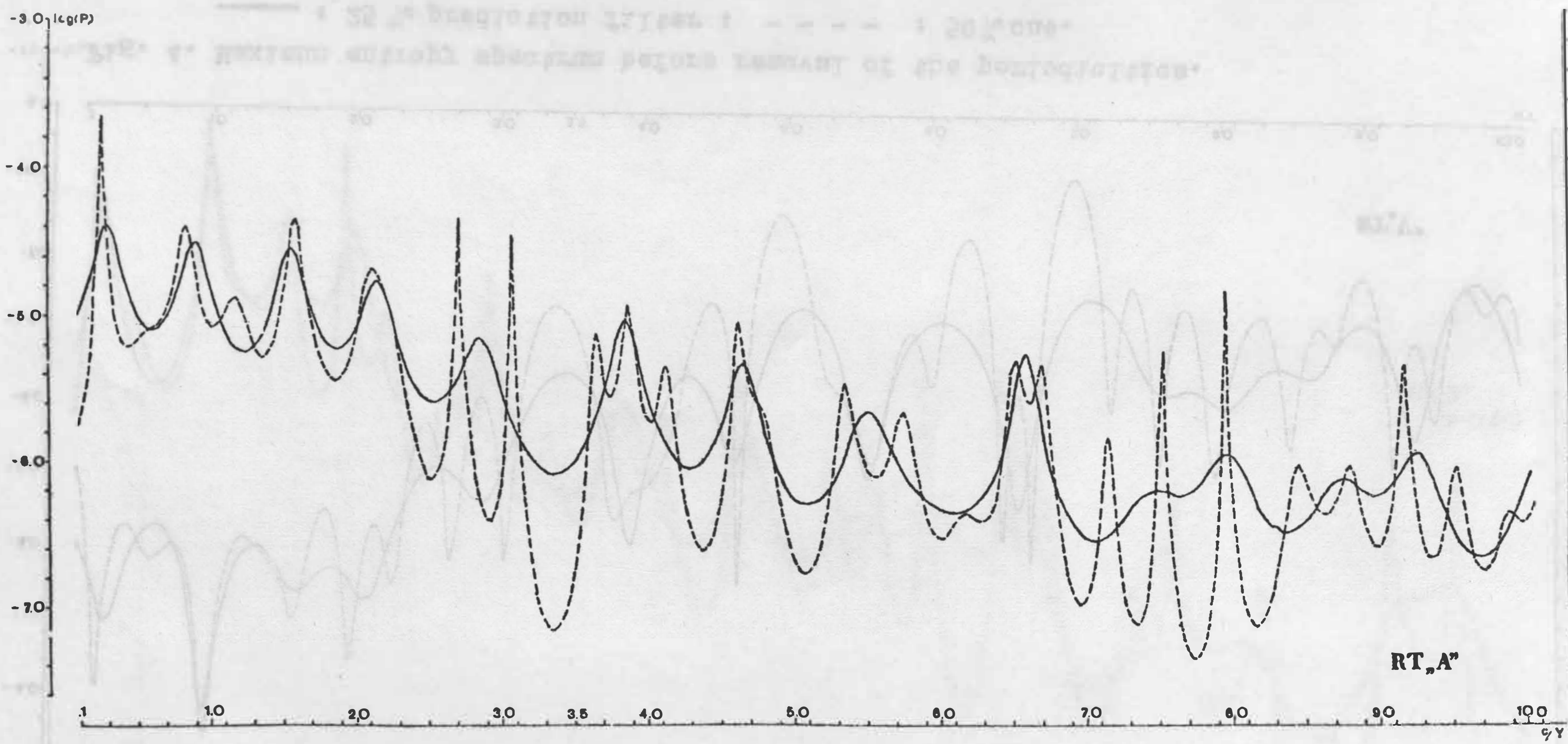

Fig. 5. Maximum entropy spectrum before removal of the periodicitics.
—— : 25 % prediction filter ; - - - - : 50 % one.

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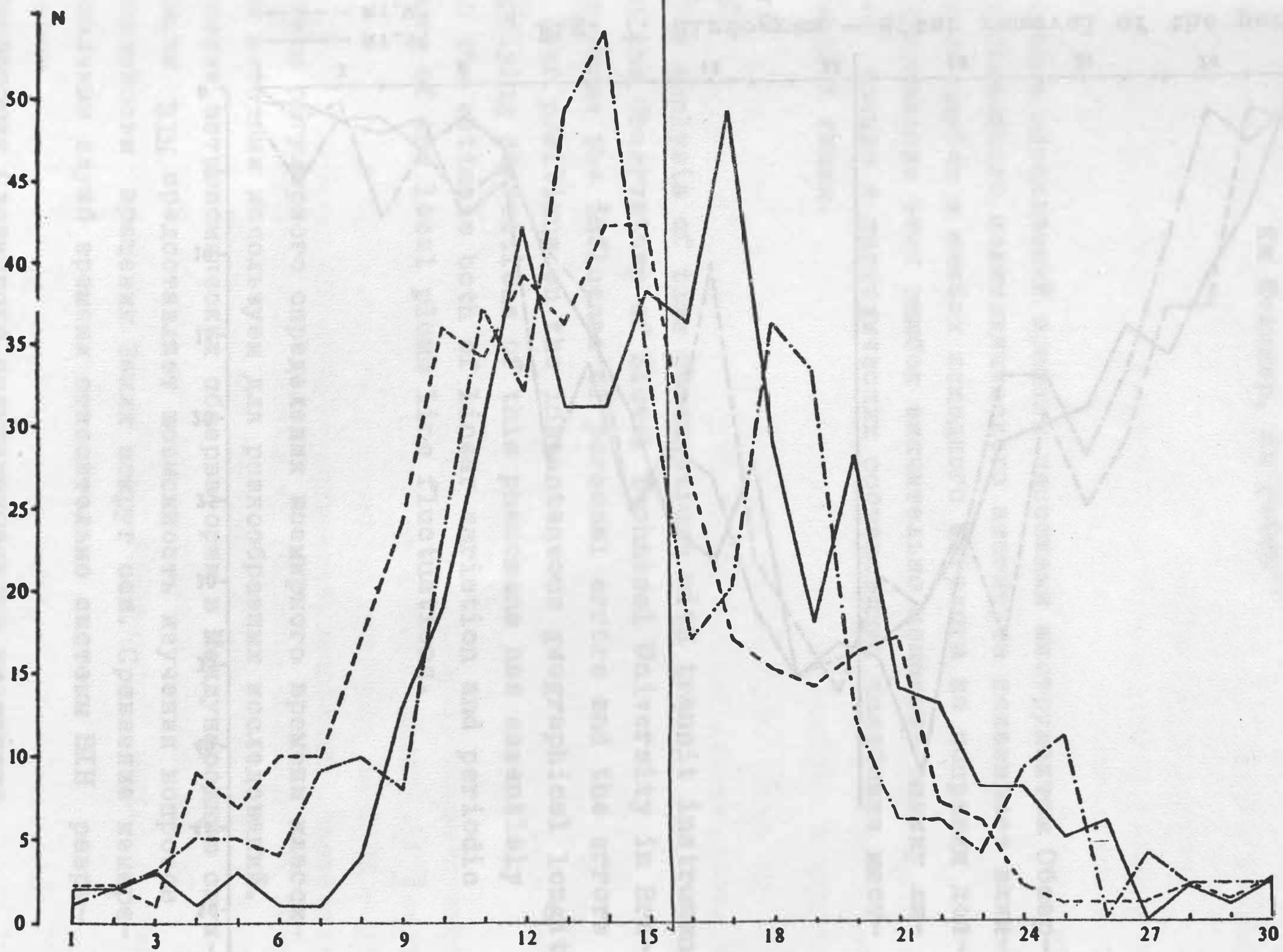

Fig. 6. Histogram - before removal of the periodicitics.
(In % = N×100/440).

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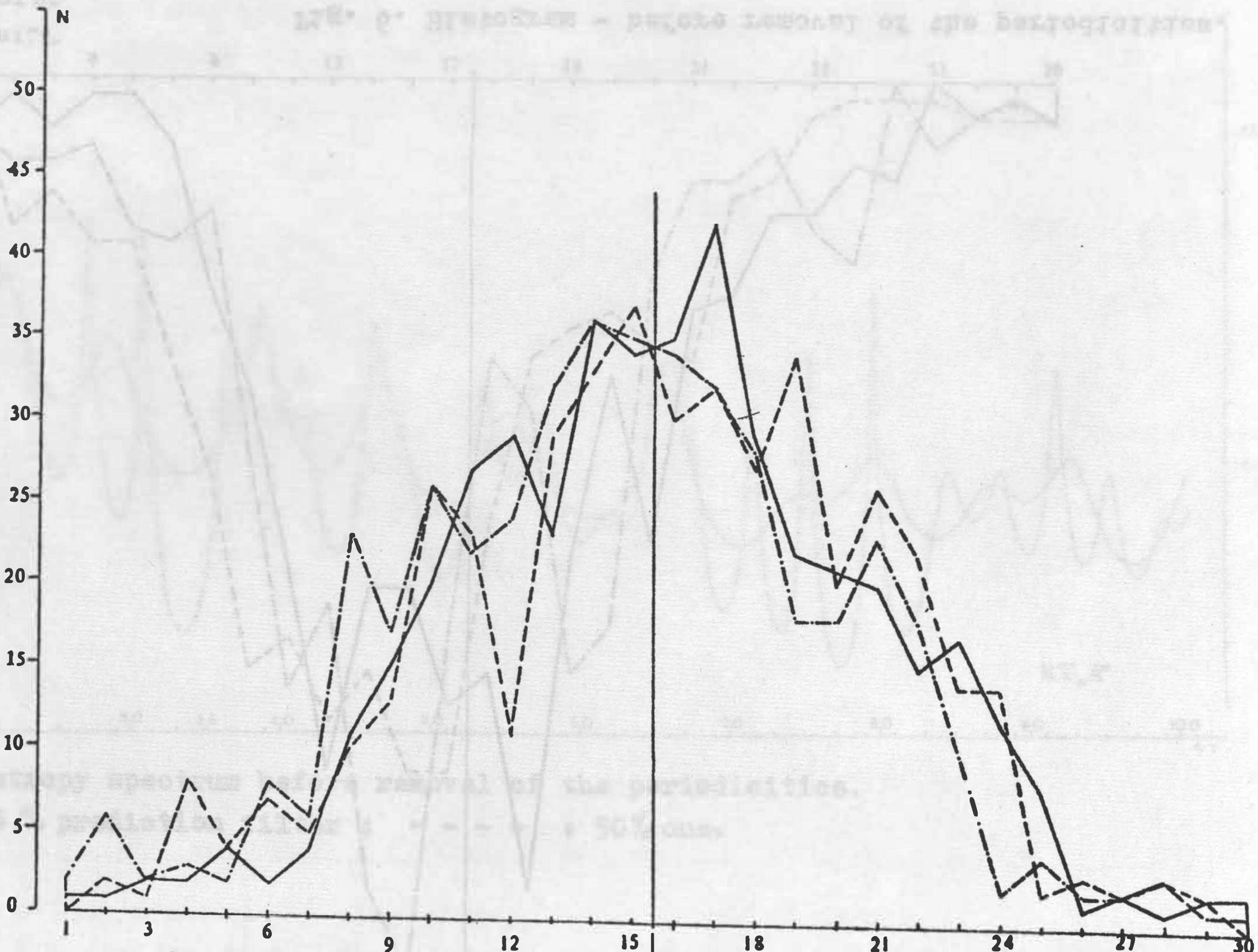

Fig. 7. Histogram - after removal of the periodicitics.
(In % = N×100/440).

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О НЕКОТОРЫХ ОШИБКАХ АСТРОНОМИЧЕСКОГО ОПРЕДЕЛЕНИЯ ВРЕМЕНИ И ГЕОГРАФИЧЕСКОЙ ДОЛГОТЫ

Ян Мелихер, Ян Гефты[1]

Резюме

Анализ определений времени пассажным инструментом Обсерватории Словацкого политехнического института показывает влияние личных ошибок и ошибок исходного каталога на поправки долготы. Исправление этих ошибок значительно изменяет оценку линеарного тренда и периодических составляющих колебания местной отвесной линии.

Summary

The analysis of time observations with transit instrument made on the Observatory of Slovak Technical University in Bratislava shows the influence of personal errors and the errors in the star positions on the instantaneous geographical longitude. Applying corrections of this phenomena has essentialy changed the estimate both of linear variation and periodic structure of the local plumb line fluctuations.

Результаты регулярного определения всемирного времени классическими методами используем для разнообразных исследований. Объединение астрономических обсерватории в Международную службу времени BIH предоставляет возможность изучения вопросов неровномерности вращения Земли вокруг оси. Сравнение измерений отдельных служб времени относительно системы BIH разре-

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шает сделать оценку локальных аномалий связанных с местом наблюдения, инструментом, наблюдателями и программой наблюдений. Многие анализы этих аномалий показывают существование разностей между априорной точностю определенной внутренней сходимостю результатов и апостериорной определенной реальным использованием результатов в BIH.

Причинами являются

- изменения отвесной линии обсерватории связанные с горизонтальным движением (локальным и происходящим из смещений материка) и изменения наклона уровенной поверхности,
- систематические ошибки измерений.

Для использования определений времени в целях исследования геодинамических явлений желательно в возможно большей мере исключить систематические ошибки или хотя бы знать их величину и характер.

Из этой точки зрения мы сделали анализ наблюдений пассажным инструментом Цейсса 100/1000 Обсерватории Словацкого политехнического института в Братиславе (BR).

Исходим из определения поправки часов $(UT0 - UTC)_{BR}$ из одной группы содержащей в среднем 10 звезд. После исправления из-за движения полюса мы вычислили разности

$$\Delta\lambda = (UT\,1 - UTC)_{BIH} - (UT\,1 - UTC)_{BR}$$

Математическое сглажение результатов мы выполнили методом Кабелача [3]. Таким образом из почти 1400 значений $\Delta\lambda$ в годах 1971 - 1978 мы получили сглаженные $\overline{\Delta\lambda}$ отдельно для каждого наблюдателя. Из многих возможных источников систематических ошибок мы обратили внимание на влияние лично-инструментальных ошибок и ошибок прямых восхождений звезд исходного каталога.

