

# Web-based solutions in modeling and analysis of geomagnetic field and its variations

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## Abstract

Today modeling and analysis of the Earth's magnetic field is a key to understand how geomagnetic field parameters are distributed on the Earth's surface, its subsoil and in circumterrestrial space. Geomagnetic data collected by the sets of geomagnetic stations and observatories, various scientific organizations, space vehicles and individual researchers requires its systematization, interpretation and analysis with special approach, which is based on methods of mathematical and spatial modeling and allows representing the cuts of geomagnetic data in easily accessible web-oriented way. However, the analysis proved that despite of wide variety and dynamic evolution of modern information technologies, special program complexes and tools for data processing, analysis and visualization, the approach of modeling and analysis of geomagnetic field data is not enough developed. In the paper the authors suggest web-based solution, which provides the mechanisms to calculate, analyze and visualize parameters of geomagnetic field and its variations and one of the services called "Geomagnetic Calculator".

## 1 Introduction

One of the most important components of near-Earth space is the Earth's magnetosphere, where natural and anthropogenic factors cause a number of variations and anomalies, which are dangerous for the bio- and technosphere. It is well known that geomagnetic variations and magnetic anomalies with a high degree of probability can provoke short-term rearrangements of the vegetative-humoral and cardiovascular systems of man, which is fraught with serious disastrous consequences. Extreme geomagnetic phenomena lead to complete failure of power

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In: Marco Schaerf, Massimo Mecella, Drozdova Viktoria Igorevna, Kalmykov Igor Anatolievich (eds.): Proceedings of REMS 2018 – Russian Federation & Europe Multidisciplinary Symposium on Computer Science and ICT, Stavropol – Dombay, Russia, 15–20 October 2018, published at <http://ceur-ws.org>

supply networks, the emergence of strong currents in pipelines, almost complete cessation of radio communications at all frequencies, the so-called "magnetic braking" of the Earth's artificial satellite.

Such an impact on the technosphere often causes irreparable economic damage. And this is far from a complete list of the consequences to which the changes in the normal state of the geomagnetosphere can lead. The main way to prevent adverse effects of geomagnetic factors on the bio- and technosphere is the forecast and monitoring of the geomagnetic situation. The importance of solving the problem of modeling and analysis of geomagnetic field and its variations is difficult to overestimate.

On the one hand, it is a system for observing and evaluating the current geomagnetic situation, and on the other hand, a means of informational support for the process of preparing and making managerial decisions in the relevant applied field (biology, medicine, geophysics, geology, meteorology, etc.). Registration of the parameters of the geomagnetic field is traditionally conducted both on the surface of the Earth and from outer space. So, among the ground-based instruments, the most important are magnetic observatories and stations recording both the total vector of the magnetic field and its variations. The maximum density of magnetic observatories falls on the territory of the European part of the continent, while there is a complete absence in most countries of Asia, Africa and South America, whose population is many times larger than the countries of Western Europe. Measurements of the Earth's magnetic field from outer space are currently carried out mainly by the European system of SWARM satellites. A large number of sources of geomagnetic data, both global and local, as well as a huge number of their consumers require an integrated and easily access approach to solving this problem. It is obvious that the solution is to be based on modern information technologies, which will provide a significant increase in the level of information and intellectual support for the ecological monitoring of geomagnetic variations and anomalies of the natural and anthropogenic nature of origin.

The analysis of the problem solutions proved, that information technologies providing calculation, analysis and visualization of geomagnetic data are poorly developed. One of the known solutions is the information service, which is provided by NOAA and available at <http://www.ngdc.noaa.gov/geomag-web> [NOAA Magnetic Field Calculators]. Although the calculation results are acceptable enough, the solution has a lot of disadvantages, such as no visualization tools, low ergonomics and efficiency. The same disadvantages are inherent to other similar services, which are provided by BGS, CIRES (<http://geomag.org/models/igrfplus-declination.html>) and other leading organizations [Thomp14].

