ISSN 0016-7932, Geomagnetism and Aeronomy, 2014, Vol. 54, No. 5, pp. 666–672. © Pleiades Publishing, Ltd., 2014.
Original Russian Text © V.P. Smagin, S.V. Semkin, V.N. Savchenko, 2014, published in Geomagnetizm i Aeronomiya, 2014, Vol. 54, No. 5, pp. 713–719.

Geomagnetic Field Variations Induced by Internal and Surface Waves in the Four-Layer Model of the Marine Environment

V. P. Smagin[a], S. V. Semkin[a], and V. N. Savchenko[b]
[a] Vladivostok State University of Economy and Service, Vladivostok, Russia
[b] Far East Federal University, Vladivostok, Russia
e-mail: Li15@rambler.ru
Received August 21, 2013; in final form, October 24, 2013

Abstract—The layered model of the marine environment, including the atmosphere, two seawater layers with different conductivity and density, and the bottom rock layer, has been considered. The geomagnetic field variations, generated by internal and surface waves with different frequency and propagation direction, have been found in the scope of this model. The effect of magnetic permeability and electric conductivity of bottom rocks on induced magnetic field has been taken into account. The transfer functions and spectral densities of these variations have been analytically determined and numerically estimated.

DOI: 10.1134/S0016793214040203

1. INTRODUCTION

As is known, the World Ocean water substantially differs in the main physical characteristics (density, temperature, and electric conductivity) at different depths (Brekhovskikh, 1956; Shuleikin, 1968; Monin et al., 1974; Belyaev and Gezentsveig, 1980; Van'yan and Shilovskii, 1983), being a complex stratified medium. The bottom rocks underlying the ocean water also have rather different electrophysical properties (Van'yan et al., 1980). Various seawater motions in the geomagnetic field cause geomagnetic variations in a wide frequency range (Bullard and Parker, 1971; Sochel'nikov, 1979; Savchenko et al., 1999), and the layered nature of the ocean water is also taken into account (Brekhovskikh, 1956; Smagin and Savchenko, 1980). The historiography and bibliography of the works on the marine geomagnetism problems are contained in the (Smagin et al., 2013) monograph. In the present work, we consider the magnetic variations related to seawater motion, mainly in the ULF band with periods varying from several tens to several thousands of seconds. It is known that ULF waves, generated by extra- and intra-terrestrial sources in the Earth's magnetosphere and core (Guglielmi, 2007) as well as in seas and oceans, are very different. We are interested here in natural ULF electromagnetic variations that accompany the propagation of marine surface (Bullard and Parker, 1971; Sochel'nikov, 1979; Savchenko et al., 1999; Sochel'nikov and Savchenko, 2004) and internal waves (Beal and Weaver, 1970) (in this case, the wave periods on the shelf can account for several thousands of seconds). Marine electromagnetism in this range was experimentally studied at the Pacific Oceanological Institute (Medzhitov and Burov, 1983).

Previous theoretical studies, which were as a rule performed in a quasi-static approximation, ignored the effect of self-induction and electromagnetic characteristics of underlying bottom rocks in seas and oceans. One of these factors (self-induction) was taken into account in our work (Semkin and Smagin, 2012), where we also consider and indicate the effect of bottom rock electric conductivity (σ_3) and magnetic permeability (μ), together with self-induction. The effect of sea waves on the electromagnetic field was usually studied with regard only to wave electric conductivity (Cox et al., 1971; Leibo and Semenov, 1975), since sedimentary bottom rocks as a rule have no pronounced magnetic properties.

However, cases when bottom rocks show both electric and magnetic properties are quite possible in the offshore and shelf zones of seas (Savchenko et al., 1999). Moreover, Leibo and Semenov (1975) indicated that currents can flow into conductive bottom mediums only because of induction effects, i.e., the effects of self-induction, during the potential motion of a liquid.

Thus, all of the most important factors of the effect of marine and bottom mediums on sea wave electromagnetic fields have been taken into account in the proposed work. This makes it possible to differentiate rather exactly the hydrodynamic wave source from all other sources and to use it in sounding the electric and magnetic characteristics of bottom rocks.

2. FOUR-LAYER MODEL OF THE MARINE ENVIRONMENT

We consider the four-layer model of the marine environment: the atmosphere, two seawater layers,

No Body Text -- translate me!
Page 2

and bottom rocks. We assume that each layer is characterized by the eigenvalues of electric conductivity (σ), permittivity (ε), and magnetic permeability (μ). We believe that $\sigma = 0$ and $\varepsilon = \mu = 1$ in air, whereas $\mu = 1$ in both water layers. We write μ for magnetic permeability of bottom rocks. We denote water permittivity (identical in both layers) and bottom rock conductivity and permittivity by ε_2, σ_3 and ε_3, respectively. The thickness, density, and conductivity of the upper oceanic layer (up to pycnocline) are marked by d, ρ_1, and σ_{21}, respectively; the ocean total depth and the lower layer density and conductivity are D, ρ_2, and σ_{22}, respectively. The origin of the Cartesian coordinate system (x, y, z) is located on the sea surface, and the z axis is directed vertically down.

