FINE STRUCTURE OF THE EARTH'S FUNDAMENTAL SPHEROIDAL MODE $_0S_2$ IN GEOMAGNETIC VARIATIONS

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ABSTRACT

As the initial data, we used the results of recording the Earth's magnetic field at the Geophysical observatory "Mikhnevo" of the Institute of Geospheres Dynamics (54.959ºN, 37.766ºE), carried out in the period 2010-2015. On the basis of the results of instrumental observations, it is shown that in the spectra of geomagnetic variations the quasiharmonic component is clearly distinguished, the frequency of which is close to the basic spheroidal mode of the Earth $_0S_2$. In periods of 15 days after three major earthquakes, in the absence of strong magnetic disturbances, a fine structure of the $_0S_2$ mode in the geomagnetic variations in the form of singlets is established. The established features of the spectrum of geomagnetic variations develop a new method for studying the deep structure of the Earth, the properties of internal geospheres, estimating the viscosity of the outer core of the Earth, describing the geomagnetic dynamo, developing new models of the motion of the inner core of the Earth, and the dynamics of current systems in the outer (liquid) core.

Keywords: Earth's free oscillations, splitting, singlet, geomagnetic field.

INTRODUCTION

There are two independent types of free oscillations of Earth: spheroidal oscillations (*S*) and toroidal or torsional oscillations (*T*). The general displacement for spheroidal oscillations has both radial and tangential components. The displacement for toroidal oscillations is always perpendicular to the radius vector and so is confined to the surfaces of concentric spheres within the Earth. Such oscillations, which involve only the crust and mantle (the outer core is liquid and so cannot sustain shear), do not change the shape or volume of the Earth. Both spheroidal and toroidal oscillations have an infinite number of modes (or, as in music, overtones). The notation used to describe free oscillations is $_nS_m$ and $_nT_m$. The first subscript, n, indicates the overtone: $n = 0$ is the fundamental mode while higher-frequency modes with $n > 0$ are overtones. The second subscript, m, the harmonic degree, indicates the number of nodes in latitude (places with zero displacement).

The spheroidal $_nS_m$ and toroidal $_nT_m$ modes of the Earth's eigenoscillations contain very important information about the internal structure of the Earth and its dynamics [1]-[4]. Separation of $_nS_m^k$ and $_nT_m^k$ singlets from multiplets $_nS_m$ and $_nT_m$ allows estimating Earth's asphericity, non-uniformity of its rotation speed, and lateral heterogeneity of the Earth [5] - [7]. The most common methods for determining the Earth's eigenfrequency spectrum are based on the use of broadband seismometers, superconducting gravimeters, strainmeter and GPS arrays.

The lowest frequency mode of the oscillations is the fundamental spheroidal mode ${}_0S_2$ that has a period of about 54 min. The Earth's departure from spherical symmetry such as diurnal rotation, ellipticity, and lateral heterogeneity splits the mode ${}_0S_2$ into five components spaced about 50 s apart. The first observations of these components occurred after very large earthquakes with a magnitude $M > 7$ [8]. However, subsequently they were also observed on seismically quiet days [9].

It seems promising to use geophysical fields, for example, the geomagnetic field as an indicator of the Earth's free oscillations. In particular, oscillations with a period of about 54 min and even the splitting inherent in the ${}_0S_2$ mode have been observed in geomagnetic variations [10].

Despite the considerable interest in the problem and the large number of publications devoted to Earth's free oscillations, there is a lack of experimental material.

In this paper, the results of splitting of the fundamental spheroidal mode ${}_0\mathrm{S}_2$ from observations of variations in the geomagnetic field during periods of three strong earthquakes are given.

DATA ACQUISITION AND DATA PROCESSING

As the initial data, the results of recording the Earth's magnetic field at the Geophysical observatory "Mikhnevo" of the Institute of Geospheres Dynamics (54,959ºN, 37,766ºE), carried out in the period 2010-2015 are used. The observatory is located far from the technogenic sources of electromagnetic fields, which ensures a stable registration magnetic field over a wide frequency range.

Three components of the magnetic field induction were registered using a LEMI-018 ferrosonde magnetometer (manufactured by Lviv Centre of Institute of Space Research, Ukraine) with own built-in digital datalogger. The measurement accuracy was 0.1 nT and the sampling rate was set at 1 Hz.

The spectral characteristics of the variations in the modulus of the magnetic field induction vector *B* were investigated. For the analysis, digital series of data were formed with a discreteness of 1 min.