Личные ошибки присутствующие во всяком визуальном измерении, в случае определения времени пассажным инструментом

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являются одними из главных источников ненадежности результатов. Оценка этих ошибок возможна либо сравнением определения времени несколькими наблюдателями, либо непосредственным измерением при помощи специальных устройств. Для использования астрономических измерений с целю обнаружить долговременные колебания отвесной линии является более целесообразным выполнять независимие измерения, например прибором с исскуственной звездой. Во время анализируемого интервала каждый наблюдатель регулярно измерил свою личную ошибку. После сглажения вычислены личные поправки для всех определений $(UTO - UTC)_{BR}$.

Обработка наблюдений производится в системе каталога FK4. Для оценки его систематических ошибок вида $\Delta\alpha_{\alpha}$ мы применили груповой способ уравнения поправок часов[1]. График этих ошибок приведен на рис. 1. Явный период 12 часов с амплитудой примерно 0.007 с трансформируется в полугодовое калебание известное для Обсерватории BR также из бюлетиннов BIH.

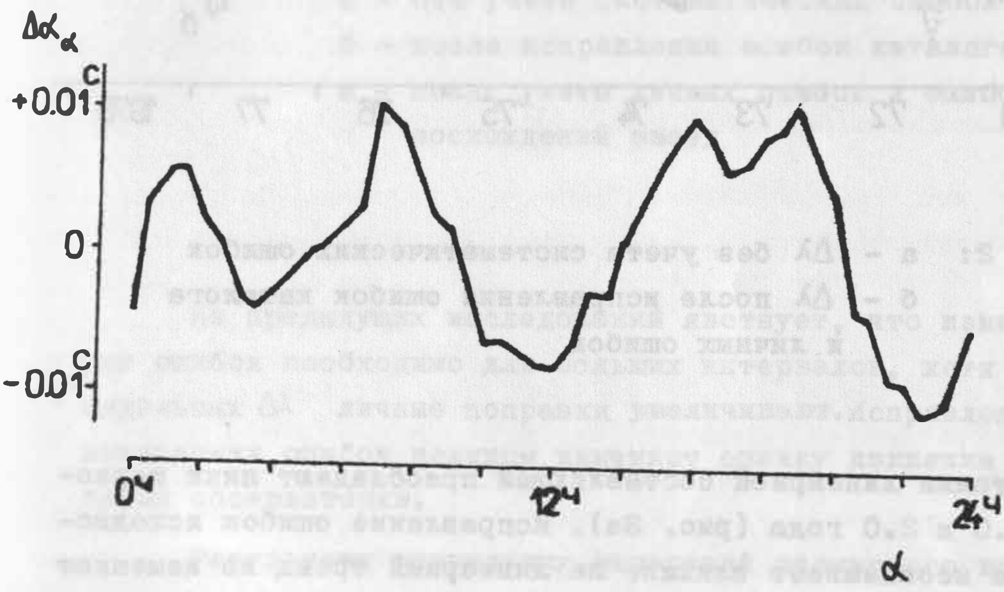

Рис. 1: Оценка систематических ошибок вида $\Delta\alpha_{\alpha}$

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Для исследования динамических явлений нужны информации о временных изменениях географической долготы данной точки. Покажем влияние личных ошибок и ошибок звездного каталога на оценку линеарного тренда и периодических составляющих процесса определения $\Delta\lambda$. Пунктиром на рисунке 2 представлен график $\Delta\lambda$ без учета описаных систематических ошибок. Оценка годого линеарного тренда представляет +0.0049 с $\pm$ 0.0004 с. В спектральном анализе $\Delta\lambda$ (полученном методом максимальной энтропии [2])

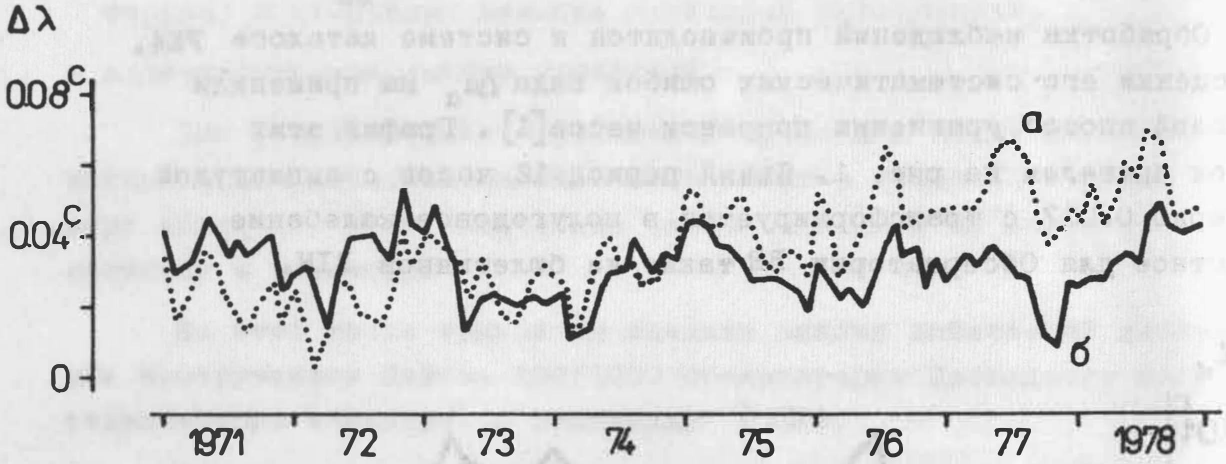

Рис. 2: а – $\Delta\lambda$ без учета систематических ошибок
б – $\Delta\lambda$ после исправления ошибок каталога и личных ошибок

после вычитания линеарной составляющей преобладают пики периодов 0.5, 1.0 и 2.0 года (рис. 3а). Исправление ошибок исходного каталога неоказывает влияние на линеарный тренд но изменяет оценку спектральной плотности (рис. 3б). Остался только один заметный пик для периода двух лет. Исправлением личных ошибок (сплошная линия рис. 2) мы получим оценку тренда – 0.0005 с $\pm$ 0.0004 в год. Периодические составляющие в этом случае незна-

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чительно изменились.

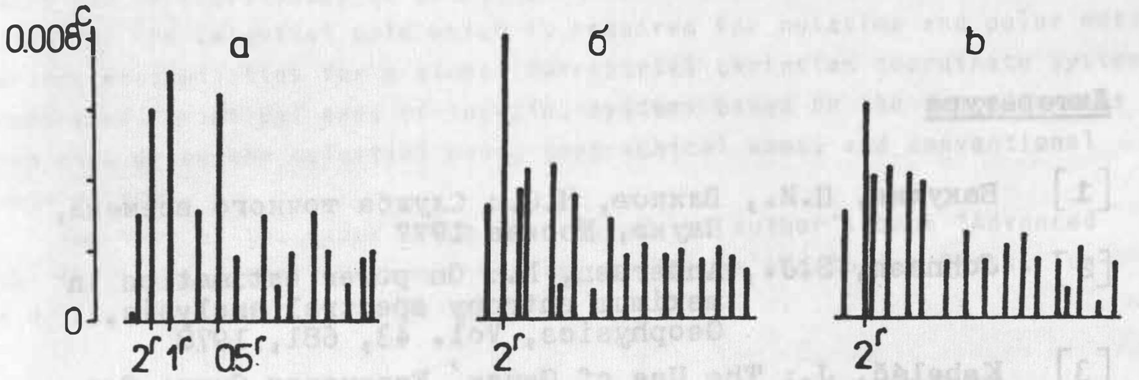

Рис. 3: Спектральный анализ $\Delta\lambda$ методом максимальной энтропии после вычитания линеарного тренда
а - без учета систематических ошибок
б - после исправления ошибок каталога
в - после учета личных ошибок и ошибок прямых восхождений звезд

Из предыдущих исследований явствует, что измерение личных ошибок необходимо для больших интервалов, хотя дисперсию отдельных $\Delta\lambda$ личные поправки увеличивают. Исправление систематических ошибок целиком изменяет оценку движения отвесной линии обсерватории.

Результаты визуальных измерений всемирного времени часто используются для глобальных тектонических исследований. Но отдельные обсерватории неучитывают влияние описанных ошибок в значениях (UT0 - UTC) предоставляемых в BIH. Это искажает

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прежде всего представления о долговременных явлениях. Кроме того, сделаный нами анализ потверждает необходимость большего числа обсерваторий участвующих в исследованиях надежного определения вращения Земли.

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GEODYNAMIC EFFECTS IN PHYSICAL GEODESY

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Abstract:

The usual theories of physical geodesy are based on the following idealized situation: the earth is a rigid body and rotates with constant angular velocity around an axis which is fixed with respect to the earth and passes through the earth's center of mass. This center of mass is taken as the origin of of a reactangular coordinate system, and the rotation axis is used as its z-axis. In this way, neither the earth's figure nor its gravity field nor the coordinate system to which the earth is referred, vary in time.

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This simple model is in general accurate to about 10^{-7}. For higher accuracies, geodynamic effects such as earth tides must be taken into account and temporal variations of reference frames must be examined more closely.

The present paper reviews the effect of earth tides on the figure of the earth and on coordinates of points on the earth's surface, the precise definition of the celestial pole which is required for nutation and polar motion, and various possibilities for a global terrestrial cartesian coordinate system: Tisserand axes, principal axes of inertia, systems based on the instantaneous rotation axis or on the celestial pole, geographical axes, and conventional reference systems.

The text of the paper is Section 55 of the author's book "Advanced Physical Geodesy", Herbert Wichmann Verlag, Karlsruhe and Abacus Press, Tunbridge Wells, Kent, 1980.

Zusammenfassung:

Die üblichen Theorien der physikalischen Geodäsie beruhen auf folgender idealisierten Situation: die Erde ist ein starrer Körper und rotiert mit konstanter Winkelgeschwindigkeit um eine Achse, die mit der Erde starr verbunden ist und durch ihren Schwerpunkt geht. Dieser Schwerpunkt wird als Ursprung eines rechtwinkeligen Koordinatensystems betrachtet; die Rotationsachse dient als z-Achse. Auf diese Weise unterliegt weder die Erdgestalt noch das Bezugssystem zeitlichen Veränderungen.

Dieses einfache Modell hat i.a., eine Genauigkeit von rund 10^{-7}. Für höhere Genauigkeiten muß man geodynamische Effekte wie Erdgezeiten betrachten, und zeitlichen Veränderungen der Bezugssysteme muß genauere Aufmerksamkeit gewidmet werden.

Das vorliegende Referat gibt einen Überblick über den Einfluß der Gezeiten auf Erdfigur und Punktkoordinaten, über die genaue Definition eines geeigneten Himmelspols, die für Nutation und Polbewegung erforderlich ist, und über verschiedene Möglichkeiten für die Definition eines globalen Koordinatensystems: Tisserand-Achsen, Hauptträgheitsachsen, Systeme, die auf der augenblicklichen Drehachse oder auf dem Himmelspol beruhen, sowie geographische Achsen und konventionelle Bezugssysteme.

Den Text des Referats bildet Abschnitt 55 des Buches "Advanced Physical Geodesy", Herbert Wichmann Verlag, Karlsruhe und Abacus Press, Tunbridge Wells, Kent, 1980.

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FLUCTUATIONS IN THE SEASONAL VARIATIONS OF THE LENGHT OF THE DAY AND THE EARTH'S WOBBLE

by

Angelo Poma[1] and Edoardo Proverbio[2]

Abstract

Evidence of fluctuations in the amplitude of seasonal components in the rate of rotation of the Earth has been recently emphasized by Okasaki and Lambeck & Cazenave and attributed in large part to changes in the zonal wind circulation. The effect of zonal winds on wobble should be small and other possible causes cannot be neglected. The analysis of the Earth's rotation for the period 1962-1978 shows the existence of 4 year and to a lower extent of 7 year fluctuations in the annual variations of the l.o.d.. These fluctuations are associated to variation of the energy function $2T^{-1}\int_o^T S^2\,dt$. Oscillations in the angular moment or in the moment of inertia of the atmosphere could be responsable of observed fluctuations. The latter could explain also fluctuations of about 7 years in the annual component of polar motion emphasized by some authors.

Résumé

L'existence de fluctuations de l'amplitude des composantes saisonniers dans la rotation de la Terra à été récemment mise en évidence par Okasaki et Lambeck et Cazenave at attribuée en gran part a la circulation de vents zonals, tandis que sur le mouvement du pole cette action est presque négligeable et d'autres causes ne pouvant pas étre négligées. En analisant la rotation de la Terre pendant la période 1962-1978 nous montrons l'existence de fluctuations dans la variation annuelle avec périodes de quatre années et probablement de 7 années. Cettes fluctuations sont associées a des variations de la function de l'energie $2T^{-1}\int_o^T S^2\,dt$ que pourraient étre attribuées à des variations du moment angulaire ou du moment d'inertie de l'atmosfere de la Terre. Ce dernier pourrait expliquer les fluctuations d'environ 7 années dans la composante annuelle du mouvement du pole mise en evidence par quelque auteur.

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1. Introduction

In the last forty years the analysis of series of latitude and time observations carried out with more and more precise instruments has shown up the existence of periodic and semi-periodic fluctuations in the motion of the instantaneous rotation axis of the Earth and in the rotation of the Earth. If we disregard annual, semi-annual and quasi-biennal oscillations the causes of these fluctuations depending on astronomical and geophysical events are not entirely clear. Analogously the variations in amplitude of the annual and semi-annual terms emphasized by some authors are difficult to interpret (Okasaki, Lambeck & Cazenave, 1977). The problem become even more complicated when one wishes to point up a possible relation between these two movements. In a recent paper the authors have show that there esist an apparent relationship between changes in the rate of the Earth's rotation and variations in polar motion (Poma & Proverbio, 1980). The cause of these common fluctuations could be attributed to non-axially symmetrical forces acting upon the Earth. In any case, this conclusion seem to be in contrast with some results reported by other authors.

