Modeling and 2D/3D-visualization of Geomagnetic Field and Its Variations Parameters

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Abstract: In the modern World, specialists in biology, medicine, geophysics, geology, technics and many other sciences pay great attention to correlation between external geomagnetic variations (GVM) with possibilities of objects and systems existence and evolution. Well-known scientific publications give a quite wide review of approaches to estimation of weak magnetic fields parameters, creation of magnetometric information measurement systems on their base and definition of their metrological characteristics. But today due to the recently formulated relevance of geomagnetic field (GMF) and its variations parameters monitoring there is no unified and effective approach to development of geoinformation magnetometric systems. In spite of the wide variety of specialized geoinformation systems (GIS) there are no advanced hard- and software, which provide a calculation, geospatial connection, visualization and analysis of GMF and its variations parameters calculation results. It is important to mention, that due to low-efficiency, limited functionality and incorrect work of the known solutions the topicality, scientific and applied interest to such a solution development continuously increases.

1 INTRODUCTION

In the modern World, specialists in many spheres pay great attention to correlation between external geomagnetic variations (GVM) with possibilities of existence and evolution of objects and systems. This interest is based on idea, that some components of GMV or their combinations can influence on biological, technical, geological and other objects and systems in common and on human in particular. As a result, the distorted normal conditions of existence force these objects and systems to either adapt to the changes of magnetic state (via deformation, mutation, etc.) or keep existing there in stressed (unstable) mode (Chizhevskii, 1976); (Vernadsky, 2004).

Today monitoring, registration, visualization, analysis, forecast and identification of GMV is a relevant sophisticated fundamental scientific problem with strong applied character.

In contemporary world the problem of monitoring of geomagnetic field (GMF) and its variations parameters is partially solved by a number of magnetic observatories [Vorobev, 2012]. The magnetic observatory is a scientific organization, which is specialized on parametric and necessary for them astronomical observations of the Earth's magnetosphere. The registered information about magnetic field and ionosphere state is regularly sent to the International centers in Russia, USA, Denmark and Japan. In these centers the information is registered, analyzed and partially available to the broader audience with some delay. Today there are about 100 geomagnetic observatories, and one third of them are in Europe.

In spite of the wide variety of specialized geoinformation systems (GIS) there are no advanced hard- and software, which provide a calculation, geospatial connection, visualization and analysis of GMF and its variations parameters calculation results.

An example of modern programming solution with GIS features is the service, which is provided by NOAA (National Oceanic and Atmospheric Administration) and available at http://www.ngdc.noaa.gov/geomag-web. However the calculation results are out of limits of permissible errors. It is takes no much time to ensure about incorrect work of some tools, absence of visualization tools and multilingual support, bad geolocation and non-informative interface.

It is important to mention, that due to low-

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efficiency, limited functionality and incorrect work of the known solutions the topicality, scientific and applied interest to such a solution development continuously increases.

2 MATHEMATICAL MODELING OF GEOMAGNETIC FIELD AND ITS VARIATIONS

The full vector of the Earth's magnetic field intensity in any geographical point with spatiotemporal coordinates is defined as follows:

$$\boldsymbol{B}_{ge} = \boldsymbol{B}_1 + \boldsymbol{B}_2 + \boldsymbol{B}_3,$$

where $\boldsymbol{B}_1$ is an intensity vector of GMF of intraterrestrial sources; $\boldsymbol{B}_2$ is a regular component of intensity vector of GMF of magnetosphere currents, which is calculated in solar-magnetosphere coordinate system; $\boldsymbol{B}_3$ is a GMF intensity vector component with technogenic origin.

Normal (undisturbed) GMF is supposed as a value of $\boldsymbol{B}_1$ vector with excluding a component, which is caused by rocks magnetic properties (including magnetic anomalies). So this component is excluded as a geomagnetic variation:

$$\boldsymbol{B}_0 = \boldsymbol{B}_1 - \Delta \boldsymbol{B}'_1,$$

where $\boldsymbol{B}_0$ is undisturbed GMF intensity in the point with spatiotemporal coordinates; $\Delta\boldsymbol{B}'_1$ is component of intraterrestrial sources GMF, which represents magnetic properties of the rocks.

