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Dipole sources of the main geomagnetic field

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Abstract

The parameters of 15 arbitrary dipoles that, in aggregate, represent the main geomagnetic field (MGF) are estimated to obtain information on the distribution of MGF sources within the Earth in the form of dipoles with an arbitrary position and value of the magnetic moment vector. For an adequate estimation of the results, the method of obtaining the data is described, including: the eccentric dipole model and the derivation of the basic formulas for the magnetic field components of an arbitrary dipole; the method of estimating the parameters of these dipoles, including the computational scheme and optimization method; necessary constraints on the dipoles parameters and a justification of the choice of the initial values in the optimization fitting of the parameters. The results are presented as a map of the location of the centers of the dipoles and their northern axial poles for the epochs 1955 and 2005 and plots of changes in all six parameters of 15 dipoles for 50 years. Most of the dipole centers are located in the lower mantle. The results suggest the existence of current systems in the lower mantle that produce dipole magnetic fields. These currents are provided by the high conductivity of wüstite, an important component of the mantle, which, at a depth of 1000–2200 km, transforms to the low-spin state of iron with increased density and electrical conductivity.

Keywords: main geomagnetic field; eccentric dipoles; instability of dipole representation; initial values; constraints; wüstite; systems of currents in the lower mantle

Introduction

In the history of geomagnetism, numerous attempts have been made to represent the main geomagnetic field (MGF) as the sum of the fields of a system of eccentric fields. The theoretical possibility of such a representation is known. Although a dipole is a mathematical abstraction as applied to the main magnetic field, model, the physical sources of dipole fields are eddy currents in the Earth's interior. The main geomagnetic dipole is a system of eddy currents in the outer core. They are distributed around the inner core in the form of coils oriented almost along the rotation axis of the Earth with the oppositely directed current lines in the northern and southern hemispheres (Jacobs, 1987).

The dipole representation of the geomagnetic field had two objectives.

The first is an analytical description of the field measured by various systems of discrete observations (observatories, secular variation, ground, aeromagnetic, marine surveying, and satellite measurements) using smooth functions. For this, the dipole representation was used along with spherical harmonic analysis for some time as long as the accuracy of the Gauss series was low and the description of the field by a system of dipoles gave the same accuracy (Kolesova, 1985; Kropachev and Kolesova, 1967). In this case, the orientation of each dipole was of little significance, so that the system of simple radial (vertical) dipole was used fairly widely (Kolesova, 1985; Pudovkin et al., 1968; Yanovskii, 1978). At present, the more complex description of the MGF cannot compete in accuracy with spherical harmonic analysis and interest in the latter waned.

The second objective was to describe the MGF sources, their distribution within the Earth in the form of dipoles with an arbitrary position, value, and orientation of the magnetic moment vector. The present work was performed with this objective.

The leading line of research on the problem of the MGF sources is the modeling of these sources in the outer core of the Earth by integrating the magnetohydrodynamic (MHD) equations with the boundary conditions:

– the structure of the dipole field, which is considered axial and is therefore specified by the first three coefficients of the Gauss series;

– variations in the dipole field—changes in the modulus and direction (inversion) of the magnetic moment;

– variations in the nondipole part of the field—westward drift (Starchenko, 2013).

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In our study, the region of the dipole sources was confined to the volume of the Earth. It turned out that the centers of 13 of 15 dipoles are in the lower mantle.

In practice, difficulties in the description of the MGF by a set of dipole fields are associated with the solution of the problem by multiparameter optimization fitting. Description of each dipole requires six parameters that determine the coordinates of its center and the value and elements of orientation of the magnetic moment vector. Until recently, the problem was also compounded by the lack of convenient formulas for computing the magnetic field components of an eccentric dipole on the Earth's surface, which is necessary for comparing the fields of the set of dipoles with the geomagnetic field on the Earth's surface. The dipole parameters have often been estimated using solutions of the direct problem in the form of spherical harmonic coefficients for given dipole parameters (Fraser-Smith, 1987; Kalinin, 1963; Stearns and Alldredge, 1973).

