GEOPHYSICAL GEODESY BEYOND 2000

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Abstract

In this paper some of the problems of the physical geodesy, not solved till the end of the second millennium are discussed. They are the problems connected to the Newtonian law of gravity first of all. The gravitational constant is the most inaccurately determined constant of the nature and the questions of the so-called non-Newtonian gravimetry are also not answered. An another problem which needs further investigations is connected to the Mac Cullagh theorem: the time derivative of the second zonal geopotential coefficient obtained from satellite orbit determinations is of about 50 times bigger than those obtained from the spindown value. The study of the tidal friction attracted a lot of interest in the course of the XXth century. So great names as G. Darwin, A. Einstein, H.Jeffreys expressed their interest in this field. In spite of this there are many important questions unsolved. Among them should be mentioned the problem of the rotational history of our planet, the temporal variation of the figure, of the normal gravity field of the Earth and the problem of the changes in its inner structure.

1. Introduction

Our knowledge on the Earth increased dramatically in the course of last two, our three decades. The progress in Earth sciences and among them in geophysical geodesy was reached first of all due to the development in the technology. The new possibilities in computing techniques, in physics of very low temperatures, in satellite sinence allows to produce equipment's the realization which was possible only in the world of scifies earlier. The methods of space geodesy, as Very Long Base Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR and LLR), Global Positioning System (GPS), the new absolute (ballistic) and relative (criogenic) gravimeters allows to determine the figure and the gravity field together with their temporal variations. The close cooperation of researchers, working in different branches of geo-sciences, allows the progress in interpretation of observed geodynamical phenomena. The use of results of seismology, of plate tectonics, of reology, of earth magnetism studies among others render possible better understanding the figure and the gravity field of the Earth and time dependent phenomena influencing the development of our planet.

To illustrate the progress the comparison of earth tidal research targets of sixties can be compared with those of the present. Thirty years ago the tidal potential catalogue consists 377 elementary waves and the accuracy of the tidal development was ~ 1 nm · s^{-2}. Today we have 12935 waves and the accuracy of this serie is ~700 times higher as earlier. In the course of sixties it was supposed that the best places for tidal studies are the central part of continents because at that places the indirect effect of oceanic tides not modifies the earth tidal data. Today we know that it is not true, the oceanic tidal influence is significant everywhere on the mainland's, but this effect can be removed with the use of the most modern cotidal maps. Thirty years ago nobody beleived that the microgal level can be reached in the future with recording gravimeters. At the end of XXth century we are near to talk about nanogal level in gravimetry. Earlier it was supposed that from the global tidal response significant new information's can be obtained - beyond the information's derived from seismology - on physical properties and on inner structure of the Earth. The optimism of "earth-tidalists" was connected first of all with possible detection of lateral in homogeneities within the Earth from their observations. This hope was not confirmed by the development in the science, but there are another fields, where tidal research is able to provide knowledge which seismology can not. This is first of all the study of the nearly diurnal resonance of the Earth. At the same time the modern criogenic recording gravimeters are able monitor beside the tides the polar motion and environmental phenomena, too.

2. Problems related to Newtonian law of gravity

First of all the scale dependence of the Newtonian gravitational constant G will be discussed in this section.

At astronomical distance no *G* values can be provided due to the unknown masses, but the Newton's law can be tested with high accuracy. (Hubler, Cornaz, Kündig, 1995). In the range of 10^3 m - 10^7 m the inverse - square law has been confirmed satisfactory from a comparison of the Earth-surface data with orbital parameters of the LAGEOS satellite. At geophysical distances (10^2m-10^4m) many experiments ware carried out. G_∞ obtained from this determinations differs significantly from the results of G_0 values obtained in laboratories at distances 10^{-2} - 10° m (Stacey et at.,1987) . A theoretical basis for this deviation in principle can be given by introduction of the so called Yukawa type non-Newtonian gravity potential (Stacey et al., 1987):

$$V = -\frac{G\infty m_1 m_2}{r}(1+\alpha \cdot e^{-\beta}) = V_N + V_Y \tag{1}$$

If $\alpha = 0, V = V_N$ where V_N is the Newtonian potential. If $\alpha \neq 0$ V_Y appears additionally which is called the Yukawa term.