Solving the problem of $\boldsymbol{B}_0$ parameters analytical estimation, it is helpful to represent the main field model by spherical harmonic series, depending on geographical coordinates.

The scalar potential of intraterrestrial sources GMF induction U [nT·km] in the point with spherical coordinates r, θ, λ is defined by the expression (1).

$$U = R_E \sum_{n=1}^{N} \sum_{m=0}^{n} \left(g_n^m \cos(m\lambda) + h_n^m \sin(m\lambda) \right) \left(\frac{R_E}{r} \right)^{n+1} \times \times P_n^m \cos\theta, \quad (1)$$

where r is a distance from the Earth's center to observation point (geocentric distance), [km]; λ is a longitude from Greenwich meridian, [degrees]; θ is a polar angle (collatitude, $\theta = (\pi/2)\text{-}\varphi'$, [degrees], where φ' is a latitude in spherical coordinates, [degrees]); R_E is an average radius of the Earth, R_E = 6371.03, [km]; $g^n{}_m(t)$, $h^n{}_m(t)$ are spherical harmonic coefficients, [nT], which depend on time; $P^n{}_m$ are Schmidt normalized associated Legendre functions of degree n and order m.

In geophysical literature the expression (1) is widely known as a Gaussian and generally recognized as an international standard for undisturbed state of GMF.

The amount of performed spherical harmonic analysis is significant. However a problem of spherical harmonic optimal length of still acute.

Thus, the analyses with great amount of elements prove Gauss hypothesis about convergence of spherical harmonic, which represents a geomagnetic potential. As usual in spherical harmonic analyses the harmonics are limited by 8–10 elements. But for sufficiently homogeneous and highly accurate data (for example, as like as in satellite imaging) the harmonics series can be extended up to 12 and 13 harmonics. Coefficients of harmonics with higher orders by their values are compared with or less than error of coefficients definition.

Due to the main field temporal variations the coefficients of harmonic series (spherical harmonic coefficients) are periodically (once in 5 years) recalculated with the new experimental data.

The main field changes for one year (or secular variation) are also represented by spherical harmonics series, which are available at http://www.ngdc.noaa.gov/IAGA/vmod/igrf11coeffs .txt.

Schmidt normalized associated Legendre functions $P^n{}_m$ from expression (1) in general can be defined as an orthogonal polynomial, which is represented as follows (2).

$$P_n^m(\cos\theta) = 1\cdot 3\cdot 5 \ldots (2n-1) \cdot \sqrt{\frac{\varepsilon_m}{(n+m)!(n-m)!}} \times \times \sin^m\theta \Big[\cos^{n-m}\theta - \frac{(n-m)(n-m-1)}{2(2n-1)} \cos^{n-m-2}\theta + + \frac{(n-m)(n-m-1)(n-m-2)(n-m-3)}{2\cdot 4(2n-1)(2n-3)} \cos^{n-m-4}\theta - \ldots \Big], \quad (2)$$

where ε_m is a normalization factor ($\varepsilon_m = 2$ for $m \geq 1$ and $\varepsilon_m = 1$ for $m = 0$); n is a degree of spherical harmonics; m is an order of spherical harmonics.

3 GEOMAGNETIC PSEUDOSTORM EFFECT

Here it is supposed to enter the term geomagnetic pseudostorm (GMPS), which is intended to represent real GMF influence on the object in conditions of its non-zero speed and undisturbed GMF anisotropy (Vorobev and Shakirova, 2014). Let us describe some main parameters of GMPS effect (Vorobev, 2013).

GMPS range is a difference between maximal and minimal values of GMF induction in area of the object, which is moving in anisotropic magnetic field during the time period or at the distance:

$$\boldsymbol{B}_{\text{GMPS}} = \boldsymbol{B}_{0\,\max} - \boldsymbol{B}_{0\,\min}, \tag{3}$$

where $\boldsymbol{B}_{0\ \max}$ and $\boldsymbol{B}_{0\ \min}$ are maximal and minimal values of GMF induction, [nT] in area of the object, which is moving in anisotropic magnetic field.