The spectrum of variations of *B* was estimated on the basis of the maximum entropy spectral analysis (MESA) [11]. MESA is based on the statistical modeling of a time series $\{Z_n\}$ by an autoregressive model of order *p*, AR(*p*):

$$Z_n = a_{1,p}Z_{n-1} + a_{2,p}Z_{n-2} \ldots + a_{n,p}Z_{n-p} + e_n$$

where a present value Z_n may be seen as a weighted average of *p* past values plus white noise, e_n, of mean zero and variance σ_p^2, *p* - order of the AR process, $a_{k,p}$, $k = 1, \ldots, p$, - AR coefficients.

Then, the power spectrum $S(\omega)$ of the AR(*p*) process was estimated:

$$S(\omega) = \frac{1}{2\pi\left|1 + \sum_1^p a_n e^{-i\omega n}\right|},$$

Table 1. Earthquake parameters

Event	Date	Time (UT)	Latitude (grad)	Longitude (grad)	Magnitude
Pakistan	2013/04/16	10:41:17	28.14	62.06	7.8
Nepal	2015/04/25	06:11:24	84.78	84.78	7.9
Chili	2015/09/16	22:54:30	- 31.6	- 71.61	8.4

where ω is the frequency, and i is the imaginary unit.

The parameters of the AR(p) model were estimated using the Yule-Walker equations coupled with the Durbin-Levinson algorithm.

In order to increase the level of discrimination of frequency components that are close in frequency, in addition to parametric spectral analysis, a method was used to isolate harmonic components using narrow-band adaptive notch filters [12].

Three earthquakes were selected for the analysis, the main characteristics of which are given in Table 1. The selected portions of the time series of the modulus of the magnetic induction vector B, 15 days long after the earthquake with a sampling interval of 1 min, were filtered with a 7th-order Butterworth bandpass filter in the interval of 53 to 54 min. Then, in accordance with the above technique, a notch filtering was performed at the frequencies of the singlet, which was selected in accordance with the theoretical data [13] and the autoregressive spectrum of the obtained series was calculated.

By fitting a synthetic Lorentzian resonance function to each singlet of the spectrum [14], we can determine the 5 frequencies and their error bars. The singlet frequencies estimated by geomagnetic field data at observatory "Mikhnevo" were compared with the predicted values of ${}_0S_2$ computed for the Earth model 1066 A [15] by Dahlen and Sailor [13] following a perturbation method of the equations to the second order in rotation and ellipticity. Any substantial deviation of the observed from the predicted splitting can therefore be ascribed to the Earth’s lateral heterogeneity. It has been generally assumed that for the lowest frequency multiplets, rotation and ellipticity must be the dominant perturbations. Earth model 1066A is given in a layered structure with 160 layers, where the top layer of 11km is homogenous. In this case, derivatives vanish and the layered inner structure cannot be fully reflected.

RESULTS

Figure 1 shows an example of the spectrum of variations of B for 2014 for the frequency interval from 0.1 till 4 mHz. Data analysis indicates that the spectrum of modulus of the magnetic field induction vector contain pronounced quasiharmonic components with frequencies close to the eigenfrequencies. The spectrum peaks can be identified with the most of the fundamental spheroidal modes of degree. The some overtones of first and second degrees are pronounced too.

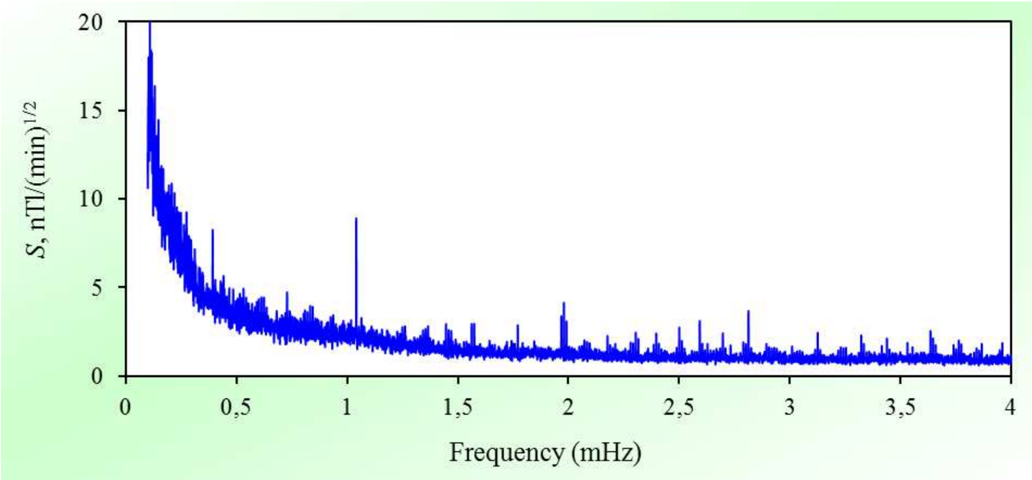

Figure 1. Spectrum of geomagnetic variations at the Geophysical observatory "Mikhnevo" for 2014 year.

