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A Mechanism of Variations of the Earth Rotation at Different Timescales

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Abstract. To explain the observed effects in the Earth's polar motion, a mechanism of the relative motion of the lower mantle and upper mantle with a boundary at 670 km of depth is proposed. According to the new approach, the Earth's layers (including separate plates) are considered as nonspherical, heterogeneous celestial bodies, interacting with each other, with the Moon and the Sun and executing a wide spectrum of relative motions in different timescales. The small displacements of the centers of masses of the lower and upper mantles and their relative rotations have here a primary importance. These displacements display themselves at various time scales (from a few months to millions of years), and their manifestations are readily detected in the regularities of the distribution of geological structures as well as in many geodynamical processes. Important regularities of the ordered positions of the plate centers, of their triple junctions, hot spots, systems of fractures and cracks, geographic structures, fields of fossils, *etc.*, are observed as consequences of certain displacements and inclined rotations (Barkin, 1999). At geological time intervals, the slow motion of the layers causes mutually correlated variations of the processes of rifting, spreading, subduction, regressions and transgressions of the sea, of the plate motion, formation and breakdown of super continents, *etc.* The motions and the accompanying tectonic mass redistribution cause variations of the components of the Earth's inertia tensor and geopotential, which lead to variations of its diurnal rotation and polar motion. Explanation of the main properties of the perturbed Chandler polar motion has been done.

1. Dynamics of Earth's layers as new geodynamical conception

Many celestial bodies — planets, large satellites, stars and other objects can be considered to be systems of layers. Only in the first approximation these objects can be presented as concentric and with definite concentric distribution of densities. Layers are characterised by definite physical properties, sizes and mass distribution. They can have different physical states (rigid, elastic, non-elastic, liquid, gaseous and other). Layers are mutually interacting (including their gravitational interaction) and interact with external celestial bodies. In more detailed consideration density distributions in the layer are quasi-concentric and generally non-homogeneous and non-spherical and with changing physical properties.

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Layers of the Earth, of course, are studied (atmosphere, hydrosphere, crust, mantle, liquid core and rigid core) by seismic, tomography, gravimetry methods and by space dynamics methods.

In our approach we suggest that phenomena of the eccentricity and relative displacement of the centers of mass of layers are fundamental and general. These phenomena have gravitational nature and are caused by mutual gravitational interaction of the non-spherical and non-homogeneous envelopes and external celestial bodies (Barkin, 1999).

2. Eccentricity of the Earth's layers

Centers of mass of the Earth's layers could be coincident only in the ideal case when they have spherical form and concentric distribution of densities. In reality these envelopes are eccentric. Eccentricity of positions of the envelopes are caused by their nonsphericity and heterogeneities, by mutual gravitational interactions with the Moon and Sun in the geological history of the Earth.

From our studies we find that the center of mass of the lower layer has an eccentric position and is displaced relative to the Earth's center of mass 6.50 km in the direction 15.4°S, 30°W (Barkin, 1999). The Cartesian coordinates of the center of mass of the lower mantle are:

$$x = 5.43km, \quad y = 3.13km, \quad z = -1.73km. \tag{1}$$

The corresponding displacement of the center of mass of the upper layer in the opposite direction will be 4.462 times more, so the mass of the layers are 0.8169 and 0.1831 of the Earth's mass. The displacement of the center of mass of the upper layer is 29.00 km toward 15.4°N, 150.0°E (direction to the Earth's magnetic center).

The displacements are confirmed indirectly by the asymmetry of the Earth's gravitational field. These displacements explain the values of the coefficients of the second harmonic of the Earth's gravitational field. Parameters of the second harmonic of the the gravitational field (Barkin, 1999) define the direction of displacement of the center of mass of the lower mantle with respect to the center of mass of the Earth toward 61°54′W, 28°71′S. Similar values also were obtained from interpretation of the planetary distribution of the δ factors of the Earth's tides and from analysis of the relative motion of the liquid core (Barkin, 1999). It is worthwhile to note that theoretical values of parameters (1) are correlated with independent data about variations of the geopotential coefficients due to subduction and accumulation of the masses of the ocean plates. They are in agreement with direction of the global tectonic processes and with kinematical characteristics of the plates and with many regularities of the geological and geographic structures (Barkin, 1999).