GMPS frequency spectrum is a function of distribution of GMPS amplitude spectrum in frequency area for continuous and discrete variants, which is defined by the following expressions:

$$B^*(f) = \int_{-\infty}^{+\infty} \boldsymbol{B}_0(t) e^{-i2\pi f t} dt$$
$$\text{or} \quad B^*(f) = \frac{1}{M} \sum_{t=0}^{M-1} \boldsymbol{B}_0(t) e^{\frac{-i2\pi f t}{M}}, \tag{4}$$

where B^* is a GMPS frequency spectrum; $\boldsymbol{B}_0$ is a value of GMF induction in the point with spatiotemporal coordinates; M is a quantity of registered values with constant discretization step by time.

Constant component of GMPS is a vector of harmonics superposition vertical shift, which represent GMPS frequency spectrum:

$$\boldsymbol{B}_{//} = \frac{1}{M} \sum_{t=0}^{M-1} \boldsymbol{B}_0(t), \tag{5}$$

where M is a quantity of registered values with the discretization step.

GMPS intensity is a physical quantity, which is numerically equal to the speed of undisturbed GMF characteristic change in time relatively to the frame of reference, which is connected to the moving object and depends on the object speed:

$$\boldsymbol{I}_{\text{GMPS}} = \frac{\partial \boldsymbol{B}_0}{\partial t}, \tag{6}$$

where $\boldsymbol{I}_{\text{GMPS}}$ is GMPS intensity, [nT/s];

GMPS potentiality (geomagnetic induction gradient) is a vector, which is oriented in three-dimensional space and points to the direction of the fastest increase of undisturbed GMF induction absolute value. The vector by its absolute value is equal to the increase speed of $\boldsymbol{B}_0$ in the geographical direction, [nT/rad; nT/rad; nT/km] and depends on the object position.

$$G_B = \nabla \boldsymbol{B}_0(\theta, \lambda, r) = \text{grad}\, \boldsymbol{B}_0(\theta, \lambda, r) = \left(\frac{\partial \boldsymbol{B}_0}{\partial \theta}, \frac{\partial \boldsymbol{B}_0}{\partial \lambda}, \frac{\partial \boldsymbol{B}_0}{\partial r} \right), \tag{7}$$

where $\boldsymbol{B}_0$ is an induction (intensity) of GMF in the point with spatiotemporal coordinates:

$$\begin{aligned} \boldsymbol{B}_0^{\,2}(\theta, \lambda, r)[\text{nT}] = \\ = \left[\frac{1}{r}\frac{\partial U}{\partial \theta}\cos(\varphi - \varphi') - \frac{\partial U}{\partial r}\sin(\varphi - \varphi') \right]^2 + \\ + \left[-\frac{1}{r \cdot \sin\theta}\frac{\partial U}{\partial \lambda} \right]^2 + \\ + \left[-\frac{\partial U}{\partial r}\cos(\varphi - \varphi') - \frac{1}{r}\frac{\partial U}{\partial \theta}\sin(\varphi - \varphi') \right]^2. \end{aligned} \tag{8}$$

So the analysis of GMF induction gradient distribution allows defining an area of possible GMPS maximal intensity of in the geographical region. So, the parameter G_B must be taken into account in developing aerospace navigation maps and flight paths (Milovzorov and Vorobev, 2013).

Next to study the GMPS effect there is an example of the flight route AA-973 of «American Airlines» from New York (JFK) to Rio de Janeiro (RIO). The flight path is represented as an array of spatial coordinates, which describe the airplane position, taken during flight in equal time intervals. The array allows calculating GMF parameters for each set of spatial coordinates.

The results of amplitude and frequency analysis of flight data and parameters of GMF are represented on Figure 1. Here are some special points (Figure 1, *a*): *t*1-*t*2 – takeoff time; *t*2-*t*4 – flight on cruise speed at the altitude of 11033 m; *t*4-*t*5 – landing time; *t*3 – passing the equator.

4 VISUALIZATION OF GEOMAGNETIC FIELD PARAMETERS

An effective solution for complicated problem of modeling and visualization of GMF and its variations parameters is a key to understand the principles of GMF parameters distribution on the Earth's surface, its subsoil and in circumterrestrial space.

Modern information technologies provide wide variety of tools for both in mathematical modeling and computer graphics. However a problem of parametric GMF and its variations model is still not solved.

So, one of the effective approaches to solve the problem is a functionality of modern GIS, which special and applicative implement supposes rather suitable result.