The theoretical bases of the motion of the solid Earth are the well known equations of Liouville which, with the notation given by Munk and Mac Donald (1960) and neglecting second order terms, are represented by the scalar equations

(1) $\sigma_2 \Omega^{-1} \dot{\omega}_2 - \omega_1 = - \emptyset_1 \qquad \sigma_2 = B/(C - A)$

(2) $\sigma_1 \Omega^{-1} \dot{\omega}_1 + \omega_2 = \emptyset_2 \qquad \sigma_1 = A/(C - B)$

(3) $(\omega_3 - \Omega) \Omega^{-1} = \triangle \omega_3 \Omega^{-1} = m_3 = \emptyset_3$

in which the geophysical functions $\emptyset_1 = \xi \Omega$, $\emptyset_2 = -\eta \Omega$ and $\emptyset_3$ are related to the astronomical observed quantities

$$\omega_1 = \Omega x, \qquad \omega_2 = - \Omega y, \qquad \omega_3 = (1 + m_3)\Omega$$

where (x, y) are the coordinates of the instantaneous rotation pole referred to the reference frame fixed with the Earth, the origin of which in the so-called Conventional International Origin (CIO), and (ξ, η) the coordinates of the polar axis of inertia with respect to the same reference frame; Ω is the mean nominal angular velocity of the Earth and ω_3 the instantaneous angular velocity about the rotation axis. As the instantaneous rate of rotation is related to the angular momentum of the Earth H_3 and to the mean polar moment of inertia $C = I_{33}$ by the relation $\omega_3 = H_3 C^{-1}$,

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we can easily obtain the relevant equation of the motion

(4) $$\Omega^{-1} \triangle \omega_3 = (\Omega C)^{-1} \triangle H_3 - C^{-1} \triangle C = m_3$$

or, with the notation

$$\triangle H_3 = \int_o^t L_3 \, dt - \triangle h_3$$

where L_3 is an exterior torque component along the axis of rotation acting on the solid Earth and $\triangle h_3$ a relative angular momentum about the same axis,

$$m_3 = C^{-1} \triangle C + (\Omega C)^{-1} \left(\int_o^t L_3 \, dt - \triangle h_3 \right)$$

Given the formal equivalence of the torque and relative angular momentum approaches it is possible to use in the preceding formula either quantity according to circumstances, while $\triangle C = \triangle I_{33}(t)$ is the time dependent variation in the mean moment of inertia C.

2. Effects of torque and relative angular momentum on the Earth's motion

The different mechanism by which the excitation functions $\varnothing_i$ influence polar motion and the Earth's rotation and the difficulty in singling out,case by case,the astronomical and geophysical causes of these excitations makes the study of the Earth's motion quite complex. In Table 1 beside the different types of excitation functions are listed some possible causes capable of influencing the Earth's motion. Today it appears ascertained that the seasonal variations in the Earth's rotation are mostly caused by fluctuations in the angular momentum of the atmosphere and only partially can be attributed to a tidal causes. As regards polar motion on the other hand, annual variations seem to be attributable to oscillations of the Earth's polar inertia momentum (Table 2). In Table 3 are summarized the theoretical data calculated by Okasaki (1979) and Lambeck & Cazenave (1973) as regards the know periodical terms in the Earth's motion. The lack of reliable data relating to the influence that variations of the inertia momenta or the existence of stresses or torques acting upon the Earth crust may have on the Earth's motion is significant. In reality geophisical phenomena contributing to $\triangle I_{33}(t)$ such as solid earth tides and annual fluctuations in groundwater could also explain the discrepancies between the calculated exitation functions due to the action of the wind and astronomical observations.

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Table 1. Different excitation functions and geophysical & astronomical phenomena influencing the astronomically observed motion of the Earth.

Torques:	Atmospheric, ocean & terrestrial tides
	Crust-atmosphere mechanical torque
	Core-mantle electromagnetic coupling
	Electromagnetic interation with interplanetary plasma
Inertia:	Melting and storage of ice and snow
	Storage of water in the ocean
	Mass transfer in the atmosphere
	Mantle convection
	Meteoric dust
	Continental drift (not significant)
	Variation of the gravitational constant
Angular Momentum:	Variations in the total angular momentum of the atmosphere
	Difference in the two hemispheric angular momenta
	Oceanic circulation
	Mantle convection
	Passive core-mantle coupling (changing the mantle's rate)

This has almost inevitably led to the indication of the cause of the long-term fluctuations in the Earth's rotation as due to the action of the winds only. In recent works Sidorenkov (1979a) (1979b) showed in fact that also long term fluctuations in the Earths rotation could be due to mechanical action of the atmosphere on the Earth's surface. Without detracting anything from the importance of these results, it seems to us, however, that the problem of the study of short and long term fluctuations in the Earth rotation and in polar motion must be investigated further with the search for more significant correlations between observed astronomical data and the geophysical phenomena which present analogous characteristics of periodicity as well as has been done in the study of seasonal variations in the Earth's motion.

Table 2. Observed periodical components in the polar motion and speed of the Earth's rotation

	x	y	m
	(0".001)	(0".001)	(10^{-9})
Semi-annual	(C)	(C)	3.8
Annual	103	91	4.1
Biennal	(?)	(?)	1.0

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Table 3. Summarized evidence of the influence of different excitation functions on the seasonal motion of the Earth

	Angular momentum			Torque			Moment of Inertia		
	ϕ_1/Ω	ϕ_2/Ω	ϕ_3	ϕ_1/Ω	ϕ_2/Ω	ϕ_3	ϕ_1/Ω	ϕ_2/Ω	ϕ_3
	(0".001)	(0".001)	(10^{-9})	(0".001)	(0".001)	(10^{-9})	(0".001)	(0".001)	(10^{-9})
Semi-annual	($\subset$)	($\subset$)	2.4	(?)	(?)	1.7	(?)	(?)	(?)
Annual	($\subset$)	($\subset$)	5.2	(?)	(?)	(?)	27	8	(?)
Biennal	($\subset$)	($\subset$)	0.9	(?)	(?)	(?)	(?)	(?)	(?)

($\subset$) no significant values

For this reason we have tried in this work, to show up the existence of possible periodic fluctuations in short-term variations of the Earth rotation associated to known geophysical phenomena.

3. <u>Evidence for the existence of periodical fluctuations exceeding two years.</u>

Values of the angular velocity of the Earth about its axis or, what is the same, of the opposite quantity, the lenght of day (l.o.d.), are deduced by comparing the astronomical scale of Universal Time (UT) based on the rotation of the Earth with an assumed uniform time scale. For the last 25 years the reference time scale has been established by the Bureau International de l'Heure (BIH) on the basis of data derived from atomic clocks. At present it is denominated International Atomic Time (IAT). Data of the differences UT1 - IAT are published by the BIH from which one can derive the variation in the rate of rotation

$$\phi_3 = m_3 = \Delta\,(UT1 - IAT)\,/\,\Delta t$$

From 1955 July to December 1961 the data were provided by BIH for every ten days while from 1962.0 to the present for every five days. A small dishomogeneity exists between the two data sets; the latter is based on the 1968 BIH system (Guinot et al., 1970) and only this will be used for our analysis.

The generic trend of the changes in the rate of rotation is shown in Fig. 1 where the annual means of m_3 expressed in ms/day are plotted for the period 1956-1978.

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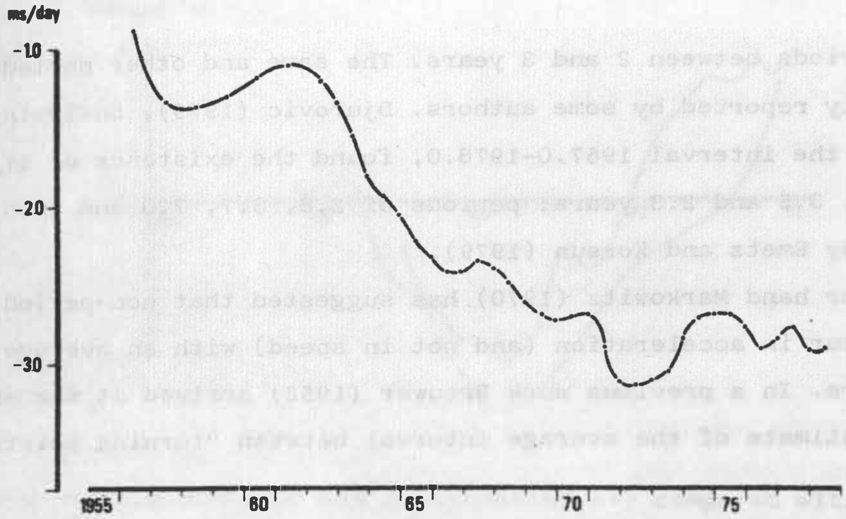

Fig. 1. Annual means values of changes in the rotation rate of the Earth.

Apart from a secular deceleration which is estimated to be about -1.5×10^{-2} ms/day per year attributed almost entirely to the action of tidal forces, there appears to be a common accordance in almost all the papers on how to consider the two types of variations: seasonal variations, fairly regular and of chiefly meteorological origin, and irregular and long-term variations, less well explained and suspected to be associated with interaction of the core with the mantle. This paper is mainly concerned with seasonal variation; but it is not possible, in our opinion, to make estimates of seasonal without discussing the other variations. Firstly, and most simply, because analysis over short intervals may be seriously affected by not well removed terms; secondly, we cannot exclude a priori, as noted before, that all there variations may be of the same nature.

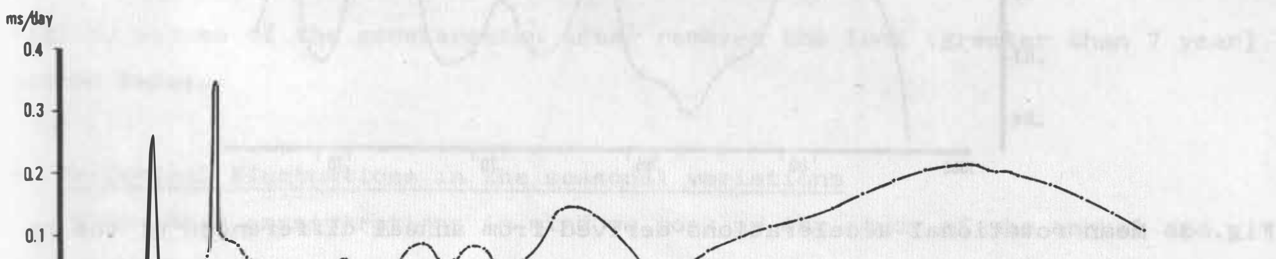

Fig. 2. Harmonic analysis of the Earth's rotation variations

The harmonic analysis of m_3 suggests that, apart from annual semi-annual and biennal terms, several periodic changes are present in rotation speed; as shown in Fig. 2 there is evidence of a period near to 4 and 7 years and, less

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delineated, periods between 2 and 3 years. The same and other periods have also been recently reported by some authors. Djurovic (1979), analysing the data of UT2-IAT for the interval 1967.0-1978.0, found the existence of significant periods of 7.4, 3.5 and 2.3 years; periods of 2.8, 3.7, 7.0 and 10.5 years are also obtained by Emetz and Korsun (1979).

On the other hand Markowitz (1970) has suggested that non-periodic but sudden changes occur in acceleration (and not in speed) with an average interval of about 4 years. In a previous work Brouwer (1952) arrived at the same conclusion but his estimate of the average interval between "turning points" was about 7 years.

In a recent investigation, however, McCarthy and Percival (1979) shows that there is no statistical evidence for discrete values of acceleration over periods on the order of five years, but that only random changes occur more frequently than once per year.

We have computed the values of the rotational acceleration of the Earth for the interval 1956-1978 by means of the first difference

$$\dot{m}_3 = \triangle m_3 \; / \; \triangle t$$

with a 0.5 year step for $\triangle t$ equal to one year.

The result expressed in ms/day per year are shown in Fig. 3 and suggest the existence of an apparent oscillation of about a 4 and 7 year period. After filtering by means of 7 year running means the residuals are plotted in Fig. 4 on a larger scale.

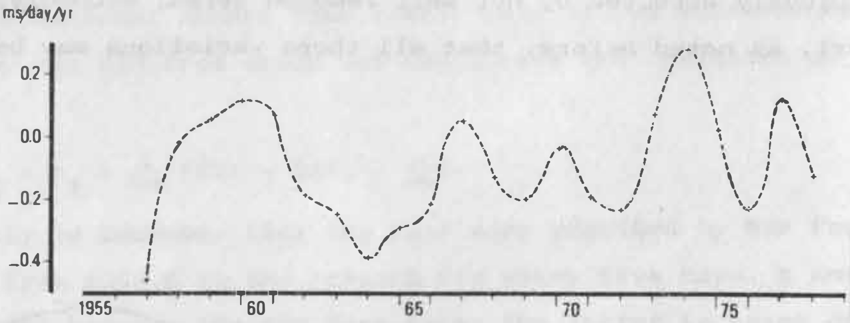

Fig. 3. Mean rotational accelerations derived from annual differences of the rate of rotation.

In order to interpret the shape of this long term a comparison has been made with a curve obtained by combining 12 long (greater than 7 year) period terms found by Lou Shi-fang et al. (1977) as results from spectral analysis of the differences between Universal and Ephemeris Time for the interval 1820-1970.

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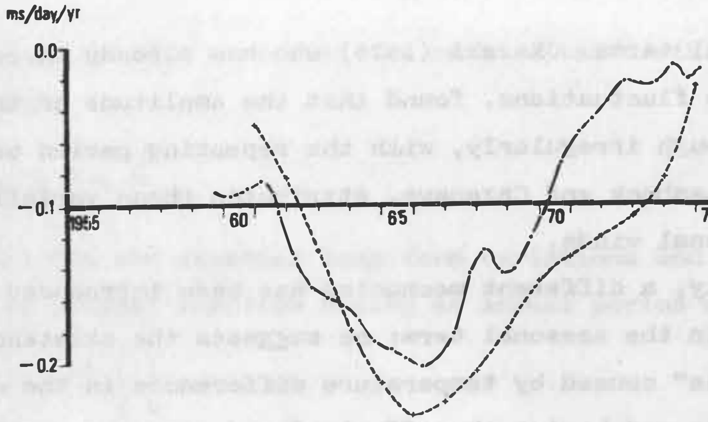

Fig. 4. 7-year running means of the acceleration (·) compared with a sum (+) of 12 long (greater than 7 year) period terms found by Lou Shi-fang et al.

The fair agreement between the observed and calculated curve suggests that probably numerous causes, completely or almost completely unknown, influence the Earth's motion and that results from short-term analyses must be accepted with caution.

It is interesting however, to note that, if the long term of Fig. 4 is removed by the values of $\dot{m}_3$, the residual plotted in Fig. 5 exhibits rather clearly a periodicity of about 7 years.