3. Oscillations of the centers of mass of the lower mantle and of the upper mantle due to lunisolar attraction

Dynamic analysis of the relative motion of the centers of mass of the lower and upper mantles in the gravitational field of the Moon and the Sun was accomplished on the basis of the inner variant of the three-body problem. A wide

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spectrum of frequencies of small relative displacements was determined. Perturbations of the relative Cartesian coordinates x, y, z are defined by

$$x = x_0 + \delta x, \quad y = y_0 + \delta y, \quad z = z_0 + \delta z. \tag{2}$$

Here x_0, y_0, z_0 are the parameters of the eccentric relative position of the centers of mass defined from indirect data about the Earth's gravitational field. They can be considered as zero approximation or as some initial values of coordinates. The nature of this constant displacement is connected with evolution and gravitational interaction of the layers considered as non-spherical and non-homogeneous celestial bodies (Barkin, 1996). Principal periodic perturbations are defined by the following simplified formulae (here we do not consider quasi-diurnal and semidiurnal oscillations):

$$\delta x = -x_0 F(t), \quad \delta y = -y_0 F(t), \quad \delta z = 4 z_0 \frac{k^2 - \omega^2}{k^2} F(t), \tag{3}$$

where

$$\begin{gathered} F(t) = \frac{3}{2} \frac{N^2}{\omega^2 - k^2} \sum_\nu B_\nu \cos \Theta \nu, \\ B_\nu = -\frac{1}{6}(3\cos^2\rho - 1) A_\nu^{(0)} - \frac{1}{2} \sin 2\rho A_\nu^{(1)} \frac{1}{4} \sin^2 \rho A_\nu^{(2)}, \\ \Theta_\nu = \nu_1 l_M + \nu_2 l_S + \nu_3 F + \nu_4 D + \nu_5 \Omega, \text{ and} \\ \rho = -23\overset{\circ}{.}439291. \end{gathered} \tag{4}$$

Here $N^2 = n_M^2 m$, $m = m_1 m_2/(m_1 + m_2)$, n_M is a mean motion of the Moon, $m_1 = 0.1831 \cdot m_\oplus$, $m_2 = 0.8169 \cdot m_\oplus$ are masses of the upper and lower mantle, $m_\oplus$ is an Earth mass, k is the elastic coefficient of the interaction of envelopes, ω is the angular velocity of the Earth. $A\nu^{(i)} (i = 0, 1, 2)$ are the constant coefficients known from theories of Earth and Moon rotation (Kinoshita, 1977). ρ is the unperturbed value of the angle between the angular momentum of the Earth and the normal to the ecliptic plane. $\Theta = \nu_1 l_M + \nu_2 n_S + \nu_3 n_F + \nu_4 n_D + \nu_5 n_\Omega$ is the linear combination with integer coefficients of the well-known arguments of the lunar orbital theory which are linear functions of the time with corresponding frequencies: $n_M, n_S, n_F, n_D, n_\Omega$. Also we will use notation: $\Omega_\nu = \nu_1 n_M + \nu_2 n_S + \nu_3 n_F + \nu_4 n_D + \nu_5 n_\Omega$. The solution to (2)–(4) was obtained on the basis of linear equations describing oscillations of the Earth's layers by lunisolar attraction and by assuming that the central elastic force acts between the Earth layers. We take into account the real properties of the lunar and solar orbital motions. (A similar treatment of the problem was given by the author in a study of relative motions of layers of the Earth (Barkin, 1996).)

The solution of (2)–(4) defines the principal direction of the layer displacements with lunar orbital frequencies along some straight line situated in the plane of the meridian of eccentric position of the centers of mass. In the case of eccentricity the trajectory is directed toward 30°W, 47°8 N. That practically coincides with the center of the largest bulge of the liquid core surface, with a region of positive gravity anomaly and an active North Atlantic spreading zone. We can suggest that this line has an important role for Earth evolution. The oscillations of the envelopes with lunar orbital frequencies can generate some slow

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motion along the line mentioned in different time-scales. In particular displacements of the lower mantle to the south along this line in the modern epoch can explain the secular reduction of the polar moment of inertia and corresponding observed positive acceleration of the Earth diurnal rotation. Now we can study variations of the components of the tensor of inertia of the Earth for the law of displacements of layers.