According to geomagnetic data analysis there is another well-known solution. It is the Interregional Geomagnetic Data Center of the Russian-Ukrainian INTERMAGNET segment, which is operated by the Geophysical Center of the Russian Academy of Sciences [Russian-Ukrainian Geomagnetic Data Center]. Geomagnetic data are transmitted from observatories located in Russia and Ukraine [Gv15, 8]. The solution is based on fuzzy logic approach and is intended to real-time recognition of artificial (anthropogenic) disturbances in incoming data [Sol13].

One more key element of the mentioned problem is concerned with a number of heterogeneous data sources, which collect and share historical and current values of parameters of space weather, geomagnetic field and its variations. These are powerful web services provided by INTERMAGNET, BGS and other organizations [Ham13][Kol17][Love13][Mac13]. The main thing here is that all these data sources are not integrated. There are no any tools, which provide to user a single access to space weather and geomagnetic data. In the paper the authors suggest a web-based solution of the problem, which provides modeling, monitoring, analytical control, two- and three-dimensional visualizations of geomagnetic field and its variations parameters. With this solution a user can get access to data, automatically analyze them and use the results for solving applied problems.

Analysis of the known research results in relative areas, such as modeling and analysis of a whole-space transient electromagnetic field [Jiang17], also proved, that they can not be applied to the geomagnetic field studies, which special features are concerned with three-component intensity vector as well as a restrict mathematical model based on 5-year calculated common coefficients (IGRF model). The known results on 2.5-dimensional FDTD geoelectric modeling do not take into account, that geomagnetic state depends on various natural and technogenic factors and strongly determined by the spatiotemporal characteristics of the geographical point, where the parameters are to be calculated.

Thus, the proposed originality is concerned with a technical solution of geomagnetic field analysis, modeling and graphical interpretation, based on the modern information technologies with a greater accent on using web technologies. So the proposed results can be available to a wide range of users with different scientific interests and competency.

## 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 (latitude, longitude, altitude, year) is defined as a sum of three components:

$$B_{ge} = B_1 + B_2 + B_3. \quad (1)$$

where  $B_1$  is an intensity vector of geomagnetic field of intraterrestrial sources;  $B_2$  is a regular component of intensity vector of geomagnetic field of magnetosphere currents, which is calculated in solar-magnetosphere coordinate system;  $B_3$  is a geomagnetic field intensity vector component with technogenic origin.

The summand  $B_3$  represents the magnetic field component of technogenic origin, which occurs due to the human life activity and usually has wide and unpredictable amplitude and frequency range and progress intention.

Normal geomagnetic field is supposed as a value of  $B_1$  vector with excluding a component, which is caused by rocks magnetic properties (including magnetic anomalies). This component is excluded as a geomagnetic variation:

$$B_0 = B_1 - \Delta B_1'. \quad (2)$$

where  $B_0$  is undisturbed geomagnetic field intensity in the point with spatiotemporal coordinates;  $\Delta B_1'$  is component of intraterrestrial sources of geomagnetic field, which represents magnetic properties of the rocks [Gv15].

So, geomagnetic variations in the point with spatiotemporal coordinates can be defined as follows:

$$B_{gmv} = \Delta B_1' + B_2 + B_3. \quad (3)$$

The main field model is based on spherical harmonic series, which are depending on geographical coordinates.

The scalar potential of intraterrestrial sources geomagnetic field induction  $U$  [nT·km] at any point with spherical coordinates  $r$ ,  $\theta$ ,  $\lambda$  as follows:

$$U = R_E \sum_{n=1}^N \sum_{m=0}^n (g_n^m \cos m\lambda + h_n^m \sin m\lambda) \left(\frac{R_E}{r}\right)^{n+1} P_n^m \cos \theta. \quad (4)$$

where  $r$  is the distance from the Earth's center to the observation point (geocentric distance), [km];  $\lambda$  is the longitude from Greenwich meridian, [degrees];  $\theta$  is the polar angle (colatitude,  $\theta = (\pi/2) - \phi'$ , [degrees], where  $\phi'$  is the 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 period;  $P_n^m$  are Schmidt seminormalized associated Legendre functions of degree  $n$  and order  $m$ .