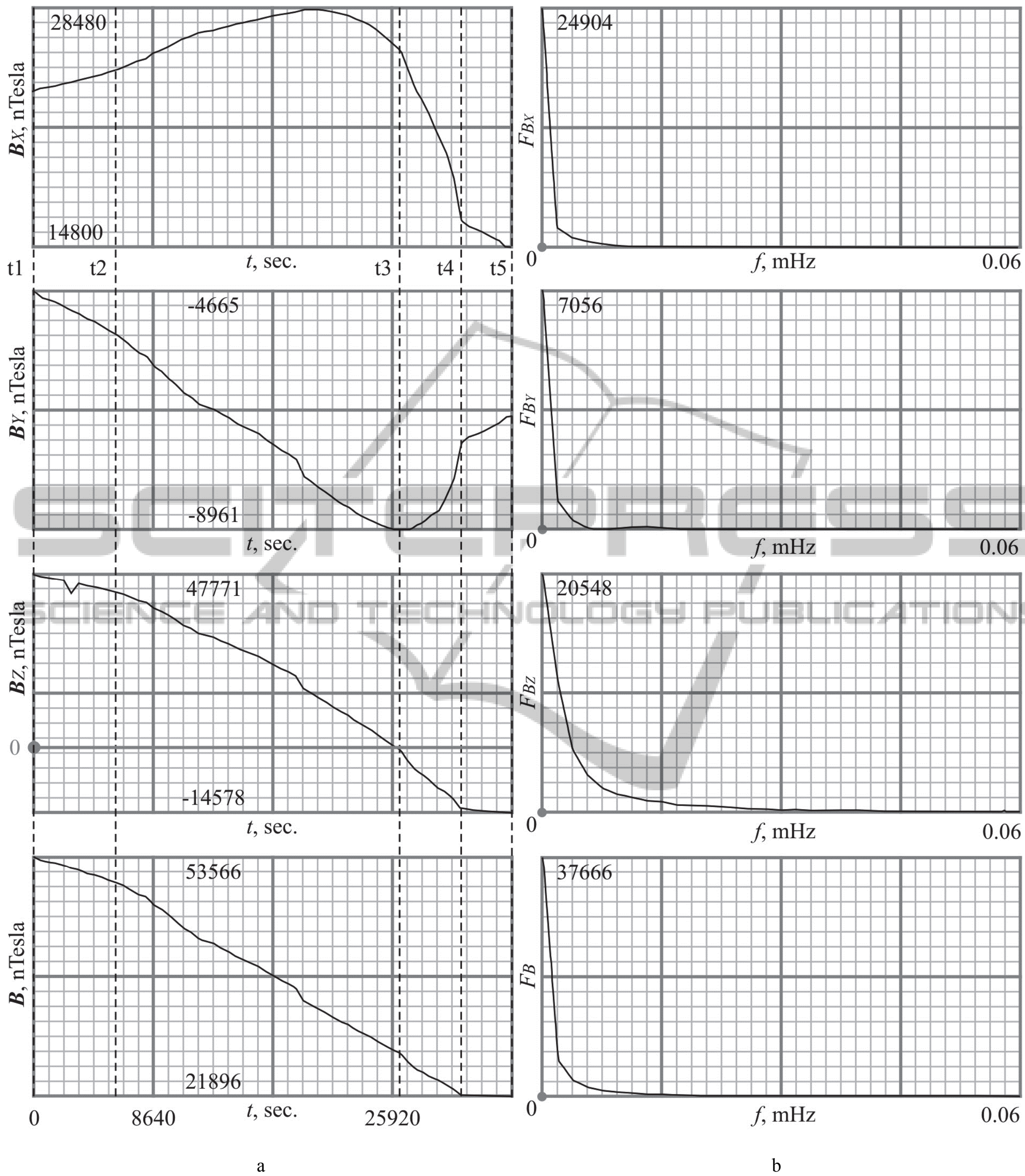

Figure 1: Experimental data analysis results.

Three-dimensional representation of research (calculation) results is one of the key aspects in solution of visualization problems of both geospatial data and GMF parameters. It is obvious, that in this case GIS provides much more information. And it is even more important due to the dynamic properties and multilevel scale ability.