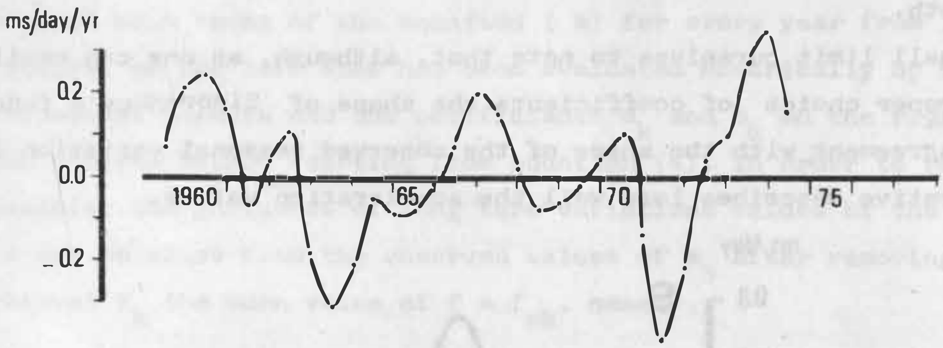

Fig. 5. Values of the acceleration after removed the long (greater than 7 year) period terms.

4. Periodical fluctuations in the seasonal variations

With these considerations in mind we took up the study of the annual and semi-annual variations in the rate of rotation.

As earlier discussed it is generally accepted that these are caused by global wind circulation and, partly, as regards semi-annual variations, by tidal terms (Lambeck & Cazenave, 1973). On the other hand the same authors pointed out that year to year fluctuations, apparently irregular, occur in the amplitu

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de of the sesonal terms. Okazaki (1975) who has already investigated in greater detail these fluctuations, found that the amplitude of the annual term varies, even though irregularly, with the repeating period of 6 years. He, in agreement with Lambeck and Cazenave, attributes these variations as well to the effect of zonal winds.

More recently, a different mechanism has been introduced by Sidorenkov (1975) to explain the seasonal term: he suggests the existence of an "inter-hemisphere engine" caused by temperature differences in the northern and southern hemispheres and having the effect of reducing the angular momentum of the atmosphere. As consequence of this hypothesis he also found that the seasonal variation can be expressed by the formula

$$m_3 = | A + B \cos(\vartheta - \beta) | \qquad (5)$$

where ϑ is the longitude of the Sun and the coefficients A, B and the phase β are constants.

This result is very interesting and ever more intersting could be the study of seasonal fluctuations by means of the function (5), but, unfortunately, we have not read the main original paper on this argument (Sidorenkov, 1975) but only a brief summary (Sidorenkov, 1979) and we cannot discuss it in any great depth.

We shall limit ourselves to note that, although, as one can easily prove, with a proper choice of coefficients the shape of Sidorenkov's function is in good agreement with the shape of the observed seasonal variation (Fig. 6), its derivative describes less well the acceleration values.

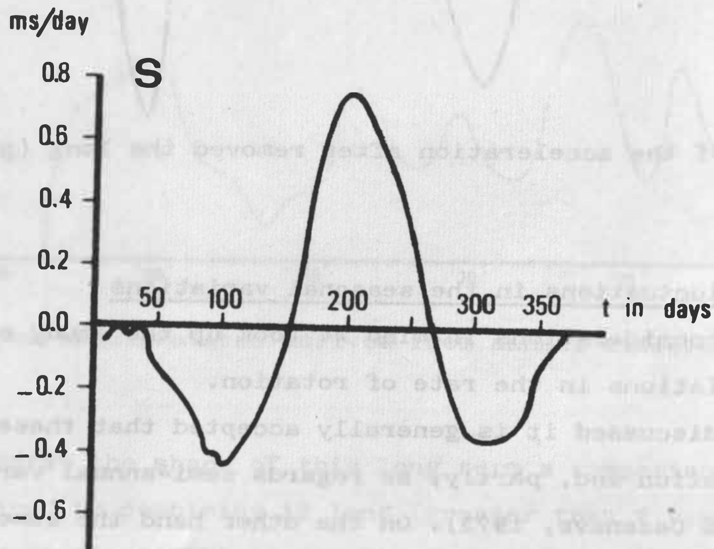

Fig. 6. Seasonal variation in the Earth's rotation rate averaged for the interval 1962-1978.

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More in general we suppose here that the rate of the Earth's rotation can be written in the form

(6) $$m_3 = f + S$$

where f contains all the non seasonal long term variations and S "seasonal function" is a quite general function having an annual period and mean value

(7) $$\bar{S} = T^{-1}\int_o^T S dt = 0$$

in the interval (O,T) equal to a year.

So S can be represented by a trigonometric series

(8) $$S = a_1 \cos 2\pi t + b_1 \sin 2\pi t + a_2 \cos 4\pi t + b_2 \sin 4\pi t$$

where t is a fraction of a year and, as observational evidence shows, the Fourier coefficients of the other harmonics can be considered small.

As a consequence of Parseval's equation the "norm" $\underline{p}$ of the function S is given by

(9) $$\underline{p} = 2T^{-1}\int_o^T S^2 dt = \sum_1^2{}_k (a_k^2 + b_k^2)$$

We have computed both terms of the equation (9) for every year from 1962 to 1978; the integral on the left side has been evaluated numerically by using Simpson's classical formula and the coefficients a_k and b_k on the right side by the least squares method starting from equation (8). In order to reduce, as well as possible, the influence of long term variations values of the "seasonal function" S are obtained from the observed values of m_3 after removing for every year interval T_k the mean value of $\underline{f} = f_{ok}$, namely

$$S_k(t) = m_{3k}(t) - f_{ok}$$

From (6) and (7) it follows

$$f_{ok} = T^{-1}\int_o^T m_{3k}(t) dt$$

Moreover we have corrected the values of $\underline{p}$ considering that the function $\underline{f}$ should be approximated by a second degree polynominal. It is found that, in general, these corrections are small. No source of error should arise from the approximation used.

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Table 4. Cosine (a_k) and sine (b_k) Fourier coefficients (in ms/day) and "norm" p of the seasonal functions S in $(ms/day)^2$

	a_1	b_1	a_2	b_2	$\sum(a_k^2 + b_k^2)$	p
1962	-0.376	-0.116	0.284	0.283	0.315	0.327
1963	-0.318	+0.099	0.302	0.427	0.384	0.365
1964	-0.393	-0.120	0.250	0.279	0.310	0.344
1965	-0.262	-0.068	0.294	0.244	0.219	0.236
1966	-0.255	-0.067	0.356	0.241	0.254	0.275
1967	-0.321	-0.199	0.267	0.273	0.289	0.291
1968	-0.271	-0.072	0.199	0.139	0.138	0.186
1969	-0.283	-0.173	0.307	0.232	0.257	0.283
1970	-0.383	-0.276	0.282	0.235	0.357	0.373
1971	-0.169	+0.058	0.316	0.405	0.295	0.324
1972	-0.244	-0.241	0.216	0.207	0.207	0.241
1973	-0.263	-0.256	0.276	0.181	0.244	0.242
1974	-0.231	-0.183	0.320	0.318	0.290	0.331
1975	-0.352	-0.147	0.248	0.268	0.279	0.295
1976	-0.211	-0.106	0.344	0.287	0.280	0.300
1977	-0.383	-0.122	0.311	0.363	0.389	0.415

The definitive values of p are summarized in Table 4 and in Fig. 7. We note that p is proportional to a mean seasonal kinetic energy. At first sight it seems to vary rythmically with period of about four and, with less evidence, seven years.

It is interesting to note that (if the curve represented in Fig. 5 is correct and there are no step functions) the maxima and minima values of p are reached in the epochs in which mean acceleration vanishes, i.e. in the epochs in which mean annual speed reaches maxima and minima values. It is also interesting to note that year to year differences of p , which are a measure of the dissipated energy, noted here as dp/dt and plotted in Fig. 8, clearly show a 4 year cyclic period.

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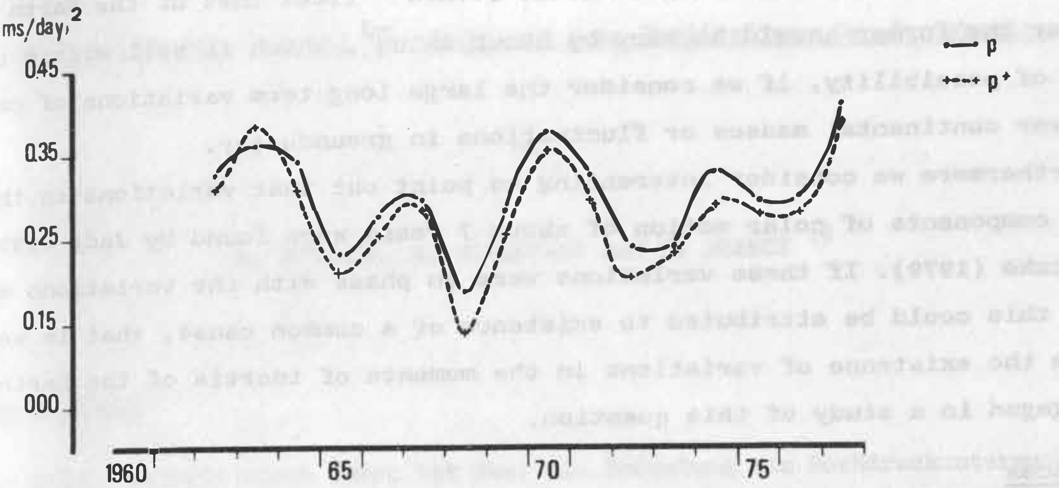

Fig. 7. $\underline{p} = 2T^{-1} \int_0^T S^2 \, dt$ is proportional to a mean seasonal kinetic energy; p^+ is the same quantity computed from $\sum_1^2 (a_k^2 + b_k^2)$ according to Parseval's equation.

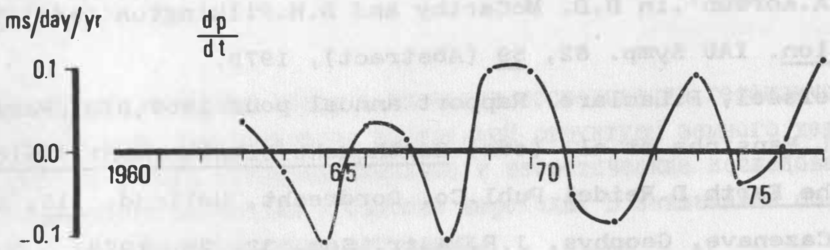

Fig. 8. Annual differences of $\underline{p}$, namely the measure of the dissipation of the seasonal kinetic energy.

Conclusions

The analysis of the Earth's annual motion has shown up periodic fluctuations in rate with a period of about 4, and to a lower extent, of 7 years. As regards acceleration the evidence for quasi-periodic fluctuations can be documented by the connection found between maxima and minima variations in rate and the zeros of acceleration itself. The changes of angular acceleration seems due neither to impulsive torque as held by De Sitter (1927) and Brown (1926) nor to abrupt change in the amplitude of torque acting on the Earth.

The amplitude variations associated with energy variations evidenced may be interpreted as the effect of "thermal engines", as suggested by Sidorenkov (1979), or as variations in total angular momentum or in momenta of inertia of the Earth. The mean variations in the rotation speed from one year to another that we found on the order of 5×10^{-9} correspond to energy variation of about 3×10^{19} erg and to variations in the Earth's angular momentum of about 3.2×10^{25} kg m^2 sec^{-1}.

If such a variations are to be attributed to variations in the moment of

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inertia of the atmosphere which is about 1.7×10^{-6} times that of the Earth we see that the former should be vary by about 3×10^{-3}, which is well within the limits of possibility, if we consider the large long term variations of pressure over continental masses or fluctuations in groundwater.

Furthermore we consider interesting to point out that variations in the annual components of polar motion of about 7 years were found by Jady (1970) and Moczko (1979). If these variations were in phase with the variations we found, this could be attributed to existence of a common cause, that is would confirm the existence of variations in the momenta of inertia of the Earth. We are engaged in a study of this question.

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State of Material Inside the Earth and Some Implications for Geodynamics

by

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Zusammenfassung

Die Arbeit enthält einen Überblick über die Bedeutung von Hochdruckuntersuchungen an geophysikalisch relevanten Materialien für das Verständnis der inneren Struktur des Erdkörpers und seiner Dynamik. Es werden sowohl experimentelle als auch theoretische Untersuchungen vorgestellt. Schwerpunkte sind unter anderem Zustandsgleichungen und Phasenübergänge. Im Schlußteil wird die Einbindung dieser Problematik in planetologische Fragen diskutiert.

Резюме

Настоящая работа содержит обзор о значении исследований геофизических веществ при высоких давлениях для понимания внутренней структуры земного тела и его динамики. Представляются экспериментальные и теоретические исследования. Важные точки - это уравнения состояния и фазовые переходы. В заключении обсуждается связь этих проблем с планетологическими вопросами.

1. Introduction

This paper is concerned with investigations on the physics and chemistry of matter relevant for the earth's interior. But there are various possibilities to get information about the interior of a planet. Some of these investigations are often called classical investigations. The most important of them are studies of the earth's interior with help of seismic waves. Using the results of seismology (including normal vibrations) and taking into account also results of gravimetry one is able to construct so-called mechanical earth models. In doing this one has to try to solve the so-called inverse problem. That means we have certain physical quantities measured at the earth surface and try to find their distribution from

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the surface down to the earth's center with temperatures of about 4000°K and pressures of about 350 GPa (3.5 Mbar). Similar problems arise in the field of heat flow measurements and in interpreting magnetic investigations.

Laboratory high pressure investigations are one important way to relate mechanical earth models to the physical properties within the planet to certain chemical substances in their various physical modifications (phases). So it is very important to measure acouctic waves (velocities, anisotropy and attenuation, see e.g. VOLAROVICH, 1979), electrical conductivity (MAO & BELL, 1977) and thermal conductivity (STILLER et al., 1978; BECK, 1978, SCHÄRMELI, 1979) at high pressure and temperatures. X-ray studies are valuable for detecting structural changes caused by pressure (e.g. YAGI, 1977). Up to now shock waves (see e.g. AHRENS, 1972; KEELER, 1978) are the only experimental method that enables to reach very high pressures relevant for the earth's deep interior and also for the interior of other planets.

Investigations on the state of planetary matter at high pressures and temperatures may also provide important contributions to the fundamental problems of the evolution of our solar system. This is connected with the so-called actualistic principle (see ALFVEN & ARRHENIUS, 1976). According to this general principle, the improvement of our knowledge on the present state in planetary interiors is a key to discover the history of our planetary system. As discussed by STILLER & FRANCK, 1980, the change of thermodynamic conditions during evolution from the protoplanetary nebula to the present state influences not all kinds of planetary matter in the same way. Therefore the application of this principle is limited.