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 [Mer96].

The change of the main field for one year (or secular variation) is also represented by spherical harmonics series.

Schmidt seminormalized associated Legendre functions  $P_n^m$  in general can be defined as an orthogonal polynomial, which is represented as:

$$P_n^m(\cos \theta) = 1 \cdot 3 \cdot 5 \cdot \dots \sqrt{\frac{\epsilon}{(n+m)!(n-m)!}} \cdot \sin^m \theta [\cos^{n-m} \theta - \frac{(n-m)(n-m-1)}{2(2n-1)} \cos^{n-m-2} \theta + \dots] \quad (5)$$

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

In a number of scientific problems, some geospatial data (for example, positions of satellites in space) is represented in coordinates  $\phi, \lambda, h$ , which are based on the Earth's surface approximation by spheroid. In these problems, the Earth's ellipticity is neglected with no difference between spherical and geodesic coordinates. But in accurate calculations, the Earth's pole compression should be taken into account [Thomp07].

So, the components  $X', Y', Z'$  of induction vector of intraterrestrial sources geomagnetic field in nT are defined as follows:

$$X' = \frac{1}{r} \frac{\partial U}{\partial t} = \sum_{n=1}^N \sum_{m=0}^n (g_n^m \cos m\lambda + h_n^m \sin m\lambda) \left(\frac{R_E}{r}\right)^{n+2} \frac{\partial P_n^m \cos \theta}{\partial \theta} \quad (6)$$

$$Y' = -\frac{1}{r} \frac{\partial U}{\sin \theta} \frac{\partial U}{\partial t} = \sum_{n=1}^N \sum_{m=0}^n (g_n^m \sin m\lambda - h_n^m \cos m\lambda) \left(\frac{R_E}{r}\right)^{n+2} \frac{\partial P_n^m \cos \theta}{\partial \Theta} \quad (7)$$

$$Z' = \frac{\partial U}{\partial r} = - \sum_{n=1}^N \sum_{m=0}^n (n+1)(g_n^m \cos m\lambda + h_n^m \sin m\lambda) \left(\frac{R_E}{r}\right)^{n+2} \partial P_n^m \cos \theta. \quad (8)$$

Thus, the geomagnetic field induction vector distribution in space is described by a number of geomagnetic elements:

- orthogonal components of geomagnetic field;
- modulus of geomagnetic field induction vector;
- angle elements of geomagnetic field (geomagnetic dipole).

The described model of geomagnetic field is the basis of web-oriented solution for analysis and modeling of geomagnetic field and its variations.

### 3 Geomagnetic Calculator

The most common problem in analyzing the Earth's geomagnetic field concerns with calculating of the parameters of normal geomagnetic field in a specific point with given geographical coordinates. Its solution is based on applying some special types that are known as geomagnetic calculators.



Figure 1: Geomagnetic Calculator

The "Geomagnetic Calculator" is a web-based application providing calculation parameters of geomagnetic field and its secular variations according to the set of coordinates and dates (Fig. 1) [Vorob15b]. A user of any level can calculate and analyze parameters of geomagnetic field at his current location or at any other point on the Earth.

The "Geomagnetic Calculator" is a responsive application, which does not depend on device type and parameters but is transferable and works similarly in any device, i.e. phones, tablets, desktops. This platform- and device-independency is realized on the basis of the special framework "Bootstrap" (<http://getbootstrap.com>) that is a set of programming libraries for HTML, CSS and JavaScript. Flexibility and performance of this application tool are also increased by supporting HTML5 and CSS3 standards.

To calculate parameters of geomagnetic field, a user has to define spatiotemporal coordinates of the point of interest on the Earth's surface. In "Geomagnetic Calculator" geodetic latitude and longitude can be defined in various ways.

The simplest way to define the current geographical position of the user is a geolocation function. This function automatically takes the IP address of the device, which a user operates to access the Internet. This functionality allows the user to get on his location without searching for it on the map or filling the appropriate input fields.