As a result of our research there was developed the special GIS, which is based on modern web technologies and provides great functionality for both calculation of GMF, its variations and anomalies parameters calculation and visualization of the results distribution in terrestrial and circumterrestrial space. The developed Web GIS combines the development principles and possibilities of distributed client-server web application and geoinformation systems. This GIS provides the complex calculation and visualization of GMF parameters with any scale (The service is available at http://gimslab.url.ph). The main modules of the suggested GIS are Web GIS "GIMS-Calculator" and "GIMS-Pseudostorm Analyzer" (Vorobev and Shakirova, 2013); (Vorobev and Shakirova, 2014).

The main functionality of Web GIS "GIMS-calculator" provides effective and reliable calculation and analysis of parameters of normal (undisturbed) GMF by the spatiotemporal coordinates with error value no more than 0.1%.

To provide the ergonomics of software the "GIMS-calculator" window is logically divided into two functional areas (panels). Left panel (Figure 2) is supposed for loading and rendering the Earth's surface maps fragments in either scheme or photo. Right panel is supposed for representing the input parameters / initial conditions, calculation results and "GIMS-calculator" functionality control. (The initial conditions are defined as spatiotemporal default coordinates: 54.7249° N, 55.9425° E, 0.172 km amsl).

For the appropriate tasks a user defines the spatiotemporal coordinates of the Earth's surface point. These coordinates can be described by one of the following ways:

- pick the point on the map (coordinates set up and geocoding are performed automatically);
- latitude, longitude, altitude values input to the appropriate input fields in the right panel of application "GIMS-calculator";
- automatic detection of the user position on the basis of the computer (or mobile device) geolocation by IP address.

An important feature of "GIMS-calculator" is data representation in one of the two formats: DD (decimal degrees) and DMS (degrees – minutes – seconds). Depending on the chosen format a user gets the appropriate input mask. Also the application supposes the automatic transformation of coordinate systems via checking the appropriate radio button.

On the basis of latitude and longitude input values "GIMS-calculator" automatically calculates the altitude and represents the result in International System of Units or Imperial and US customary measurement systems. As in previous case, the direct and indirect transformations are available.

User-defined spatiotemporal coordinates put the center of the map visible fragment relatively to the geographical point, which is defined by them. The point is outline by the marker with geolocation results.

"GIMS-calculator" special feature is a function of detecting the current location. Geospatial coordinates of user location are defined by IP address of device, which is used for accessing the Internet. This possibility allows the user to get the point without its searching on the map or filling the appropriate input fields. This feature increases its efficiency and speed of the research.

The results of GMF parameters complex calculation are represented in International System of Units. This allows analyzing the data without any preliminary calculations.

To extend the functionality of the developed Web GIS "GIMS-calculator" there were programmed an option of generating electronic report about the research results with file or printer form and a possibility of three-dimensional modeling.

On the logical and programming levels the web application is a set of complex procedures, which provide the realization of geospatial data visualization and analysis of GMF parameters in the point with spatiotemporal coordinates.

With the lower abstraction the web application is a special case of web page, which is developed according three-tier client-server architecture. The visible and adapted to the user (after rendering) markup of the page is realized via W3C-standardized markup language HTML (specifically, its XML-type modification XHTML).

The page design is performed in traditional table style: each region of the page is the table cell of various levels. However, the table-like layout of the page is not the only design solution here: there is also block-type layout via HTML-elements div, which logically structure the page by its semantics. For example, one block HTML-element stands for the region with map, another – for the region with spatiotemporal coordinates, and the last – for the region with GMF parameters calculation results.