If $\beta \langle\langle 1$ we get

$$G_0 = G_\infty(1+\alpha) \tag{2}$$

On the basis of experiments with scale (10^{-2}m - 10^{-4}m) - Airy type experiments - Stacey et al. (1987) got for G_∞ a value which is bigger than the G_0 value obtained in laboratories (10^{-2} - 10^0 m distances). The difference $G_\infty - G_0 \sim 0.01$ what leads to $\alpha \sim 0.0075 \pm 0.0036$.

For the investigation of the reliability of $G_0 \neq G_\infty$ a special experiment was carried out at the Geodynamical Observatory in Budapest deeply under the surface of the Earth. An underground calibration line was set up which consists of 14 stations with a range of 1400±1 μ Gal. Gravity differences, separation and the elevation difference between neighbouring stations are 100 μ Gal, 2-5 m, less than 2 cm respectively.

The gravity values for this horizontal line were determined with a computer regulated Eötvös torsion balance. The instrumental constant of the torsion balance was obtained by the measurement of sensor masses, the length of the arm of the balance and the torsion of the wire. This means: the gravity values of the underground calibration line were obtained without the use of the gravimeters.
On the other hand a new gravimeter calibration device was proposed and designed by Varga (1989) and it also was installed is the underground laboratory of the Geodynamical Observatory Budapest. The principle of this instrument is simple. The artificially induced gravity changes are generated by a suspended cylindrical ring with an inner diameter somewhat bigger than the width of the gravimeter (usually LCR instruments) to be calibrated. The ring is raised and lowered vertically and moved over the gravimeter equipped by a distant reading device and installed on a column of suitable height.

There are many advantages of this calibration procedure:

- The homogeneity of the generated gravity field is very high at the extrema;
- The moved vertically ring does not load the ground around the instrument;
- The gravimeter is stationary during the procedure what is necessary for a small instrumental drift;
- The experiment is symmetrical with respect to the gravimeter and owing to technical reasons the gravity change brought about by the ring is greater than that caused by another geometrically regular body.

Due to this positive features similar device was used in Italy (Achilli et al., 1995) and in the United States (Schwartz, J.P. et al., 1998). All technical problems and the results of the calibrations are described in Varga et al., (1991) and in Varga et al., (1995). With this device absolute calibrations with accuracy of 0.l-0.2% can be carried out.

The difference of the calibration factors obtained for the same gravimeter along the calibration line (i.e. by means of gravitational effect of 10^2-10^4 m scale, air type experiment and derived from measurements with the heavy cylindrical mass (10^{-2}-10° m distances)) is of the order of 10^{-3}, what means that the difference between the G_∞ and G_o is also at most 10^{-3} and not 10^{-2} as was supposed earlier (Stacey et al., 1987).

Another problem connected to the gravitational constant *G* is its, supposed by many authors, temporal variation. The need of $\frac{dG}{\partial t} \neq 0$ follows from the cosmological considerations. Dirac’s expanding Universe model proposed in 1937 naturally leads to a decreasing constant of gravitation and to the theory of the expanding Earth of course. Using Dirac’s theory Jordan concluded (1966) that the Earth radius increases with a speed *da/dt* = 0.5 mm· y^{-1}. Similar value for the expansion was derived by Egyed (1997) *da/dt* = 0.7 mm·y^{-1}, who supposed that originally the surface of our planet was as big as the areas of all recent continents together. The most recent and complete description of these theories can be found in the book by Carey (1988).