Another way to define a point is to pick it on the map. A user can move over the map (using keyboard or mouse) and click on the specific point. All necessary spatiotemporal parameters of the point are calculated automatically and are immediately displayed on the screen.

Both the aforementioned ways of location definition do not require the exact coordinates of location as all necessary geospatial data are obtained automatically. A good, even though more complicated, way to calculate parameters of geomagnetic field and present the specific point on the map with high accuracy (up to a few meters) is by entering manually the coordinates into the input fields and hereafter the application displays the point on the map and the parameters of normal geomagnetic field.

In addition, the "Geomagnetic Calculator" provides a geocoding functionality to define a specific point. Geocoding is the transformation from of an address of full form, i.e. "postal code, country, city, street, building number" or of short form, i.e. just one item or their combination, into the coordinates set "north latitude, east longitude". Thus, in order to find the point to be calculated, one can just enter in the "Search" field the address of the location he is interested in.

The main functionality of the "Geomagnetic Calculator" provides effective and re-liaible calculation and analysis of parameters of normal (undisturbed) geomagnetic field by the spatiotemporal coordinates with an error value of no more than 0.1% . "Geomagnetic Calculator" provides the calculation of the following parameters of geomagnetic field: north component of geomagnetic field induction vector; vertical component of geomagnetic field induction vector; magnetic declination and dip; scalar potential of geomagnetic field induction vector.

## 4 Geomagnetic Data Analysis Tools

The authors suggested solution uses classic mechanisms of digital signal processing (DSP) to provide a set of tools for digital processing of data about space weather, GMF and GMV parameters, such as following [Vorob15b]:

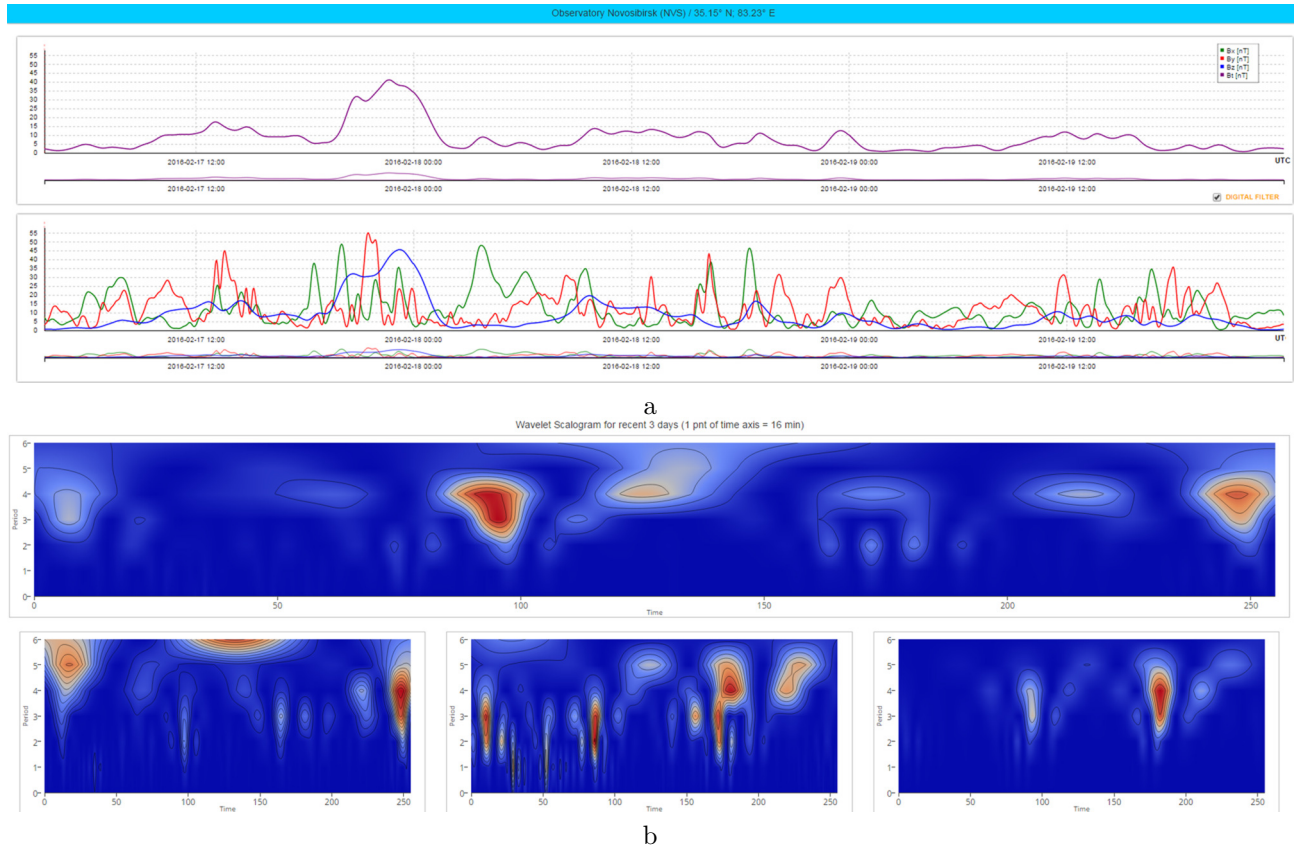


Figure 2: Geomagnetic Data Analysis Results: a — in amplitude-frequency domain, b — wavelet scalogram

- linear, nonlinear and adaptive filtering of information signal, which provides noise reduction and signal bandpassing in frequency domain as well as analysis of correlation of adjacent information signals parameters

(Fig. 2, a);

- signal analysis in time domain, which provides a calculation of maximal, minimal and average values, variance and standard deviation of information signal;
- spectral and time-frequency analysis, which is implemented by two ways. First way is an analysis of periodogram as an estimation of power spectral density based on calculation of square of data sequence Fourier transformation module with statistical averaging of information signal. Second way is an estimation of wavelet scalogram of information signal (Fig. 2, b).

Main methodic of DSP, which is used in authors solution, includes the following steps.

- Reading the discrete information signal (IS) as JSON/CSV/XML array
- Detection, analysis and exclusion of missing measurements
- Calculation and exclusion of IS constant component
- Calculation of IS variance
- Calculation of numerical value of IS frequency threshold detector
- Calculation of direct Discrete Fourier Transformation (DFT) and periodogram based on Fast Fourier Transform (FFT)
- Calculation of the biggest IS frequency with power spectral density less than IS frequency threshold detector
- Calculation of low frequencies digital filter cutoff frequency
- Preparation of discrete IS (original array) for digital filtering
- Calculation of direct DFT of IS, which is prepared to filtering
- Multiplication of Fourier image and transfer function
- Calculation of reverse DFT of IS on the basis of FFT
- Preparation of the array to save / output
- Save / output of the filtered array in JSON/CSV/XML format

## 5 Geomagnetic Data Visualization Tools

The proposed software solution [Vorob15][Vorob15b][Vorob17] for visualizing the parameters of the main geomagnetic field is based on a combination of modern information technologies for computer visualization of Cesium and WebGL data, which in turn are based on an innovative web-oriented HTML5 platform that effectively implements the presentation of multimedia data (in particular, 3D images) in web applications. Through these technologies, a three-dimensional graphical interpretation of the geospatial binding of the visualized parameters of the main geomagnetic field is realized at the level of a specialized component - a virtual globe designed to represent both the Earth's surface and the nature of the distribution of the geomagnetic field parameters on it. When working with a web application, the end user interacts directly with the interactive virtual globe, managing it with the mouse cursor to update the data in a timely manner, display individual geographical points or areas, and change the scale of their presentation.

In general, the solution of the task of visualizing the parameters of the main geo-magnetic field can be represented in the form of the following generalized stages:

1. Create a virtual globe instance.
2. Configuring a virtual globe instance (scaling constraint, camera control, widget display, basic graphic layer).
3. Select the type of data source (KML, JSON, etc.) to display on the virtual globe.
4. Configuring the data source (boot method, refresh rate, color gamut, etc.).