A two-dimensional harmonic wave with amplitude a (which is assumed to be small as compared to d, D, and wavelength λ) and frequency ω propagates along the x axis. The water motion is considered potential ($\mathbf{v} = \mathbf{v}_0(z)e^{i(kx-\omega t)} = \mathrm{grad}\varphi$), the velocity potentials in the upper and lower layers (φ_1 and φ_2, respectively) obey the Laplace equation ($\Delta\varphi_{1,2} = 0$), and the following conditions are satisfied at the boundary between the layers

$$\left.\frac{\partial\varphi_1}{\partial z}\right|_{z=d} = \left.\frac{\partial\varphi_2}{\partial z}\right|_{z=d} \quad \text{and} \quad \rho_1\left(\frac{\partial\varphi_1}{\partial z} - \frac{1}{g}\frac{\partial^2\varphi_1}{\partial t^2}\right)_{z=d} = \rho_2\left(\frac{\partial\varphi_2}{\partial z} - \frac{1}{g}\frac{\partial^2\varphi_1}{\partial t^2}\right)_{z=d}.$$

The boundary conditions at the bottom and on the free surface have the form:

$$\left.\frac{\partial\varphi_2}{\partial z}\right|_{z=d} = 0 \quad \text{and} \quad \left.\frac{\partial\varphi_1}{\partial z} - \frac{1}{g}\frac{\partial^2\varphi_1}{\partial t^2}\right|_{z=d} = 0.$$

The hydrodynamic potential of a two-dimensional harmonic wave, which propagates along the x axis and obeys the Laplace equation and boundary conditions, has the form $\varphi_{1,2} = f_{1,2}(z)e^{i(\omega t - kx)}$, where

$$f_1(z) = A\left(\cosh kz - \frac{\omega^2}{gk}\sinh kz\right),$$
$$f_1(z) = -A\cosh k(D-z)\frac{\sinh d - \frac{\omega^2}{gk}\cosh kd}{\sinh k(D-d)}. \quad (1)$$

Wavenumber k is connected to wave frequency ω by the dispersion relation, which can be written as an equality to zero of the vanishing determinant:

$$\begin{vmatrix} 1-\frac{\omega^2}{gk}\coth kd; & 1; \\ \rho_1\left(1-\left(\frac{\omega^2}{gk}\right)^2\right); & \rho_2\left(1-\frac{\omega^2}{gk}\coth k(D-d)\right); \end{vmatrix} = 0.$$

This dispersion relation has two branches corresponding to internal and surface waves. In a $\theta = (\rho_2 - \rho_1)/\rho_1$ zeroth-order approximation, the root corresponding to the internal wave disappears, and the dispersion relation is reduced to

$$\omega^2 = gk\tanh kD, \quad (2)$$

which is a close approximation for the dispersion relation of surface waves and for ρ_1, which are not very much different from ρ_2. In a first approximation in θ, we obtain the dispersion relation for internal waves

$$\omega^2 = gk\theta(\coth kd + \coth k(D-d))^{-1}. \quad (3)$$

Coefficient A entering into (1) has different values for internal and surface waves:

$$A = -\frac{iag}{\omega}, \quad (4)$$

for surface waves and

$$A = -\frac{ia\omega}{k\left(\sinh kd - \frac{\omega^2}{gk}\cosh kd\right)} \quad (5)$$

for internal waves.

To determine the electromagnetic field induced by the seawater motion at velocity $\mathbf{v}$ in geomagnetic field $\mathbf{F}$, we use the system of Maxwell equations (neglecting the bias current), Ohm's law $\mathbf{j} = \sigma(\mathbf{E} + [\mathbf{v}, \mathbf{F}])$, and boundary conditions at the bottom and for a moving free surface (Zommerfel'd, 1958).

For a two-dimensional harmonic wave, the induced magnetic field is specified by the $\mathbf{B} = \mathbf{B}_0(z)e^{i(\omega t - kx)}$ expression. The amplitude of the magnetic field vertical component (B_{0z}) in all media is the solution to the equation (Smagin et al., 2013)

$$B''_{0z} - (k^2 + i\mu_0\mu\sigma\omega)B_{0z} = i\mu_0\mu\sigma k[\mathbf{v}_0, \mathbf{F}]_y \quad (6)$$

with the corresponding μ and σ values. (In the bottom rocks and atmosphere, the right-hand side of this equation naturally vanishes.) The remaining components of the induced magnetic field are as follows: $B_{0y} = 0$, $B_{0x} = -\frac{i}{k}B'_{0z}$. The induced electric field and surface charges at the boundary between the mediums can be found in the same way (Smagin et al., 2013); however, in this work we analyze only magnetic variations.

No Body Text -- translate me!