The critical review of *da/dt* and consequently of *dG/dt* can be carried out on the basis of the study of the influence of tides on the long-term variations of the angular speed. Study of this type are usually based on the principle of conversation of angular momentum and it is supposed that the Earth-Moon system is isolated. For the sake of simplicity it can be supposed that the Moon revolves around the Earth on a circular orbit in the plane of the terrestrial equator. In this case Euler’s equation can be written as

$$\frac{\partial(C\omega)}{\partial t} = L$$

$$L = \frac{1}{3}\frac{MM_m}{M + M_m} R_m^2 \frac{\partial n_m}{\partial t} \tag{3}$$

In (3) *M, C,* ω are the mass, the polar moment of inertia and the angular speed of the Earth respectively. M_m, R_m and n_m stands for the mass of the Moon, for the Earth-Moon distance and for the orbital speed of the Moon. Kepler’s law can be written as

$$n_m^2 R_m^3 = G(M + M_m)$$

and its time derivative is

$$2n_m R_m^3 \frac{\partial n_m}{\partial t} + 3n_m^2 R_m^2 \frac{\partial R_m}{\partial t} = \frac{\partial G}{\partial t}\left(M + M_m\right) + G\frac{\partial\left(M + M_m\right)}{\partial t}$$

In r.h.s. of above equation it can be evidently supposed that the time derivative of *G* is not time dependent $\left(\partial G / \partial t = C\right)$ while the second term is zero. This way

$$\frac{\partial n_m}{\partial t} = -\frac{3}{2}\frac{n_m}{R_m}\frac{\partial R_m}{\partial t} + \frac{\partial G}{\partial t}\frac{M + M_m}{2n_m R_m^3} = \frac{3}{2}\frac{n_m}{R_m}\frac{\partial R_m}{\partial t} + C^*$$

C^* is of course a constant value. Introducing $\partial n_m / \partial t$ into (3)

$$\frac{\partial(C\omega)}{\partial t} = -\frac{1}{2}\frac{MM_m}{M + M_m} n_m R_m \frac{\partial R_m}{\partial t} + \frac{1}{6}\frac{MM_m}{n_m R_m}\frac{\partial G}{\partial t} = L + \frac{1}{3}\frac{MM_m}{M + M} R_m^2 C^* \qquad (4)$$

From astronomical data

$$\frac{\partial(C\omega)}{\partial t} \approx -4.1 \cdot 10^{16} N_m$$

The total tidal torque is composed by the atmospheric (L_{AT}), the earth (L_{ET}) and the oceanic (L_{OT}) tidal torque's:

$$L = L_{AT} + L_{ET} + L_{OT} = 5 \cdot 10^{15} N_m - \left(5 \cdot 10^{15} + 5 \cdot 10^{16}\right) N_m = -5 \cdot 10^{16} N_m$$

Consequently in (4) $\dfrac{\partial G}{\partial t} \geq 0$ what is in contradiction with the theories on the expanding Universe and Earth, because an increasing gravitational constant requires compression.

The third problem which will be discussed in this study in connection of the Newtonian law is the problem of the numerical value and the accuracy of the gravitational constant. The value of the gravitational constant *G* is known with much less accuracy than other fundamental constants of physics. Authors of the best determinations of this universal constant claim to their results an accuracy of 10^{-4}, but the following list of the *G* values obtained by different scientists shows that the disagreement between the individual results is of the order of 10^{-3}.

AUTHORS	YEAR	$G \cdot 10^{11}\, Nm^2 kg^{-2}$
Rose et al.	1969	6.6699±0.0014
Facy & Poinkis	1970, 1971	6.6714±0.0006
Renner	1974	6.668±0.0002
Sagitov et al.	1978	6.6745±0.0008
Luther & Towler	1982	6.6726±0.0005
De Boer	1987	6.6670±0.0007
Michaelis et al.	1996	6.7154
Schwarz et al.	1998	6.6873±0.0094

Moreover it can be concluded that G is the least known constant of fundamental physics. The following compilation shows the relative errors of basic physics constants:

Avogadro constant	$5.2 \cdot 10^{-10}$
Boltzman's constant	$1.2 \cdot 10^{-4}$
Elementary charge	$2.8 \cdot 10^{-6}$
Faraday constant	$2.8 \cdot 10^{-6}$
Gravitational constant*	$8.5 \cdot 10^{-4}$
Mass of the neutron	$5.1 \cdot 10^{-6}$
Planck's constant	$5.5 \cdot 10^{-6}$
Rydberg's constant	$8.3 \cdot 10^{-6}$
Spead of the light	$4.0 \cdot 10^{-4}$

∗ The error value of G is the value given by CODATA (Cohen &Taylor, 1986)

There are several explanations why *G* is known with a low accuracy. First of all should be mentioned the weakness of gravitational attraction in scales used in laboratories. For example: a force interaction of two masses of 1g at the distance of 1 cm is 10^{-12} Newton while the pressure of the light of the Sun is 10^{-10} Newton or the forces acting between a proton and a neutron are 10^{-8} Newton. Additionally there is a metrological difficulty: G is defined by the fundamental quantities time, length and mass in absolute scale, what leads of course to experimental difficulties. And finally there is a "psychological problem" too: at this time there are no big research problems in the science, which would urgently need a more accurate value of *G*.

The scatter of the G data listed above suggests that there can be systematic error in gravitational constant values determined in different experiments. The hearth of them - expect the two last ones in the table – is a torsion balance which was used in the beginning in static way and later on – after the successful attempt of Eötvös at the very and of XIX century – dynamically. It was discovered however that the torsion force is dependent on the frequency with which the torsion bar is oscillating. The variability of the elastic constants is particularly significant at low frequencies used in laboratory experiments. According to Maddox (1995) the frequency dependence of the elastic parameters of the materials used in torsion balances is the main source of the systematic and big differences between the laboratory *G* determinations.

In spite of the considerable difficulties it is important to try to increase the accuracy of *G* determinations. It seems that one way can be in this direction the use of the laboratory calibration device developed by us. This experimental tool has a clear geometry and the used quantities (mass of the ring, its position etc.) are already or can be obtained with an accuracy necessary to get *G* with a relative error of 1 part in 10^4 (or even a ten times 10^5). (Varga et al., 1995). To reach this level in our knowledge about the value of the gravitational constant some development of the calibration device in needed.

1. The influence of microseismic noise must be reduced significantly. The systematic beating with a period of some minutes caused by the microseisms characterised with a period of some minutes caused by the microseisms characterised with periods between 5 and 10 s produces gravity variation of about 10 μGal.
2. Because of the need of very accurate determination of the extreme it is necessary to introduce adjustment calculations. This can be the least square method (the L_2 norm) in case of Gaussian error (noise) distribution. In the observations of the gravity during the calibration procedure a number of outliers - possibly due to the long-periodic beating of microseisms – were detected which can be handled with the robust estimations (Somogyi & Závoti, 1993).
3. If the construction of new superconducting gravimeters allows, an effective way to increase the gravity effect is the reduction of the inner diameter of the ring from 30 cm to 20 or to 15. The

corresponding gravity effect generated by the cylindrical ring of mass 3200 kg will be 178 or 236 μGal, instead of 112 μGal.

Of course to get uncertainties of 10^{-4} or even better the spring gravimeters - used until now - must be replaced by new, transportable superconducting gravimeters with reduced diameter which are under development recently at GWR company.
The superconducting gravimeters should be calibrated first along the calibration lines, measured with absolute gravimeters. The accuracy of these calibration lines is 10^{-5} (Atzbacher & Gerstenecker, 1993). Afterwards with the calibrated gravimeters the gravity effect generated by a ring moved up and down must be measured. The gravity effect caused by the ring is known with an accuracy of $\sim 10^{-5}$. If the *G* value is suitable the measured and the generated gravity values should coincide. With other words: the comparison of these two gravity values allows to determine the *G* value.