Quasiharmonic components with frequencies close to the eigenfrequencies are characterized by high repeatability on the spectra of variations of *B*. As an example, Figure 2 shows the spectrum fragments for the section containing the $^0S^2$ mode (calculations based on data obtained from 2012 to 2013). The degenerated mode $^0S^2$ is clearly exposed in the spectrum of Figure 1.

The spinning of the Earth produces the Coriolis force, which is spherically asymmetric. This effect as well as the ellipticity of the Earth lead to a breakdown of the degeneracy of the eigenfrequencies for $2l+1$ values for each spherical harmonic of l degree. The result is called splitting, with the split eigenfrequencies being close together. So, the spheroidal mode $_0S_2$, the longest-period fundamental *(n* = 0) mode of the Earth, is split to five components.

To determine the fine structure of the $_0S_2$ multiplet, the time series sections of the modulus of the magnetic induction vector *B* were analyzed, which, firstly, were characterized by the absence of strong geomagnetic disturbances camouflaging the relatively weak manifestations of singletons and, secondly, precipitated by periods of strong earthquakes.

In Figure 2, the results of the estimations of the spectra of geomagnetic variations are shown for observations carried out during three strong earthquakes (Table 1). Figure 2 demonstrates the result obtained for the fine resolution of the quintet $_0S_2$. The vertical lines represent the theoretical values of quintet periods. The three highest peaks can, with reasonable certainty, be identified as, from left to right, k = - 2, $k = 0$, and $k = 2$. Two others peaks of the quintet corresponded to $k = -1$, and $k = 1$, are completely resolved. The partial resolution of the quintet and the non-symmetrical shapes of the resolved peaks can be explained by the fact that the data is rather contaminated by noise.

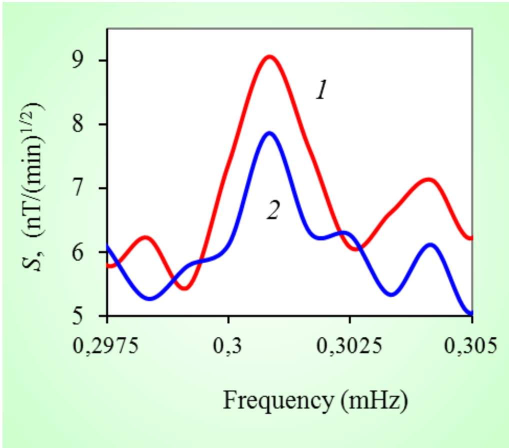

Figure 2. Fragment of the spectrum of geomagnetic variations at the Geophysical observatory "Mikhnevo" for 2012 (1) and 2013 (2) years.