5. Bind the data source to the virtual globe instance.
6. Cleaning the existing layers (except for the base layer).
7. Display a new layer (layers) on the virtual globe based on the specified data source.

At the software level, all of the above steps are implemented by the authors through the JavaScript programming language, as well as functions and methods of the Cesium library.

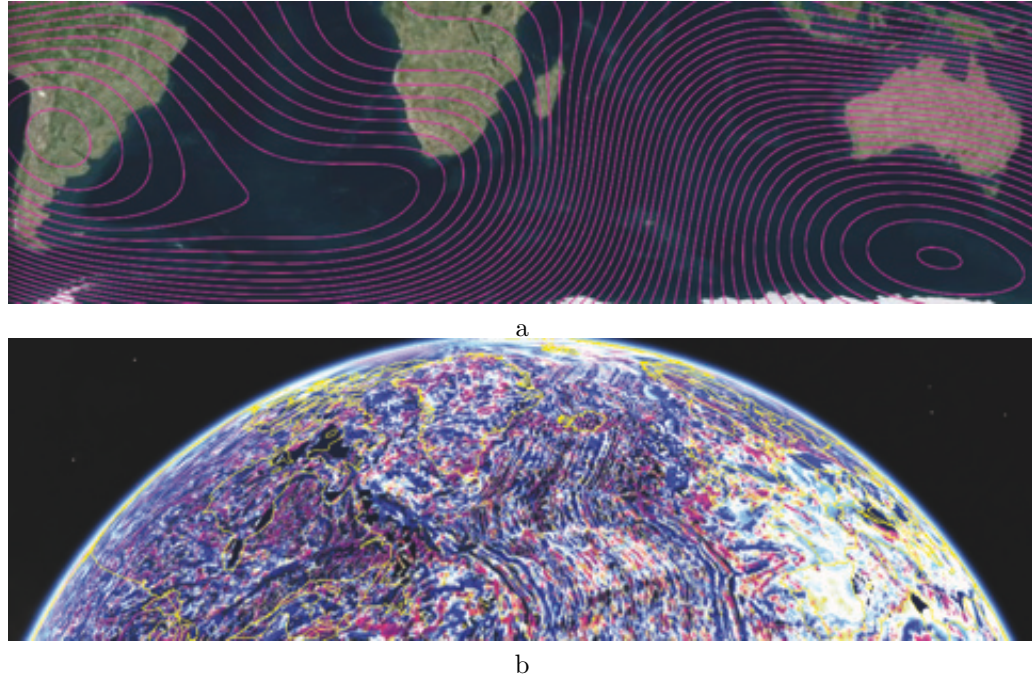


Figure 3: Results of 2D / 3D visualization of parameters of the main geomagnetic field using Cesium

A feature of Cesium technology is the ability to switch between different rendering modes (two- and three-dimensional or pseudo-3D image) through standard tool widgets implemented in one API and not requiring additional program code. In this connection, all graphic solutions for visualizing the parameters of the main geomagnetic field at the software level are realized once and do not reconfigure under the change of the presentation. In this case, the level lines automatically adapt to the mode of graphical interpretation chosen by the user without any distortion or loss of functionality, which is also an essential advantage of the chosen visualization technology.

Another advantage of the Cesium software library and technology is the default geo-location and reverse geocoding tools, which allows to take full advantage of the capabilities of modern geoinformation technologies when solving geospatial data visualization problems. With this functionality, the end user can find their location on a virtual globe at the touch of a button or move to a point corresponding to the text address they have entered (in Russian or English). At the same time, the implementation of such functionality does not require additional program code from the application developer.