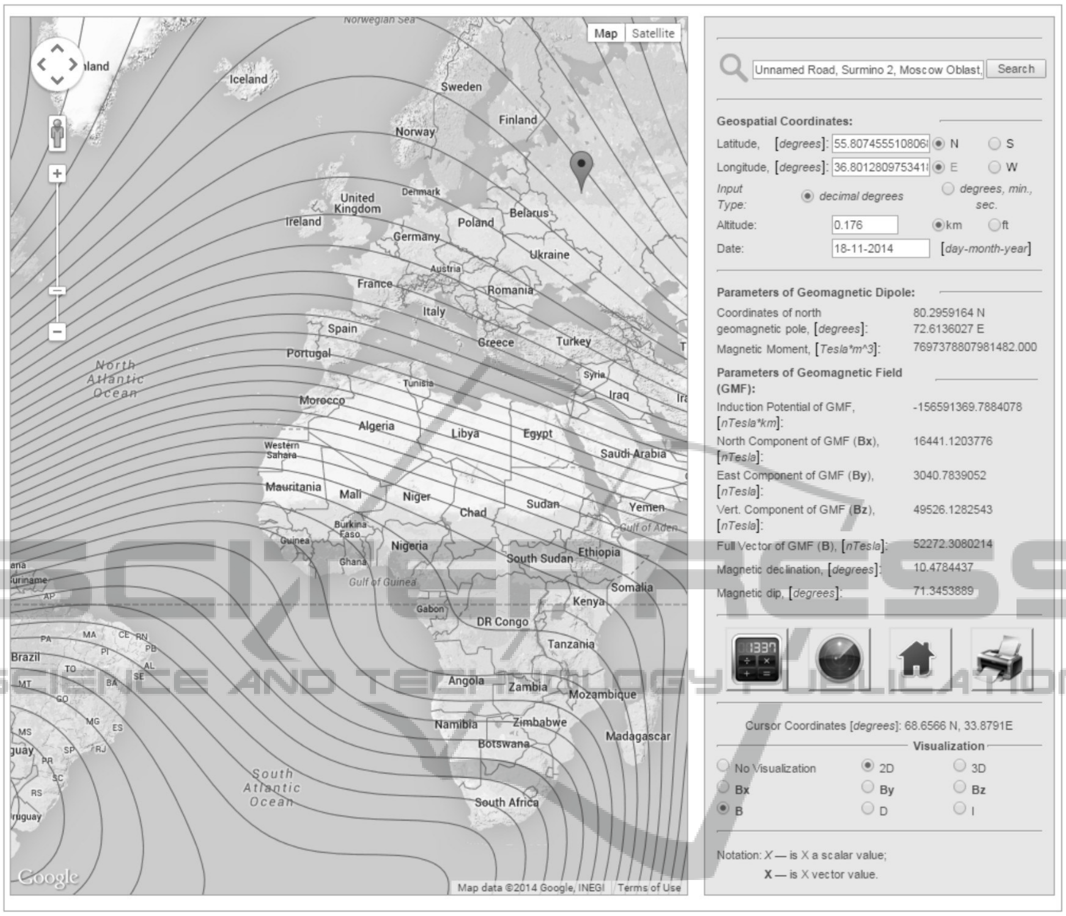

Figure 2: Detailed (regional level) interface of "GIMS-calculator".