It is important to remark that in particular (2)–(4) contain the perturbation with frequency $n_M - n_F$ with a corresponding period of 411.78 days. We will show below that this perturbation produces variations of the products of inertia which control the observed Chandler polar motion, excluding full damping.

Of course the amplitudes of displacements of the centers of mass of layers depend on eccentric parameters in a given epoch and on the mechanism of the elastic and viscoplastic interactions of the envelopes and on specifics of their deformations. Here we use an extremely simple model of the layers and their interaction.

4. Variations of the Earth's products of inertia

We will consider only variations of the products of inertia of the Earth E and D since their variations have more impact to the right side of the equations of rotational motion of the deformable body (Barkin, in press). Taking into account that the displacements of the centers of mass generate similar mass redistribution in the upper layers of the Earth we have:

$$\begin{aligned} \delta E &= -K[3mR_{\oplus} r_0 \cos\phi \sin\phi \cos\lambda F(t)], \\ \delta D &= -K[3mR_{\oplus} r_0 \cos\phi \sin\phi \sin\lambda F(t)]. \end{aligned} \tag{5}$$

Here K is a coefficient of proportionality. This coefficient also takes into account the elastic factor k. Here we have assumed that variations of the products of inertia are proportional to the displacement of the lower mantle. The value K was evaluated on the basis of data about variation of the Chandler motion with a period of 38.6 years ($K \simeq 190$).

We will consider only one variation of the products (5) and CPM with a period of 411.78 days, which plays a main role in the excitation of the CPM. For this variation we have $\nu = (1, 0, 0, -1, 0)$ and

$$\delta E = E_\nu \cos\lambda \cos(l_M - F), \quad \delta D = E_\nu \sin\lambda \cos(l_M - F), \tag{6}$$

where

$$E_\nu = -\frac{9}{2J} K m \left(\frac{r_0}{R_{\oplus}}\right) \cos\phi \sin\phi \left(\frac{n_M^2}{\omega^2 - k^2}\right) \left(\frac{m_M}{m_{\oplus} + m_M}\right) C_{\oplus} B_\nu .$$

In (5), (6) $R_{\oplus}$ and $C_{\oplus}$ are the mean radius of the Earth and its polar moment of inertia. For numerical values of the parameters $B_\nu = 5.7962 \cdot 10^{-6}, \phi = -15^\circ\!.4$, $\lambda = -30^\circ\!.0$, $m_M/(m_M + m_{\oplus}) = 0.01251$, $J = C_{\oplus}/m_{\oplus} R_{\oplus}^2 = 0.33068$, $(n_M/\omega)^2 = 1.3401 \cdot 10^{-3}$) we obtain $E_\nu = K \cdot 0.2822 \cdot 10^{-12} C_{\oplus} = 0.536 \cdot C_{\oplus}$ for $K = 190$. Also we introduce two new parameters: $M = E_\nu \omega / 2\sigma C_{\oplus} = 0.3781 \cdot 10^{-6}$ and $L_\nu = M_\nu \sigma$, where $\sigma = n_M - n_F$, $\omega/\sigma = 14108.2$.

5. Explanation of the Excitation of the Chandler Motion

To explain the CPM we use the equation in the Andoyer variables θ, l, and g. Here θ is the nutation angle between the angular momentum vector and polar axes of the deformable body. It can be interpreted also as the amplitude of the CPM. l defines the CPM along the polar trajectory. The angle g we consider as the angle of diurnal rotation of the deformable body. These variables and the corresponding equations of the rotational motion of the deformable body are described in Barkin (in press). We will study the influence on the rotation only of variations of the dynamical structure of the body and will not consider direct action of the external celestial bodies. Also we will not consider the role of the relative angular momentum of the deformable body. Equations of the deformable isolated body can be presented in the form of equation (5) of the paper Ferrándiz & Barkin of this proceedings. Here we present only a simplified form of these equations of the angular momentum motion taking into account only the most remarkable terms. (Here we use fact that for the Earth $\theta \approx 10^{-6}$.) Therefore, we have in the right sides of equations only variations of the products of inertia. Using formulae (6) we obtain:

$$\frac{d\theta}{dt} = \cos\theta \sum_{\nu} [\cos(\Theta_n u + l + \lambda) + \cos(\Theta\nu - l - \lambda)],$$

$$\frac{dl}{dt} = -\cos\theta\Omega_{CH} - \cos ec\theta \cos 2\theta \sum_{\nu} [\sin(\Theta_n u + l + \lambda) - \sin(\Theta\nu - l - \lambda)], \quad (7)$$

where $\Omega_{CH} = -G(1/C_0 - 1/A_0) \geq 0$ is the unperturbed Chandler frequency for which we adopt the value of $T_{CH} = 424.16$ days.

Considering L_ν as small we obtain the following analytical expressions of perturbations of the first order for variables θ, l and for the variation of $T_{CH}^{PM} = 2\pi/(dl/dt)$ of the Chandler pole motion:

$$\begin{aligned} d\theta &= \sum_{\nu} \theta_{\nu,1} \sin(\Theta_n u + l + \lambda) + \theta_{nu,-1} \sin(\Theta_n u - l - \lambda), \\ dl &= \sum_{\nu} \theta_{\nu,1} \cos(\Theta_n u + l + \lambda) + l_{nu,-1} \cos(\Theta_n u - l - \lambda), \end{aligned} \quad (8)$$

where

$$\delta T_{CH}^{PM} = T_{CH} \sum_{n} u\{T_{\nu,1} \sin(\Theta_n u + l + \lambda) + T_{\nu,-1} \sin(\Theta_n u - l - \lambda)\},$$

$$\begin{aligned} \theta_{\nu,\pm 1} &= \frac{L_\nu \cos\theta}{\Omega_\nu \mp \Omega_{CH}}, \\ l_{\nu,\pm 1} &= -\frac{L_n u \Omega_{CH} \cos\theta}{(\Omega_n u \mp \Omega_{CH})^2} \pm \frac{L_\nu \cos ec\theta \cos 2\theta}{\Omega_n u \mp \Omega_{CH}}, \\ T_{\nu,\pm 1} &= -\frac{L_n u \sin\theta \cos\theta}{\Omega_n u \mp \Omega_{CH}} \mp \frac{L_\nu \cos ec\theta \cos 2\theta}{\Omega_{CH}}. \end{aligned} \quad (9)$$

In (8), (9) $\theta = \theta_0$, $l = \cos\theta\Omega_{CH} t + l_0$ is a zero approximation which describes the unperturbed Chandler motion; θ_0, l_0 are initial values of the corresponding

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variables. Let us consider only the principal perturbation from (8), (9) with indexes $\nu = (1,0,0,1,0)$. A theoretical solution was obtained for accepted parameters of the problem: $\theta_0 = 0''175$, $T_{1.0.0-1.0} = 2\pi/\Omega_{1.0.0-1.0} = 411.78$ days, $T_{CH} = 424.16$ days. On the basis of these values and formulae (8), (9) we obtain the final formulae for perturbations of the amplitude and period of the CPM:

$$\delta\theta = 0''07799 \sin(\Theta_{1.0.0.-1.0} + l + \lambda) + 0''001155 \sin(\Theta_{1.0.0.-1.0} - l - \lambda),$$

$$\delta T_{CH} i^{PM} = T_{CH}[0.013399 \sin(\Theta_{1.0.0.-1.0} + l + \lambda) - 0''013399 \sin(\Theta_{1.0.0.-1.0} - l - \lambda)]. \tag{10}$$

First terms from (10) give the forced polar motion with period $T_{res} = 38.6$ years. They present the main effect in the observed evolution of the CPM in the last century (Vondrák 1996). The second terms in (10) have period $T' = 0.572$ years. The solution (10) in particular describes the variations of the amplitude and period of the CPM with period T_{res} ($0''156$ and 11.4 days). Observed values are about $0''165$ and 12.5 days. More detailed studies of the problem let us determine a new set of variations in the CPM with periods which are also observed, in the diurnal rotation and in the many geophysical processes (31.8y, 19.3y, 12.6y, 11.8y, 9.3y, 7.2y, 3.6y, 3.0y, 2.1y and others).