3. Tidal friction, paleogeodesy and the development of the dynamical properties of the Earth in geological time scale

Fossils and tidal deposits as well as the possibility to compute values of the lunisolar tidal torque for different geological epochs allow us to model the variations in time the angular speed, the despinning rate and the time variations of the Earth's figure, assuming that the latter remains, on global scale, close to a hydrostatic equilibrium figure. On this basis we were able to infer the most important kinetic parameters over much of the geological past.
Lambeck (1980) performed a linear regression of paleontological data of Phanerozoic (last (5-6) 10^{8} years of geological history) and obtained a constant despinning rate of $-5.4 \cdot 10^{-22}$ rad $\cdot s^{-2}$ similar but somewhat higher rates follows from SLR and LLR ($-5.98 \cdot 10^{-22}$ rad $\cdot s^{-2}$ and $-6.07 \cdot 10^{-22}$ rad $\cdot s^{-2}$). These last data differ to a certain extent obtained from astronomical observations ($-5.6 \cdot 10\text{-}^{22}$ $\cdot$rad s^{-2}) (see e.g. Varga et al., 1998). It was found on the basis of more complete paleontological and sedimentological data sets, that the mean despinning rate was smaller in the Proterozoic than in the Phanerozoic. The linear trend in the variation of length of day (l.o.d.) in the Phanerozoic ca be modelled as

$$LOD = 24.00 - 4.98\tau \tag{5}$$

On the other hand for the linear trend in the Proterozoic it can be suggested tentatively

$$LOD = 21.43 - 0.97\tau \tag{6}$$

Where τ is the time before present (BP) in 10^{9} years.

It is clear from (5) and (6) that during the Poterozoic (Ptz) $\left((2.5-0.5)\cdot 10^{9} \text{ years BP}\right)$ the despinning rate was five time smaller than during the Phanerozoic (Pz).

The result concerning the low despinning rate in the Proterozoic solves the problem of the Moon having been ever too near to the Earth. But on the other hand significant difference in the despinning reflected in (5) and (6) between Pz and Ptz needs explanation. At least two mechanisms may be invoked, but both of them are liable to be critized . The first involves the idea that the world ocean was less deep two or three billion years ago than it is now, and the shelf lines were shorter in global scale. The second idea is that the formation of the core was not completed entirely soon after the Earth it self was formed intensively up to $5 \cdot 10^{8}$ years BP. On the basis of tidal friction data it makes sence to estimate the paleogeodetic and geodynamical parameters of the Earth. The next table shows the Earth angular speed (ω), length of day (l.o.d.), geometric flattening (f), dynamic shape factor (J_2) and precession constant (H) in the course of geological history:

Time BP	*ω*	*l.o.d.*	$10^3 f$	$10^3 J_2$	$10^3 H$
(in 10^6 years)	°/*hr*	Hours			
0	15.00	24.00	3.35	1.08	3.27
50	15.00	23.68	3.44	1.11	3.36
100	15.31	23.50	3.49	1.13	3.41
200	15.33	23.52	3.56	1.13	3.42
300	15.73	22.58	3.69	1.19	3.60
400	16.60	21.69	4.11	1.33	4.00
500	17.25	20.87	4.43	1.43	4.31
800	17.44	20.64	4.53	1.46	4.41
1000	17.84	20.18	4.74	1.53	4.61
1400	18.32	19.65	5.01	1.61	4.87
1600	18.53	19.43	5.12	1.65	4.98
2000	18.74	19.21	5.23	1.69	5.08

These data set renders possible the study of the geodetic – geodynamical development of our planet during its history.