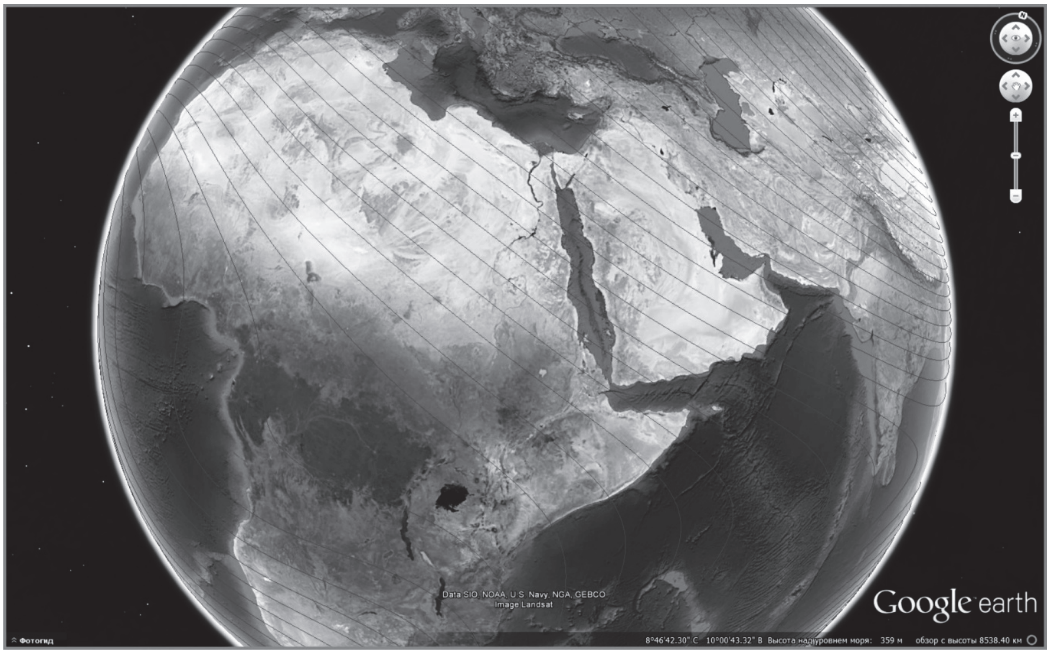

Figure 3: Integration of GMF parameters research results with technologies KML and Google Earth.

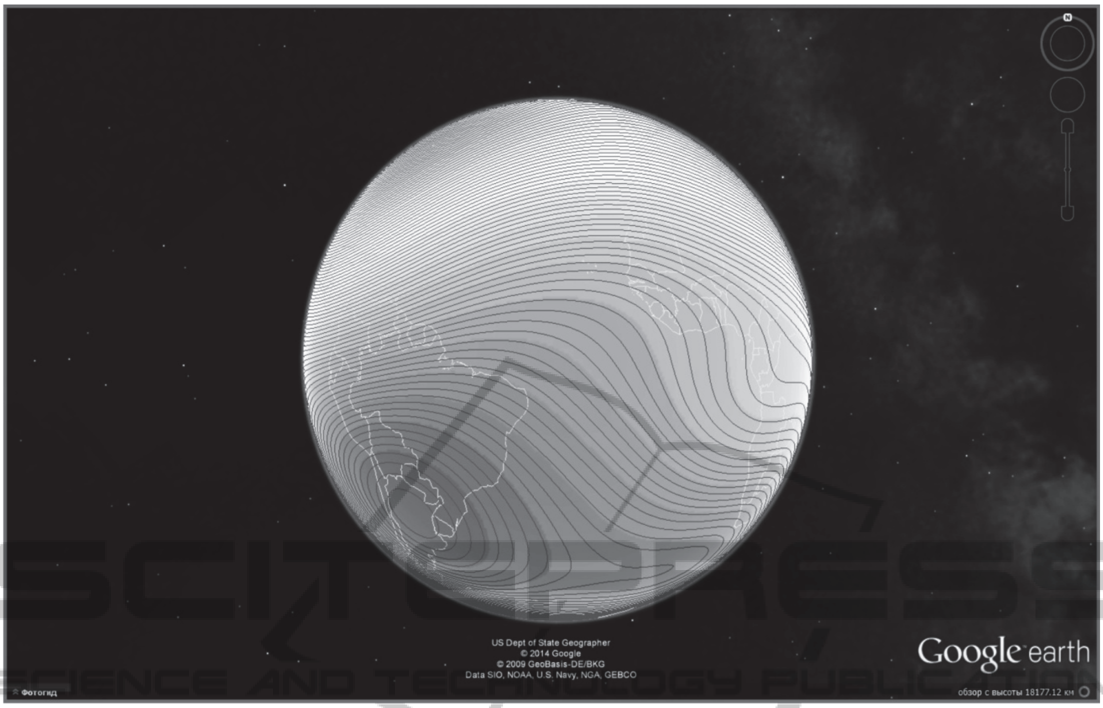

Figure 4: Fragment of intraterrestrial sources GMF induction full vector distribution on the Earth's surface three-dimensional model.

The technology of rendering the data by spatiotemporal coordinates is based on the principle of drawing geographical maps via mapping services and specifically – one of the most functional and popular Google Maps (Svennerberg, 2010); (Mapes, 2008); (Hu and Dai, 2013).

One of the most effective solutions for GMF parameters calculation and research results visualization is an approach, which is based on three-dimensional web modeling. Usually this approach supposes information representation on two levels: geographical and attributive. Geographical description of geospatial data supposes three-dimensional visualization of the Earth's surface with variable zoom and detail parameters. And the attributive component of the data is a set of numerical values, which correspond to GMF parameters values for spatial coordinates with an appropriate step.

Today a problem of geographical and attributive spatial data three-dimensional visualization is usually solved via web applications of special type, which are known as virtual globes. It is important to mention, that virtual globes technology is based on the Earth's surface representation as a sphere with applied graphical layers.