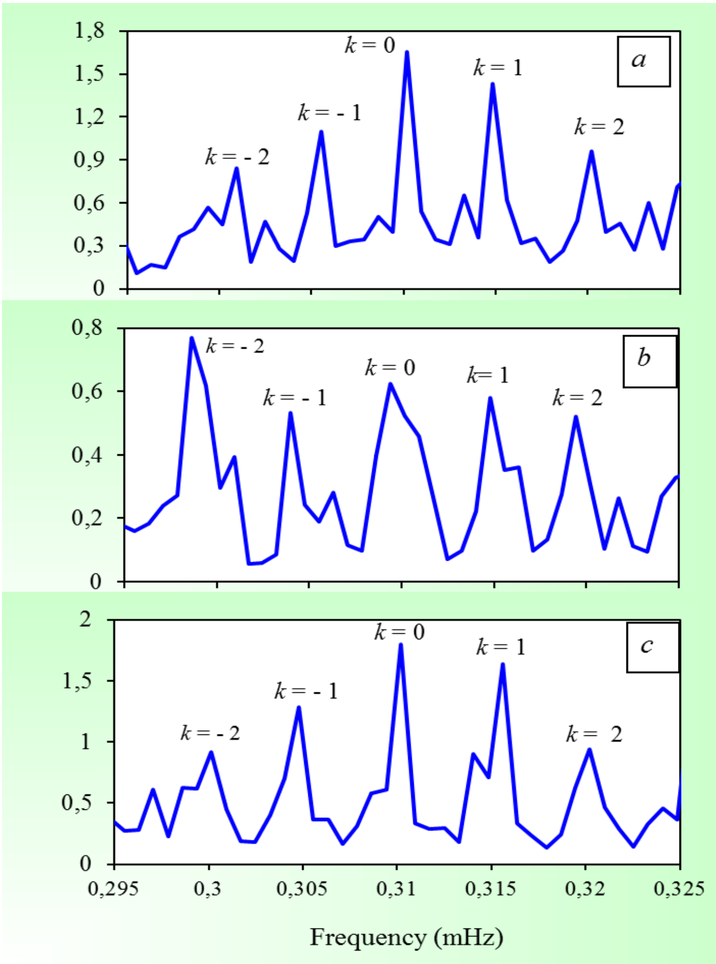

Figure 3. Fine structure of the fundamental spheroidal mode of the Earth's natural oscillations ${}_0S_2$ in geomagnetic variations at the Geophysical observatory "Mikhnevo" after earthquakes: *a* - in Pakistan on April 16, 2013; *b* - in Nepal on April 25, 2015; *c* - in in Chile on September 16, 2015 (the spectrum was evaluated for an interval of 15 days after the earthquake)

Table 2. Singlet's frequency of multiplet ${}_0S_2$ determined resulting from spectral analysis of the experimental data ${}_0f_2^k$ and calculated based on the Earth model 1066 A f_2^k

Parameter	${}_0f_2^{\,k}$(mHz)				
	k = - 2	k = - 1	k = 0	k = 1	k = 2
Earthquake in Pakistan					
${}_0f_2^{\,k}$	0.3009	0.3055	0.3101	0.3148	0.3202
$f_2^{\,k}$	0.2999	0.3048	0.3095	0.3140	0.3184
$({}_0f_2^{\,k} - {}_0f_2^{\,k})/ {}_0f_2^{\,k}$ (%)	0.333	0.223	0.164	0.223	0.565
Earthquake in Nepal					
${}_0f_2^{\,k}$	0.2986	0.3040	0.2986	0.3148	0.3194
$f_2^{\,k}$	0.2999	0.3048	0.3095	0.3140	0.3184
$({}_0f_2^{\,k} - {}_0f_2^{\,k})/ {}_0f_2^{\,k}$ (%)	- 0.433	- 0.269	- 0.061	0.245	0.314
Earthquake in Chili					
${}_0f_2^{\,k}$	0.3001	0.3047	0.3100	0.3155	0.3202
$f_2^{\,k}$	0.2999	0.3048	0.3095	0.3140	0.3184
$({}_0f_2^{\,k} - {}_0f_2^{\,k})/ {}_0f_2^{\,k}$ (%)	0.067	- 0.039	0.132	0.468	0.565

The estimated singlet frequencies ${}_0\mathrm{f}_2^k$ in comparison with theoretical ones f_2^k computed for the Earth model 1066A [13, 15] are summarized in Table 2. Table 2 shows that there is good agreement between the values ${}_0f_2^k$, identified using the analysis of instrumental observations, and the theoretical values of f_2^k (the discrepancy between these values does not exceed 0.387% for k = -2, 0.305% for k = -1, 0.31% for k = 0; 0468% for k = 1 and 0.641% for k = 2).

CONCLUSION

This paper presents an attempt of split of the fundamental spheroidal mode ${}_0S_2$ from observations of variations in the geomagnetic field during periods of three strong earthquakes. Recording geomagnetic variations during strong earthquakes allow us to detect modes ${}_0S_2$. In periods of 15 days after major earthquakes, in the absence of strong magnetic disturbances, it is possible to distinguish the fine structure of the basic spheroidal mode of the earth ${}_0S_2$ in the geomagnetic variations. The estimated singlet frequencies of ${}_0S_2$ are good agreement with theoretical ones computed for the Earth model 1066A. This indicates that the Earth's magnetic field is very sensitive to mechanical processes occurring in the Earth. Moreover, the received data confirm the fact that the Earth, for all the complexity of its structure, and the presence of geospheres that are very different in their properties, represents a single geophysical system consisting of constantly interacting geospheres and geophysical fields.

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