2. Theoretical and experimental methods

Equations of state are the most important theoretical methods for the study of the state of materials inside the earth. We know many methods and approximations for the equations of state (see e.g. ZHARKOV & KALININ, 1971), but we think that they all may be classified according to the schema shown in figure 1. If an expression for the free energy F (T, V) is found with help of continuum mechanics the corresponding derivative of the free energy to volume is called phenomenological equation of state. So-called empirical equations of state (see e.g. O.L. ANDERSON, 1966) and the new structure of the equation of state found by ULLMANN & PANKOV, 1976, also belong to this group of equations. Phenomenological equations of state may be used for the description of the compressional behaviour of many different materials if various free parameters are fitted. A disadvantage of such equations consists in the fact that those equations allow no insight into the microscopic processes which cause the corresponding compressional behaviour.

Therefore it is favourable to use microscopic equations of state which may be derived if one has computed the partition function Z (V, T) within a microscopic model. There exist good approximations for the partition function of gases and of

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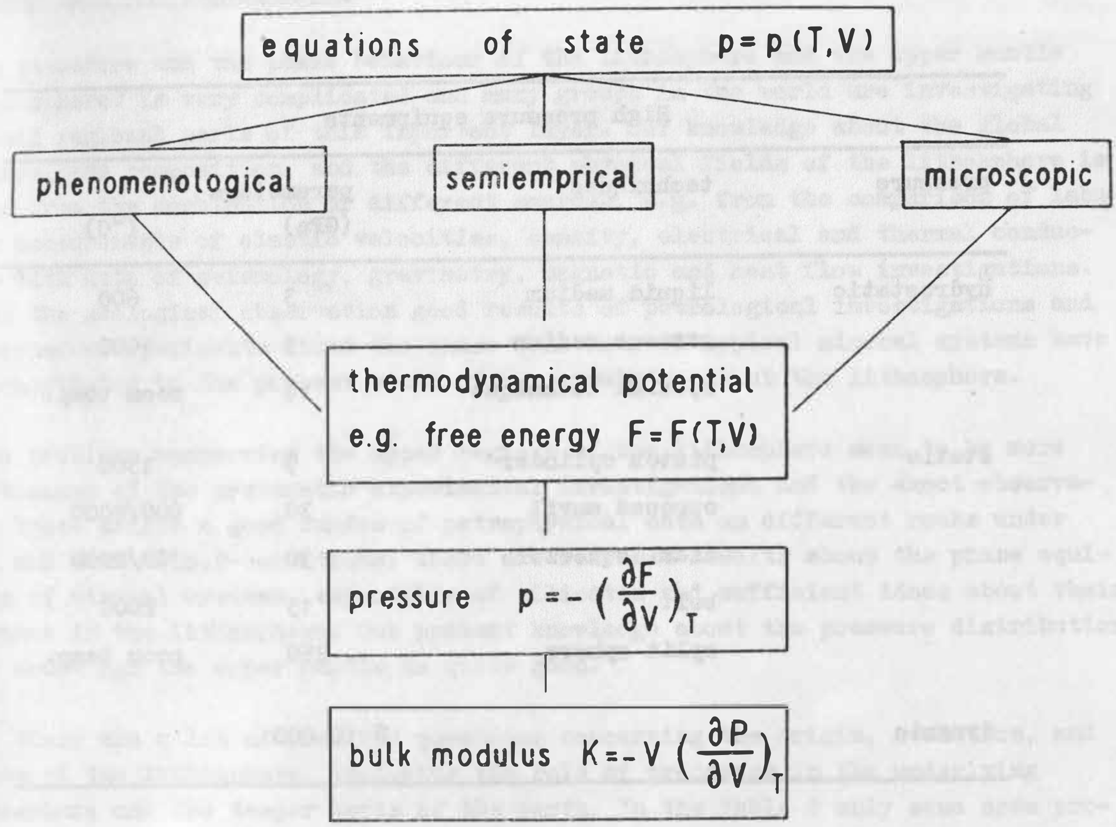

Fig. 1. Scheme and classification for equations of state

lattices (see e.g. LANDAU & LIFSHITZ, 1966). Another microscopic equation of state may be derived from the statistical theory of the atom developed by THOMAS, FERMI & DIRAC (see GOMBAS, 1949). But such approximations neglect all structural effects and also the shell structure of the electron distribution. Therefore they may be used only in the very high pressure region from about 10 TPa (100 Mbar).

Semiempirical equations of state may be used for various typs of solids (ionic crystals, metals, valence and molecular crystals). This method (DAVIDOV, 1956) employs empirical expressions (n-m-pot ntials, exponential form) between the lattice particles.

An important task for the theory of equation on state consists in finding relationships between certain types. Another important problem is to find equations which describe the behaviour of matter in its various phases. To simulate the chemical and physical behaviour of different regions inside the earth there is a system of high pressure - high temperature laboratory equipments (see table 1).

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Table 1. High pressure laboratory equipments

High pressure equipments			
pressure	teohniques	parameters (GPa)	(^{o}C)
hydrostatio	liquid medium	3	600
	gaseous medium	3	1000
	special technique	10	room temp.
static	piston cylinder	5	1500
	opposed anvil	30	600/2000
	diam. squeezer	30	300/2000
	belt	15	2000
	split sphere	250	room temp.
dynamic		$\leq$ 10 000	

They can be used for measurements of certain physical and physico-chemical parameters under extreme thermodynamic conditions. For the investigation of the behaviour of the lithosphere and the upper mantle hydrostatic measurements are mainly used. Very important is to involve the parameter time to investigate the rheological behaviour. On the other hand petrophysical investigations need more petrological experiments to understand the genesis and the chemical state of the lithosphere.

For the investigations of materials which are relevant for the lower mantle solid state high pressure chambers are used. With help of belt-type-chambers and chambers after BRIDGMAN (oopposed anvil type) phase changes are investigated. The problem for these measurements is to increase both the temperature and the pressure up to for the earth's mantle relevant values. A special opposed anvil type, the squeezer, is the best present way to determine structural changes at polyorystals. Using diamond anvils the ohamber allows opti al and X-ray measurements in situ.

Pinally the state of the material until now oan be investigated by a split-sphere-apparatus, which arises pressures up to 200 GPa. Experiments on melting under high pressure need a speoial chamber of a belt-type.

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3. Lithosphere and upper mantle

The structure and the phase behaviour of the lithosphere and the upper mantle (asthenosphere) is very complicated and many groups in the world are investigating in detail regional parts of this important layer. Our knowledge about the global structure, the composition, and the different physical fields of the lithosphere is derived from the combination of different sources, e.g. from the comparison of laboratory measurements of elastic velocities, density, electrical and thermal conductivity with data of seismology, gravimetry, magnetic and heat flow investigations. Besides the geological observation good results of petrological investigations and high pressure experiments about the phase behaviour of typical mineral systems have been contributed to the present state of our knowledge about the lithosphere.

Some problems concerning the upper regions of the lithosphere seem to be more clear because of the systematic experimental investigations and the exact observations: There exists a good fundus of petrophysical data on different rocks under normal and extreme p,T-conditions; there are reliable results about the phase equilibrium of mineral systems, especially of silicates and sufficient ideas about their occurrence in the lithosphere. Our present knowledge about the pressure distribution in the crust and the upper mantle is quite good.

But there are a lot of unsolved questions concerning the origin, evolution, and dynamics of the lithosphere, including the role of processes in the underlying asthenosphere and the deeper parts of the earth. In the table 2 only some open problems are listed.

Table 2. Open problems in studying the lithosphere (selection)

- satisfactory explanation for the causes and mechanics of the plate motions
- intraplate volcanism, deformations and earthquakes
- mechanism of subduction processes
- exact properties of the major discontinuities (e.g. microstructure, phase boundaries)
- complex interpretation of low velocity zones, anisotropy, attenuation, and phase changes to formulate a complex model of the lithosphere
- mechanism and history of differentiation (esp. formation of the continental lithosphere)
- thermal models of the ancient and recent lithosphere
- differences between continental and oceanic lithosphere

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A special problem is the dependence of temperature from the depth. In present time the temperature - depth functions of different authors vary considerable, considering the regional differences. There is one field for laboratory measurements to improve the results and the models. Figure 2 shows the large range of the geotherms and the possibilities for the formation of rock melts in the lithosphere.

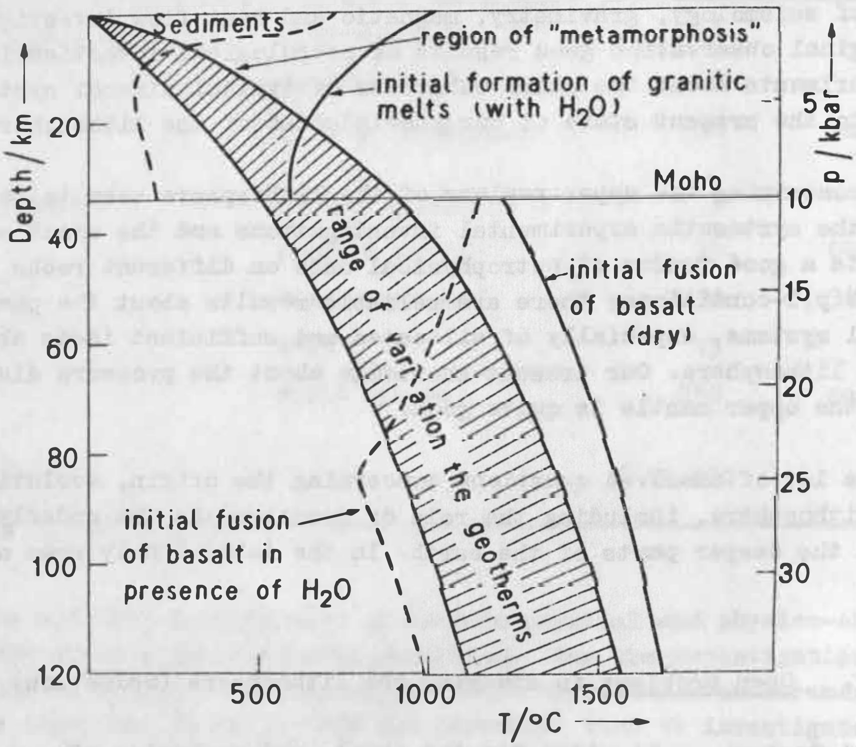

Fig. 2. Range of geotherms in the lithosphere (after R. SCHWAB, 1974)

Another dificile problem represents the complicated stability field of the large numer of multiphase systems of silicate minerals (see fig. 3). It is obvious that the genesis and the metamorphism of rocks is influenced by the amount of fluid compounds, especially water.

Concerning the state of the upper mantle we have some good ideas owing to the fundamental experiments of RINGWOOD and co-workers. The consequent use of high pressure laboratory experiments led to interesting results about the phase diagrams op upper mantle relevant systems.

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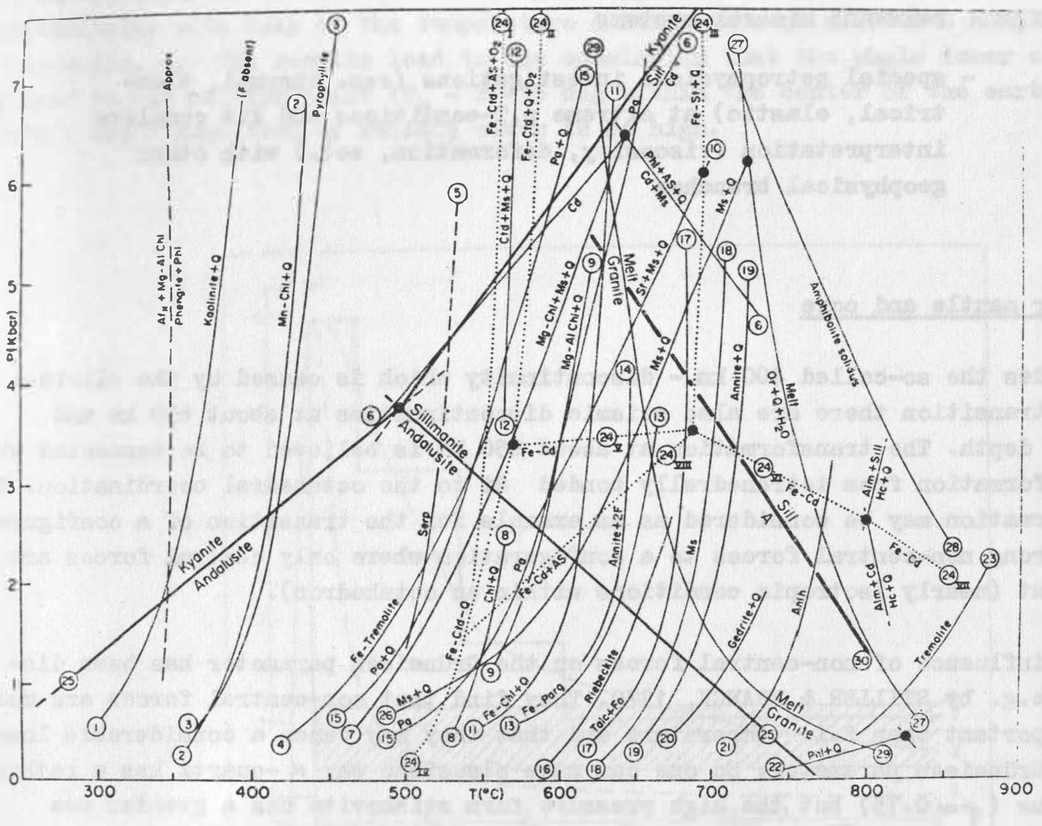

Fig. 3. Metamorphic facies in pressure - temperature projection (after GREENWOOD, 1976)

Therefore we need in future - and this is also one of the aims of the new International Programme - in the same way more systematic high pressure experiments under conditions and at substances relevant for the lithosphere. Table 3 gives a selection of important problems which can be more clarified with help of laboratory investigations under extreme p,T-conditions.

Table 3. Petrological investigations and high pressure laboratory experiments for the lithosphere (selection)

- strengthening of high pressure/high temperature experiments in closed systems with volatiles (esp. H_2O, CO_2)

- experimental investigations of migration mechanism (radioactive ones, metals)

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- investigation of the melting behaviour of the lithosphere relevant mineral systems
- special petrophysical investigations (esp. thermal, electrical, elastic) at extreme p,T-conditions and its complexe interpretation (viscosity, deformation, ect.) with other geophysical branches

4. Lower mantle and core

Besides the so-called 400 km - discontinuity which is caused by the olivine-spinel-transition there are also seismic discontinuities at about 650 km and 1050 km depth. The transformation at about 650 km is believed to be connected with a transformation from tetrahedrally bonded Si to the octahedral coordination. This transformation may be considered as an example for the transition of a configuration with strong non-central forces to a configuration where only central forces are important (nearly isotropic conditions within an octahedron).