6. Discussion

The CPM is a forced motion. It is caused by the gravitational influence of the Moon and Sun on the relative positions of the Earth's layers. Orbital perturbation of the Moon with period 412 days leads to a variation of the products of inertia of the Earth with the same period. The last mechanism excites perturbations in the CPM of definite properties. The central role here is the intermediate mechanism of the displacements of the Earth's layers. The possible important role of the lunar orbital perturbations in the CPM was earlier pointed out by Avsjuk (1996).

Of course our mechanism of the displacements of the Earth's layers must have manifestations practically in all geophysical processes. They must naturally display mutual correlation. (Some of them are confirmed by observations.) The important peculiarity of the above-mentioned geodynamic properties is their property of inversion with respect to the Earth's opposite hemispheres. The centers of masses of the layers execute motions along the line of centers of these hemispheres. Similar displacements of the envelopes allow us to explain the observed reversals of the Earth's antisymmetry and the development of the Gondwana-Laurasia system as well as of the east and west hemispheres of the Earth.

The mechanism proposed has similar effects also at comparatively short time intervals (in the last 100 years). I propose an explanation of the observed inversion in the activity of the volcanism of the subduction zones and zones of spreading. The mirror phenomenon in the seismic activity in the east and west (north and south) hemispheres of the Earth has a similar explanation. The peculiarities of the trend of volcanism and seismicity and their correlation with variations of the Earth's diurnal rotation and its polar motion, observed in the last 150 years, have been confirmed and explained. The displacements of the layers, accompanied by tectonic mass redistribution, lead to the Earth's rotation

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variations and to correlated variations of the volcanism, seismic activity, geyser activity, sea level, climatic changes, biological changes, El Niño phenomenon, *etc.* The eccentricity of the positions of layers' centers of masses, their displacements and relative rotations are generated by their gravitational interaction with each other as well as with the Moon and the Sun under the conditions of the rotating and precessing Earth. The mechanism proposed explains all the correlation, detected earlier, and allows us to predict some new correlations. In particular, the observed positive acceleration of the Earth's rotation can be explained by a displacement of the center of mass of the lower mantle from its present eccentric position toward the Earth's center of mass. This is also consistent with the general tendency of volcanism in the subduction zones in the last 150 years. The mechanism proposed enables us to explain some irregular effects observed in the displacement of the Earth's center of mass, for instance its deviation in 1997–1998 and the El Niño phenomenon, migration of seismic activity along the Pacific Belt in 1949–1960, *etc.*

References

Avsjuk, Yu. N., 1996, Tidal Forces and Natural Processes. M., RAN.

Barkin, Yu.V. 1996, Dynamics of the Earth's Inner Core. Proceedings of the Sternberg Astronomical Institute. MSU. Moscow. 1996, pp. 107–129. In Russian.

Barkin, Yu. V., 1999, Global Properties of the Structure, Evolution and Interactions of the Lithosphere and other Covers of the Earth. Proccedings All-Russian Conference "Interaction in the System of the Lithosphere, Hydrosphere and Atmosphere." (Moskow, November 28–30, 1996). V.2, MSU. Moscow, pp. 46–60. In Russian.

Barkin, Yu. V. Astronomical and Astrophysical transactions (in press).

Ferrándiz, J. M. & Barkin, Yu. V., 2000 Nature and Properties of the Chandler Motion and Mechanism of its Damping and Excitation. This proceedings.

Kinoshita, H., 1977, *Celestial Mechanics*, **15**, 277–326.

Vondrák, J. & Ron, C. 1996 In: N.Capitaine, B. Kołaczek, S. Débarbat, *Journées 1995 Système de Référence Spatio-temporels*, Space Research Centre Warsaw, 95–102.