Some researchers have constructed models for the distribution of sources with a large number of radial dipoles (Alldredge and Stearns, 1969; Nevanlinna, 1980; Pudovkin et al., 1968) (Yu. A. Bishaev, 2005, personal communication). This simplifies the problem since such a dipole is determined by only four parameters. For this dipole, there are simple formulas for calculating the field on the Earth's surface. There are no physical grounds for models with a radial orientation of dipoles, and these models have mainly been used for approximation of the geomagnetic field.

Kas'yanenko et al. (2002) solved the problem of representing the MGF as a system of dipoles of optimal orientation and location, there are formulas for calculating the field components of an eccentric dipole on the Earth's surface. However, it is difficult to use them because of errors (typos) in the text, which is why these formulas lead to incorrect results in the particular cases of the central and nonaxial dipoles. The paper cited does not offer an opportunity to verify the formulas based on the method of their derivation since they were derived from the formula for the eccentric dipole potential proposed by Yu. D. Kalinin in 1953. The authors do not give this formula, but in the notation used in it there is an obvious inconsistency. The parameters determining the orientation of the dipole axis were introduced as follows (Kas'yanenko et al., 2002, p. 838): "ψ is the angle between the magnetic dipole moment and the plane tangential (at what point?—A.L.) to a sphere concentric with the Earth's surface; ω is the angle between the magnetic dipole moment and the plane of the meridian" (which meridian?—A.L.). This does not allow a comparison of the results of (Kas'yanenko et al., 2002) with our results presented below.

Necessary formulas for calculating the magnetic field components of the eccentric dipole (ED) were obtained in (Ladynin 2008; Ladynin and Popova, 2009). This made it possible not only to estimate the ED parameters from the spatial distribution of the geomagnetic field for any time for which data (IGRF) are available, but also to determine the changes in the parameters the main ED for 50 years from values of the magnetic field components on the Earth's surface and (Ladynin and Popova, 2009).

In this paper, we present estimates of the parameters of 15 dipoles of free position and orientation that, in aggregate, represent the MGF of the epochs from 1955 to 2005. The initial data were the values of the magnetic field components X, Y, and Z (IGRF-10) at the nodes of a $30° \times 30°$ grid, obtained using BGS Geomagnetism data www.geomag.bgs.ac.uk. The same initial values were used in (Ladynin and Popova, 2009).

Since the results cannot be assessed without knowing the method used to obtain them, below we present:

(a) the eccentric dipole model, its parameters, the derivation of the basic formulas for the magnetic-field components of a dipole with arbitrary values of the modulus of the magnetic moment, the coordinates of its center, and its orientation, which is given by the coordinates of the north axial pole;

(b) description of the method of estimating the parameters of dipoles of free position: the computational scheme, the optimization method;

(c) the necessary constraints on the dipole parameters and a rationale for selecting the initial values in the optimization parameter fitting according to the criterion of minimum standard deviation of the field of each dipole from the input data; these data are the values of the residual-field components after eliminating the effect of the dipole with the preceding number.

Magnetic field of an eccentric dipole

The magnetic field of a dipole of arbitrary position and orientation within the Earth is described using three coordinate systems:

– spherical system: 0 is at the center of the Earth, ρ is the radius, θ and λ are the colatitude and longitude of the point at which the field is determined;

– rectangular system used in geomagnetism: 0 is at the point of determination of the field on the Earth's surface, the z axis is directed vertically downward, x along the geographical meridian to the north, and y along the parallel to the east;

– Cartesian system: 0 is at the center of the Earth, the z ax is directed along the axis of rotation, x along the line of intersection of the planes of the equator and the Greenwich meridian, and y along the line of intersection of the planes of the equator and the 90° meridian.

The potential of a dipole with a magnetic moment M is given by the formula

$$U(A) = \frac{M}{r^2} \cos \gamma, \quad (1)$$

where r is the modulus of the radius vector of the dipole at the point A; γ is the angle between the dipole axis and the radius vector $\mathbf{r}$ of the point at which the potential is determined.

The sides of the triangle with the vertices at the center of the dipole D (x_D, y_D, z_D), at the north axial geomagnetic pole N (x_N, y_N, z_N), and at the point A of determination of the