The influence of non-central forces on the Grüneisen parameter has been discussed e.g. by STILLER & FRANCK, 1979. They find that non-central forces are much more important than f.i. temperature and that they may cause a considerable lowering of the Grüneisen parameter. So one can make plausible why α-quartz has a rather low value ($\gamma \approx 0.75$) but the high pressure form stishovite has a greater one ($\gamma \approx 1.52$).

The nature of the core-mantle boundary (CBM) is one of the most important problems in geo- and planetary physics. The hypothesis of a chemical boundary at the CMB and an iron core is supported for instance by the occurrence of iron in meteorites. But there are certain difficulties in explaining the formation of mantle and core by using the iron-hypothesis (see e.g. VITYAZEV et al., 1977). Therefore some scientists favour the so-called LODOCHNIKOV-RAMSAY hypothesis (LODOCHNIKOV, 1939; RAMSEY, 1948). They proposed that the high density of the core could be due to pressure-induced transformation of magnesium-iron silicate into a high-dense phase. Against this hypothesis it has been considered unlikely that such a density change of about 70 % could take place during the phase transition of the CMB. This shortcoming is removed e.g. within a modified hypothesis proposed by ARTJUSHKOV, 1970. According to ARTJUSHKOV the lower mantle near the CMB consists of two materials which are called metallogen and nonmetallogen. Metallogen is assumed to have a much higher density than nonmetallogen and only metallogen makes the phase transition to the liquid metallic state of the outer core. So the density change during the phase transition of metallogen needs to be only about 20 %. The inner core boundary (ICB) is usually assumed to be the solid-liquid boundary of the core material. DOORNBOS, 1974, has published a distribution of the attenuation coefficient of seismic P-waves within the earth's core. He finds a

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sharp peak at the ICB and rather high values within the inner core. STILLER et al., 1979, showed that the data of DOORNBOS may be explained very well (that means also quantitatively) with help of the temperature distribution of HIGGINS & KENNEDY, 1971 (see fig. 4). The results lead to the conclusion that the whole inner core is very near to its melting point ($T_m - T \approx 15$ deg within the center of the earth) and therefore the attenuation of seismic waves is so high.

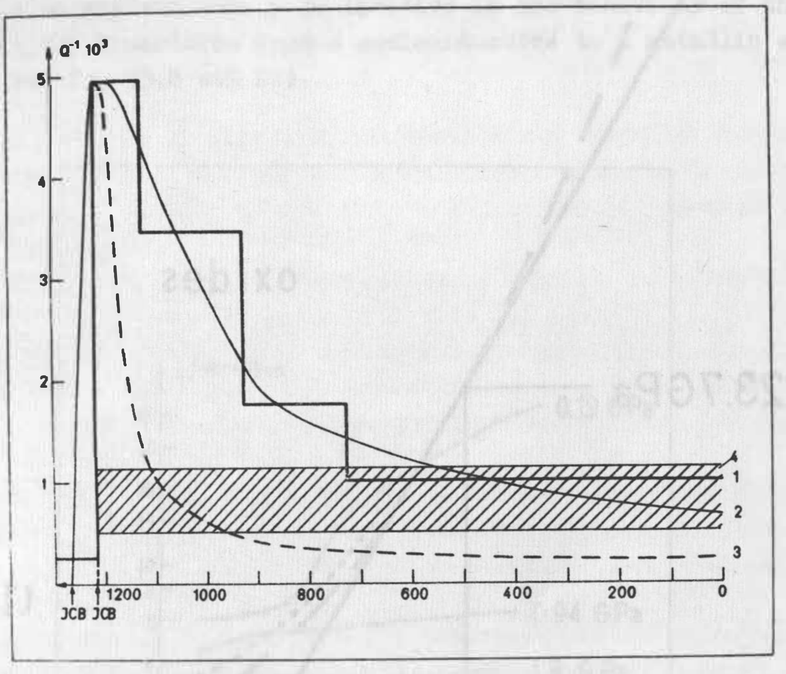

Fig. 4. Attenuation coefficient of seismic P-waves in the earth's core. 1: data of DOORNBOS, 1974, 2: calculated model with temperature distribution of HIGGINS and KENNEDY, 1971, 3: calculated model with temperature distribution of STACEY, 1977, 4: contribution from attenuation in inhomogeneous matter (see STILLER et al., 1979)

Using the different equipment for generation of very high static pressure or shock waves a lot of different substances have been investigated which are relevant for the lower mantle (e.g. AHRENS, 1972). With that have been found the transition of spinel into oxides and a correlation with inhomogeneitis in the mantle. Some laboratories in present time are strengthening the experiments to reach the metallic state of such compounds to be able to support the ideas of RAMSEY and LODOCHNIKOV. There are also a number of interesting calculations to support and interprete the experimental results for the lower mantle state (KOPYSTYNSKI & BAKUN-CZUBAROV, 1978). In figure 5 are shown the calculations of phase equilibrium

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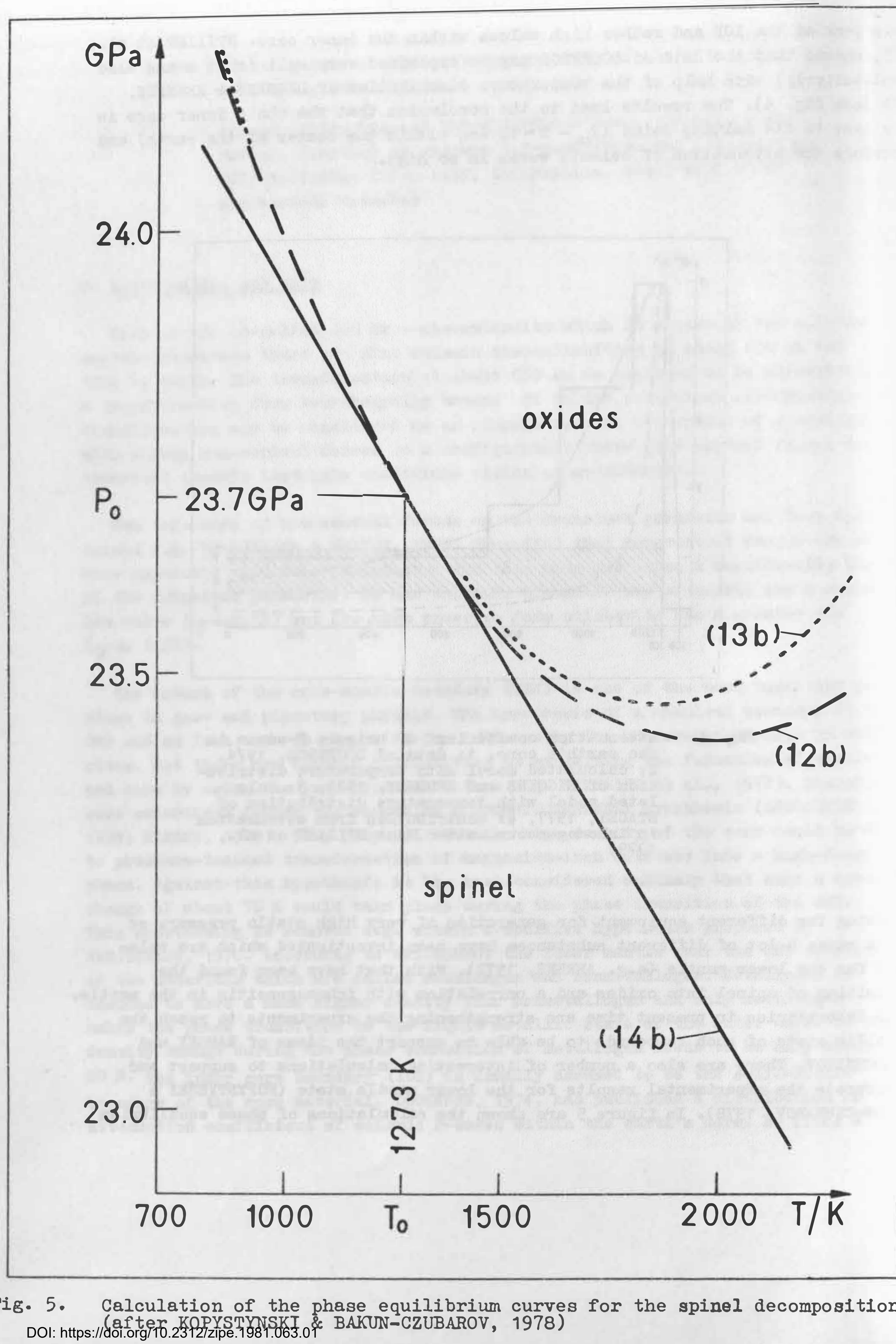

Fig. 5. Calculation of the phase equilibrium curves for the spinel decomposition (after KOPYSTYNSKI & BAKUN-CZUBAROV, 1978)

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curves for the spinel-stishovite + periclase decomposition. 12b considers compressibility and thermal expansion, 13b neglects this influence, 14b neglects the compressibility and thermal expansion too, assuming that entropy of transformation is constant.

On the other hand there is a group of scinetists investigating the Fe-Ni-S system which can be relevant for the state of the core (KEELER, 1978; VOLLSTÄDT et al., 1978). There by the solid solution of the monosulfides in the Fe-Ni-S system seems to be suitable to explain some peculiarities in the behaviour of the outer core. Figure 6 shows the transition from a semiconductive to a metallic state of a MSS sample (29,8 wt% Fe, 33,8 wt% Ni).

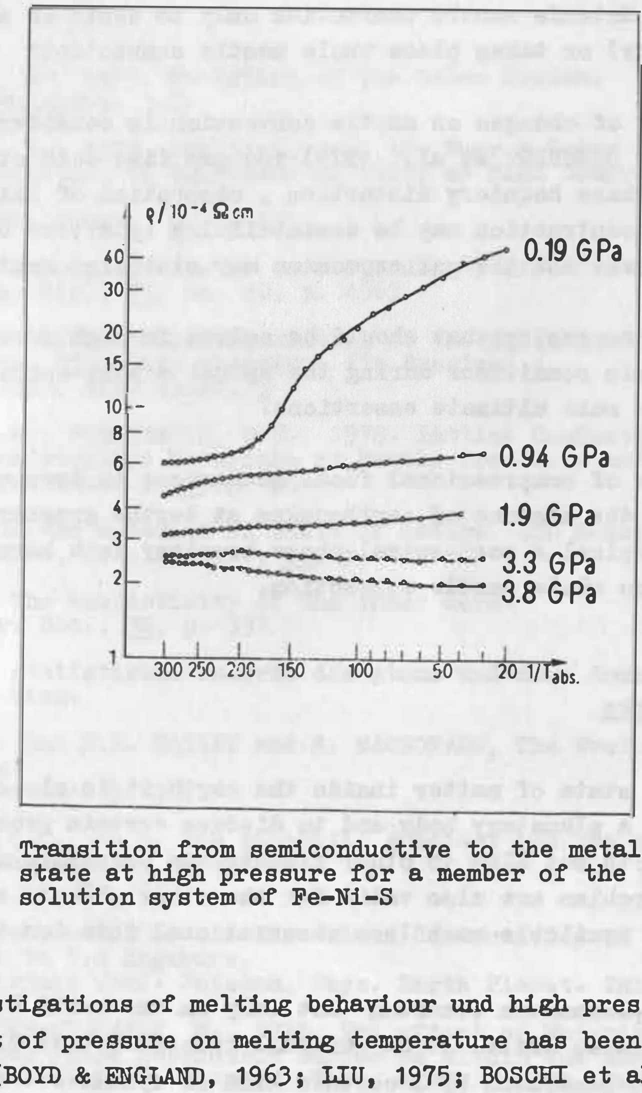

Fig. 6. Transition from semiconductive to the metallic state at high pressure for a member of the solid solution system of Fe-Ni-S

Experimental investigations of melting behaviour und high pressure condition are very rare. The effect of pressure on melting temperature has been investigated above all on metals (BOYD & ENGLAND, 1963; LIU, 1975; BOSCHI et al., 1979). The problem is to find ways for extrapolating the melting curves up to pressures much higher than those at which the experimental data are available (at about 20 GPa).

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Very important is the knowledge of different parameters as a function of melting pressure, e.g. the relative change of volume V/V_s, the entropy of melting. Finaly we need for the discussion of the state of core material values about the conductivity at the melting temperature under high pressure conditions.

5. Phase transformations and mantle convection

The lithospheric plates of plate tectonics are created from hot mantle rock at ocean ridges and descend into mantle at ocean trenches. The plates are by definition, part of mantle convection alls.

The influence of phase transformations on mantle convection enters in the following problem: Extends mantle convection only to depth of about 700 km (spinel → post-spinel boundary) or takes place whole mantle convection?

If the influence of changes on mantle convection is considered in somewhat greater detail (cf. SCHUBERT et al., 1975) you may find both stabilizing and destabilizing effects. Phase boundary distortion , absorption of latent heat of transformation and thermal contraction may be destabilizing (positive buoyancy forces). Release of latent heat and thermal expansion may stabilize mantle convection.

So we arrive at a problem that should be solved in high pressure physics. Up to now the thermodynamic conditions during the spinel → post-spinel transformations are not clear enough to make ultimate assertions.

The predominance of compressional focal mechanisms in deep earthquakes between 500 and 700 km and the absence of earthquakes at depths greater than 700 km support the view that the spinel → post-spinel phase boundary is a barrier to convection and that there is no whole mantle convection.

6. Concluding remarks

Considering the state of matter inside the earth it is also important to consider the earth as a planetary body and to discuss certain problems not only in relation to the earth but also to other planets. On principle our remarks concerning the inverse problem are also valid for the other planets of the solar system, although there are available much less observational data for the other planets.

An interesting phenomenon occuring not only on the earth but also at other planets is the magnetic field. It is generally accepted that planetary and stellar magnetic fields are generated by a certain kind of dynamo action. This dynamo

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action is based on the rotation of the planet or star and on the convection of fluid material with high electrical conductivity (see e.g. STIX, 1977). Such conditions may be re lized on various ways. For example in the earth there is convection of fluid iron compounds or fluid metallized silicates while in Jupiter metallic hydrogen and also semiconducting molecular hydrogen (SMOLUCHOWSKI, 1979) convect. In the sun only the convection of metallic hydrogen is relevant.