An important feature of the technology is its availability in both user (client) and programming services. A user version of virtual globe is oriented on creation or load of applied layers, their visualization and analysis of the synthesized model. Typically the layers of the virtual globe are represented as an optionally using markup (for example, KML or KMZ archive).

Today one of the most popular versions of virtual globes is Google Earth technology, which combines the possibilities of desktop and web applications (Haklay, 2008); (Dalton, 2013). This technology provides a wide variety of functions for visualization and multiaspect analysis of the Earth's surface. GMF analysis via client-type virtual globe is concerned with rendering the thematic layer and legend, which represent the calculated parameters in the Earth's surface points. In turn, this task can be solved by a majority of known GIS (for example, ArcGIS 10.2).

Geoformat of markup allows integrating spherical representation of the surface with the map, which is developed with GIS tools in some format, for example, KML (Keyhole Markup Language is one of the most popular formats of geodata representation, which is supposed as XML-oriented description of three-dimensional model of the Earth's surface and the objects on it. The description on KML is a set of geographical and attributive data). As a result there is a spherical representation of the Earth’s surface with spatial data about GMF parameters.

Virtual globes integration with applications is provided by special API, which is a set of programming functions for creation, visualization and manipulation of three-dimensional spatial data.

Programming interface is used by an application as a set of local or remote functions. These functions can be used with the special possibilities of interpreter, which is already used or additionally loaded on user computer.

Typical example of virtual globes programming interface is a plug-in Google Earth and its API on the basis of JavaScript (Flanagan, 2011). Functionality of the API provides the Earth’s three-dimensional model inbuilt into the web application and extend it with markers, infowindows, analytical functions, etc.

So, Figure 3 demonstrates an example of integrating the GMF parameters research results with KML and Google Earth technologies. The GMF induction full vector is visualized as a set of isolines.

Isoloines are represented in special KML layer, which in necessity can be overlaid on any other layer (for example, data about seismic, volcanic activities, medical statistics, geological maps, etc.). It provides an effective tool for complex analysis of various parameters, correlation and principles definition. Numerical value of the parameter (physical value), which is distributed along the one isoline, is available via picking the appropriate line with mouse cursor.

Various methods of visual data representation (color outlining, gradient, etc.) increase the model informativeness to maximum (Figure 4). Active layers (country borders, cities, rivers, etc.) managing keeps the key points of the model with decreasing the probability of possible error.

So, GMF and its variations models, which are represented and described here, meet the requirements of specialists in various areas. They effectively provide formatting and structuring the data about the Earth’s magnetosphere parameters and their further analysis.

5 CONCLUSIONS

- GMF is a complex structured natural matter with ambiguous field characteristics, which is distributed in the Earth (and near-Earth) space and interacts with both astronomical objects and objects / processes on the Earth’s surface, subsoil and in near-Earth space. Research and analysis of natural events, which cause GMV, allowed to define the most probable amplitude and frequency range for GMV:

  ΔB [3·10-9–20·10-6] T; f [0–8] Hz.

- Approaches, criteria and classification features for GIS description and classification on various abstraction levels are defined, described and scientifically proved.
- Analysis of modern tendencies of GIS evolution proved, that the optimal direction of further research is concerned with development, realization and implementation of special GIS. The special GIS is based on modern web technologies and provides great functionality for both calculation of GMF, its variations and anomalies parameters calculation and visualization of the results distribution in terrestrial and circumterrestrial space.
- Web GIS "GIMS-Calculator" и "GIMS-Pseudostorm Analyzer" are developed and realized. These solutions provide the complex calculation, analysis and visualization of GMF and its variations parameters. According to previous chapters visual models of the main GMF parameters distribution on the Earth’s surface are developed and represented (for 2014 year). These parameters are: north component of GMF induction vector; vertical component of GMF induction vector; magnetic declination and dip; scalar potential of GMF induction vector.
- On the basis of web technologies in general and technologies of modern virtual globes in particular there were developed and described innovative three-dimensional dynamic models of GMF parameters distribution in circumterrestrial space. The model provides multilayer visualization as an effective tool for complex analysis of various geophysical parameters and definition of the appropriate correlations and principles.

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