The approach presented in this paper to visualize the parameters of the main geo-magnetic field provides an increase in the efficiency and efficiency of the analytical control of the corresponding geomagnetic data by presenting it to the end user in the form most adapted for visual analysis and making appropriate decisions in the subject area. Thus, the comparative analysis of the values of the parameters of the main geo-magnetic field for the period 2010-2015 made it possible to conclude that during this period the northern magnetic pole shifted from the point with coordinates ( $-80.015^{\circ}$  N,  $72.219^{\circ}$  E) to the point with coordinates ( $-80.312^{\circ}$  N,  $-72.621^{\circ}$  E), which is about 33.93 km in the southern (geographical) direction.

## 6 Conclusion

In the paper the authors suggested a number of solutions, which are based on a paradigm of heterogeneous data sources (satellite, air, marine, ground observations, and magnetic observatories) combination into integrated information space with platform-independent mechanisms of DSP and data interpretation. Also the authors proposed an approach whose goal was to replace the traditional textual and tabular representation of geomagnetic data with the results of their graphical two- and three-dimensional interpretation for subsequent visual analysis by specialists in the relevant applied field of knowledge.

On the basis of the solution formalized by the authors, a specialized web-based service was developed and implemented that provides interactive visualization of the parameters of the main geomagnetic field and its variations through innovative plug-in independent graphics acceleration technologies with the ability to vary image modes (2D, 3D, 2.5D), control the granular representation of geomagnetic Data and support for geolocation and geocoding functions.

## 7 Acknowledgement

The reported study was partly funded by RFBR according to the research project No.18-07-00193.

## References

- [Gv15] A.D. Gvishiani, R.Yu. Luk'janova. Geoinformatics and the Earth's magnetic field observations: Russian segment. *Fizika Zemli — Physics of the Earth*, 2:3–20, 2015.
- [Ham13] B. Hamilton. Rapid modelling of the large-scale magnetospheric field from Swarm satellite data. *Earth, Planets and Space*, 65:129–130, 2013.
- [Jiang17] Z. Jiang, S. Liu, R. Malekian. Analysis of a Whole-Space Transient Electromagnetic Field in 2.5-Dimensional FDTD Geoelectric Modeling. *Access IEEE*, 5:18707–18714, 2017.
- [Kol17] S. Kolios, A.V. Vorobev, G.R. Vorobeva, C. Stylios. *GIS and Environmental Monitoring. Applications in the Marine, Atmospheric and Geomagnetic Fields*. Springer, 2017. 174 p.
- [Love13] J. Love. An international network of magnetic observatories. *EOS, transactions, American geophysical union*, 94(42): 373–384, 2013.
- [Mac13] S. Macmillan, N. Olsen. Observatory data and the Swarm mission. *Earth, Planets and Space*, 65(11):1355–1362, 2013.
- [Mer96] R.T. Merrill, M.W. McElhinny, P.L. McFadden. *The magnetic field of the Earth*. Acad. Press, New York, 1996.
- [Sol13] A. Soloviev, A. Gvishiani. Mathematical Tools for Geomagnetic Data Monitoring and the INTER-MAGNET Russian Segment. *Data Science Journal*, 12:WDS114–WDS119, 2013.
- [Thomp07] A. Thomson, V. Lesur. An improved geomagnetic data selection algorithm for global geomagnetic field modelling. *Geophys. J. Int.*, 169(3):951–963, 2007.
- [Thomp14] A. Thomson. Geomagnetic observatories: monitoring the Earth's magnetic and space weather environment. *Weather*, 69(9):234–237, 2014.
- [Vorob15] A.V. Vorobev, G.R. Shakirova. Modeling and 2D/3D-visualization of geomagnetic field and its variations parameters. *Proceedings of GISTAM 2015 - 1st International Conference on Geographical Information Systems Theory, Applications and Management*, 35–42, 2015.
- [Vorob15b] A.V. Vorobev, G.R. Shakirova. Web-based information system for modeling and analysis of parameters of geomagnetic field. *Procedia Computer Science*, 59:73–82, 2015.
- [Vorob17] A.V. Vorobev, G.R. Vorobeva. Weboriented 2D/3D-visualization of geomagnetic field and its variations parameters. *Scientific Visualization*, 9(2):94–101, 2017.