The author would like to express his thanks at this place to Erik W.Grafarend who called his attention to the MacCullagh theorem and to its role in understanding geodynamical phenomena.
In case of hydrostatic equilibrium the external potential of the Earth can be written as

$$V = \frac{GM}{r}\left[1 - \sum_{n=2}^{\infty}\left(\frac{a}{r}\right)^{2n-2} J^{\circ}_{2n-2} P^{\circ}_{2n-2}(\sin\Phi)\right]$$

(*a* is the semimajor axis of the Earth *r* is the distance, and Φ the latitude) In case of hydrostatic equilibrium J°_n decrease with the increase of *n* as $f^n \sim \frac{1}{300}$. J°_n values are of the order of 10^{-6} except $J^{\circ}_2 = 1.08 \cdot 10^{-3}$. The mentioned above MacCullagh formula based on the first two terms of the r.h.s. of above equations is

$$V = -\frac{GM}{r}\left(1 - \frac{a^2}{r^2} J^{\circ}_2\right) = -\frac{GM}{r}\left(1 - \frac{C - A}{Mr^2}\right) \tag{7}$$

Equation (7) – in which *C* and *A* are the polar and equatorial moments of inertia – is one of the important starting points of the study of the dynamics and structure of the Earth.

Because in the scientific literature the MacCullagh formula (7) is, as a rule, without a reference to its author it seems necessary to give some basic information on its discoverer James MacCullagh (1809-1847). He was an Irish mathematician and physicist, had a brilliant carrier at the Trinity College in Dublin and was an elected fellow of the Royal Irish Academy. He held at first the chair of mathematics (1832-43) and made a mathematical center from his university. From 1843 he worked at the chair of natural philosophy. His main field of interest was geometry and optics, published also different remarkable studies in gravimetry and on rotation solid bodies. With the use of (7) the external gravity potential of a rotating body *(U)* for n=0,2 is

$$U = V + W = -\frac{GM}{r} + GMa^2 J^{\circ}_2(\sin\Phi) - \frac{1}{2}\omega^2 r^2 \cos^2\Phi \tag{8}$$

The last term of the r.h.s. is the potential of the centrifugal force, which generates variations in gravity if ω is time dependent due to the despinning of the Earth axial rotation for example.
The second term in r.h.s. of (8) can be expressed as

$$-W = \frac{1}{2}\omega^2 r^2 \cos^2\Phi = \frac{1}{3}\omega^2 r^2 \left(1 - P_2^{\circ}(\sin\Phi)\right) \tag{9}$$

Here the last term contributes to the dynamics of the Earth similarly to the second term in the MacCullagh equation

$$V^* = GM\frac{a^2}{r^3} J_2 P_2^{\circ}(\sin\Phi) \tag{10}$$

The second term of r.h.s. of (9) would be equal to the r.h.s. of (10) if a coefficient of proportionality k is introduced which involves the integrated mechanical properties of the Earth.
Therefore with the use of the r.h.s. of (9)

$$W^* = \frac{k}{3}\omega^2 r^2 P_2^{\circ}(\sin\Phi) \tag{11}$$

and introducing the Helmert's geodynamical constant

$$m = \frac{\omega^2 a^3}{GM} \tag{12}$$

ω^2 in (11) can be replaced

$$W^* = \frac{km}{3} GM \frac{r^2}{a^3} P_2^{\circ}(\sin\Phi)$$

If – as it was assumed above $-V^* = W^*$

$$J_2^{\circ} = \frac{k}{3} m \frac{r^5}{a^5} \tag{13}$$

At the surface of the Earth (13) gives

$$J_2^{\circ} = \frac{k}{3} m \tag{14}$$

The time derivative of the second zonal geopotential coefficient J_2° can be obtained from (14) with the use of (12) as

$$\frac{dJ_2^{\circ}}{dt} = \frac{2}{3} k \frac{a^3\omega}{MG}\frac{d\omega}{dt} \tag{15}$$

On the basis of spindown value valid for the present epoch and for the last $0.5\cdot 10^9$ years (*Pz*) with the use of (15)

$$\frac{dJ_2^{\circ}}{dt} = (-5.12 \pm 0.48) \cdot 10^{-13} \text{ year}^{-1} \tag{16}$$