In our opinion such comparative studies on the state of matter inside the earth and the planets will become very important in the following years when space probes will provide a lot of new information on the subject.

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The Introduction of the Improved Stellar Catalogue into the Ondřejov PZT Results

by

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Summary

The observations obtained with PZT Zeiss at Ondřejov observatory in the years 1973 - 1978 were used to improve the mean places and proper motions of 304 stars. In order to obtain the proper motions with higher accuracy, the PZT observations were combined with the positions of the stars in AGK2 and AGK3 catalogues. All the PZT observations from the years 1973 - 1979 were uniformly re-reduced in the system of the new catalogue. It is shown that the results are in better agreement with the BIH 79 system than with the old BIH 68 system. The stability of the new results with respect to BIH both in time and latitude is substantially higher as compared with the stability of the results in the system of the old star catalogue.

Резюме

Наблюдения на ФЗТ в Ондржейове за 1973 - 1978 гг. были использованы для уточнения средних мест и собственных движений 304 звезд. Наблюдения на ФЗТ комбинировались с положениями звезд из каталогов АГК2 и АГК3 чтобы получить больщую точность собственных движений. Все наблюдения с 1973 по 1979г. были затем вновь обработаны в системе полученного каталога. Показано, что результаты согласуются лучше с системой МБВ 79 чем со старой системой МБВ 68. Стабильность новых результатов по отношению к МБВ по времени и широте существенно выше чем стабильность результатов в системе старого звездного каталога.

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1. Introduction

The regular observations with PZT Zeiss began at Ondřejov observatory in 1973. The observations obtained during the first two years were used by Webrová and Weber [4] to determine the mean positions of 192 stars, their proper motions being taken over from SAO catalogue without change. The resulting catalogue will be further referred to as PZT75. In 1977 the new reduction method [2] was adopted and in 1978 the observing programme was enlarged by adding 113 fainter stars (up to eleventh magnitude). At the same time 8 stars had to be excluded. The mean positions of these stars were determined relatively with respect to the stars contained in the same group during the 1978 campaign, their proper motions were taken over from AGK2/AGK3. The corresponding catalogue was given the name PZT75a.

Since the beginning of 1979 the new observing programme is used. It consists of 16 groups each of which contains 14 stars. With the exception of only one star, all these stars were selected from the stars observed within the preceeding six years. During 1979, the positions and proper motions from the tentative catalogue PZT75a were used. Since the positions and proper motions of PZT75a were not homogenous, it was decided to use all the observations obtained during the years 1973 - 1978 to improve both mean positions and proper motions. The time span of six years, covered by our own observations, being too short to give the proper motions with sufficient accuracy, the PZT observations were combined with the positions of the respective stars in AGK2 and AGK3 catalogues. The procedure used has recently been published in detail in [3] , thus only a short outline will be given here.

All the observations (more than 15 thousands transits of stars) were reduced by the method [2] . As a by-product, the values of latitude and time correction for each individual star were calculated. The whole interval of six years was divided into four subintervals (1973/74, 1975/76, 1977 and 1978), in each of which the corrections to declinations and right ascensions of individual stars were found together with the adjusted values of latitude and time correction for each night by the method of least squares. In order to avoid the singularity of normal equations, the constraint that the sum of corrections to declinations and right ascensions be zero for all the stars from the original PZT75 catalogue was imposed. The average rms errors in declination and right ascension of a single observation of a star

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(calculated from the residuals after adjustment) are 0.14" and $0^s.013$, respectively.

Then for each star six observational equations (for the four PZT subintervals, AGK2 and AGK3) were formed with the following unknowns:

i) for each star the correction to its mean position and proper motion (for the epoch 1950.0),

ii) for each of the four subintervals of PZT observation a constant shift of all the positions. If the equinox, equator and the system of proper motions of the initial catalogue PZT75 were identical with those of AGK2/AGK3, these unknowns should be zero.

The weights of the PZT observations were put equal to the number of plates from which the corrections to coordinates in the corresponding subinterval were derived, the weights 2 and 1 were assigned to the positions taken from AGK2 and AGK3, respectively. Then the system of normal equations was formed and solved. The results showed that there existed large discrepancy both in equinox and equator between PZT75 and AGK2/AGK3 with a slow drift ($+0^s.0631+0^s.00026(t-1950)$ and $+0''.064+0''.0019(t-1950)$ respectively), reflecting the fact that the system of PZT75 positions and proper motions was based on only one group of SAO stars. On the other hand, the difference between the new catalogue and AGK2/AGK3 both in position and proper motion averaged over all the 304 stars is zero. The average rms errors of the new catalogue (called PZT78) are less for the stars that were observed during the whole interval of six years than for those observed in 1978 only. In general, the rms error of the position at epoch t can be expressed as

$$m_t^2 = m_o^2 + \mu_o^2 (t-t_o)^2 .$$

The constants m_o, μ_o and t_o for both coordinates and both groups of stars are given in Tab. 1.

Table 1.

Stars observed in	declination			right ascension		
	m_o	μ_o	t_o	m_o	μ_o	t_o
1973 - 1978	$0''.026$	$0''.0033$	1974.6	$0^s.0024$	$0^s.00030$	1974.6
1978	0.054	0.0033	1971.3	0.0050	0.00031	1971.3

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2. The Results Obtained with PZT78 Catalogue

The PZT78 catalogue is in current use since January 1980. In order to keep the new system of the instrument close to the previous one, the conventional longitude has been changed from $-0^h 59^m 08^s.621$ to $-0^h 59^m 08^s.550$ and we ceased to subtract 0.1" from all our latitude results (the practice which was used since the very beginning in order to keep the results in accordance with the originally reported mean latitude of the instrument).

All the existing PZT observations were re-reduced with the new PZT78 catalogue and the results of individual groups compared with both BIH68 and BIH79 system (BIH Annual Reports, Tab. 6A for the years 1973 - 1978, BIH Circular D for the year 1979). It should be noted that, using the new reduction method, we succeeded in reducing several tens of plates the results from which were not originally sent to BIH or IPMS. This holds especially for the first two years of observations. Harmonic analysis of the individual residuals for each year seperately was fulfilled and, following the practice of BIH, the residuals expressed by means of the formulae

$$R = a + b \sin 2\pi t + c \cos 2\pi t + d \sin 4\pi t + e \cos 4\pi t$$

$$S = a' + b' \sin 2\pi t + c' \cos 2\pi t + d' \sin 4\pi t + e' \cos 4\pi t$$

The coefficients a, b, c, ... are displayed, together with the coefficients calculated by BIH in the system of our old catalogue PZT75 and BIH68 (BIH Annual Reports, Table 3), in Tab. 2. In the column headed "diff." the following notation is used: I for PZT75-BIH68, II for PZT78 - BIH68 and III for PZT78-BIH79. In the lowest three rows of the table, the arithmetic means of the coecficients are given.

The agreement of the PZT results with either BIH68 or BIH79 system can be considered if the values of coefficients in the lowest two rows of the table are compared. Adopting for the "measure of fitness" the sum of squares $A = b^2 + c^2 + d^2 + e^2$, we obtain for the ratios A_{BIH68}/A_{BIH79} the values 1.83 and 1.07 in case of latitude and time, respectively. This means that the PZT results are in better agreement with BIH79 than with BIH68, especially in case of latitude.

The stability of the results can be, according to Feissel [1], considered in terms of the expression

$$Q_n = \sum_1^n (a_i - a_n)^2 + \frac{1}{2} \sum_1^n [(b_i - b_n)^2 + (c_i - c_n)^2 + (d_i - d_n)^2 + (e_i - e_n)^2],$$

where a_n through e_n are the arithmetic means of the individual coefficients over the period of n succesive years. In the present study,

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Table 2.

year	diff.	R (in 0.001")					S (in $0\overset{s}{.}0001$)				
		a	b	c	d	e	a'	b'	c'	d'	e'
1973	I	+18	+24	-49	+ 3	-11	-155	-34	-241	-116	-69
	II	+65	+ 2	-54	+20	-55	-35	+ 8	-109	-24	-37
	III	+65	-11	-35	+26	-58	-35	+12	-104	-25	-44
1974	I	+30	+29	-15	- 8	+14	-20	+64	+16	+21	-14
	II	+56	- 7	-38	- 8	+ 4	-15	+15	+23	+38	- 5
	III	+56	-20	-19	- 2	+ 1	-15	+19	+28	+37	-12
1975	I	+74	+26	-29	-15	+23	+ 1	+47	- 9	-31	-25
	II	+89	-22	-62	- 8	+ 8	+14	+18	- 9	-21	-16
	III	+89	-35	-43	- 2	+ 5	+14	+22	- 4	-22	-23
1976	I	+62	+41	-47	-22	-35	+17	+42	-21	-19	+31
	II	+79	0	-74	-26	-47	+32	+ 5	-12	-10	+25
	III	+79	-13	-55	-20	-50	+32	+ 9	- 7	-11	+18
1977	I	+111	+27	-39	-23	- 8	+10	+23	-37	+32	-13
	II	+138	+ 2	-34	-25	- 3	+15	- 3	-23	+41	-21
	III	+138	-11	-15	-19	- 6	+15	+ 1	-18	+40	-28
1978	I	+141	+48	-10	- 3	-19	-24	+14	-102	-26	-16
	II	+125	+ 8	-47	-11	-20	-30	-18	-119	-21	-42
	III	+125	- 5	-28	- 5	-23	-30	-14	-114	-22	-49
1979	II	+80	-15	- 8	-53	+19	-11	+ 6	-93	+37	0
	III	+80	-28	+11	-47	+16	-11	+10	-88	+36	- 7
73/78	I	+73	+32	-32	-11	- 6	-28	+26	-66	-23	-18
73/79	II	+90	- 5	-45	-16	-13	+ 1	+ 4	-49	+ 6	-14
73/79	III	+90	-18	-26	-10	-16	+ 1	+ 8	-44	+ 5	-21

the comparison of Q_6 (for the years 1973/1978) in the system of PZT75 and PZT78 catalogues is taken into consideration. The ratio $Q_{PZT75}/Q_{PZT78} > 1$ shows the increase in stability of the results. The values calculated from the data in Tab. 2 are 1.50 and 3.38 in case of latitude and time, respectively.

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3. Conclusions

The positions and proper motions of the stars in the catalogue PZT78 were derived combining PZT observations with AGK2 and AGK3 catalogues. The equinox and equator as well as the system of proper motions of the new catalogue are very close to those of AGK2/AGK3 and hence of FK4. The average rms errors of the derived positions will not exceed the limit of ±0.08" within the next decade. The new catalogue ensures higher stability of the results with respect to BIH. Besides, the results based on the catalogue PZT78 are in better agreement with the newly adopted BIH79 system than with the elder system BIH68. All the results were submitted both to BIH and IPMS. We hope that the new catalogue will form a good basis for our cooperation in the coming MERIT campaigns.

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ОБ ОСНОВНЫХ КООРДИНАТНЫХ СИСТЕМАХ, ПРИМЕНЯЕМЫХ В ГЕОДИНАМИКЕ

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Р е з ю м е

Дан обзор современного состояния проблемы установления основных координатных систем, применяемых в геодинамике. Рассмотрены перспективы использования новых методов и средств наблюдений для решения этой проблемы.

A b s t r a c t

Ya.S.Yatskiv "On the basic reference coordinate systems for Earth Dynamics"

Current state of establishing the basic coordinate systems for Earth Dynamics is reviewed. The possibilities of new observing methods and techiques are considered for solving this problem.

I. Введение

При проведении высокоточных геодинамических исследований важное место занимает выбор, задание и практическое построение основных координатных систем, к числу которых относят:
I) невращающуюся в пространстве систему небесных координат (НСНК);
2) земную геоцентрическую систему координат (ЗСК).
Требования, предъявляемые к определению и практической реализации

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указанных систем координат, широко обсуждались на Коллоквиуме МАС № 26 „Об опорных системах координат для геодинамики" (Торунь,1974) [15] , рассмотрены в работах Е.П.Федорова [7] и Я.С.Яцкива и В.С.Губанова [8] , опубликованных в специальном сборнике статей, посвященном 100-летию со дня рождения А.Я.Орлова, и других публикациях [2,6] . В настоящее время ведется подготовка Второго коллоквиума МАС № 56 по рассматриваемой проблеме, который состоится в Польше в сентябре этого года.

Поэтому здесь мы дадим только краткую характеристику состояния работ по заданию и построению основных координатных систем, применяемых в геодинамике, и остановимся на тенденции развития исследований по этой проблеме в связи с применением новых методов и средств наблюдений.

2. Принципы задания и построения основных систем координат

Основные системы координат ничем не отмечены ни на небесной сфере (первая система), ни на поверхности Земли (вторая система), а материализуется в виде списков некоторого числа объектов Вселенной или соответственно пунктов земной поверхности, координаты которых заданы в этих системах. Как известно, в астрометрии непосредственно измеряются только углы, а не расстояния, до удаленных объектов Вселенной. Астрометрия не располагает возможностью связать начало координат с этими объектами и найти таким образом его движение. Приходится использовать для задания начала первой системы координат тела Солнечной системы, а для задания направлений ее осей - внегалактические источники (до недавнего времени звезды). В то же время для решения многих задач геодинамики можно ограничи-

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ться системой координат, в которой заданы только направления осей и все построения выполняются в пространстве изображений - на поверхности вспомогательной сферы [I,5,6]. Такой системой координат является фундаментальная система, по существу реализующая невращающуюся систему небесных координат, а не инерциальную, как это часто отмечают в руководствах по астрометрии.

В отличие от первой, основной системы (НСНК) координат, земная геоцентрическая система координат (ЗСК) связывается только с телом Земли, а именно, направление ее осей задается по отношению к совокупности отвесных линий в разных точках земной поверхности или по отношению совокупности опорных баз на Земле. Начало ЗСК совмещается с центром массы Земли.

При задании и построении основных систем координат используются геометрические и динамические принципы, описание которых дано в [7,8].

3. Современная точность построения основных координатных систем

3.I. Невращающаяся система небесных координат (НСНК).

В настоящее время в качестве НСНК используют среднюю экваториальную систему координат определенной эпохи, которая материализуется в виде фундаментального каталога положений и собственных движений звезд. В качестве международного стандарта принят каталог FK4. В принципе достаточно знать положения двух звезд в каталоге FK4, чтобы задать направление осей НСНК. Однако из-за ошибок собственных движений этих звезд оси такой системы координат будут менять свое направление по отношению к осям инерциальной системы отсчета. Более того, система, связанная только с двумя звездами, не может быть применена в широких масштабах на практике.