The time derivative of the dynamic shape factor J_2° has undergone significant variations in the course of geological history. As a consequence of (5) and (6) the variations of the dynamics of our planet is different in the Ptz and the Pz:

$$\begin{aligned}
&\frac{dJ_2^{\circ}}{dt} = -4.5 \cdot 10^{-13} \text{ year}^{-1} && \text{during the last } 10^9 \text{ years} \\
&\frac{dJ_2^{\circ}}{dt} = -3.1 \cdot 10^{-13} \text{ year}^{-1} && \text{during the last } 2 \cdot 10^9 \text{ years} \\
&\frac{dJ_2^{\circ}}{dt} = -1.6 \cdot 10^{-13} \text{ year}^{-1} && \text{in the time-interval (2.0-1.0)}10^9 \text{ years BP}
\end{aligned} \tag{17}$$

With (17) the time derivatives of the polar and equatorial momentums of the polar and the equatorial momentums of inertia are

$$\begin{aligned}
\frac{dC}{dt} &= \frac{2}{3} Ma^2 \frac{dJ_2^{\circ}}{dt} = (-4.1 \pm 0.9) \cdot 10^{25} \text{ kgm}^2 \text{ year}^{-1} \\
\frac{dA}{dt} &= -\frac{1}{3} Ma^2 \frac{dJ_2^{\circ}}{dt} = (2.1 \pm 0.5) \cdot 10^{25} \text{ kgm}^2 \text{ year}^{-1}
\end{aligned} \tag{18}$$

Values obtained in (17) and (18) are tools for the study of geodynamical processes acting long time (say longer than 10^6-10^7 years). They are expressing changes in the inner structure of the Earth. (16) and (17) apparently contradict to results obtained for the secular changes in J_2 obtained with the laser data of geodetic satellites. The mean of these data is (Varga 1998)

$$-2.7 \cdot 10^{-11} \text{ year}^{-1} \tag{19}$$

yields

$$\begin{aligned}
&\frac{dC}{dt} = -4.2 \cdot 10^{27} \text{ kgm}^2 \text{ year}^{-1} \\
&\frac{dA}{dt} 2.1 \cdot 10^{27} \text{ kgm}^2 \text{ year}^{-1}
\end{aligned} \tag{20}$$

what is evidently too high for long lasting (longer than 10^6-10^7 years) geological processes. If, for example, the question is: when A will be – hypothetically - equal C on the basis of present day data the following relation can be derived from (18)

$$\Delta t = \frac{C - A}{\frac{dJ_2}{dt} Ma^2} = (3-5) \cdot 10^7 \text{ years}$$

What means that *A* will be equal to *C* in case of (16) within $2.1 \cdot 10^9$ years. Studies of the present glacial discharges show that dJ_2/dt deduced from satellite data can be explained by this phenomenon.
As it was shown by Vermeersen et al.(1997), time derivative of J_2 allows us a study of the viscosity profile of the Earth's mantle and the dependence of dJ_2/dt on mantle viscosity. The secular variation of the second degree zonal harmonic has its maximum when the viscosity is about 10^{20} Pa·s in the

upper and 10^{21} Pa·s in the lower mantle. In case of decreasing viscosity, the magnitude of dJ_2/dt gets significantly reduced. This circumstance can be important for the explanation of the difference between satellite (18) and geological (16) values for the time derivative of the second degree component of the geopotential.

4. Conclusion

The above described unsolved problems of geodynamics are subjectively selected. There were not mentioned many still not solved questions. For example the excitation mechanisms of the Chandler wobble not understood yet, the frequency of the core notations is different from observations and from theory possibly due to the use of simplified theoretical model of the Earth. The scientist of XXI century shall solve these questions of course together with many another ones. One of the varantiy for this is the excellent school of theoretical geodetic research founded and led by Professor Erik W. Grafarend at the Stuttgart University.

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