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Приходится для задания направлений осей НСНК использовать каталожные положения многих звезд. В этом случае говорят о системе координат, задаваемой каталогом. Ее отличие от идеальной может быть описано матрицей вращения R и систематическими уклонениями $\Delta\alpha$ и $\Delta\delta$, которые показывают, что каталог, используемый для задания НСНК, не является внутренне согласованным. Обычно систематические уклонения $\Delta\alpha$ и $\Delta\delta$ описывают некоторыми функциями, зависящими от положения звезд на небесной сфере, звездной величины и др., а отличие направлений осей (недиагональные элементы R) считают незначимыми. Систематические уклонения $\Delta\alpha$ и $\Delta\delta$, в строгом смысле этого слова, определить невозможно. Поэтому находят их оценки по результатам сравнения каталогов. Кроме того, точность положений звезд в каталогах зависит от случайных ошибок наблюдений, обусловленных влиянием на процесс измерений, наблюдателя и инструмент целого ряда неконтролируемых факторов. Существуют различные подходы к точности положений звезд в каталогах. В дальнейшем мы будем придерживаться классического подхода к этой проблеме и приведем средние квадратические ошибки положений звезд в каталоге (по оценкам Ледерле [13]) отдельно для северного и южного полушарий неба. Направление осей НСНК, задаваемой каталогом $FK4$, близко к направлению осей динамической системы координат, задаваемому орбитальным и вращательным движениями Земли. По оценкам, полученным в ГАО АН УССР Д.П.Думой и его сотрудниками, расхождение нуль-пунктов каталога $FK4$ и динамической системы координат составляет $\Delta\alpha_0 = +0.20'' \pm 0.08''$ и $\Delta\delta_0 = +0.02'' \pm 0.02''$. Кроме того, точность построения НСНК зависит от ошибочности постоянной прецессии, принятой в качестве основной, фундаментальной постоянной астрономии. В новой системе астрономических постоянных - МАС, 1976 ошибка столетнего значения общей прецессии в долготе на эпоху

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$J2000$ оценивается близкой $\pm 0\overset{''}{.}1$. Таким образом, суммарная ошибка построения НСНК для современных эпох составляет около $0\overset{''}{.}2$, что на два порядка превышает требуемую.

Таблица I

Средние квадратические ошибки положений звезд в каталоге $FK4$ для различных эпох

Эпоха	Прямые восхождения		Склонения	
	$\sim$	S	$\sim$	S
1925.0	$\pm 0\overset{''}{.}04$	$\pm 0\overset{''}{.}08$	± 0.04	± 0.05
1950.0	6	9	5	9
1975.0	11	18	8	15

Для решения научных и практических задач астрономии, космической геодезии и геодинамики нужно знать координаты возможно большего числа небесных объектов в системе фундаментального каталога, в частности распространить эту систему на слабые звезды. Этой цели служат сводные каталоги звезд. Информация о некоторых из них приведена в табл.2, в которой для сравнения даны сведения о фундаментальных каталогах $FK4$ и $N30$, а также о сводных каталогах SRS и KSZ, работа по составлению которых в настоящее время ведется. Как видно из табл.2, случайная ошибка таких распространенных каталогов как SAO, не говоря о расхождении системы этого каталога и $FK4$, составляет около $\pm 0.5''$. Таким образом, несмотря на огромный труд, затраченный многими поколениями астрометристов, достигнутая точность построения первой основной системы координат не удовлетворяет современным запросам науки и практики. Мы здесь не касались сложных вопросов определения начала отсчета этой системы координат и шкалы расстояний в астрономии, которые обсуждались в [7].

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Таблица 2

Средние квадратические ошибки положений звезд в каталогах (в случайном отношении)

Каталог	Средняя эпоха наблюдений T_m	Число звезд в тысячах	Ср. кв. ошибки T_m	1975
FK4	1916	1.5	±0".04	±0".11
N30	1932	5.0	9	22
AGK3R	1958	21.5	11	16
AGK3	1960	180.0	20	25
SAO	1963	259.0	50	51
SRS	1970	20.0	10	10
KSZ	1967	41.0	10	10

3.2. „Земная" система координат.

Если бы Земля была абсолютно твердой, то построение высокоточной „земной" системы координат, в которой положения пунктов Земли не изменяются во времени, не вызывало бы затруднений. В случае реальной Земли необходимо учитывать такие явления как упругие деформации ее мантии, относительные перемещения блоков земной поверхности, движения в ядре Земли и др. „Земная" система координат в настоящее время реализуется в виде списка средних прямоугольных координат станций на определенную эпоху. Временные изменения этих координат, за исключением некоторых хорошо известных геодинамических эффектов, принимаются равными нулю. Ось OZ и плоскость нулевого меридиана ЗСК выбираются такими, как в известных системах Международного условного начала - CIO и Международного бюро времени BIH1968. В табл.3 приведены сведения о числе станций, числе

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инструментов и периодах наблюдений, использовавшихся при создании и построении этих систем.

Таблица 3

Системы отсчета CIO и BIH 1968

Наименование	Число обсерваторий	Число инструментов: Широта	Число инструментов: Время	Период наблюдений
CIO	5	5	-	1900.0 - 1906.0
BIH 1968	51	39	48	1964.0 - 1967.0

Рассмотрим возможные источники ошибок построения ЗСК. Ориентация системы в теле Земли зависит от точности построения и сохранения стабильности систем CIO и BIH 1968, осуществляемых международными службами движения полюса и определения времени. Из исследований, выполненных в ГАО АН УССР, следует, что указанные системы не обладают преимуществами перед системой, у которой ось oz проходит через средний полюс эпохи наблюдений, т.н. полюс Орлова [5]. Эта система была принята в [19] за стандартную, по отношению к ней были определены характеристики нестабильности систем CIO и BIH 1968 (см. табл.4). Как видно, система CIO из-за небольшого числа станций наблюдений подвержена значительным линейным и периодическим изменениям направлений ее осей по отношению к другим системам.

Таблица 4

Нестабильность систем отсчета CIO 1903 и BIH 1968

Составляющая	CIO 1903	BIH 1968
Линейный тренд	10 см/год	-
Периодические изменения (~ 24 года)	±108 см	-
Короткопериодическая и случайная составляющие	± 27 см	± 30 см

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Совмещение начала ЗСК с геоцентром осуществляется динамическими методами по данным наблюдений ИСЗ, Луны и др. В настоящее время точность такой привязки составляет для лучших реализаций ЗСК несколько десятков сантиметров[15].

Точность построения ЗСК с каждым годом повышается. Если на первом этапе работ по созданию общеземных систем относимости по наблюдениям ИСЗ координаты станций определялись с меньшей точностью, чем направления координатных осей в теле Земли, то в дальнейшем ситуация изменилась. Ошибки определения координат станций стали сравнимыми с ошибками ориентации осей ЗСК. Возникла задача совместного улучшения координат и ориентации ЗСК. При этом системы CIO или BIH 1968 используются как исходные системы на первом этапе работы по построению ЗСК. Таким образом, было составлено несколько сводок координат станций, задающих различные реализации ЗСК, например, Стандартная Земля Ш, NWL-9 и др. Среднее значение ошибки определения координат станций, характеризующее внутреннюю согласованность таких систем, приблизительно равно ± I м. Однако между отдельными системами имеются большие систематические различия. Анализ точности определения параметров ориентрования отдельных реализаций ЗСК позволяет сделать вывод, что в настоящее время можно построить сводный каталог координат пунктов Земли, задающий ЗСК с точностью до нескольких десятков сантиметров. Это на один порядок ниже точности, требуемой для геодинамических исследований.

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4. Перспективы повышения точности реализации основных систем координат

4.I. Невращающаяся система координат (оптическая астрометрия)

По решению Международного астрономического союза с I973 г. в Гейдельберге (ФРГ) под руководством проф. В.Фрике ведется работа по составлению нового фундаментального каталога FK5, который будет принят с I984 г. в качестве международного стандарта. Этот каталог будет содержать около 4 тыс. звезд до 9 звездной величины [I0]. При его составлении будет использована новая система астрономических постоянных, а также приняты меры по уточнению нуль-пунктов и уменьшению систематических ошибок. По прогнозным оценкам точность каталога FK5 на эпоху наблюдения составит около $\pm0.''05$, в том числе в случайном отношении $\pm0.''0I$ - $\pm0.''02$. Возможность дальнейшего улучшения фундаментальной системы координат по наземным наблюдениям в оптическом диапазоне спектра излучений проблематична. Из резервов наземной астрометрии следует отметить организацию наблюдений в пунктах с хорошими астроклиматическими условиями, создание высокопроизводительных автоматических инструментов, точный учет инструментальных погрешностей и влияния атмосферы, и, наконец, разработку методики создания однородной на всей небесной сфере системы координат. От того, в какой мере удастся в будущем использовать эти резервы, зависит роль наземной оптической астрометрии в изучении геометрических и кинематических характеристик Вселенной.

4.2. Невращающаяся система координат (радиоастрометрия).

В последние годы наметился переход к использованию новых методов построения НСНК, ведущее место среди которых занимает метод длиннобазисной радиоинтерферометрии (РСДБ). Объектами наблюдений

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методом РСДБ в первую очередь являются компактные внегалактические радиоисточники (квазары, ядра галактик), собственные движения которых очень малы. Поэтому такие объекты являются идеальными реперами для задания направления осей НСНК, построение которых в радиоастрометрии возможно двумя принципиально разными методами:

а) испытанным в оптической астрометрии методом абсолютных определений координат;

б) специальным методом измерений дуг между источниками [3,12].

При применении первого метода необходимо тщательное изучение вращения Земли и определение коэффициентов в разложениях ее прецессионно-нутационного движения. Кроме того, определение методом РСДБ начала отсчета прямых восхождений встречается с рядом трудностей [2]. Поэтому в созданных недавно каталогах положений радиоисточников начало отсчета прямых восхождений совмещено с началом прямых восхождений в каталоге FK4 путем фотографической привязки отдельных квазаров к звездам FK4 [16]. Внутренняя точность таких каталогов составляет в лучшем случае около $\pm 0\overset{''}{.}01$, в то время как различия между отдельными каталогами достигают секунд дуги.

Параметры прецессионно-нутационного движения Земли в будущем могут быть определены методом РСДБ с высокой точностью, в частности по абсолютным наблюдениям склонений. Основным ограничением рассматриваемого метода построения НСНК является необходимость точного учета влияния инструментальных и метеорологических факторов на результаты наблюдений.

Во втором случае, если допустить возможность реализации такого метода измерений, проблемы построения НСНК и изучения сложного поступательно-вращательного движения Земли становятся независимыми. Измеренные дуги между радиоисточниками, расположенными более или менее

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равномерно по всей небесной сфере, могут быть уравнены в единой автономной системе координат, направления осей которой можно выбрать произвольно. Все же предполагается, что на первом этапе создания такой системы координат ее нуль-пункты будут совмещены для удобства с нуль-пунктами каталога FK5 . Дальнейшее улучшение радиоастрономической НСНК не будет зависеть от фундаментальной системы координат.

Модельные расчеты, а также выполненные в последние годы эксперименты свидетельствуют о том, что с помощью метода РСДБ может быть построена НСНК с точностью, близкой к $\pm 0.''001$ [3,11,12] . Из других методов реализации НСНК следует отметить очень перспективный проект HIPPARCOS, предложенный Европейским космическим агентсвом для определения высокоточных относительных положений звезд и их параллаксов [18] .

4.3. „Земная" система координат (новые методы).

В [15] рекомендуется материализовать ЗСК в виде списка средних прямоугольных координат некоторого числа станций, заданных на определенную эпоху T_0 , с указанием их изменений во времени. При этом предполагается, что предсказуемые периодические изменения положений станций, например приливного происхождения, должны моделироваться и учитываться с точностью около 1 см.

Для практического использования построенной таким образом ЗСК необходимо иметь постоянно действующую службу вращения Земли, которая определяет координаты полюса и всемирное время. В табл.5 приведены данные о точности определения параметров вращения Земли существующими и планирующимися к созданию службами:

IPMS - Международная служба движения полюса, астрономические наблюдения.

BIH - Международное бюро времени, астрономические наблюдения, допплеровские наблюдения ИСЗ.

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DMATC – Служба движения полюса Топографического центра Военно-топографического управления США, допплеровские наблюдения ИСЗ.

SLR – Лазерная локация ИСЗ.

LLR – Лазерная локация Луны.

VLBI – Длиннобазисная радиоинтерферометрия.

Таблица 6

Точность определения движения полюса и неравномерности вращения Земли /по внутренней сходимости/

Служба вращения Земли	Временное разрешение	Ср. кв. ошибки	
		Координаты полюса в м.	UT1 / в мс.
IPMS	0.05 года	± 0.5	–
BIH	5 суток	± 0.5	± 1.0
DMATC	5 суток	± 0.2	–
		Прогнозные оценки	
SLR	I сутки	±0.02 - ±0.05	–
LLR	–"–	±0.05 - ±0.10	± 0.1
VLBI	–"–	± 0.05	± 0.1

Как видно, требованиям, предъявляемым к точности построения ЗСК удовлетворяют службы, базирующиеся на лазерных наблюдениях Луны и наблюдениях с РСДБ. В настоящее время предпринимаются попытки достижения указанной точности в экспериментальном порядке, например, в проектах POLARIS [9], фазостабильного интерферометра NRAO [II] и в программе EROLD [I4]. Что касается лазерных наблюдений ИСЗ, то здесь особые надежды возлагаются на наблюдения спутника типа Лагеос. Первые результаты наблюдений этого спутника, которые велись Годдардским центром космических поле-

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тов на 8 станциях с точностью около ±10 см, позволили определить координаты станций с точностью от ±20 до ±50 см и 5-ти суточные координаты полюса с точностью, сравнимой с точностью результатов BIH [17]. Определение всемирного времени по лазерным наблюдениям ИСЗ затруденено из-за влияния ошибок гравитационного поля и неточности учета приливов.

В перспективе предполагается, что наблюдения с помощью стационарных установок для лазерных наблюдений Луны и ИСЗ, а также комплекса многоэлементного интерферометра будут служить для изучения глобальных геодинамических явлений и задания земной геоцентрической системы координат. Лазерные и радиоинтерферометрические установки передвижного типа, а также различного рода допплеровские и другие системы измерений будут использоваться в программах изучения движения блоков земной коры, локальных геодинамических явлений, а также для сгущения опорной геодинамической сети станций.

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